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Observations of vertebral deformities during a routine automatic grading step of juvenile pikeperch (*Sander lucioperca*) – A case study

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Abstract. The production of larvae and juveniles remains one of the major bottlenecks in pikeperch (*Sander lucioperca*) aquaculture due to high mortality rates and skeletal deformities, which lead to economic losses. Recent studies indicated a potential effect of grading on spinal deformities in pikeperch. As part of a project on the potential effects of grading on spinal deformations in *S. lucioperca*, we compared spinal structures of juveniles with fully formed spinal structures during the first automatic grading step in an industrial setting. We analyzed specimens at the age of 57 (pre-grading) and 58 dph (post-grading) using comparisons of morphometric parameters and skeletal analyses based on clearing and double-staining. Within our sample group, we did not observe direct influences of the observed grading step on spinal deformities. However, the observations made revealed region-specific susceptibility to certain deformity types. Lordosis and scoliosis occurred most frequently in the spinal areas near the second dorsal fin. Vertebral compression was predominantly found in the spine sections around vertebra 5 and from 24 to 30, whereas vertebral fusions peaked in the caudal region from vertebrae 40 to 43. Comparisons of internally and externally detected deformation rates demonstrate the importance of skeletal analyses for detailed identification of deformities. This can help to develop standardized deformity assessment protocols in the future, which can enhance both production efficiency and animal welfare in pikeperch aquaculture.

1 Introduction

Pikeperch (*Sander lucioperca*) represents notable aquaculture potential due to its ability to support the development and economic success of the aquaculture industry (Policar et al., 2019). However, its husbandry remains challenging, primarily due to an insufficient provisioning of fish for stocking and quality-limiting factors such as skeletal deformations (Cantillo et al., 2024; Chandra et al., 2024; Panana et al., 2024; Péter et al., 2023; Policar et al., 2019). Deformities contribute to economic losses at various stages of the production process due to reduced growth efficiency and lowered commercial value (Boglione and Costa, 2011). Deformation prevalence and severity are strongly influenced by a broad range of factors, including genetic predisposition, environmental conditions, and nutritional factors (Berillis, 2015; Chandra et al., 2024; Eissa et al., 2021). Recently, the connection between early grading and increased incidence of spinal deformities has been demonstrated for pikeperch (Franz et al., 2025). However, as intra-cohort cannibalism is a remaining challenge for pikeperch aquaculture, preventative measures such as grading are necessary and commonly applied (Król et al., 2019; Policar et al., 2019; Szczepkowski et al., 2011). In this context, various grading methods and tools are used. Traditional grading typically involves manual handheld sorting devices like cradles or grading whips, commonly used for smaller and more fragile larval stages (Gabriel et al., 2016; Lekang, 2013). Automatic grading systems are gener-

ally applied to juveniles and older stages. However, as with any handling procedure, these methods can induce stress and physical injury, potentially leading to increased mortality rates (Ashley, 2007).

Because a broad range of husbandry conditions influences a fish's skeletal system and its development, the condition of the skeletal system is an important quality marker. Skeletal deformations can be defined as structural changes due to extrinsic or intrinsic factors (Martini et al., 2023). Changes such as vertebral compressions and fusions can lead to lordosis, an abnormal dorsoventral curvature of the vertebral column, or result in lateral deviations, classified as scoliosis (Hattori et al., 2003; Witten et al., 2009). The vertebral column of fishes can be broadly divided into two main regions: the anterior precaudal, also known as the abdominal region (which is characterized by the presence of ribs), and the posterior caudal region (Hilton, 2011; Rockwell et al., 1938). Generally, spine structures are formed out of a combination of cartilaginous and calcified tissues, which arise from different developmental origins. Except for the caudal fin skeleton, the vertebral column develops in a defined ontogenetic pattern, with the centra mineralizing progressively in a sequence from anterior to posterior (Ott et al., 2012; Schultze and Arratia, 2013). In particular, the precursor structures of the vertebral column show heightened sensitivity to environmental conditions (Boglione et al., 2013b; Witten and Hall, 2015). Consequently, certain areas of the later mineralized caudal spine could be more susceptible to external factors.

As part of a project on these potential influences of grading procedures (Franz et al., 2026), this observational case study aims to gain first insights into the susceptibility of pikeperch spines to a grading step after vertebral structures are fully formed. For this, juvenile specimens with these fully formed spinal elements were analyzed, as previous studies already focused on earlier developmental stages (Franz et al., 2025). In addition, we want to compare before and after grading specimens based on external and internal evaluations to investigate the occurrence of lordosis, scoliosis, vertebral compressions, and fusions along the spine. Furthermore, we wanted to test the hypothesis that the grading process selectively influences juveniles of *S. lucioperca* with deviating body shapes.

2 Material and methods

2.1 Specimen husbandry

Sander lucioperca specimens were obtained from a commercial rearing structure of an aquaculture facility in Germany. The details are described in Franz et al. (2026) and are briefly summarized here. Fertilized eggs were incubated in McDonald jars until hatching at 7 d post-fertilization (dpf). Larvae were reared in larval tanks until 29 d post-hatch (dph), then transferred to larger juvenile systems: round tanks of 3 m in diameter and 1 m in water height. During rearing, water temperature gradually increased from 13.5 to 19.0 °C, with pH 7.9, dissolved oxygen 6.5–7.0 mg L^{-1}, hardness 4.4° dH, Ca^{2+} 27.4 mg L^{-1}, Mg^{2+} 2.5 mg L^{-1}, and P 42 µg L^{-1} (Oceamo e.U. water analysis). From 3 dph, larvae received pure and DHA-enriched *Artemia nauplii* (brine shrimp eggs, Ocean Aquaculture; Easy DHA, INVE), which were replaced at 23 dph by pelleted larval feed (Otohime B1, B2, and C2; 2.5 % Ca^{2+}, 2.2% P), provided according to the aquaculture facility's protocol. Lighting followed an 08 : 16 h light–dark cycle at low intensity.

2.2 Grading and sampling

Pikeperch larvae were initially graded at 33 dph, followed by a periodic grading step per week. For the first three gradings, manual grid graders were used. At each grading, all fish were carefully netted and manually sorted using fixed-distance bar boxes. Grid distances differed by 0.5 mm during the first grading and 1.0 mm during subsequent grading steps. At 57 dph, the pikeperch juveniles went through the first automatic grading using a bar grading machine (Akuakare BB1, Fish Grading Machine Balikteknik). In this system, specimens are transported along a water-lubricated plate beneath spinning bars with progressively increasing distance. Depending on their body width, specimens pass through the gap at different positions and are sorted into three size categories. For this study, samples were obtained on 2 consecutive days, before (57 dph) and after (58 dph) the first automated grading. The pre-grading and post-grading groups were sampled with 42 and 40 specimens, respectively. To focus on the impact on already formed spine structures, only specimens from the largest size group were considered here, both prior to and after automatic grading (rolling bar distance > 8 mm). To obtain a representative sample from the rearing tank, fish were netted from different areas and depths. Following this, specimens were euthanized with an overdose of MS222 (Merck-Sigma) in a 0.5 g L^{-1} solution (pH 7.2 in $1 \times$ PBS) for a minimum of 3 min. The cessation of opercular movements was closely monitored to ensure euthanasia. Afterwards, specimens were stored in 70 % ethanol solution for further laboratory analysis. Handling and euthanasia complied with EU Directive 2010/63/EU and the German Animal Welfare Act (TierSchG).

2.3 Morphometry

Ten external morphometric parameters were determined. These comprised total length (TL); standard length (SL); head length (HL); preanal length (PRA); postanal length (POA); body height at two points (at the first dorsal fin – BHF, at the anus – BHA); body width at two points (at the first dorsal fin – BWF, at the anus – BWA), expressed in mm (Fig. 1); and weight, expressed in g. Parameters were measured with a digital caliper (MIT 500-171-30 Absolute Digimatic, Mitutoyo Corporation) before staining. The wet

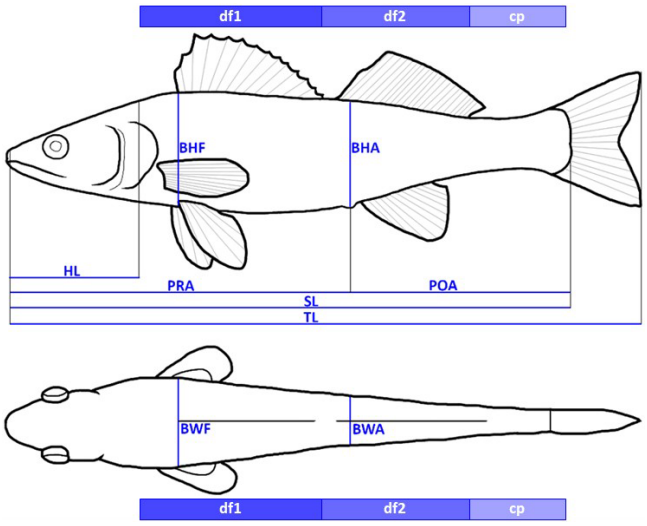


Figure 1. External morphometric parameters measured on *S. lucioperca* juveniles and body regions. BHA: body height at the anus; BHF: body height at the first dorsal fin; BWA: body width at the anus; BWF: body width at the first dorsal fin; HL: head length; POA: postanal length; PRA: preanal length; SL: standard length; TL: total length (all parameters expressed in mm). Body regions df1: operculum to posterior end of first dorsal fin, df2: anterior end of first dorsal fin to posterior end of second dorsal fin, and cp: posterior end of second dorsal fin to posterior notochord end.

weight of the samples was determined with a precision scale (Sartorius CP2245) after drying them for 3 s to remove excess ethanol solution. The process was done uniformly for all specimens to keep potential effects from the ethanol storage on weight and length similar for all specimens.

Furthermore, the externally visible deformation status of the spine in three body sections was determined. Body sections were defined as df1, operculum to posterior end of first dorsal fin; df2, posterior end of first dorsal fin to posterior end of second dorsal fin; and cp, posterior end of second dorsal fin to posterior notochord end (Fig. 1). Externally visible deformations, such as the dorsoventral bending (lordosis) and lateral curvature (scoliosis) of the vertebral column, were documented before staining. Accordingly, these abnormal spine curvatures were attributed to the three anatomical sections of the spinal column.

2.4 Clearing and staining procedure, and skeletal analysis

For internal examination of the skeletal system, the cleaning and staining of bone and cartilage was adapted after Taylor and Van Dyke (1985). Using this method, the cartilage matrix is stained with alcian blue (Roth, no. 3082), and calcified tissue is stained with alizarin red (Roth, no. 0348). The digestion was prolonged to adapt to the specimens' size, using a trypsin solution (borax solution, 0.375 g L^{-1}, 1000–2000 BAEE units mg^{-1} trypsin) for up to 12 d for the largest specimens. Here, the solution was renewed approximately every 3–4 d when it became bluish in color. For bleaching, a solution of 0.5 % KOH and 25 mL L^{-1} 3.5 % H_2O_2 was applied for 4–5 h. For long-term storage, the specimens were gradually transferred to a mixture of 85 % glycerol and 15 % KOH (0.5 %) with thymol to prevent the formation of mold. To improve the visibility of the spine, the specimens were descaled and stored in glycerol for about 14 d to maximize the effect of transparency.

2.5 Deformation analysis

After clearing and staining, abnormal curvatures in the areas of the vertebral column were again examined according to the body areas (compare Fig. 1). Following this, single vertebrae were analyzed in more detail. For this, all individual vertebrae were counted. In addition, they were categorized into the anatomically distinct spine areas of postcranial vertebrae, precaudal vertebrae, and caudal vertebrae (Fig. 2), as these can possess different mechanical properties due to different vertebral anatomy. Postcranial vertebrae are directly adjacent to the cranial region and have no ribs. The precaudal vertebrae feature medial arches, neural spines, parapophyses, and ribs. Caudal vertebrae are equipped with a centrum, and neural and haemal arches and spines (Hilton, 2011; Ott et al., 2012; Schultze and Arratia, 2013).

The pikeperch juveniles were analyzed for vertebral deformities before and again after staining, as described above, using a stereo microscope (Leica SD9, Leica Microsystems GmbH). The external appearance of deformities is illustrated by a comparison of normal (Fig. 4A1) and deformed juveniles (Fig. 4B1, 4C1, 4D1). Exemplary photographs were taken using a digital microscope camera (Moticam 5.0 Plus, Motic) and Motic Images Plus 3.0 Software (version 3.0.14.80, Motic). Image processing and illustration were performed with GIMP software (version 2.10.38). The now-visible internal single-vertebra deformations (Fig. 4B2, 4C2, 4D2) were recorded in the same manner, with a focus on compressions and fusions.

2.6 Statistics

Morphological data are presented as mean ± standard deviation (SD) and deformation prevalence in percent of examined juveniles. Statistical analyses and data visualizations were conducted with GraphPad Prism (version 10.6.1, GraphPad Software Inc., now part of Dotmatics). We initially removed outliers using the ROUT method ($Q = 1\,\%$), based on robust regression and outlier detection (Motulsky and Brown, 2006). Distribution normality was tested with the Shapiro–Wilk test, and variance homogeneity was examined using the Brown–Forsythe test. Comparisons of unpaired groups with differing sample sizes were performed using the Kruskal–Wallis test by ranks. Pairwise post hoc testing was performed

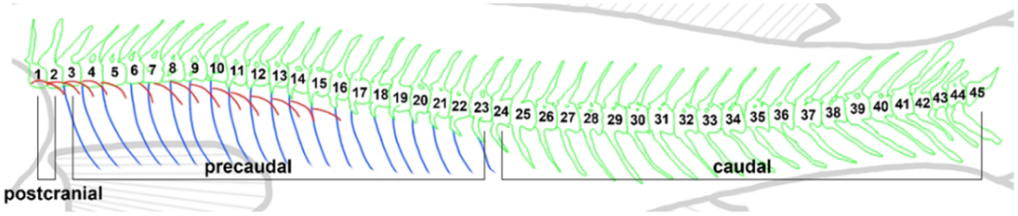


Figure 2. Schematic representation of the spinal elements of *S. lucioperca*. The individual sections of vertebral column are numbered postcranial vertebrae (1–2), precaudal vertebrae (3–23), and caudal vertebrae (24–45).

using the Dunn's test to adjust for multiple comparisons. Values of $p < 0.05$ were considered statistically significant.

3 Results

3.1 Morphometry

Within the specimens' groups, the overall size, independently of separated grading size groups, was 56.2 ± 8.5 mm (min 36.8 mm, max 78.9 mm) before and 54.9 ± 9.3 mm (min 35.8 mm, max 80.8 mm) after the automatic grading step. The largest group pikeperch juveniles examined here were assessed for main growth parameters length and weight. Total length (TL) of non-deformed juveniles at this age was 67.7 ± 5.3 mm (pre-grading) and 71.7 ± 4.1 mm (post-grading), in contrast to 58.4 ± 6.8 mm (pre-grading) and 58.1 ± 6.6 mm (post-grading) in deformed pikeperch. Standard length (SL) displayed the same pattern. TL and, respectively, SL, showed significantly lower values in deformed animals before and after grading (Fig. 3A and 3B). The average head length (HL) of the examined juvenile pikeperch were around 13 mm in both groups. After grading, the HL was significantly greater in non-deformed animals (15.1 ± 1.1 mm) than in deformed specimens (Fig. 3C). In contrast, the wet weight was equal in the four examined groups (range 2.8–3.2 g) (Fig. 3D). In addition, parameters of body height at two points (BHF, BHA) and body width at two points (BWF, BWA) showed no significant differences (Fig. 3E to 3H), regardless of grading process or deformation status. In contrast, juveniles were longer in terms of the preanal and postanal length (PRA, POA) in non-deformed fish (average: 38.2 mm PRA; 33.0 mm POA) compared to deformed offspring (average: 31.3 mm PRA; 27.6 mm POA), whereby this effect became significantly pronounced after sorting (Fig. 3I and 3J).

3.2 Spinal morphology and deformation analysis

The vertebral column of the juvenile pikeperch was fully developed and contained 45 pre- and postcranial vertebrae in both the pre- and post-grading groups. Of the total 82 specimens, 39 (47.6 %) specimens showed externally visible deformations of different types (Fig. 4). Before grading, 20 (47.6 %) affected pikeperch were counted and, after grading, 19 (47.5 %). After using clearing and staining techniques, the internal analysis revealed a total of 37 (45.1 %) affected specimens, with 17 (40.5 %) in the pre-grading group and 20 (50 %) in the post-grading group, respectively.

To investigate the association between abnormal spinal curvatures in the dorsoventral and lateral axes in pre-grading and post-grading juvenile pikeperch, data were analyzed for the predefined body regions df1, df2, and cp (Fig. 1). The occurrence of lordosis and scoliosis in the examined fish was observed separately, externally, and internally, and varied depending on the analysis method (Table 1). External examination resulted in a lower estimation of abnormal spinal bends. The most evident difference was observed in the case of scoliosis in anatomical section df1 before grading (external: 0 %, internal: 45.5 %) and after grading (external, 9.5 %, internal: 61.5 %). The center of the body in the anatomical section df2 was most affected by lordosis and scoliosis, both before and after grading. The caudal segment cp exhibited the lowest deformation rates (range 23.8 % to 47.6 %), independent of detection method and grading process.

All cleared and stained specimens were inspected for vertebral compression and fusion in the individual vertebrae (Figs. 5 and 6). Prior to automatic grading, 60 % of pikeperch displayed no vertebral compression. Pre-existing compressions followed a distinct regional pattern, with segments of precaudal and anterior caudal vertebrae showing a higher incidence. The trend peaked at vertebrae 5 and 17, as well as 25. Post-grading, the proportion of deformed fish increased slightly from 40 % to 45 %. The pattern was similar, with only slightly shifted peaks at vertebrae 5, 20, and 28. The individual vertebrae in region 32 to 45 were largely unaffected by compression in both groups (Fig. 5).

In contrast to compression, vertebral fusion occurred at a low overall frequency along the vertebral column. Fusion of two or more vertebrae was observed in 21 % of juveniles before grading and 33 % after grading. The spatial distribution was similar in both groups, with isolated events in the postcranial and precaudal regions. Peaks were observed in the caudal vertebrae, increasing posteriorly to vertebra 30 and occurring particularly at vertebrae 40–43 (Fig. 6).

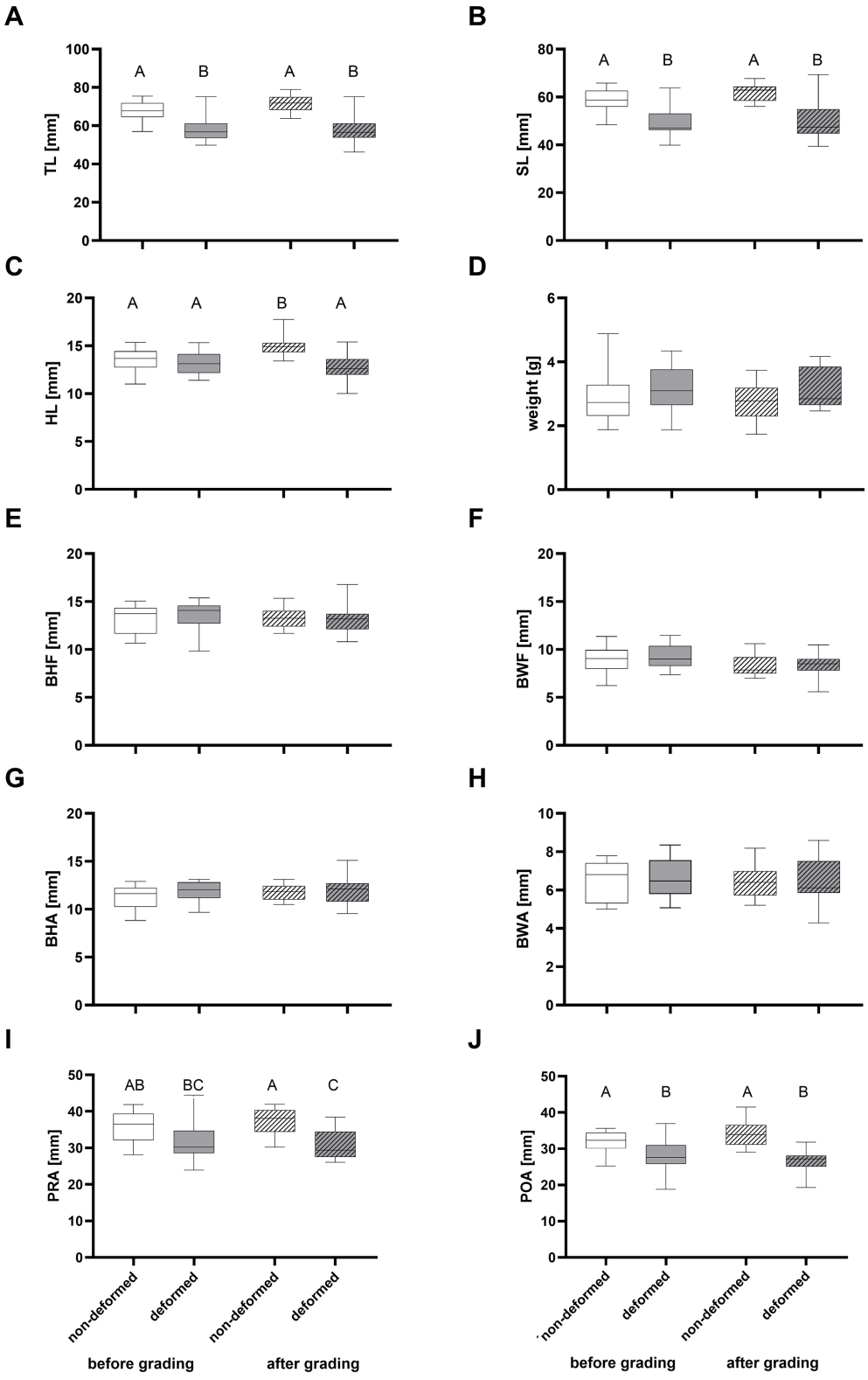


Figure 3. Comparison of morphometric parameters in non-deformed and deformed pikeperch (*S. lucioperca*) juveniles before (57 dph) and after (58 dph) automated grading. Non-deformed (white bars) and deformed (gray bars) specimens are shown. **(A)** TL: total length, **(B)** SL: standard length, **(C)** HL: head length, **(D)** weight, **(E)** BHF: body height at the first dorsal fin, **(F)** BWF: body width at the first dorsal fin, **(G)** BHA: body height at the anus, **(H)** BWA: body width at the anus, **(I)** PRA: preanal length, **(J)** POA: postanal length. Significantly different groups are marked by different letters, and groups without letters are not significantly different ($p < 0.05$).

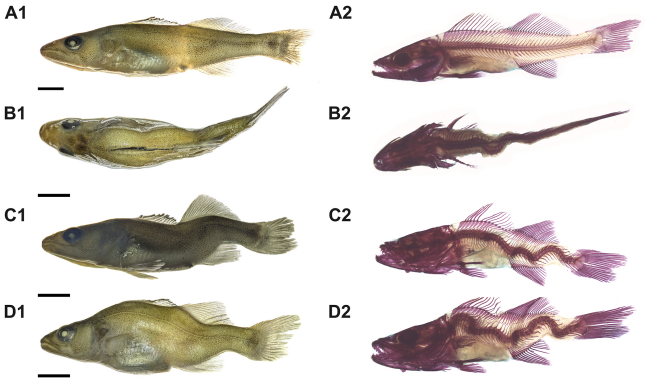


Figure 4. Types of deformations found in pikeperch (*S. lucioperca*) specimens during the external and internal deformation analysis. General examples of externally evaluated specimens: **(A1)** normal fish; **(B1)** scoliosis; **(C1)** lordosis; **(D1)** combined scoliosis and lordosis. Internal evaluation example specimen with spinal structures visible after clearing and staining: **(A2)** normal fish; **(B2)** scoliosis; **(C2)** lordosis; **(D2)** combined scoliosis and lordosis. Scale bar = 5 mm.

Table 1. Comparison of abnormal spine curvature types in % of examined pikeperch (*S. lucioperca*) juveniles in body regions df1 (gill cover to posterior end of first dorsal fin), df2 (anterior end of first dorsal fin to posterior end of second dorsal fin), and cp (posterior end of second dorsal fin to posterior notochord end). "External" relates to curvatures identified before and "internal" to observations after the clearing and staining.

Defect type (detection)	Affected body region		
	df1	df2	cp
Pre-grading ($n = 22$ juvenile)			
Lordosis (external)	45.5 %	63.6 %	36.4 %
Lordosis (internal)	54.6 %	72.7 %	36.4 %
Scoliosis (external)	–	22.7 %	40.9 %
Scoliosis (internal)	45.5 %	50.0 %	31.8 %
Post-grading ($n = 21$ juvenile)			
Lordosis (external)	52.4 %	76.2 %	38.1 %
Lordosis (internal)	57.1 %	66.7 %	47.6 %
Scoliosis (external)	9.5 %	52.4 %	23.8 %
Scoliosis (internal)	61.9 %	66.7 %	23.8 %

4 Discussion

As part of a broader project investigating the potential effects of grading processes, this observational case study was designed to gain initial insights into the vulnerability of the vertebral structures of the pikeperch (*S. lucioperca*) to the first automatic grading after vertebral formation is completed. Within this limited data set, only preliminary insights into the influences of automatic grading have been possible. However, we were able to find associations with morphometric parameters, indicating selective sorting of deformed specimens, and furthermore found region-specific prevalence of vertebral deformation types. No specific indicators of influences of the single grading step on the fully formed spine were found, but a long-term accumulation of small influences from mechanical stressors during earlier developmental stages seems likely, potentially resulting in the observed rates of existing deformities.

The examined pikeperch juveniles exhibited pronounced size heterogeneity between deformed and non-deformed individuals. As a result of their spinal bends, deformed individuals were significantly shorter than their non-deformed counterparts, while possessing similar body widths (BWF). BWF is widely used for length classification, representing the smallest distance that fish must be able to pass through grids during sorting (Gabriel et al., 2016). As a result, specimens with deformities appeared to be selectively sorted into larger size classes during the grading step, likely due to differences in body shape. To a lesser extent, this sorting pattern may also have resulted from smaller individuals remaining on top of larger individuals during the grading process (Lekang, 2013). This selectivity can also be assumed to occur during earlier manual grading steps, as it was already observed in the pre-grading group. Potentially, a combination of camera- and AI-assisted grading tools could exploit this length bias to remove deformed specimens more easily in future scenarios.

Differences between the externally and internally observed rates of spinal bends became obvious. On the one hand, external observations of spine curvatures might not always enable the detection of minor changes. On the other hand, the observation of cleared and stained specimens might lead to an overestimation of vertebral column bends, as stabilizing tissues were removed during digestion (Smith et al., 2018). As internally observed deformity rates were mostly higher in the specimens examined, it can be considered that the de facto rate of deformities in facilities should be higher than indicated by the purely external checks applied there. Also, certain types are more likely to be overlooked externally, such as scoliotic lateral bends in the anterior body (Table 1). The small data set presented here makes follow-up studies necessary; however, this also raises the question of how these overlooked defects change over the long-term during development.

For the vertebral compressions and fusions, regional susceptibility was found. Compressions were more prevalent in the anterior and mid-body regions (body region df1 and df2), whereas fusions occurred predominantly in the tail area (body region cp). It remains unclear whether compression results in a later fusion or whether both conditions arise independently in response to similar stressors. Nevertheless, vertebral compression of single or multiple vertebrae results in further reduced body length, as exhibited by the "short-tail" or "stuntbody" phenotype (Boglione et al., 2013b). Such posterior spine alterations have also been de-

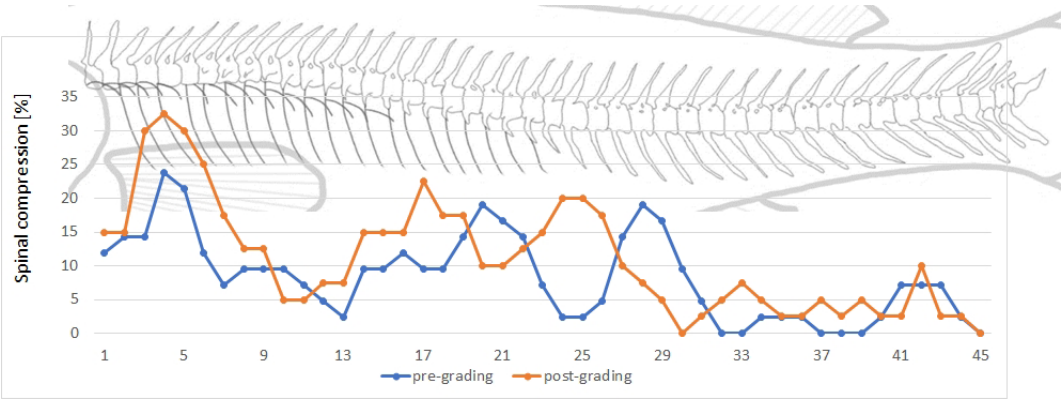


Figure 5. Incidence of vertebral compressions in individual vertebrae (1–45) of juvenile pikeperch pre-grading (57 dph, $n = 42$, blue line) and post-grading (58 dph, $n = 40$, orange line). Values are given as a percentage of the animals examined in each group. The visualization of the spine serves to illustrate the body position of affected vertebrae.

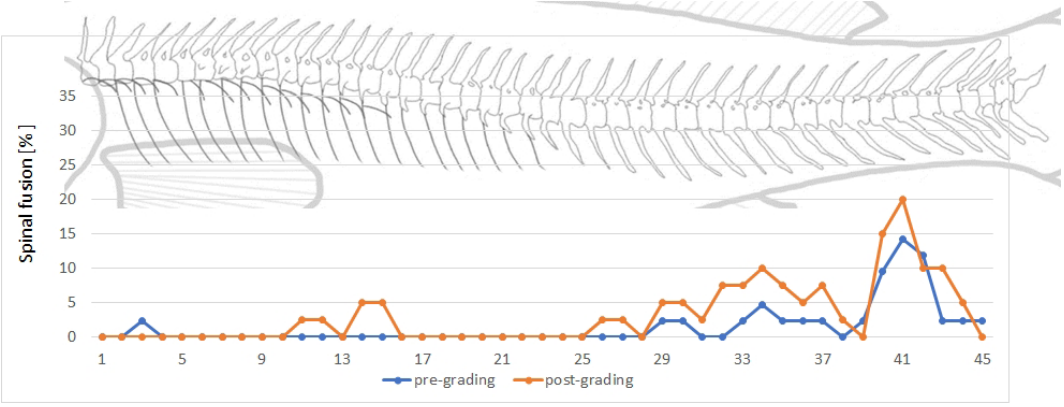


Figure 6. Incidence of vertebral fusion in individual vertebrae (1–45) of juvenile pikeperch pre-grading (57 dph, $n = 42$, blue line) and post-grading (58 dph, $n = 40$, orange line). Values are given as a percentage of the animals examined in each group. The visualization of the spine serves to illustrate the body position of affected vertebrae.

scribed for *Pagrus pagrus* and *Danio rerio* kept under intensive rearing conditions (Izquierdo et al., 2010; Printzi et al., 2021). Similarly, comparing the curvatures of the different spinal areas of pikeperch juveniles demonstrated a distinct pattern for dorsoventral lordotic bends, whereas lateral scoliotic changes were more variably distributed. This may be a result of a structural susceptibility of certain spinal areas to increased mechanical stress during the early life stages of pikeperch. The mid-body area especially seems to be predisposed to dorsoventral changes and compression events. This spinal region between the two dorsal fins may represent a potential mechanical weak point since the spine is less encompassed laterally. Therefore, future studies should take into consideration that the design of grading machines might influence rates of certain types of spinal deformities.

In the specimens examined, no definite effects of the single automatic grading step on the spinal skeletal structures, such as fractures, were found in this study. It could be assumed that, if an effect of grading is present, it accumulated over time. Different developmental timings of spinal areas might have contributed to the observed rates. Exemplarily, the tail body region (cp) is not fully ossified before initial manual grading at 33 dph (Franz et al., 2025; Ott et al., 2012). It is therefore more likely that the deformities in the cp area occurred at a younger age, before the grading procedure examined in this study. Consequently, a decisive period for spinal deformations resulting from mechanical influences can be assumed to occur earlier, during embryonic to larval development. Similarly, an increase in spinal deformation rates over time was described for pikeperch early life stages, with vertebral column deformity rates in larvae aged < 36 dph ranging from 7.5 % to 22.4 % (Hamza et al., 2008; Kestemont et al., 2007), rising to rates of up to 65 % in juveniles aged 45 and 67 dph (Franz et al., 2025; Ljubobratovic et al., 2017). However, these comparisons should be interpreted with caution, as differences in rearing systems and detection methods, such as X-ray analyses (Grini et al., 2011), have to be considered.

The proportion of deformed individuals observed before grading further supports the assumption that earlier stressors influence the observed deformity rates. As pikeperch are particularly susceptible during early developmental stages due to ongoing vertebral development and calcification (Ott et al., 2012), and handling is generally associated with physiological and behavioral stress (Dunlop et al., 2004; Ashley, 2007), earlier grading may have contributed to the observed prevalence of spinal deformities. Generally, mechanical stress is a key factor influencing the transdifferentiation of notochord cells into chondroblastic cells, resulting in cartilaginous changes (Hall, 2015; Witten et al., 2005). These processes could lead to compression as well as fusion of the vertebrae and vary with the level of vertebral calcification. During early developmental stages, minor skeletal deformities of vertebrae may undergo partial remodeling or compensatory growth (Witten et al., 2006). The potential for structural adaptation was demonstrated by the partial correction of vertebral deformities in fish larvae when reared under improved conditions and provided with adjusted diets (Kranenbarg et al., 2005; Witten et al., 2006). However, the capacity for spontaneous structural adaptation is reduced in the fully formed vertebrae observed here (Boglione et al., 2013a). Future studies are therefore recommended to analyze whether deformed pikeperch juveniles would be able to recover during further growth and development after initial deformation occurrences.

5 Conclusion and implications for aquaculture practice

In this case study, no definite influence of the automatic grading step on the fully formed vertebrae of pikeperch juveniles was found. Observed deformity rates indicate that stressors during earlier, more sensitive stages should be considered to be a more likely cause of deformities. Furthermore, body width (BWF) may not be a suitable predictor of the total length of deformed individuals, as these measurements exhibit comparable widths despite being shorter. The observed size misclassification of deformed individuals further complicates management, as it may inadvertently contribute to the accumulation of affected fish in certain size classes. This biased length ratio might be a useful way of detecting deformed individuals in groups, allowing for the removal of deformed specimens in production batches. In addition, a prevalence of deformity types in certain spinal regions was found, which may provide a way to determine the influence of stressors in the future. The insights gained can be useful for adapting grading and handling procedures, and developing supportive tools, thereby enhancing both animal welfare and production efficiency in pikeperch aquaculture.

Data availability. All data are included within the article.

Author contributions. GF and BG designed the experiments, and KW, KT, and GF carried them out. KT, KW, and GF prepared the paper, with contributions from all co-authors.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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