Environ Biol Fish (2026) 109:160
https://doi.org/10.1007/s10641-026-01925-6

Early findings on the effects of fluctuating temperatures and hypoxia on sex determination in pejerrey, *Odontesthes bonariensis* (Atheriniformes)

Carina Gisele Quesada · Agustín Boan · Javier Herdman · Santiago Salinas · Leandro Andrés Miranda

Received: 13 April 2026 / Accepted: 12 October 2026
© The Author(s), under exclusive licence to Springer Nature B.V. 2026

Abstract Pejerrey (*Odontesthes bonariensis*) exhibit thermolabile sex determination (TSD). Because most studies use constant temperatures, we tested how diel temperature fluctuations (±2 °C around means of 19, 24, and 28 °C) and chronic hypoxia (~4 mg O_2 L^{-1}) affect sex ratios and sex reversal during the thermosensitive period. Fluctuating temperatures altered sex reversal rates in a mean-temperature-dependent manner, enhancing masculinization at thermal extremes but reducing it at intermediate temperatures. Hypoxia produced a modest, non-significant trend toward masculinization. These results highlight the complexity of environmental sex determination under ecologically realistic conditions. We report these exploratory results now because they indicate that constant-temperature designs may not predict sex ratios under natural thermal regimes, a limitation relevant to experimental work on TSD and to climate-driven projections of sex ratios in this commercially important species.

C. G. Quesada · A. Boan · J. Herdman · L. A. Miranda (✉)
Instituto Tecnológico de Chascomús (CONICET-UNSAM), Chascomús, Argentina
e-mail: lmiranda@intech.gov.ar

C. G. Quesada · A. Boan · J. Herdman · L. A. Miranda
Escuela de Bio y Nanotecnologías (UNSAM), San Martín, Argentina

S. Salinas
Department of Biology, Kalamazoo College, Kalamazoo, MI, USA

Keywords Thermolabile sex determination · Temperature fluctuations · Anoxia · Sex reversal

Introduction

Shallow lakes of the Pampas region Argentina are highly dynamic ecosystems, particularly vulnerable to climate change and anthropogenic pollution (Diovisalvi et al. 2015; Miranda and Somoza 2022). These water bodies are inhabited by the pejerrey, *Odontesthes bonariensis* (Valenciennes, 1835), an emblematic fish of the region due to its commercial value and sporting interest (Somoza et al. 2008; Berasain et al. 2015; Colautti et al. 2015; Mechally et al. 2026). Understanding how environmental conditions shape population dynamics in this species is thus critical for both ecological and economic reasons.

The sex determination mechanism of pejerrey is strongly influenced by temperature through a process known as thermolabile sex determination (TSD; Strüssmann et al. 1996, 1997). Under this system, phenotypic sex is partially or totally determined by water temperature during a critical developmental window (Strüssmann and Patiño 1995). Unlike species where environmental conditions determine sex exclusively (e.g., *Menidia menidia* (Linnaeus, 1766); Conover and Kynard 1981), pejerrey possess a testis-determining gene (*amhy*, anti-Müllerian hormone linked to the Y chromosome) that functions at intermediate temperatures (Yamamoto et al. 2014).

Published online: 23 October 2026

However, *amhy* expression is strongly regulated by temperature, resulting in possible sex reversal: genotypically female individuals (XX) may develop as phenotypic males, and vice versa.

Most studies of TSD have been conducted under constant laboratory temperatures, where developing larvae experience fixed thermal conditions throughout the thermosensitive period (Morash et al. 2018). While these experiments were fundamental for characterizing sex determination mechanisms, they do not reflect natural thermal environments. In shallow lakes, water temperatures fluctuate substantially on diel cycles, and such fluctuations may alter sex determination outcomes in ways that constant-temperature studies cannot predict. Hancock et al. (2023), for example, found that diel fluctuations influenced sex ratios in *Menidia menidia*, and del Fresno et al. (2023) observed sex reversal in pejerrey under semi-natural conditions. In reptiles with TSD, thermal variance around mean temperatures has been shown to induce paradoxical sex reversal compared to constant conditions (Georges et al. 2004; Neuwald and Valenzuela 2011), raising the question of whether similar effects occur in fish.

In addition to thermal variability, shallow Pampas lakes experience frequent hypoxic episodes (periods when dissolved oxygen drops to 2–4 mg O_2 L^{-1}), well below normoxic levels of 7–8 mg O_2 L^{-1} (Diaz and Rosenberg 1995; Gray et al. 2002). Hypoxic zones have been increasing globally in both extent and frequency (Díaz and Rosenberg 2008; Rabalais et al. 2010; Jenny et al. 2016), including in pejerrey habitats such as Chascomús lake (Buenos Aires province, Argentina), which is impacted by sewage effluent discharge (Quesada et al. 2023). Hypoxia acts as an endocrine disruptor, altering the brain-pituitary–gonadal axis and key enzymes involved in steroidogenesis (Saha et al. 2022; Quesada and Miranda 2024). Critically, hypoxia has been shown to masculinize sex ratios in multiple fish species, producing F1 generations biased toward males (Thomas and Rahman 2012; Cheung et al. 2014; Hattori et al. 2020). Given that hypoxia can override genetic and environmental sex determination cues in other species, understanding whether it exerts similar effects in pejerrey is essential.

Here, we experimentally tested how these two ecologically relevant stressors affect sex ratios in *O. bonariensis*, asking: (1) do fluctuating temperatures during the thermosensitive period produce different sex ratios and sex reversal patterns compared to constant temperatures? and (2) does chronic hypoxia alter sex determination outcomes in this species? By characterizing both phenotypic and genotypic sex, we quantified sex reversal rates and assessed how environmental variability shapes sexual differentiation.

Materials and methods

We conducted two complementary experiments at the Instituto Tecnológico de Chascomús (INTECH) aquaculture facility using newly hatched larvae from the INTECH broodstock. In the temperature experiment, 2400 larvae were distributed among six 60-L tanks (400 per tank) and maintained for 8 weeks, corresponding to the thermosensitive period for sex determination. Each tank was assigned to one of six thermal regimes comprising three mean temperatures (19, 24, and 28 °C), each tested under constant and fluctuating (±2 °C) conditions. In the fluctuating treatments, temperature followed a diel sinusoidal cycle, reaching the minimum at midnight and the maximum at midday, with continuous linear transitions between extremes (e.g., for the 19±2 °C treatment: 17 °C at midnight, 21 °C at midday). Temperatures were regulated using submersible heaters controlled by programmable controllers (Apex, Neptune Systems, USA) on an hourly basis. Due to logistical constraints, each thermal treatment was maintained in a single tank, precluding formal statistical inference at the tank level; this experiment is therefore exploratory. All tanks were maintained in a closed recirculating system with salinity adjusted to 5 g L^{-1}, a 12L:12D photoperiod, and larvae were fed *Artemia* nauplii ad libitum.

In the hypoxia experiment, newly hatched larvae were placed in 50-L cages (400 per cage, two replicate cages per treatment; total $n=800$ per treatment) within one 1,000 L tank per treatment covered with plastic lids and equipped with a closed recirculating system in which dissolved oxygen (DO) was adjusted by controlling artificial aeration and nitrogen gas blowers. Treatments were normoxia (actual DO: 7.06±0.63 mg O_2 L^{-1}) and hypoxia (actual DO: 3.94±0.45 mg O_2 L^{-1}) at a constant 24 °C with a 13L:11D natural photoperiod for eight weeks. After both experiments, larvae were transferred to 130-L

(2 per treatment) flow-through tanks at 19 °C and reared until they reached approximately 6 cm total length (~8 months post-hatching), at which point phenotypic sex can be reliably identified by macroscopic gonadal inspection (del Fresno et al. 2023). A subsample of 50 individuals per treatment (temperature experiment) or all surviving individuals (hypoxia experiment, $n = 400$ per treatment) were euthanized with benzocaine (ELEA, Buenos Aires) 100 ppm, measured (total length), and weighed (total weight). Gonads were examined macroscopically to determine phenotypic sex. Genotypic sex was assessed by PCR amplification of the Y-linked *amhy* gene from caudal fin clips preserved in 96% ethanol (Yamamoto et al. 2014; del Fresno et al. 2023). Individuals in which *amhy* was amplified were classified as genotypic males (*amhy*+, XY), while those lacking amplification were classified as genotypic females (*amhy*−, XX). Mismatches between phenotypic and genotypic sex defined sex reversal. Differences in sex ratios were assessed using Fisher's exact test. For the hypoxia experiment, data from the two replicate cages per treatment were pooled for analysis.

Results

The temperature experiment revealed marked variation in sex reversal rates across thermal regimes that differed in both mean temperature and presence of diel fluctuations (Fig. 1). At 19 °C, the fluctuating regime (17–21 °C) produced 36% total sex reversal (18/50; 4 XY females, 14 XX males) compared to 24% under constant conditions (9/37; 4 XY females, 5 XX males). Notably, the fluctuating treatment produced 15% more reversal from females to male. At 24 °C, fluctuations reduced reversal (25%, 7/28; 3 XY females, 4 XX males) relative to constant conditions (30%, 16/53; 2 XY females, 14 XX males). At 28 °C, the fluctuating regime (26–30 °C) produced the highest reversal rate observed across all treatments

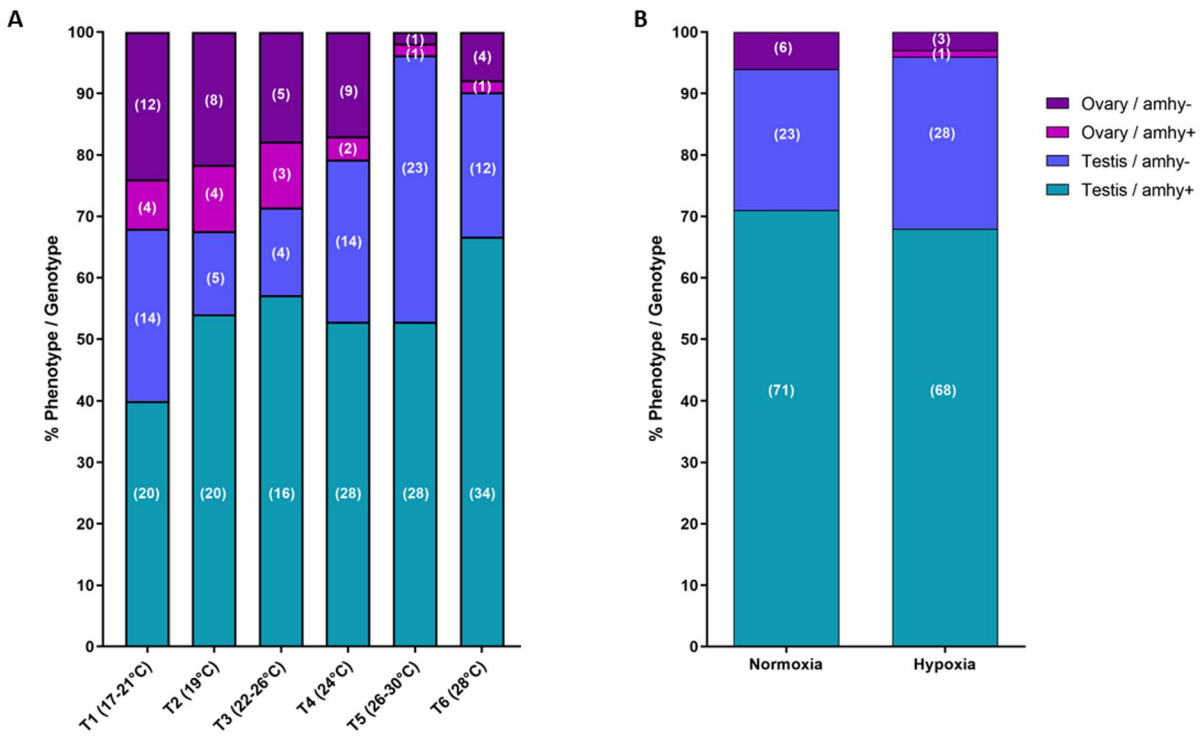


Fig. 1 Phenotypic and genotypic proportions of the pejerrey *Odontesthes bonariensis* in temperature fluctuations (**A**) and hypoxic treatment (**B**). Testis/*amhy*$^{+}$: pejerrey specimens with male phenotype, male genotype. Testis/*amhy*$^{-}$: pejerrey with male phenotype, female genotype. Ovary/*amhy*$^{-}$: pejerrey with female phenotype, female genotype. Ovary/amhy+: pejerrey with female phenotype, male genotype. The number of fish analyzed in parentheses inside each bar

(45%, 24/53, 1 XY females, 23 XX males), exceeding constant 28 °C (25%, 13/51, 1 XY females, 12 XX males). Overall, sex reversals were predominantly in the female-to-male direction (XX individuals developing testes). The impact of thermal fluctuation appeared to depend on mean temperature, with fluctuating regimes enhancing reversal at temperature extremes (low and high) but reducing it at the intermediate temperature.

In the hypoxia experiment, hypoxia exposure (3.94 ± 0.45 mg O_2 L^{-1}) maintained over the 8-week thermosensitive period at 24 °C showed minimal impact on sex determination compared to normoxic controls (7.06 ± 0.63 mg O_2 L^{-1}). Phenotypic sex ratios were strongly male-biased in both treatments, with 96% males (383/400) under hypoxia and 94% males (376/400) under normoxia. This male bias was unexpected given that 24 °C is typically associated with balanced sex ratios under constant, well-oxygenated conditions. Genotypic analysis of phenotypic males revealed 68% *amhy* + and 28% *amhy* − (sex-reversed XX males) under hypoxia, compared to 71% *amhy* + and 23% *amhy* − under normoxia (Fisher's exact test on pooled cage data, $p = 0.06$, two-tailed), though the direction was consistent with mild masculinization under hypoxia. Among the small number of phenotypic females, all successfully genotyped individuals (hypoxia: 4%, 16/400; normoxia: 6%, 24/400) were *amhy* − (genotypic females), indicating no male-to-female reversal (Fig. 1B).

Discussion

Our results reveal that both fluctuating thermal regimes and hypoxia can influence sex determination outcomes in *O. bonariensis*, though in distinct and context-dependent ways. The temperature fluctuation experiment showed that the effect of diel thermal cycling on sex reversal depended on mean temperature, with fluctuations enhancing masculinization at low and high temperatures but reducing it at intermediate temperatures. The hypoxia experiment showed a trend toward increased masculinization under low dissolved oxygen, though this effect was modest against an unexpectedly high baseline of male-biased sex ratios. Together, these findings highlight the complexity of environmental sex determination under ecologically realistic conditions and underscore the limitations of extrapolating from constant-temperature laboratory studies to natural settings.

The interaction between thermal fluctuation and mean temperature on sex reversal rates represents, to our knowledge, the first such observation in a fish with TSD. In reptiles, analogous context-dependent effects have been well documented: Neuwald and Valenzuela (2011) showed that fluctuations feminized painted turtles around cool means but masculinized them around warm means, and Warner and Shine (2011) demonstrated that sex ratios in the jacky dragon were determined by an interaction between mean temperature and diel amplitude rather than by either parameter alone. In fish, Hancock et al. (2023) found that diel fluctuations around a masculinizing mean of 28 °C produced more females in *Menidia menidia*, but their design tested only a single mean temperature. Our results extend this work by showing that the direction and magnitude of the fluctuation effect in pejerrey varies across three mean temperatures. This is broadly consistent with predictions from the Constant Temperature Equivalent (CTE) framework developed for reptilian TSD (Georges 1989; Georges et al. 1994), which is an application of Jensen's inequality (i.e., when a rate function is non-linear, the mean output under variable inputs differs from the output at the mean input; Ruel and Ayres 1999), potentially shifting sex ratios in ways that constant-temperature experiments cannot predict. However, the CTE model alone may not fully explain our results, particularly the reversal of the fluctuation effect at 24 °C, suggesting that other mechanisms may also play a role. These patterns should be interpreted cautiously given the lack of tank replication, and confirmation with fully replicated designs is necessary before definitive conclusions can be drawn.

An unexpected finding was the strong male bias in both hypoxia treatments (94–96% males), despite 24 °C being typically associated with balanced or moderately male-skewed sex ratios in pejerrey (Yamamoto et al. 2014; Strüssmann et al. 1997). Several non-mutually exclusive factors may explain this result: genetic background of the broodstock, given that TSD thresholds vary among families and populations in atherinids (Conover and Kynard 1981; Conover 1984; del Fresno et al. 2023); activation of the stress-cortisol-masculinization pathway by rearing

conditions such as density or water quality, as García-Cruz et al. (2020) demonstrated that crowding alone masculinizes pejerrey at 25 °C; and an extended window of environmental sensitivity when conditions conflict with genetic sex (Wu et al. 2025).

Hypoxia exposure produced a trend toward increased masculinization compared to normoxia (28% vs. 23% XX males; $p = 0.06$), consistent in direction with the masculinizing effects of hypoxia reported in zebrafish *Danio rerio* (Hamilton, 1822) (Shang et al. 2006), medaka *Oryzias latipes (*Temminck & Schlegel, 1846) (Cheung et al. 2014), and Atlantic croaker *Micropogonias undulates* (Linnaeus, 1766) (Thomas and Rahman 2012). The proposed mechanism for hypoxia-driven masculinization converges with that of temperature-induced sex reversal: both stressors activate the hypothalamic-pituitary-interrenal (HPI) axis, elevating cortisol, which then has cascading effects (Fernandino et al. 2012, 2013). This shared mechanistic pathway may explain why the hypoxia effect was marginal: if temperature had already driven most susceptible XX individuals toward male development, as evidenced by the high baseline masculinization, then the additional cortisol stimulus from hypoxia would encounter a largely depleted pool of reversible individuals. This is consistent with the argument by Hattori et al. (2020) that temperature, hypoxia, and acidity act through a common stress-response axis. Whether hypoxia would produce a stronger masculinizing effect under conditions with a lower baseline male proportion (for example, at temperatures closer to the feminizing range) remains an important question for future research.

From an ecological perspective, our findings suggest that pejerrey populations in shallow Pampas lakes face sex-determination pressures from multiple co-occurring stressors. These lakes are characterized by pronounced diel temperature fluctuations, seasonal thermal extremes, and increasingly frequent hypoxic episodes exacerbated by eutrophication and sewage discharge (Diovisalvi et al. 2015; Elisio et al. 2015; Quesada et al. 2023). Although our experiments addressed these stressors separately, the shared cortisol-mediated mechanism (Hattori et al. 2020) raises the possibility of additive or synergistic effects when they co-occur, a scenario that warrants explicit experimental testing. Persistent male-biased sex ratios could reduce effective population size and reproductive output, with consequences for both the ecological integrity and fisheries productivity of these systems (Miranda et al. 2013; Somoza et al. 2008). We acknowledge that the temperature experiment was conducted without replicated tanks and that the hypoxia experiment lacked independent tank replication; therefore, the results should be viewed as hypothesis-generating rather than definitive. Nonetheless, if the patterns reported here hold, they would indicate that current and projected environmental changes in Pampas shallow lakes are acting on sex determination through multiple, converging pathways, with potentially serious consequences for the long-term viability of wild pejerrey populations.

We report these results as a Brief Communication because their value is methodological and time-sensitive. If the direction of the fluctuation effect depends on mean temperature, then constant-temperature designs cannot be assumed to predict outcomes in the wild, and this bears directly on experiments currently being planned. Given that Pampas lakes are warming and experiencing increasingly frequent hypoxia, and that sex ratio projections for this commercially important species currently rely on constant-temperature thresholds, we consider it more useful to report the pattern now, with its limitations stated, than to withhold it pending a more substantial experimental effort.

Author contributions Carina Quesada, Agustín Boan: data curation, formal analysis, investigation, methodology, software, visualization, writing—original draft. Leandro Miranda, Santiago Salinas: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, visualization, writing— review and editing.

Funding This study was supported by a grant to L.A.M. (UNSAM 29-2025-26)

Data availability Data will be made available on request.

Declarations

Ethical approval All embryos and larvae were handled according to the manual of the Universities Federation for Animal Welfare Use and Care Committee on the care and Handling of Laboratory Animals and, according to the local regulations of San Martín University (260/08).

Competing interests The authors declare no competing interests.

References

Berasain GE, Colautti DC, Remes Lenicov M, Argemí F, Bohn VY, Miranda LA (2015) Impact of water salinity on *Odontesthes bonariensis* (Actinopterygii, Atherinopsidae) fisheries in Chasicó Lake (Argentina). Hydrobiologia 752:167–174. https://doi.org/10.1007/s10750-014-1980-8

Cheung CHY, Chiu JMY, Wu RSS (2014) Hypoxia turns genotypic female medaka fish into phenotypic males. Ecotoxicology 23:1260–1269. https://doi.org/10.1007/s10646-014-1269-8

Colautti DC, Baigún C, Llompart F, Maiztegui T, Garcia de Souza J, Solimano P, Balboni L, Berasain G (2015) Fish assemblage of a Pampean shallow lake, a story of instability. Hydrobiologia 752:1751–1786. https://doi.org/10.1007/s10750-0142062-7

Conover DO (1984) Adaptive significance of temperature-dependent sex determination in a fish. Am Nat 23:2973–3013

Conover DO, Kynard BE (1981) Environmental sex determination: interaction of temperature and genotype in a fish. Science 213:577–579. https://doi.org/10.1126/science.213.4507.577

del Fresno PS, Garcia de Souza JR, Colautti DC, Yamamoto Y, Yokota M, Strüssmann CA, Miranda LA (2023) Sex reversal of pejerrey (*Odontesthes bonariensis*), a species with temperature-dependent sex determination, in a seminatural environment. J Fish Biol 102:75–82. https://doi.org/10.1111/jfb.15241

Diaz RJ, Rosenberg R (1995) Marine benthic hypoxia: a review of its ecological effects and the behavioural responses of benthic macrofauna. Oceanogr Mar Biol 33:245–303 https://www.researchgate.net/publication/236628341

Díaz RJ, Rosenberg R (2008) Spreading dead zones and consequences for marine ecosystems. Science 321:926–929. https://doi.org/10.1126/science.1156401

Diovisalvi N, Bohn VY, Piccolo MC, Perillo GME, Baigún C, Zagarese HE (2015) Shallow lakes from the Central Plains of Argentina: an overview and worldwide comparative analysis of their basic limnological features. Hydrobiologia 752:5–20. https://doi.org/10.1007/s10750-014-1946-x

Elisio M, Vitale A, Miranda LA (2015) Influence of climate variations on Chascomús shallow lake thermal conditions and its consequences on the reproductive ecology of the Argentinian silverside (*Odontesthes bonariensis*). Hydrobiologia 752:155–166. https://doi.org/10.1007/s10750-014-1945-y

Fernandino JI, Hattori RS, Kishii A, Strüssmann CA, Somoza GM (2012) The cortisol and androgen pathways cross talk in high temperature-induced masculinization: the 11β-hydroxysteroid dehydrogenase as a key enzyme. Endocrinology 153:6003–6011. https://doi.org/10.1210/en.2012-1517

Fernandino JI, Hattori RS, Moreno Acosta OD, Strüssmann CA, Somoza GM (2013) Environmental stress-induced testis differentiation: androgen as a by-product of cortisol inactivation. Gen Comp Endocrinol 192:36–44. https://doi.org/10.1016/j.ygcen.2013.05.024

García-Cruz EL, Yamamoto Y, Hattori RS, de Vasconcelos LM, Yokota M, Strüssmann CA (2020) Crowding stress during the period of sex determination causes masculinization in pejerrey *Odontesthes bonariensis*. Comp Biochem Physiol Part A 245:110701. https://doi.org/10.1016/j.cbpa.2020.110701

Georges A (1989) Female turtles from hot nests: is it duration of incubation or proportion of development at high temperatures that matters? Oecologia 81:323–328. https://doi.org/10.1007/BF00377078

Georges A, Limpus C, Stoutjesdijk R (1994) Hatchling sex in the marine turtle *Caretta caretta* is determined by proportion of development at a temperature, not daily duration of exposure. J Exp Zool 270:432–444. https://doi.org/10.1002/jez.1402700504

Georges A, Doody JS, Beggs K, Young JE (2004) Thermal models of TSD under laboratory and field conditions. In: Valenzuela N, Lance VA (eds) Temperature dependent sex determination in vertebrates. Smithsonian Institution Press, pp 79–89

Gray JS, Wu RS, Or YY (2002) Effects of hypoxia and organic enrichment on the coastal marine environment. Mar Ecol Prog Ser 238:249–279. https://doi.org/10.3354/meps238249

Hancock GM, Sancho G, Munch SB, Salinas S (2023) Effects of daily thermal fluctuations on the Atlantic silverside, a fish with temperature-dependent sex determination. J Fish Biol 102:27–35. https://doi.org/10.1111/jfb.15372

Hattori RS, Castañeda-Cortés DC, Arias Padilla LF, Strobl-Mazzulla PH, Fernandino JI (2020) Activation of stress response axis as a key process in environment-induced sex plasticity in fish. Cell Mol Life Sci 77:4223–4236. https://doi.org/10.1007/s00018-020-03532-9

Jenny JP, Francus P, Normandeau A et al (2016) Global spread of hypoxia in freshwater ecosystems during the last three centuries is caused by rising local human pressure. Glob Change Biol 22:1481–1489. https://doi.org/10.1111/gcb.13193

Mechally AS, Miranda LA, Fernandino JI et al (2026) The current state of research on pejerrey (*Odontesthes bonariensis*) physiology and challenges for aquaculture development. Rev Aquacult 18:e70121. https://doi.org/10.1111/raq.70121

Miranda LA, Somoza GM (2022) Effects of anthropic pollutants identified in Pampas lakes on the development and reproduction of pejerrey fish *Odontesthes bonariensis*. Front Physiol 13:939986. https://doi.org/10.3389/fphys.2022.939986

Miranda LA, Chalde T, Elisio M, Strüssmann CA (2013) Effects of global warming on fish reproductive endocrine axis, with special emphasis in pejerrey *Odontesthes bonariensis*. Gen Comp Endocrinol 192:45–54. https://doi.org/10.1016/j.ygcen.2013.02.034

Morash AJ, Neufeld C, MacCormack TJ, Currie S (2018) The importance of incorporating natural thermal variation when evaluating physiological performance in wild species. J Exp Biol 221:jeb164673. https://doi.org/10.1242/jeb.164673

Neuwald JL, Valenzuela N (2011) The lesser known challenge of climate change: thermal variance and sex-reversal in vertebrates with temperature-dependent sex determination. PLoS ONE 6:e18117. https://doi.org/10.1371/journal.pone.0018117

Quesada CG, Miranda LA (2024) Effects of hypoxia on the reproductive endocrine axis of the pejerrey (*Odontesthes bonariensis*). Fish Physiol Biochem 50:2505–2517. https://doi.org/10.1007/s10695-024-01401-x

Quesada CG, Herdman J, Berasain GE, Miranda LA (2023) Influence of sewage discharge on dissolved oxygen concentration and fish diversity in the Girado stream and Chascomús lake. Environmental Monitor Asses 195:1433. https://doi.org/10.1007/s10661-023-12070-3

Rabalais NN, Díaz RJ, Levin LA, Turner RE, Gilbert D, Zhang J (2010) Dynamics and distribution of natural and human-caused hypoxia. Biogeosciences 7:585–619. https://doi.org/10.5194/bg-7-585-2010

Ruel JJ, Ayres MP (1999) Jensen's inequality predicts effects of environmental variation. Trends Ecol Evol 14:361–366. https://doi.org/10.1016/s0169-5347(99)01664-x

Saha N, Koner D, Sharma R (2022) Environmental hypoxia: a threat to the gonadal development and reproduction in bony fishes. Aquacult Fish 7:572–582. https://doi.org/10.1016/j.aaf.2022.02.002

Shang EHH, Yu RMK, Wu RSS (2006) Hypoxia affects sex differentiation and development, leading to a male-dominated population in zebrafish (*Danio rerio*). Environ Sci Technol 40:3118–3122. https://doi.org/10.1021/es0522579

Somoza GM, Miranda LA, Berasain GE, Colautti D, Remes-Lenicov M, Strüssmann CA (2008) Historical aspects, current status and prospects of pejerrey aquaculture in South America. Aquacult Res 39:784–793. https://doi.org/10.1111/j.1365-2109.2008.01930.x

Strüssmann CA, Patiño R (1995) Temperature manipulation of sex differentiation in fish. In: Goetz FW, Thomas P (eds.), Proceedings of the Fifth International Symposium on the Reproductive Physiology of Fish. Fish Symp 95, Austin, Texas, pp 153–157

Strüssmann CA, Moriyama S, Hanke EF, Calsina Cota JC, Takashima F (1996) Evidence of thermolabile sex determination in pejerrey. J Fish Biol 48:643–651. https://doi.org/10.1111/j.1095-8649.1996.tb01459.x

Strüssmann CA, Saito T, Usui M, Yamada H, Takashima F (1997) Thermal thresholds and critical period of thermolabile sex determination in two atherinid fishes, *Odontesthes bonariensis* and *Patagonina hatcheri*. J Exp Zool 278:167–177. https://doi.org/10.1002/(SICI)1097-010X(19970615)278:3

Thomas P, Rahman MS (2012) Extensive reproductive disruption, ovarian masculinization and aromatase suppression in Atlantic croaker in the northern Gulf of Mexico hypoxic zone. Proc R Soc B Biol Sci 279:28–38. https://doi.org/10.1098/rspb.2011.0529

Warner DA, Shine R (2011) Interactions among thermal parameters determine offspring sex under temperature-dependent sex determination. Proc R Soc B Biol Sci 278:256–265. https://doi.org/10.1098/rspb.2010.1040

Wu C, Baba W, Nakagawa R, Yamamoto Y, Strüssmann CA (2025) Genotype-by-environment interactive effects and conflict solving during gonadal sex differentiation of pejerrey *Odontesthes bonariensis*. Biol Sex Differ 16:79. https://doi.org/10.1186/s13293-025-00768-7

Yamamoto Y, Zhang Y, Sarida M, Hattori RS, Strüssmann CA (2014) Coexistence of genotypic and temperature-dependent sex determination in pejerrey *Odontesthes bonariensis*. PLoS ONE 9:e102574. https://doi.org/10.1371/journal.pone.0102574

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.