Biological Attributes of Bogue (*Boops boops*) Captured inside Marine Fish Cages in the Eastern Adriatic Sea

Biološke značajke bukve (Boops boops) ulovljene unutar morskih uzgojnih kaveza u istočnom Jadranskom moru

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Abstract

The bogue (*Boops boops*, Linnaeus, 1758) is a demersal and semi-pelagic fish common in Mediterranean catches and a dominant species among wild fish associated with aquaculture systems. This study analysed the biological characteristics of bogue cohabiting with farmed fish in the eastern Adriatic Sea, from January to June 2023. Total length ranged from 17.9 to 39 cm, and mass from 55.18 to 808.58 g. Bogue females were significantly heavier than males (p = 0.009), while positive allometric growth was observed in both sexes (b = 3.22–3.27). Condition (CI), gonadosomatic (GSI), and hepatosomatic (HSI) indices indicated enhanced physiological values than those reported for wild bogue populations. GSI peaked in March–April, while perivisceral fat remained high across all periods, suggesting a partial decoupling of energy storage and reproduction. PCA further supported a trade-off between fat reserves and gonadal development. Increased body indices of bogue sampled from the aquaculture cages indicate high adaptability to cohabitation with European seabass (*Dicentrarchus labrax*) and gilthead seabream (*Sparus aurata*).

KEY WORDS

Boops boops
length-weight relationship
condition index
gonadosomatic index
Adriatic Sea

Sažetak

Bukva (Boops boops, Linnaeus, 1758) je pridnena i polupelagička riba uobičajena u ulovima na Sredozemlju i dominantna vrsta među divljim ribama prisutnima u područjima akvakulture. U ovom istraživanju analizirane su biološke značajke bukvi koje su boravile u suživotu s uzgajanim ribama u istočnom dijelu Jadranskog mora od siječnja do lipnja 2023. godine. Ukupna duljina kretala se od 17,9 do 39 cm, a masa od 55,18 do 808,58 g. Ženke su bile značajno teže od mužjaka (p = 0,009), dok je kod oba spola utvrđen pozitivan alometrijski rast (b = 3,22–3,27). Indeks kondicije (CI), gonadosomatski (GSI) i hepatosomatski (HSI) indeksi ukazali su na povećane vrijednosti u usporedbi sa publiciranim podacima o divljim populacijama bukvi. Maksimalne vrijednosti GSI-a su utvrđene u razdoblju ožujak–travanj, dok je perivisceralna mast imala visoke vrijednosti tijekom cijelog razdoblja istraživanja, što upućuje na djelomično razdvajanje pohrane energije i reprodukcije. PCA analiza je dodatno potvrdila balans između ulaganja u masne rezerve i razvoj gonada. Povećani tjelesni indeksi bukvi uzorkovanih iz uzgojnih kaveza ukazuju na njihovu visoku prilagodljivost suživotu sa brancinom (Dicentrarchus labrax) i podlanicom (Sparus aurata).

KLJUČNE RIJEČI

bukva
dužinsko-maseni odnos
indeks kondicije
gonadosomatski indeks
Jadransko more

1. INTRODUCTION / *Uvod*

Global aquaculture has expanded rapidly over recent decades, driven by increasing demand for aquatic food due to population growth and declining capture fisheries [1]. Beyond food production, aquaculture plays a vital role in supporting employment, particularly in coastal and island communities [2]. In the Mediterranean, production is dominated by European seabass (*Dicentrarchus labrax*) and gilthead seabream (*Sparus aurata*), although species diversification has become a key priority to improve resilience to climate change, disease, environmental challenges, and market fluctuations [2]. Despite these efforts, the successful introduction of new aquaculture species has been limited, as producers continue to prioritise fast-growing, economically profitable species [3,4].

The attraction of aquaculture areas to wild species populations has already been observed, especially in the western Mediterranean area [5, 6, 7, 8]. Constant food availability, e.g., commercial feed pellets and cage biofouling, together with farm structures that provide protection from predators, have been reported as a major reason for the assemblage of aquaculture-associated wild species [8, 9]. Although trophic subsidies naturally occur through the transfer of energy and organic matter between ecosystems, aquaculture-derived subsidies, primarily waste feed and faecal material, substantially increase nutrient and organic

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carbon inputs to surrounding waters. These additional subsidies can alter the distribution, abundance, growth, and reproductive performance of wild fish. Aquaculture-associated wild species often exhibit improved somatic and liver condition, higher body fat content, and altered fatty acid composition, compared with individuals caught far from the farm area. However, the long-term consequences of aquaculture-derived trophic subsidies for individual fitness, population dynamics, and broader ecosystem functioning remain poorly understood [10, 11, 12, 13].

Understanding interactions between aquaculture and the surrounding environment is also essential for developing a sustainable aquaculture industry and supporting effective marine spatial planning. While fish farms may attract some wild species through enhanced food availability, they may also repel others because of husbandry-related disturbances, including noise, artificial light associated with boating and cage maintenance, and local eutrophication [14]. Furthermore, movements of wild fish around aquaculture facilities have important management implications, as they may facilitate disease transmission between wild and farmed populations. Wild fish can also damage net pens, increasing the risk of farmed fish escapes [15].

Most studies reported the wild fish species structure and abundance around fish farms, with comparison of some biometric parameters between wild and aquaculture-associated fish [5, 9, 16]. However, data on the biology of the wild fish species within the aquaculture area are still scarce, especially for the Adriatic Sea [9, 17, 18].

Besides being found around and in the aquaculture area, wild fish may also enter the breeding cages and remain within farm conditions for a certain time. In the Adriatic Sea, wild fish species from families: Carangidae, Clupeidae, Mugilidae, Moronidae, and Sparidae were found in European seabass and gilthead seabream cages, while in greater amberjack (*Seriola dumerili*), meagre (*Argyrosomus regius*), and common dentex (*Dentex dentex*) cages, no wild fish were reported [18]. Bogue (*Boops boops*) and jack mackerel (*Trachurus* sp.) were the most abundant wild species captured inside commercial cages during harvesting at fish farms within the Adriatic Sea. In this study on the occurrence and community structure of aquaculture-associated species in the Adriatic Sea, only bogue was present at all studied locations in both European seabass and gilthead seabream cages, indicating this species commonly occurrence inside commercial farm cages. [18]. Besides being one of the most common aquaculture-associated species in the Mediterranean area, bogue is a demersal and semi-pelagic fish that is also abundant in fisheries catches [19]. In the Adriatic Sea, its spawning period extends from January to May, and gonad histological analyses revealed that bogue is a batch spawner [19]. A recent study from May 2023 on some biological characteristics of bogue captured inside a cage, near cages, and far from the cages revealed biometric and somatic differences between three group samples, indicating the direction for further research [9].

Accordingly, the objective of this study was to characterize the biological parameters of bogue sampled directly from farm cages during the spawning period across aquaculture locations in the northern and central eastern Adriatic Sea, focusing on: (i) bimonthly variation in gonadosomatic index (GSI) and perivisceral fat (PF); (ii) sex-specific length–weight relationships; and (iii) covariation among size-adjusted organ and energy-storage traits.

2. MATERIAL AND METHODS / *Materijali i metode*

2.1. Study area and sampling design / *Područje istraživanja i način uzorkovanja*

Bogue samples (N=311) were collected between January and June 2023 from three aquaculture sites in the central Adriatic and one in the northern Adriatic Sea (Figure 1). All samples were collected using a net with a mesh size of 14 mm during harvesting from commercial fish cages with European seabass and gilthead seabream (Table 1). The number of bogue samples per bimonthly period/farm site is presented in Supplementary Table S1.

Since this paper is part of our broader research on aquaculture–wild species interactions, we included data from 56



Figure 1 Study area - fish farm sites located in the central and northern Adriatic Sea

Slika 1. Područje istraživanja – lokacije uzgajališta (ribogojilišta) smještenih u srednjem i sjevernom Jadranskom moru

Source: Authors' own work based on Esri ArcGIS Online basemaps (World Imagery and World Topographic Map), © Esri and respective data providers, https://www.arcgis.com, accessed August 2026. [33]

Table 1 Description of the farm sites and number of bogue samples per sex
Tablica 1. Opis lokacija uzgajališta i broj uzoraka bukve po spolu

Farm	Species	Depth (m)	Site_coordinates	Male	Female	Total
Košara	DL, SA	10–52	44°01'38.25"N, 15°12'53.52"E	16	36	52
Lavdara	DL, SA	20–64	43°57'04.02"N, 15°13'31.30"E	63	116	179
Velo žalo	DL, SA	17–44	44°00'13.48"N, 15°03'39.18"E	4	16	20
Budava	DL, SA	10–40	45°00'03.00"N, 14°03'38.56"E	15	45	60
*DL - *Dicentrarchus labrax*; SA- *Sparus aurata*				98	213	311

Table 2 Sea temperature from January to June 2023 (bimonthly) per farm site, Adriatic Sea
Tablica 2. Temperatura mora od siječnja do lipnja 2023. (dvomjesečno) po lokacijama uzgajališta, Jadransko more

Farm	Period	N (days)	Mean ± SD (°C)	Min (°C)	Max (°C)	Median (°C)
Košara	Jan–Feb	59	14.16 ± 0.92	13	16	14
	Mar–Apr	60	13.78 ± 0.7	13.1	15.9	13.5
	May–Jun	61	19.23 ± 1.96	15.7	21.7	19.4
Velo žalo	Jan–Feb	59	14.23 ± 1.13	12.6	16	14.2
	Mar–Apr	61	13.72 ± 0.45	12.8	14.8	13.8
	May–Jun	61	19.19 ± 2.72	14.9	23.8	19.9
Lavdara	Jan–Feb	59	14.42 ± 1.16	13	16.2	14.2
	Mar–Apr	61	13.8 ± 0.5	13.2	15.3	13.7
	May–Jun	61	19.29 ± 2.61	15.2	23	19.5
Budava	Jan–Feb	57	12.24 ± 1.05	10.7	14.3	12.2
	Mar–Apr	61	12.29 ± 0.85	10.9	14.4	12.3
	May–Jun	61	18.84 ± 2.8	14.6	23.2	18.8

bogue individuals caught inside a fish cage at a farm site in the middle Adriatic in May 2023, previously reported by Mustać et al. [9]. These data were incorporated into the present expanded dataset, which comprises 311 bogue sampled exclusively inside marine fish cages at four farms in the northern and middle eastern Adriatic during the six-month spawning period. The previous study compared wild and aquaculture-associated bogue during a single month (May 2023), whereas the present study focuses specifically on the biology of bogue captured only inside marine fish cages across multiple farm locations and throughout the spawning period.

Sea temperature data were continuously recorded at each fish farm using temperature data loggers installed at 8 m depth directly at the fish farms (Table 2).

2.2. Biometric measurements and indices derivation / *Biometrijska mjerenja i izračun indeksa*

All bogue samples, after being captured from cages, were processed the same day in the laboratory. Total length (TL, cm) was measured to the nearest millimetre and total body mass (W, g) was recorded using a digital scale with milligram precision. Sex was determined by macroscopic examination of gonad morphology. Gonads and liver were dissected and weighed individually (g). Perivisceral fat was isolated as the total adipose tissue associated with the visceral cavity, including mesenteric fat deposits, and weighed to the nearest 0.01 g. Stomach contents could not be analysed since common fish farm practice is to stop feeding farmed fish three days before capture (harvesting).

From these measurements, length–weight relationship, Fulton's condition index (CI), gonadosomatic index (GSI) and hepatosomatic index (HSI) were calculated for each sex.

The length–weight relationship was calculated according to the equation:

$$\log W = \log a + b \log TL \quad (1)$$

where a is the intercept, and b is the allometric exponent describing the growth pattern [20].

The estimated b value was tested against the isometric value of 3 using a two-tailed t-test.

Fulton's condition index (CI), gonadosomatic index (GSI), and hepatosomatic index were calculated according to formulas [20, 21]:

$$CI = \left(\frac{W}{TL^3}\right) \times 100 \quad (2)$$

$$GSI = \left(\frac{GW}{W}\right) \times 100 \quad (3)$$

$$HSI = \left(\frac{LW}{W}\right) \times 100 \quad (4)$$

The condition factor (% CI) is the ratio of W- total body mass of the fish (g) and TL- total length of the fish (cm). The gonadosomatic index (% GSI) is the ratio of GW- gonad weight (g) and the W- total body mass of the fish (g). The hepatosomatic index (% HSI) was calculated as the ratio of the LW- liver weight (g) to the W- total body mass of the fish (g).

CI was retained as a descriptive index to allow comparison with previous studies. However, because the estimated allometric coefficient b was significantly greater than 3, Fulton's condition index was considered potentially size-dependent and was not used as the primary basis for comparing body condition

among sexes or sampling periods. Therefore, body mass was additionally analysed using a size-adjusted log-linear model, with log-transformed total body mass as the response variable and log-transformed total length, sex, bimonthly sampling period, and farm site as predictors:

$$\log W \sim \log TL + sex + period + farm\ site \quad (5)$$

Model assumptions were assessed by visual inspection of residual-versus-fitted plots, Q–Q plots of standardised residuals, scale-location plots, and residuals-versus-leverage plots.

2.3. Statistical analysis / *Statistička analiza*

Statistical analyses were performed in R version 4.5.1 using RStudio (Posit Software, PBC) with the main R packages including dplyr, car, emmeans, broom, factoextra, and ggplot2. Due to the unbalanced distribution of samples across locations and months, after bogue biometric characteristics were performed for each month/sex (Table 3), individual months from January to June were aggregated, for further analyses, into three broader bimonthly periods: January–February, March–April, and May–June. Prior to statistical analysis, data distribution was assessed using the Shapiro–Wilk test. As most variables did not meet the assumptions of normality, descriptive group comparisons were based on non-parametric tests, with p-values adjusted using the Benjamini–Hochberg false discovery rate (FDR) procedure. Since the samples were unevenly distributed across farms and periods, unadjusted comparisons were interpreted cautiously as descriptive patterns. To account for body-size effects and sampling structure, additional log-linear models were fitted for key mass-related traits, with log-transformed total length, sex, bimonthly period, and farm site included as predictors. For gonad weight, perivisceral fat was additionally included as a predictor to evaluate the adjusted relationship between fat reserves and gonad mass. Cage or harvest-batch identity was not available for all individuals; therefore, potential clustering within cage or harvest batch could not be explicitly modelled and was acknowledged as a limitation.

2.3.1. Univariate and length - weight analyses / *Univarijatne analize i analiza odnosa duljine i mase*

Differences between sex were evaluated using the *Mann–Whitney* U test, while differences among bimonthly groups were assessed using the Kruskal–Wallis test. When significant differences were detected, Dunn's post-hoc test was applied for pairwise comparisons between groups. To control for multiple testing, p-values were adjusted using the Benjamini–Hochberg FDR within each family of related tests. Sex-based comparisons of biometric and physiological traits were treated as one test family, while bimonthly comparisons and post-hoc pairwise tests were treated as separate test families. Effect sizes for bimonthly differences were quantified using Cliff's delta (δ), with 95% confidence intervals reported for each pairwise contrast. The length–weight relationship was analysed using ordinary least-squares regression on log-transformed data. The allometric exponent (b) was estimated from the slope of the regression, and the intercept was back-transformed to obtain parameter a. The 95% confidence intervals were reported for both a and b. To assess whether the estimated b value differed significantly from the isometric value of 3, a two-tailed t-test was used. Differences in length–weight slopes between sexes were evaluated using a slope-homogeneity test based on the sex × log (TL) interaction. Sex ratio was tested against the expected 1:1 distribution using the chi-square goodness-of-fit test. Associations between biological traits were evaluated using *Spearman's* correlation coefficient. The unadjusted relationship between gonadosomatic index (GSI) and perivisceral fat (PF) was evaluated for the pooled dataset and within each bimonthly period. Because GSI includes total body mass in the denominator, this relationship was further assessed using gonad weight (GW) in adjusted analyses. GW was analysed using a log-linear model with log-transformed GW as the response variable and log-transformed TL, log-transformed PF, sex, bimonthly period and farm site as predictors. Because PF included zero values, PF was transformed as log(PF + 1). Adjusted residuals of GW and PF were also extracted from separate models including TL, sex, bimonthly period and farm site, and their association was evaluated using Spearman's correlation coefficient.

2.3.2. Multivariate temporal analysis / *Multivarijatne vremenske analize*

Principal component analysis (PCA) was used as an exploratory tool to visualise covariance patterns among physiological traits after accounting for body size. Since the mass-related traits scale with total length, body mass (W), liver weight (LW), gonad weight (GW), and perivisceral fat (PF) were first transformed and separately regressed against log-transformed total length (TL). W, LW, and GW were natural-log transformed, while PF was transformed as log(PF + 1) because zero PF values were present in the dataset. The residuals from these models were used as size-adjusted variables representing variation in each trait independent of body length. PCA was then performed on the standardised residuals of W, LW, GW, and PF. Derived indices such as CI, GSI, and HSI were excluded to avoid redundancy with their component variables.

3. RESULTS AND DISCUSSION / *Rezultati i rasprava*

3.1. Biological characteristics / *Biološke karakteristike*

A total of 311 bogue individuals were analysed, including 213 females and 98 males. Females significantly dominated the sample, with a female-to-male ratio of 2.17:1 ($\chi^2 = 42.52$, $p < 0.001$). Total length did not differ significantly between sexes (FDR-adjusted $p = 0.235$), although females were slightly larger on average (Table 3). In the unadjusted comparisons, liver weight, CI and HSI were significantly higher in females after FDR correction, whereas gonad weight, GSI and PF did not differ significantly between sexes. Body mass was higher in females based on the unadjusted p-value ($p = 0.027$), but this difference was no longer significant after FDR correction (adjusted $p = 0.055$). In size-adjusted log-linear models, males had significantly lower adjusted liver weight than females (estimate = −0.525, $p < 0.001$), whereas sex was not a significant predictor of PF after accounting for total length, bimonthly period and farm site ($F = 3.21$, $p = 0.074$). Overall, sex-related differences were most consistent for liver-related traits, while gonad-related traits and PF were broadly similar between sexes.

Table 3 Biological characteristics of female and male bogue collected from fish farms, January-June, 2023, Eastern Adriatic Sea
Tablica 3. Biološke karakteristike ženki i mužjaka bukve s uzgajališta (siječanj - lipanj 2023., istočni Jadran)

	variable	min	max	mean	SD	median	Q1	Q3
Female (N =213)	CI	0.82	1.78	1.32	0.17	1.32	1.22	1.41
	GSI	0.63	17.64	5.15	2.67	4.91	3.56	6.39
	GW	0.41	68.69	21.63	14.02	19.43	11.62	28.17
	HSI	0.38	7.23	3.24	1.33	3.04	2.29	4.12
	LW	0.21	48.07	14.29	8.93	13.23	7.78	19.93
	PF	0.00	82.15	12.61	14.71	6.97	2.37	18.84
	TL	18.30	39.00	30.77	4.38	31.40	27.70	34.20
	W	55.18	808.58	412.10	170.07	414.68	272.19	541.63
Male (N= 98)	CI	0.81	1.56	1.26	0.16	1.28	1.15	1.37
	GSI	0.53	12.47	5.19	2.83	5.21	2.69	6.90
	GW	0.40	46.98	18.56	11.18	17.35	10.25	26.27
	HSI	0.37	4.23	1.90	0.73	1.89	1.33	2.37
	LW	0.44	19.42	7.23	4.39	6.60	4.03	9.99
	PF	0.00	63.67	14.63	15.37	8.60	1.58	24.42
	TL	17.90	36.60	29.98	4.44	31.10	27.13	33.65
	W	63.45	612.15	363.01	148.95	378.66	243.09	473.57

(Total length – TL, total body mass - W, liver weight – LW, gonad weight – GW, perivisceral fat – PF, condition index – CI, gonadosomatic index – GSI, hepatosomatic index – HSI)

Smaller bogue sizes were noted in earlier studies of this species from the central (TL range: 7.0-25.0 cm) and southern (TL range: 9.0-29.3 cm) Adriatic Sea [22, 23, 24, 19]. In addition, bogue larger than 30 cm were also found in a study of wild species occurrence within an aquaculture area in the Adriatic Sea [18]. This difference is likely associated with aquaculture conditions, where fish benefit from reduced predation pressure and continuous access to high-energy food sources, including commercial feed pellets and fouling organisms, resulting in enhanced growth and somatic condition [5, 6, 18, 25]. Although the present fish are much larger than fish in several mentioned studies, length range, gear selectivity, season, region, and maturity structure all affect W, CI, GSI, and HSI. Still, similar patterns have been observed in the western Mediterranean, where biometric characteristics of wild bogue (TL, W, CI, HSI and GSI) revealed lower values in comparison to aquaculture-associated bogue [6].

Although this research coincides with the spawning period of the bogue, when smaller amounts of fat would be expected, high amounts of perivisceral fat were found in samples (PF up to 82 g) (Table 3) [26]. In a study from the western Mediterranean, four species of different trophic guilds, *Sardinella aurita, Caranx rhonchus, Mullus barbatus, and Pomatomus saltatrix*, that were captured at farms, showed increased levels of total lipids and/or the terrestrial fatty acids contained in feed pellets, in comparison to those caught far from the aquaculture area [27]. An increase in tissue fat and condition was also observed in aquaculture-associated fish, both bogue and horse mackerel (*Trachurus mediterraneus*), from western Mediterranean studies [5, 6, 12]. However, fat content and fatty acid composition of aquaculture-associated fish that fed on pellets varied significantly from the wild fish samples, due to the high concentration of vegetable oils from the food pellet. Hence, increased levels of linoleic and oleic acids and decreased levels of DHA and ARA, i.e., a lower ratio of ω3/ω6 fatty acids, in aquaculture-associated fish can influence fish health, the marine trophic web, but also future reproduction through egg quality and larvae survival [5, 6, 8, 12].

GW ranged from 0.4 to 68.7 g for females and from 0.4 to 46.9 g for males. Both GW and GSI showed significant variation among bimonthly sampling periods, with the highest values observed during March–April (GW: $H = 29.21$, $p < 0.001$; GSI: $H = 57.11$, $p < 0.001$), consistent with the spawning period of bogue in the Adriatic Sea. An earlier study from the mid Adriatic channels revealed a bogue spawning period from March to June, i.e., bogue spawn in spring in offshore areas, at SST of 12.7-14.0°C and salinity of approximately 38.6 ppt [22]. In the southern part of the Adriatic Sea, bogue spawning was recorded from January to May with a peak in February (GSI for females 5.97% and males 4.21%) [16]. In Antalya Bay, GSI values of bogue were highest in March (2.19-2.11) [28].

3.2. Length-weight relationship / *Odnos duljine i mase*

The length–weight relationship showed positive allometry in the pooled sample of cage-captured bogue ($W = 0.0052 \times TL^{3.265}$). The allometric coefficient was significantly greater than the isometric value of 3 ($b = 3.265$, 95% CI: 3.172–3.358, $p < 0.001$; $n = 311$). Positive allometry was also confirmed separately in females ($b = 3.272$, 95% CI: 3.158–3.386, $p < 0.001$; $n = 213$) and males ($b = 3.221$, 95% CI: 3.063–3.378, $p = 0.006$; $n = 98$) (Figure 2). The sex × log (TL) interaction was not significant ($F = 0.267$, $p = 0.606$), indicating no evidence for different length–weight slopes between sexes. The obtained b values are consistent with previous findings from the Aegean Sea, where positive allometry was also reported for bogue [29, 30], whereas Adriatic wild-population studies reported negative allometry [19, 23, 24]. However, comparisons among studies should be

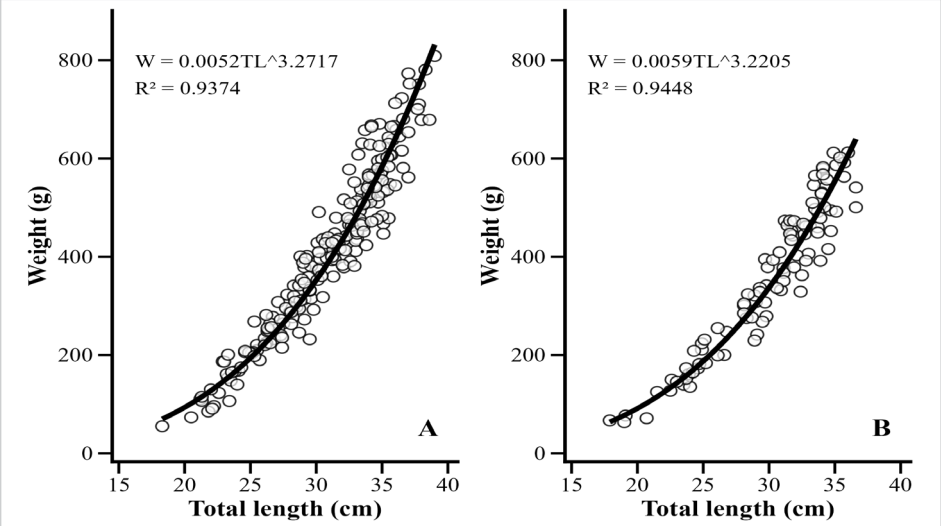


Figure 2 Length-weight relationship of female (A; n=213) and male (B; n=98) bogue sampled from fish farms, January-June, 2023, Eastern Adriatic Sea

Slika 2. Odnos duljine i mase ženki (A; n = 213) i mužjaka (B; n = 98) bukve s uzgajališta u istočnom Jadranu (siječanj – lipanj 2023.)

Source: Authors

interpreted cautiously because b is sensitive to length range, sex and maturity structure, reproductive stage, season, stomach fullness, sampling method, and geographic area [30]. In the size-adjusted body-mass model, TL was the strongest predictor of body mass ($F = 5321.99$, $p < 0.001$), while sex ($F = 11.06$, $p = 0.001$), bimonthly period ($F = 39.05$, $p < 0.001$), and farm site ($F = 4.87$, $p = 0.003$) also remained significant. After adjustment for TL, bimonthly period, and farm site, males showed slightly higher body mass than females at a given length (Male – Female = 0.046, 95% CI: 0.019–0.073, $p = 0.001$), corresponding to approximately 4.7% higher adjusted body mass. Residual diagnostics did not indicate strong violations of linear model assumptions (Supplementary Figure 1).

3.3. Variation in biological characteristics among bimonthly sampling periods / *Promjene bioloških karakteristika tijekom dvomjesečnih razdoblja uzorkovanja*

Significant differences among bimonthly sampling periods were detected for several biological characteristics of bogue, including GW ($H = 29.21$, $p < 0.001$), GSI ($H = 57.11$, $p < 0.001$), PF ($H = 29.84$, $p < 0.001$) and CI ($H = 45.29$, $p < 0.001$), while HSI showed no significant variation ($H = 0.99$, $p = 0.61$). However, sampling was unevenly distributed among farm sites and bimonthly periods; therefore, these differences should be interpreted as period-related patterns within the sampled dataset rather than as independent seasonal effects (Supplementary Table S1).

Temperatures at farm sites remained relatively stable during winter and early spring, while a pronounced warming trend was observed from May onwards (Table 2). Post-hoc Dunn tests confirmed significant differences among the three bimonthly periods for both GSI and PF (adjusted; $p < 0.05$) (Figure 3). GW and GSI values were lowest in January–February, peaking in March–April, coinciding with sea temperatures of approximately 13–14 °C, and declining in May–June, consistent with the species reproductive cycle [19, 22].

Relatively high PF values were also observed during the period of highest reproductive investment, but PF showed high variability within all bimonthly groups and did not follow a strictly consistent temporal pattern (Figure 3). This decoupling of reproduction from energy storage is likely facilitated by continuous access to high-energy commercial feed, allowing individuals to support reproduction through direct nutrient intake rather than mobilising endogenous reserves [6, 31]. Although continuous food availability in aquaculture cages may represent a possible explanation, this remains hypothetical because this study did not directly assess feed consumption, residence time, or include a comparable wild control group.

When all samples were pooled, a weak but significant negative correlation was observed between GSI and PF (Spearman $\rho = -0.224$, $p < 0.001$). In the unadjusted period-specific analysis, this relationship was most pronounced during March–April ($\rho = -0.416$, $p < 0.001$), whereas January–February showed no significant association ($\rho = -0.160$, $p = 0.243$) and May–June showed a weak positive association ($\rho = 0.236$, $p = 0.034$) (Figure 3). However, because GSI is a ratio that includes body mass in the denominator, while PF is an absolute mass that scales with body size, this relationship was further examined using adjusted analyses based on gonad mass rather than GSI. After accounting for total length, sex, bimonthly period and farm site, the pooled residual correlation between adjusted gonad mass and adjusted PF remained negative and significant (Spearman $\rho = -0.257$, $p < 0.001$, $n = 311$; Supplementary Figure S2). Period-specific residual correlations indicated significant negative associations in January–February ($\rho = -0.308$, $p = 0.022$) and March–April ($\rho = -0.411$, $p < 0.001$), whereas May–June showed no significant association ($\rho = 0.070$, $p = 0.534$).

In addition, when gonad weight was analysed directly in an adjusted model including total length, PF, sex, bimonthly period and farm site, PF explained a significant additional proportion of variation in gonad weight after adjustment for the other predictors ($F = 21.29$, $p < 0.001$), with a negative adjusted association. Gonad weight was primarily explained by total length ($F = 325.15$, $p < 0.001$) and bimonthly period ($F = 28.37$, $p < 0.001$). Model diagnostics showed mild deviations from ideal assumptions but did not indicate strongly influential observations dominating the model fit (Supplementary Figure S3).

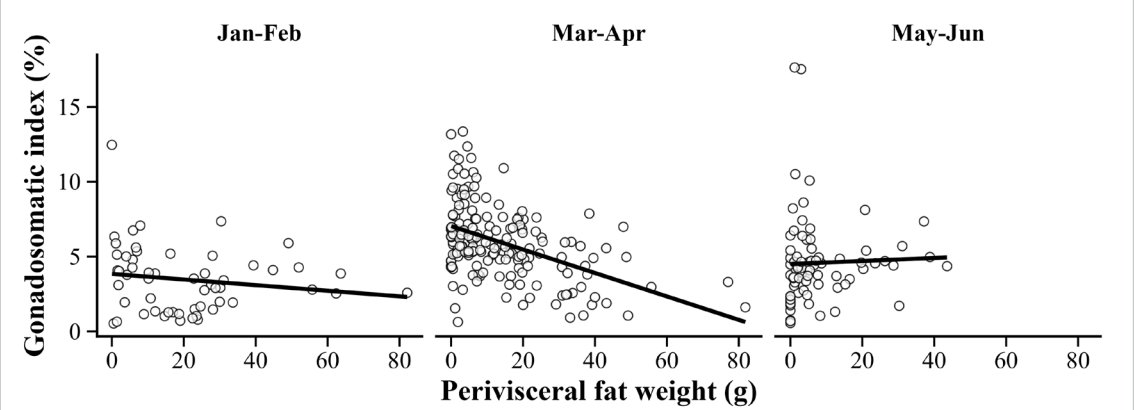


Figure 3 Bimonthly relationship between gonadosomatic index (GSI) and perivisceral fat (PF) in bogue (n=311) sampled from fish farms, January-June 2023, Eastern Adriatic Sea (points represent individual fish; black lines indicate descriptive fitted linear relationships)

Slika 3. Dvomjesečni odnos gonadosomatskog indeksa (GSI) i perivisceralne masti (PF) kod bukve (n = 311) uzorkovane na ribogojilištima u istočnom Jadranu od siječnja do lipnja 2023. (točke prikazuju pojedinačne jedinke; crne linije opisuju prilagođene linearne odnose)

Source: Authors

These results indicate that the negative association between gonad mass and PF persisted after adjustment for body size and sampling structure. However, this association should still be interpreted cautiously as a cross-sectional pattern rather than direct evidence of mobilisation of perivisceral fat reserves into gonadal tissue.

CI showed significant variation across bimonthly periods, whereas HSI remained relatively stable. The largest shift in GSI was observed between January-February and March–April, with a large effect size ($\delta = 0.58$). PF showed the greatest difference between January–February and May–June ($\delta = 0.51$), while differences between adjacent periods were generally smaller.

Comparisons by sex revealed that differences between females and males were primarily related to certain biometric (somatic) characteristics. Females had higher TL, W, LW and HSI in January–February ($p < 0.05$), and LW remained consistently higher in females across all periods ($p < 0.001$). CI differed between sexes only in March–April ($p < 0.01$), with higher values in females. HSI was also consistently higher in females across bimonthly periods ($p < 0.01$). Reproductive (GW, GSI) and energy storage (PF) parameters did not differ significantly between sexes within periods (Figure 4).

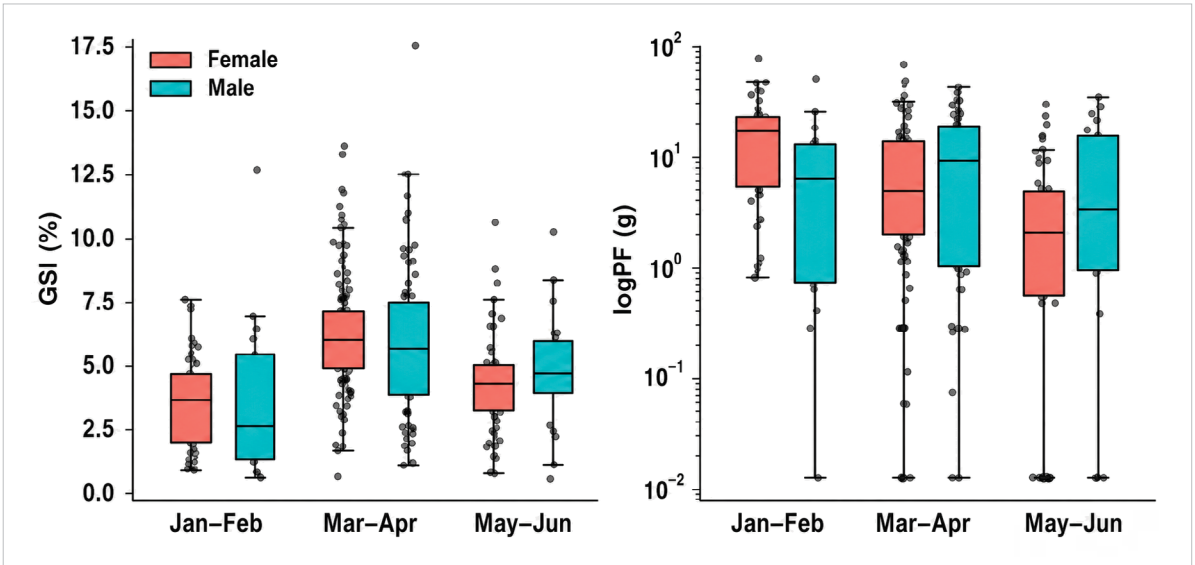


Figure 4 Bimonthly dynamics of gonadosomatic index (GSI) and perivisceral fat (PF) of female (n=213) and male bogue (n=98) sampled from fish farms, January-June, 2023, Eastern Adriatic Sea (boxes represent the interquartile range, horizontal lines indicate medians, whiskers show 1.5 × IQR, and points represent individual fish. PF is shown on a logarithmic scale)

Slika 4. Dvomjesečna dinamika gonadosomatskog indeksa (GSI) i perivisceralne masti (PF) ženki (n = 213) i mužjaka (n = 98) bukve uzorkovane na ribogojilištima u istočnom Jadranu od siječnja do lipnja 2023. (okviri prikazuju interkvartilni raspon, vodoravne crte medijane, okomite crte – brkovi 1,5 × IQR, a točkice pojedinačne jedinke. PF je prikazan na logaritamskoj ljestvici)

Source: Authors

3.4. Multivariate structure of physiological traits / *Multivarijatna struktura fizioloških karakteristika*

The size-adjusted PCA included 310 individuals and explained 80.6% of the total variance across the first two principal components. PC1 accounted for 51.4% of the variance and was mainly associated with residual body mass, residual liver weight and residual perivisceral fat. PC2 explained an additional 29.2% of the variance and was primarily related to residual gonad weight, with residual perivisceral fat loading in the opposite direction (Figure 5). Bimonthly groups showed substantial overlap in the ordination space, indicating that January–February, March–April and May–June samples were not clearly separated after body-size adjustment. Residual body mass and residual liver weight were closely aligned along PC1, whereas residual gonad weight formed a distinct gradient along PC2. Overall, the PCA indicated covariance among size-adjusted physiological traits, with residual gonad mass varying partly independently from residual somatic and fat-related traits.

Several limitations of this study should be acknowledged. During the six-month study period, bogue samples were collected exclusively during routine harvesting operations from commercial aquaculture cages, without contemporaneous wild group control. In addition, the exact time of entry of individual bogue into the cages and their residence time within the aquaculture cages were unknown, which limits inference about the duration of exposure to farm-derived food resources and cage conditions.

Furthermore, sampling was not fully balanced across farms, cages and dates, and individuals collected from the same cage or harvest batch may not be statistically independent. Age was not determined, so age-related variation in growth, condition and reproductive status could not be separated from size-related variation. Finally, reproductive status was assessed macroscopically rather than histologically, which may reduce the precision of maturity-stage classification and interpretation of gonadal development. A fish's ability to adapt to environmental changes, natural or anthropogenic, such as fishing pressure or climate change, depends on its reproductive strategy. Hence, reproductive parameters are key components of stock assessments and population dynamics, influencing the marine food web [32].

Nonetheless, these bogue samples from aquaculture cages exhibited greater values of all studied parameters than wild bogues from the Adriatic Sea [19, 22, 23, 24]. Still, obtaining more precise information on the residency time of wild fish within aquaculture cages would be valuable for future aquaculture management regarding control of wild fish entrance, as well as for improving our understanding of interactions between aquaculture and the surrounding marine environment.

4. CONCLUSION / *Zaključak*

This study provides a descriptive assessment of biological attributes of bogue captured from marine cages during the

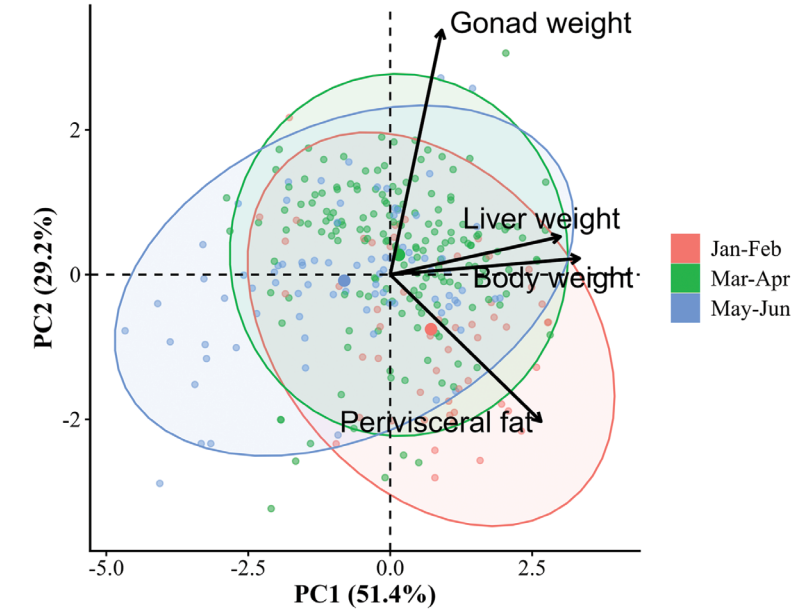


Figure 5 Principal component analysis of size-adjusted residuals of body mass, liver weight, gonad weight, and perivisceral fat transformed as log (PF + 1) in bogue sampled from fish farms across three bimonthly periods during January-June 2023 in the eastern Adriatic Sea

Slika 5. Analiza glavnih komponenti (PCA) veličinski prilagođenih reziduala tjelesne mase, mase jetre, mase gonada i perivisceralne masti transformirane kao log (PF + 1) kod bukve uzorkovane na ribogojilištima u tri dvomjesečna razdoblja tijekom siječnja – lipnja 2023. godine u istočnom Jadranskom moru

Source: Authors

harvesting of farmed European seabass and gilthead seabream in the eastern Adriatic Sea. The analysed individuals showed high values of total length (TL), body mass (W), perivisceral fat, and somatic indices compared with values reported for wild bogue populations from the Adriatic Sea and other Mediterranean regions. Reproductive traits, including gonadosomatic index (GSI) and gonad weight, also reached high values during the investigated spawning period. However, these patterns should be interpreted cautiously because the study did not include a contemporaneous wild control group, direct dietary markers, or information on the exact entrance time and residence duration of bogue within cages. Therefore, the observed biometric, somatic and reproductive characteristics cannot be attributed causally to aquaculture conditions alone. Given the rapid expansion of Mediterranean aquaculture, continued monitoring of wild fish populations within and around marine cages is important for a more comprehensive assessment of interactions between aquaculture and wild fish communities.

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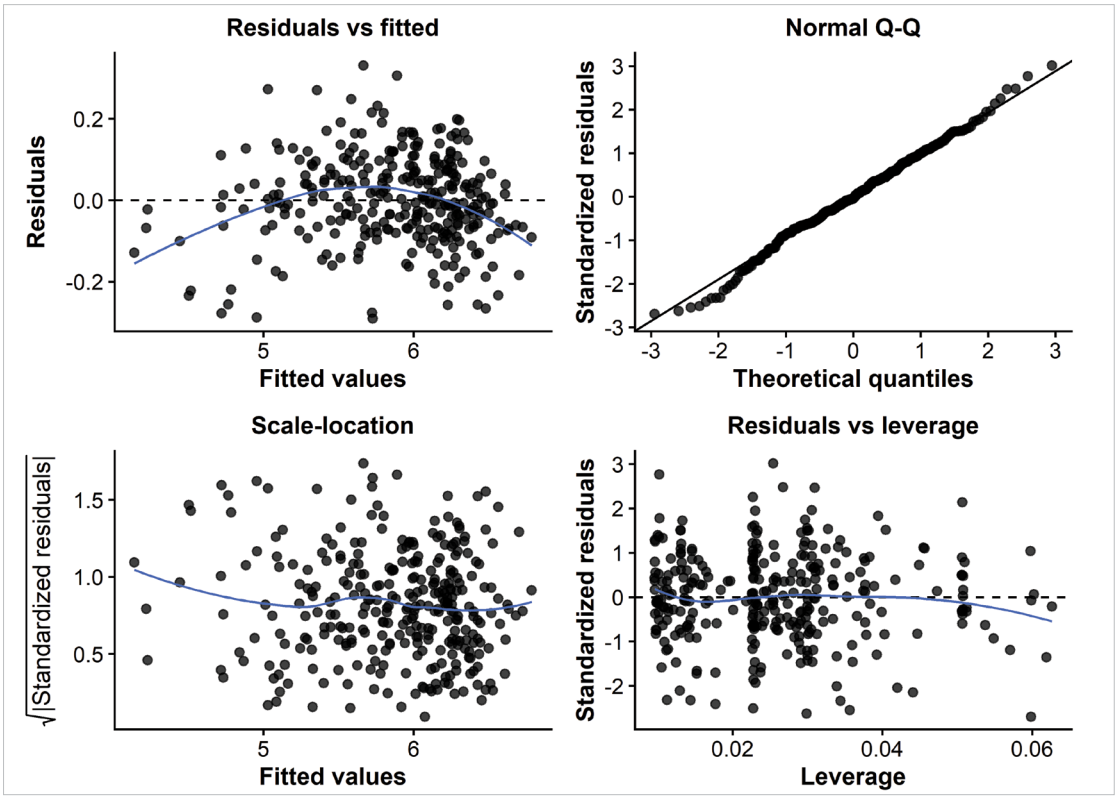
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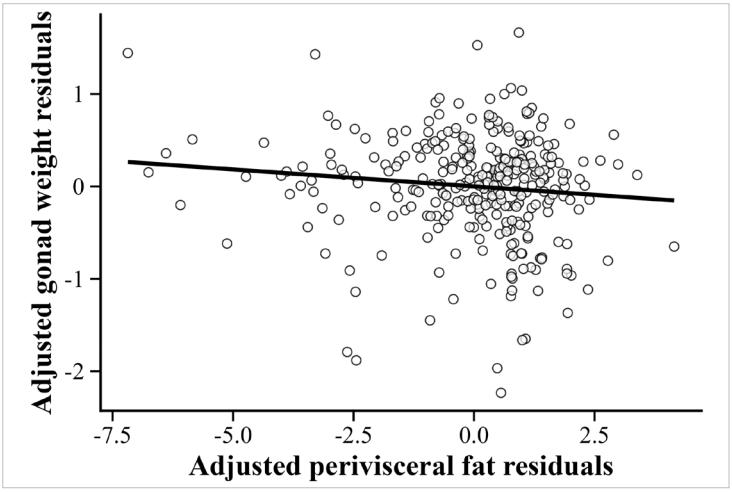
Supplementary / *Dodatak*



Supplementary Figure S1. Residual diagnostic plots for the size-adjusted body-mass model, including residuals versus fitted values, Q-Q plot of standardised residuals, scale-location plot, and residuals versus leverage

Dodatna slika S1. Dijagnostički prikazi reziduala za model tjelesne mase prilagođen veličini, uključujući reziduale u odnosu na prilagođene vrijednosti, Q-Q dijagram standardiziranih reziduala, dijagram odnosa lokacije i mjerila te reziduale u odnosu na polugu

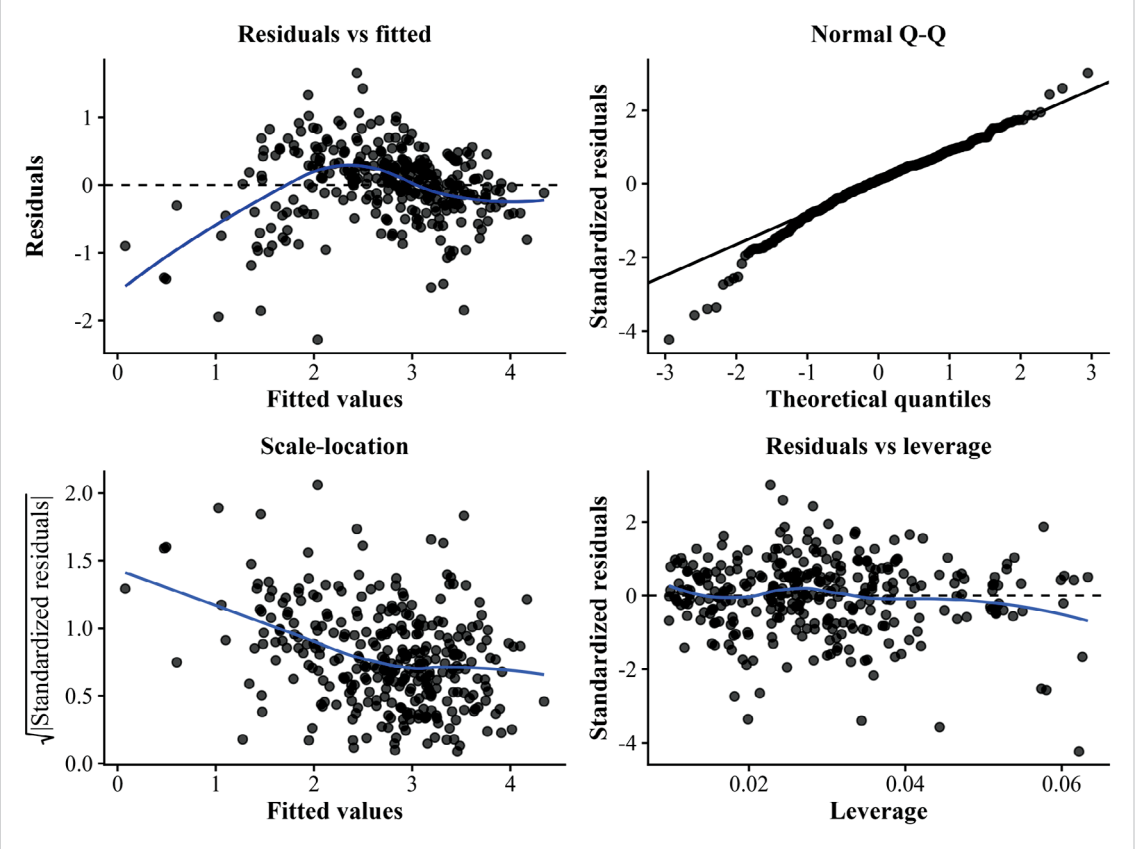
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Supplementary Figure S2. Relationship between size-adjusted perivisceral fat (PF) residuals and size-adjusted gonad mass residuals in bogue sampled from fish farms during January–June 2023 in the Eastern Adriatic Sea. Points represent individual fish; the black line represents a descriptive linear fit.

Dodatna slika S2. Odnos između reziduala veličinski prilagođene perivisceralne masti (PF) i reziduala veličinski prilagođene mase gonada u bukve uzorkovane s uzgajališta tijekom siječnja - lipnja 2023. u istočnom Jadranskom moru. Točke predstavljaju pojedinačne ribe; crna linija predstavlja opisni linearni model prilagodbe.

Source: Authors



Supplementary Figure S3. Diagnostic plots for the adjusted gonad-weight model testing the association between gonad mass and perivisceral fat (PF), while accounting for total length, sex, bimonthly period and farm site. Panels show residuals versus fitted values, normal Q–Q plot, scale-location plot, and residuals versus leverage.

Dodatna slika S3. Dijagnostički grafovi prilagođenog modela mase gonada kojim se testira povezanost između mase gonada i perivisceralne masti (PF), uz uzimanje u obzir ukupne dužine, spola, dvomjesečnog razdoblja i lokacije uzgoja. Prikazi pokazuju reziduale u odnosu na prilagođene vrijednosti, normalni Q - Q graf, graf mjerila i položaja te reziduale u odnosu na polugu.

Source: Authors

Supplementary Table S1. Number of bogue samples per bimonthly period/farm site

Dodatna tablica S1. Broj uzoraka bukve prema dvomjesečnom razdoblju i lokaciji uzgajališta

Farm site	Region	Jan–Feb	Mar–Apr	May–Jun	Total
Budava	Istria	19	20	21	60
Košara	Zadar County	3	14	35	52
Lavdara	Zadar County	33	121	25	179
Veložalo	Zadar County	0	20	0	20
Total		55	175	81	311