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Research Article

Growth Dynamics and Health Assessment of Endangered Caspian Sea Sturgeons: Length-Weight Relationships, Condition Factor, and Reproductive Insights

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ABSTRACT

This study investigated the condition factor (K) and length-weight relationship (LWR) of *Acipenser persicus* and *Acipenser stellatus* in the Iranian waters of the Caspian Sea to assess their health and growth dynamics. A total of 90 specimens were collected, including 55 *A. persicus* (Persian sturgeon) and 35 *A. stellatus* (stellate sturgeon). Fish were captured using beach seines, chosen for their effectiveness in targeting sturgeons in shallow coastal zones. The condition factor, calculated as $K = (W/L^3) \times 100$, revealed values of 0.50 for *A. persicus* and 0.39 for *A. stellatus*, indicating a slim body condition likely due to nutritional stress or environmental constraints. The LWR, expressed as $W = aL^b$, showed negative allometric growth ($b < 3$) for *A. persicus*, suggesting slower weight gain relative to length, and positive allometric growth ($b > 3$) for *A. stellatus*, indicating faster weight gain. Significant correlations were found between total length, total weight, and ovarian egg weight in both species, highlighting the reproductive potential of larger individuals. The predominance of mid-sized individuals and scarcity of larger ones suggest overfishing as a contributing factor to population declines. These findings underscore the need for species-specific management strategies, including reduced fishing pressure and habitat restoration, to support the conservation of these critically endangered sturgeons. The aim of this study was to investigate the length-weight relationship (LWR), length-length relationship (LLR), condition coefficient, and the relationship between body size and egg weight for the stellate sturgeon (*A. persicus*) and the stellate sturgeon (*A. stellatus*) in the southern Caspian Sea to provide vital data to support conservation and fisheries management efforts.

1. Introduction

Sturgeons, belonging to the family Acipenseridae, repressent a critical ecological and economic resource globally, particularly in the Caspian Sea, which hosts some of the most iconic sturgeon populations. These ancient fish are of immense value to Iran, contributing significantly to both commercial fisheries and cultural heritage. In Iran, sturgeon fishing primarily occurs along the Caspian Sea coast and its associated river systems, employing methods such as gill nets and beach seines, following the prohibition of hook-based fishing in 1952 [1]. Historically, the Caspian Sea supported some of the world's largest sturgeon stocks, and Iran was among the principal harvesters of these species. However, overexploitation, habitat degradation, pollution, and disruption of spawning grounds have led to a drastic decline in sturgeon populations, with catches plummeting from 1,200 tons in 2000 to just 85 tons by 2010 [2;3]. Recent conservation measures, including stricter fishing regulations and extended bans on commercial sturgeon harvest, further highlight the precarious status of these species and the need for robust biological data to support management decisions. These threats underscore the urgent need for conservation and sustainable management to prevent the extinction of these valuable species. Among the Caspian sturgeons, Acipenser persicus (Persian sturgeon) stands out as a commercially and ecologically significant species, predominantly inhabiting the southern Caspian Sea. Classified as critically endangered by the International Union for Conservation of

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Nature (IUCN), this species has been a cornerstone of Iran's sturgeon fishery for decades [4;5]. Similarly, Acipenser stellatus (stellate sturgeon), another key species, is widely distributed across the Caspian Sea and occasionally found in the Black and Aegean Seas. This anadromous species undertakes seasonal migrations, moving northward in spring to feed on nutrient-rich waters and returning to the southern Caspian in autumn [6]. Like A. persicus, A. stellatus is also listed as critically endangered due to habitat loss and overfishing [4]. For long-lived, data-poor species such as sturgeons, accurate length–weight relationships (LWRs), length–length relationships (LLRs), and condition factors are fundamental tools for converting length data into biomass, assessing population health over time, and evaluating the effectiveness of restoration programs. Moreover, the relationship between female body size and egg weight provides a simple but powerful proxy for reproductive investment and is directly relevant to broodstock selection and hatchery-based stock enhancement. Despite the ecological and economic importance of Caspian sturgeons, most available biometric and reproductive information originates from studies conducted more than a decade ago, before recent changes in fishing pressure, illegal harvest, and conservation policies. There is still limited consensus on how current management interventions and environmental conditions are reflected in the growth, condition, and reproductive traits of wild A. persicus and A. stellatus in the southern Caspian Sea. Updating LWR, LLR, condition factor, and body size–egg weight data for these critically endangered species is therefore essential to refine stock assessments and design more effective, size- and species-specific management strategies. This study addresses the following research questions: (1) What are the current LWRs and LLRs of A. persicus and A. stellatus in the southern Caspian Sea, and do these parameters differ between species? (2) How do condition factors vary with body size and between the two species, and what do these patterns imply for their health and growth performance in a heavily impacted ecosystem? (3) What is the quantitative relationship between female body size and egg weight, and how can this information be used to improve broodstock management and stock enhancement programs? By explicitly linking somatic growth metrics with reproductive traits, the present work contributes to the ongoing debate on whether existing conservation measures and hatchery releases are sufficient to restore viable sturgeon stocks or whether more targeted, evidence-based interventions are needed. This study aims to investigate the length-weight relationship (LWR), length-length relationship (LLR), condition factor, and the relationship between body size and egg weight for A. persicus and A. stellatus in the southern Caspian Sea, providing critical data to support conservation and fishery management efforts. The main contributions of this research are: (i) providing up-to-date biometric and reproductive data for two critically endangered sturgeon species under current management conditions; (ii) integrating growth and condition indices with egg-related traits to generate biologically interpretable indicators for broodstock selection and release strategies; and (iii) offering empirical evidence that can be directly incorporated into national and regional sturgeon management plans.

2. Materials and methods

2.1. Sampling Area and Collection

This study was conducted along the coastal waters of western Guilan Province, Iran, from Kiashahr to Astara in the southern Caspian Sea (Figure 1). Sampling was designed to coincide with the seasonal migration of sturgeons to the southern Caspian, maximizing the capture of mature individuals. A total of 90 specimens were collected, including 55 *A. persicus* (Persian sturgeon) and 35 *A. stellatus* (stellate sturgeon). Fish were captured using beach seines deployed from the shoreline, because this gear is widely used by local fisheries, allows efficient sampling of sturgeons in nearshore migration corridors, and enables rapid handling and release of individuals. Compared with gillnets and longlines, beach seines reduce the risk of deep hooking and lethal injury, which is particularly important for critically endangered species. However, this method may underrepresent larger, deeper-dwelling individuals and fish that remain offshore, potentially biasing the sample toward sturgeons that utilize shallow coastal zones during migration. We therefore interpret the results as representative of coastal-migratory components of *A. persicus* and *A. stellatus* rather than the entire population across all depth ranges. To minimize stress and adhere to ethical standards for handling endangered species, all fish were processed promptly and, where feasible, released back into their habitat [7]. Sampling was conducted under permits issued by the Iranian Fisheries Organization, ensuring compliance with national regulations for protected species.

2.2. Morphometric measurements

Each specimen was measured for total length (TL, cm), fork length (FL, cm), standard length (SL, cm), and total wet weight (W, g) using a digital caliper (accuracy ±0.1 mm) and a precision electronic balance (±0.1 g). For mature female sturgeons, gonad weight (egg weight, g) was recorded to evaluate reproductive output relative to body size. Measurements were taken immediately post-capture to ensure accuracy, and data were cross-verified to eliminate errors.

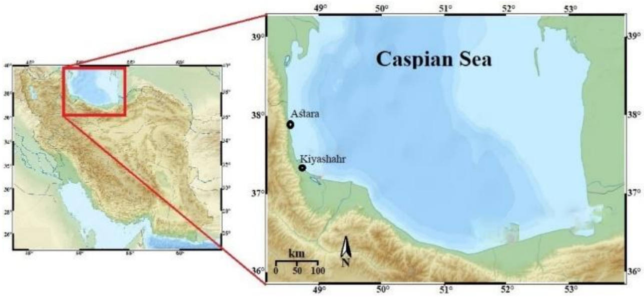

Fig. 1. Sampling areas

This rigorous approach provided a robust dataset for analyzing morphometric relationships critical to conservation and fishery management. Because all measurements were obtained by the same train-ed team using calibrated instruments and standardized procedu-res, measurement error and observer bias were minimized.

2.3. Length–weight relationship (LWR) and condition factor

The length-weight relationship was modeled using the power function:

$$W = aL^b \tag{1}$$

Where *W* shows the weight, *L* the length, *a* y-intercept, and *b* the relationship slope [8]. The growth pattern was determined by the 95% computational confidence range and Pauly -Test [9].

Data related to age, length, weight, and also growth pattern of fish have always been valued in management and evaluation of their reserves [10].

When the regression coefficient equals or is close to 3, the fish has isometric growth and the growth of fish in all dimensions will be done equally. When *b* is larger or smaller than 3, it represents the growth of allometric. The *b* value greater than 3 shows positive allometric growth and the *b* value is less than 3, showed the negative allometric growth.

Fish health can be calculated using the relationship between weight and fish length. This calculation is done through the Fulton Condition Index (CI) equation.

$$K = 100 \times (W/L^3) \tag{2}$$

where (W) is the total weight (g) and (L) is the total length (cm). This metric provides insights into the physiological health of the fish, reflecting factors such as nutritional status, reproductive condition, and environmental suitability. Higher (K) values indicate better condition, which is particularly relevant for assessing the fitness of critically endangered species like *A. persicus* and *A. stellatus* [11].

2.4. Body size–egg weight relationship

To investigate reproductive potential, the relationship between body length, body weight, and egg weight was analyzed for mature female sturgeons. Egg weight was measured using a precision balance, and regression models were employed to explore correlations between these parameters. This analysis aimed to elucidate how body size influences reproductive output, providing valuable data for stock assessment and conservation strategies [12].

2.5. Data classification

Morphometric data were classified using Sturges' rule to determine the optimal number of classes for length and weight distributions:

$$K = 1 + 3.3 \log n \tag{3}$$

$$I = \left(\max(xi) - \min(xi)\right)/K \tag{4}$$

where (*K*) is the number of classes, (*n*) is the sample size, and (*I*) is the class interval. This method ensured accurate categorization of data for comparative analyses between species.

2.6. Statistical analysis

Data were analyzed using R Statistical Software (version 4.4.1) and SPSS (version 28). Normality was assessed using the Shapiro-Wilk test, and outliers were removed based on the interquartile range method. Differences in LWR parameters and condition factors between *A. persicus* and *A. stellatus* were evaluated using analysis of covariance (ANCOVA), with length as a covariate. All statistical tests were conducted at a 95% confidence level (alpha = 0.05). To reduce potential bias associated with unbalanced sample sizes between species, model diagnostics and residual plots were examined, and sensitivity analyses were performed by re-fitting models after excluding extreme values.

2.7. Quality control and ethical considerations

To ensure data integrity, measurements were performed by trained personnel, and equipment was calibrated daily. Handling time was minimized to reduce stress on the fish, and ethical guidelines for endangered species research were strictly followed. The study complied with national and international regulations, including those outlined by the IUCN Red List for critically endangered sturgeons [7].

3. Result

The length–weight relationship (LWR) was used as a critical tool to provide insights into growth patterns and to enable the estimation of biomass from length measurements [13]. Additionally, the condition factor (K) served as an indicator of fish health, nutritional status, and habitat suitability, reflecting physiological adaptations to environmental conditions [11]. The allometric growth parameter (*b*) in the LWR equation (Eq. 1) distinguished between isometric ($b \approx 3$) and allometric ($b \neq 3$) growth patterns and therefore provided valuable information for stock assessment and fishery management [14].

Figure 2 showed the length–frequency distribution of *A. persicus* and *A. stellatus* in the sampled population. For *A. persicus*, the highest frequency was observed in the 156–168 mm length class, whereas the lowest frequency occurred in the 192–204 mm length class. For *A. stellatus*, the peak frequency was recorded in the 144–152 mm length class, with the lowest frequency in the 160–168 mm length class. These results indicated that both species were predominantly captured in intermediate length classes, suggesting a higher abundance of mid-sized individuals in the sampled area. The scarcity of individuals in larger length classes was tentatively attributed to overfishing, consistent with regional stock assessment studies that reported declining sturgeon populations under intensive fishing pressure [14;15], although additional information on fishing effort and historical catches would be required to confirm this explanation.

The length–weight relationship was determined for both species. The LWR of *A. persicus* showed negative allometric growth, whereas the LWR of *A. stellatus* showed positive allometric growth (Table 1).

The relationships between the different length measurements were presented in Table 2. There was a significant relationship between total length (TL) and fork length (FL) in both species ($p < 0.05$).

The LWR was estimated for *A. persicus* and *A. stellatus* using the standard equation $W = aL^b$, where W was total weight (g), L was total length (mm), and b was the allometric growth parameter. For *A. persicus*, the estimated b-value was lower than 3, indicating negative allometric growth, meaning that weight increased at a slower rate than length, whereas *A. stellatus* exhibited a b-value greater than 3, indicating positive allometric growth, with weight increasing faster than length (Table 1; [13]).

The relationship between TL and FL was analyzed by linear regression and was statistically significant for both species ($p < 0.05$; Table 2). In addition, a significant positive correlation was detected among total weight, ovarian egg weight, and total length in both species ($p < 0.05$, multiple regression analysis; [14]). These patterns were illustrated in Figure 3, which showed that increases in total length and total weight were associated with a corresponding increase in ovarian egg weight, as described by the fitted regression equation.

$$\text{weight of eggs}_{A.persicus} = -4.22 + 0.045_{Total\ lenght}$$

$$\text{weight of eggs}_{A.persicus} = -0.801 + 0.25_{Total\ weight}$$

$$\text{weight of eggs}_{A.stellatus} = -6.25 + 0.063_{Total\ lenght}$$

$$\text{weight of eggs}_{A.stellatus} = 0.85 + 168_{Total\ weight}$$

These findings highlighted the higher reproductive potential of larger individuals and underscored the relevance of length-based management strategies for sturgeon conservation [15].

4. Discussion

Fish growth is a continuous process throughout their lifespan, modulated by a complex interplay of biological and environmental factors. Key environmental determinants include temperature, dissolved oxygen, salinity, water flow, light intensity, food availability, and intra- or interspecific competition [14]. The condition factor (K) and length-weight relationship (LWR) are pivotal metrics in fisheries science, providing critical insights into the health, nutritional status, and growth dynamics of fish populations.

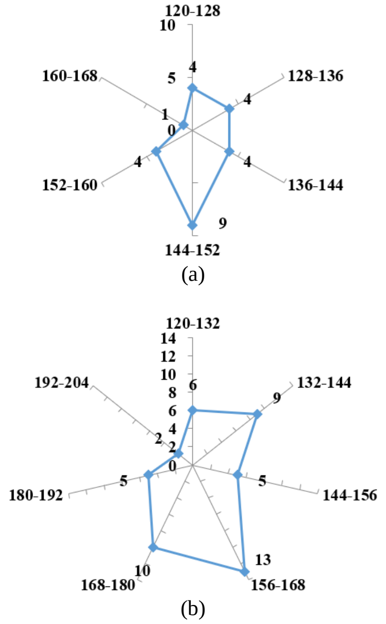

Fig. 2. The number of *A. stellatus* (a) the number of *A. persicus* (b) in length classification

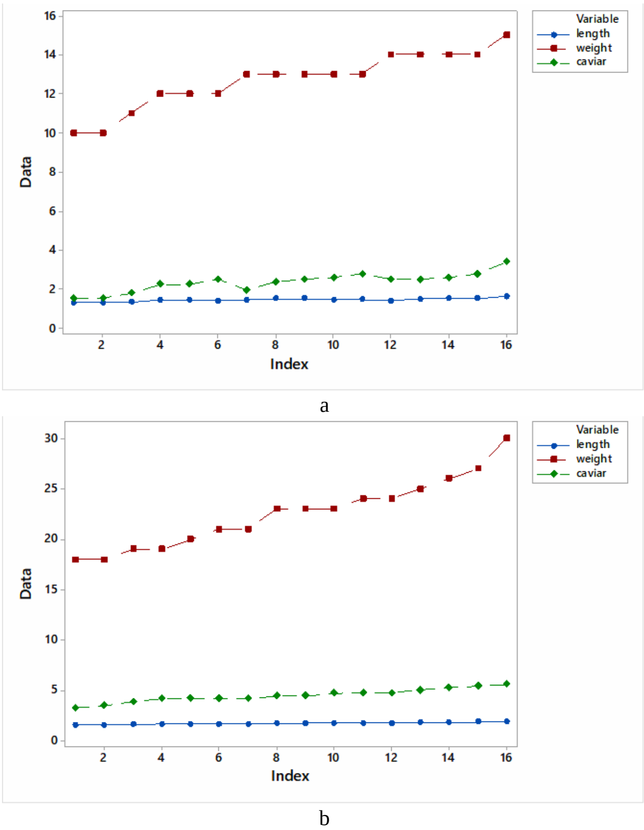

Fig. 3. Relationship between weight, length and weight of eggs in two species: *A. stellatus* (a) and *A. persicus* (b)

Table1. Length-weight relationship of *A. persicus* and *A. stellatus* in south of Caspian Sea

Species	Length characteristics (cm)		Weight characteristics (gr)		Parameters of the relationship		
	max-min	mean±SD	max-min	mean±SD	a	b	R^2
A. persicus	197-57	154.81±23.40	33000-6000	17500±5600	0.0068	2.88	0.92
A. stellatus	165-120	142.14±12.29	16000-6000	11280±2709	0.0022	3.26	0.89

Table 2. The relationship between total length (TL in cm) and fork length (FL in cm) for *A. persicus* and *A. stellatus* in south of Caspian Sea

Species	Length characteristics (cm)		Weight characteristics (gr)		Parameters of the relationship		
	max-min	mean±SD	max-min	mean±SD	a	b	R^2
A. persicus	197-57	141.82±22.30	180-49	141.82±22.30	0.725	1.04	0.97
A. stellatus	165-120	142.14±12.29	155-110	130.42±11.63	0.879	1.00	0.97

These parameters are particularly valuable for assessing the ecological and physiological status of commercially and ecologically significant species, such as sturgeons (Acipenser spp.), which are known for their high economic value and vulnerability to overexploitation [16]. This study investigated the condition factor (K) and LWR of A. persicus and A. stellatus in the Iranian waters of the Caspian Sea, revealing insights into their health, growth patterns, and potential environmental stressors. The results indicate that both species exhibit suboptimal health conditions, with A. persicus and A. stellatus having condition factors of 0.50 and 0.39, respectively, suggesting a slim body condition ($K < 1$). Additionally, the LWR analysis revealed negative allometric growth for A. persicus ($b < 3$) and positive allometric growth for A. stellatus ($b > 3$), consistent with species-specific growth patterns observed in previous studies. These findings underscore the influence of environmental and anthropogenic factors on sturgeon populations and highlight the need for targeted conservation strategies.

4.1. Condition Factor (K) and Fish Health

The condition factor (K), calculated as $K = (W / L^3) \times 100$, where W is the total weight (g) and L is the total length (cm), is a widely used index to evaluate the physiological and nutritional status of fish [17]. A K value of 1.0 indicates optimal health, reflecting a balance between energy intake and expenditure, while $K < 1$ suggests a slim condition, potentially due to poor nutrition or environmental stress, and $K > 1$ indicates a robust or fat condition, often associated with abundant food resources [12]. In this study, the condition factors of *A. persicus* ($K = 0.50$) and *A. stellatus* ($K = 0.39$) were significantly below 1, indicating that both species are in a slim state, likely reflecting suboptimal environmental conditions or resource availability in the Caspian Sea.

The low K values observed in this study may be attributed to several factors, including reduced food availability, habitat degradation, and fishing pressure. Sturgeons, as benthic feeders, rely heavily on macro invertebrates, such as amphipods, mysids, and small fish, which have been reported to decline in the Caspian Sea due to pollution, eutrophication, and invasive species like the comb jelly (*Mnemiopsis leidyi*) [18]. The introduction of *M. leidyi* in the late 1990s has disrupted the Caspian Sea food web, reducing zooplankton and forage fish populations, which are critical prey for sturgeons [19]. This reduction in prey availability likely contributes to the low condition factors observed in *A. persicus* and *A. stellatus*, as insufficient energy intake limits somatic growth and fat accumulation. Furthermore, habitat degradation, including pollution from industrial and agricultural runoff, has altered the benthic ecosystems that sturgeons depend on, further exacerbating nutritional stress [20].

Fishing pressure is another critical factor influencing the condition factor. Overfishing has significantly reduced sturgeon populations in the Caspian Sea, with historical catch data indicating a decline of over 80% in landings since the 1980s [21]. The selective removal of larger individuals, which typically exhibit higher K values due to greater energy reserves, may have skewed the population toward smaller, less robust individuals, as observed in this study. The low K values also suggest that surviving individuals may be allocating energy toward maintenance rather than growth or reproduction, a common response to environmental stress in long-lived species like sturgeons [22].

4.2. Length-Weight Relationship (LWR) and Growth Patterns

The LWR, expressed as $W = aL^b$, where W is weight (g), L is length (cm), and b is the allometric growth parameter, provides insights into the growth dynamics and body shape of fish. A b value of approximately 3 indicates isometric growth, where weight increases proportionally with the cube of length, while $b < 3$ (negative allometric) suggests that weight increases at a slower rate than length, and $b > 3$ (positive allometric) indicates that weight increases faster than length [23]. In this study, *A. persicus* exhibited negative allometric growth ($b < 3$), consistent with findings by Billard and Lecointre (2022) [16] for other sturgeon species under nutritional stress. This pattern suggests that *A. persicus* individuals in the Caspian Sea are elongating faster than they are gaining weight, potentially due to limited food resources or high energy expenditure in foraging.

In contrast, *A. stellatus* displayed positive allometric growth ($b > 3$), indicating that weight increases more rapidly than length. This finding aligns with reports by Pourkazemi and Bahmani (2024) [20], who noted positive allometric growth in *A. stellatus* populations in the southern Caspian Sea, possibly due to differences in diet or habitat preferences compared to *A. persicus*. *A. stellatus* is known to feed on a broader range of prey, including pelagic fish, which may provide a more energy-rich diet, contributing to its positive allometric growth [18]. However, the positive allometric growth observed in this study contrasts with Fazli and Moghim (2023) [24], who reported isometric growth ($b \approx 3$) for *A. stellatus* in the same region. This discrepancy may be attributed to temporal variations in environmental conditions, differences in sample size, or variations in the length range of sampled individuals. For instance, Fazli and Moghim (2023) [24] sampled a broader size range, which may have included larger individuals with different growth trajectories.

The differences in LWR between *A. persicus* and *A. stellatus* highlight species-specific responses to environmental conditions. Negative allometric growth in *A. persicus* may reflect a strategy to prioritize length over weight in resource-scarce environments, potentially enhancing swimming efficiency or predator avoidance [22]. Conversely, the positive allometric growth in *A. stellatus* suggests a more favorable energy balance, possibly due to access to higher-quality prey or less competition in its feeding niche. These findings underscore the importance of species-specific management approaches, as growth patterns can influence reproductive potential, survival rates, and resilience to environmental stressors.

The results of this study are consistent with several previous investigations of sturgeon populations in the Caspian Sea and other regions. For instance, Schneider et al. (2023) [23] examined the LWR of lake sturgeon (*Acipenser fulvescens*) in North American lakes and reported negative allometric growth ($b < 3$), similar to our findings for *A. persicus*. This similarity suggests that negative allometric growth may be a common response to environmental constraints in sturgeon species, particularly in systems affected by overfishing or habitat degradation. Similarly, Gessner and Jaric (2023) [21] reported low condition factors ($K < 1$) for *A. nudiventris* in the Caspian Sea, attributing these to reduced food availability and pollution, which aligns with the slim condition observed in our study.

However, some studies have reported contrasting results. For example, Fazli and Moghim (2023) [24] found isometric growth for *A. stellatus* in the Iranian waters of the Caspian Sea, differing from the positive allometric growth observed in this study. This discrepancy may be due to differences in sampling periods, as environmental conditions in the Caspian Sea have fluctuated significantly over the past decade due to climate change and invasive species [19]. Additionally, Bagenal and Tesch (2023) [12] reported positive allometric growth for *A. stellatus* in the northern Caspian Sea, consistent with our findings, suggesting that regional variations in prey availability or fishing pressure may influence growth patterns.

The condition factor results also align with broader trends in sturgeon populations. Nash et al. (2023) [17] reported that sturgeon species worldwide often exhibit K values below 1 in degraded habitats, reflecting chronic stress from pollution, overfishing, and habitat loss. The low K values in this study are particularly concerning given the critically endangered status of *A. persicus* and *A. stellatus* on the IUCN Red List [7]. These findings suggest that the Caspian Sea ecosystem may no longer support the nutritional needs of these species, necessitating urgent conservation measures.

4.3. Ecological and Management Implications

The low condition factors and species-specific LWR patterns observed in this study have significant implications for the management and conservation of *A. persicus* and *A. stellatus* in the Caspian Sea. The slim condition ($K < 1$) of both species indicates that individuals are likely experiencing nutritional stress, which can reduce reproductive success, growth rates, and resilience to environmental changes. For sturgeons, which are long-lived and late-maturing, poor conditions can have long-term consequences for population viability, as energy allocation to reproduction is critical for sustaining populations [16]. The negative allometric growth of *A. persicus* suggests that this species may be particularly vulnerable to food scarcity, as it is not accumulating sufficient energy reserves for growth or reproduction. In contrast, the positive allometric growth of *A. stellatus* indicates a relatively better energy balance, but the low K value suggests that even this species is under stress.

Overfishing is a primary driver of the observed patterns. The Caspian Sea sturgeon fishery has been heavily exploited for caviar production, leading to significant population declines [21]. The selective removal of larger individuals, which typically have higher K values and contribute disproportionately to reproduction, may explain the predominance of slim individuals in our samples. To address this, length-based management strategies, such as minimum size limits or slot limits, could help protect larger, reproductively valuable individuals [23]. Additionally, habitat restoration efforts, such as reducing pollution and mitigating the impacts of invasive species, are critical for improving food availability and supporting healthier populations.

The differences in LWR between *A. persicus* and *A. stellatus* also highlight the need for species-specific management plans. For *A. persicus*, conservation efforts should focus on enhancing prey availability and reducing fishing pressure to improve condition factors and support population recovery. For *A. stellatus*, maintaining access to high-quality prey, such as pelagic fish, could help sustain its positive allometric growth and reproductive potential. Stocking programs, which have been implemented in the Caspian Sea, should be tailored to the specific growth and nutritional needs of each species, with regular monitoring of K and LWR to assess the effectiveness of these interventions [20].

The findings of this study are based on robust sampling and statistical analyses, including linear and multiple regression models to assess LWR and relationships between total length, weight, and ovarian egg weight. However, several limitations should be considered. First, the sample size and length range of individuals may influence LWR estimates, as b values can vary with ontogenetic stage [17]. Future studies should aim to include a broader size range to capture the full spectrum of growth patterns. Second, the condition factor is sensitive to seasonal variations, as sturgeons may exhibit higher K values during spawning seasons due to gonad development [22]. Our study was conducted during a single season, and multi-seasonal sampling could provide a more comprehensive understanding of condition dynamics.

Additionally, the reliance on total length (TL) and fork length (FL) measurements assumes consistent measurement protocols, but slight variations in technique can affect LWR estimates. Standardizing measurement methods across studies would improve comparability [12]. Finally, the attribution of low K values to overfishing and reduced food availability is supported by regional studies, but other factors, such as temperature, salinity, or disease, could also play a role. Future research should incorporate environmental monitoring and bioenergetic modeling to quantify the relative contributions of these factors.

6. Conclusion

The condition factor and length–weight results for *A. persicus* and *A. stellatus* showed key aspects of the health and growth of these critically endangered sturgeons in the Caspian Sea. The low K values (0.50 for *A. persicus* and 0.39 for *A. stellatus*) pointed to nutritional stress, likely linked to reduced food, habitat degradation, and past overfishing. The negative allometric growth of *A. persicus* and the positive allometric growth of *A. stellatus* reflected different responses of the two species to current environmental and management conditions, with clear consequences for their reproduction and recovery. A main novelty of this study is that it provided recent field data on LWR, LLR, condition factor, and body size–egg weight relationships for both species in the southern Caspian Sea, bringing together information on body growth and reproductive output in one framework. These results broadly agree with previous reports on the decline of sturgeons but also reveal regional and temporal differences in condition and growth that need further study and can already be used in monitoring, broodstock selection, and defining size limits for protection.

6.1. Policy recommendations and future research

On the policy side, maintaining and effectively enforcing fishing restrictions, especially against illegal catches, remains essential, and simple biometric indicators such as length, weight, and K should be included in routine national and regional monitoring to track population status. Improving and protecting key habitats and feeding areas, as well as using the observed body size–egg weight patterns to select better-condition broodstock and choose suitable release sizes and times in hatchery programs, can support recovery efforts, especially if accompanied by stronger regional cooperation among Caspian countries. Future research should extend sampling over more years and areas, combine biometric data with age and movement studies, examine how environmental factors affect condition and reproduction, and evaluate how specific management measures influence these indicators and the pace of stock recovery.

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