WORKSHOP ON EMERGING METHODS AND TECHNOLOGIES FOR THE AUTOMATED ANALYSIS OF CALCIFIED STRUCTURES (WKETAC)

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i Executive summary

Calcified structures (otoliths, scales, etc) are essential to the management of commercial species. Every year, more than one million pieces are collected and analysed across the world to provide data essential to fishery management, such as age estimations and stock identification. Recent years have seen significant advances in the analysis and use of calcified structures for extracting biological information, and the development of new technologies related to image processing and analysis has shown a strong potential for automation and standardization. This workshop aimed to bring together institutes and experts across the world to provide an exhaustive review of the developments in this field, outline areas and stocks of highest interest, and develop an international framework for collaboration. More than 70 European and non-European researchers participated. The first day was devoted to presentations of projects, methods and case studies, which were discussed with all participants. It provided an opportunity to present different emerging methods, such as AI-driven image analysis and spectroscopic data. In the case of deep learning approaches, the workshop was useful in reviewing and discussing the acquisition of two-dimensional and three-dimensional images, their standardization, and the algorithms to be developed. Discussions also touched upon the advances and limitations of these new technologies and approaches. The second day was mainly devoted to discussions around the optimization of the automated analysis of calcified structures for fish population monitoring and how to develop a collaborative framework for data exchange and standardization. Among the outputs of those discussions was the creation of a dynamic repository of expertise listing for different approaches, the associated institute, the list of species and stocks of primary interest, sample availability and current limitations and challenges. Additionally, the group began discussing pilot studies to successfully implement these automated methods, which will be further developed within an international project proposal to create and support a digital twin of physical archives in which large image repositories could be curated and exchanged to assist the development of automated methods and operational tools for monitoring commercial species.

Keywords: stock identification, age, deep learning, machine learning, calcified structures

ii Expert group information

Expert group name	Workshop on emerging methods and technologies for the automated analysis of calcified structures (WKETAC)
Expert group cycle	Annual
Year cycle started	2024
Reporting year in cycle	1/1
Chairs	Côme Denechaud, Norway
	Kélig Mahé, France
Meeting venue and dates	2–3 October 2025, Boulogne-sur-Mer, France (70 participants)

1 Terms of Reference (ToRs)

Workshop on emerging methods and technologies for the automated analysis of calcified structures 2025 report

The workshop on emerging methods and technologies for the automated analysis of calcified structures (WKETAC), chaired by Kélig Mahé (France) and Côme Denechaud (Norway), met in Boulogne-sur-Mer (France) 2 to 3 October, preceding the 2025 WGBIOP meeting. It aimed to:

a) Review automated technologies and methods extracting biological information from fish calcified structures (such as otoliths, scales or spines) to derive individual data on age, life history and species or stock identification.

b) Compare the performance and limitations of these emerging analytical methods among each other (deep learning, supervised/unsupervised classifiers, two-dimensional/three-dimensional imaging, computer vision).

c) Assess the costs and benefits of implementing these automated methods in parallel with current practices.

d) Develop a list of interest species and stocks to be targeted for pilot studies implementing automated methods within the EU Data Collection Framework.

e) Create a set of guidelines and best practices to be adopted for the transparent and reproducible implementation of automated methods, following the generic ToRs provided by WGBIOP.

f) Liaise together institutes and actors involved in automated technologies and calcified structures collections to create a “forum” dedicated to sharing ideas, data and progress.

2 Presentation, review and discussion on current methods for automated calcified structure analysis

Building on the horizon scanning provided in the WGBIOP 2024 report during which WKETAC was planned, participants were invited to present recent or ongoing projects within their institutes that are exploring methods of interest (ToRs A and B: "Review automated technologies and methods extracting biological information from fish calcified structures to derive individual data on age, life history and species or stock identification" and "Compare the performance and limitations of these emerging analytical methods among each other").

Below is a summary list of each presentation and its associated abstract. Those were organized in three thematic sessions: automated ageing, stock and species discrimination, and methodological aspects.

2.1 Automated ageing

2.1.1 Step-by-step framework for automated ageing of plaice using otolith shape (speaker: Nicolas Andrialovanirina)

Otoliths are reliable biological markers used to estimate fish age and other ecological characteristics. Their shape and structure are influenced by genetic, environmental, ontogenetic, and life-stage factors, all of which affect otolith formation and growth. This study aims to develop an automated approach for fish ageing based on quantitative analysis of external otolith shape. By extracting shape descriptors from otolith images, the method enables age estimation without the need for manual counting of growth rings, a traditionally labour-intensive process requiring expert interpretation (Figure 1).

A systematic framework was established for preprocessing and standardizing otolith images prior to age estimation. Images are binarized, contours are extracted, and orientation is standardized through rotation correction, side detection, and mirror transformation. Multivariate shape features are then derived using advanced mathematical representations, including elliptic Fourier descriptors, wavelet transforms, and curvature scale space methods. Univariate parameters such as length, width, height, and area are also calculated, both for the entire contour and for each of the four otolith sides, enabling localized shape analysis. The extracted shape features serve as input for several supervised machine learning models Random Forest, Support Vector Machine (SVM), K-Nearest Neighbors (KNN), Recursive Partitioning (RPART), and linear models to predict fish age. The dataset comprises thousands of otolith images representing age classes from 0 to 7 years and older. Model performance is evaluated using Root Mean Square Error (RMSE) to quantify prediction accuracy.

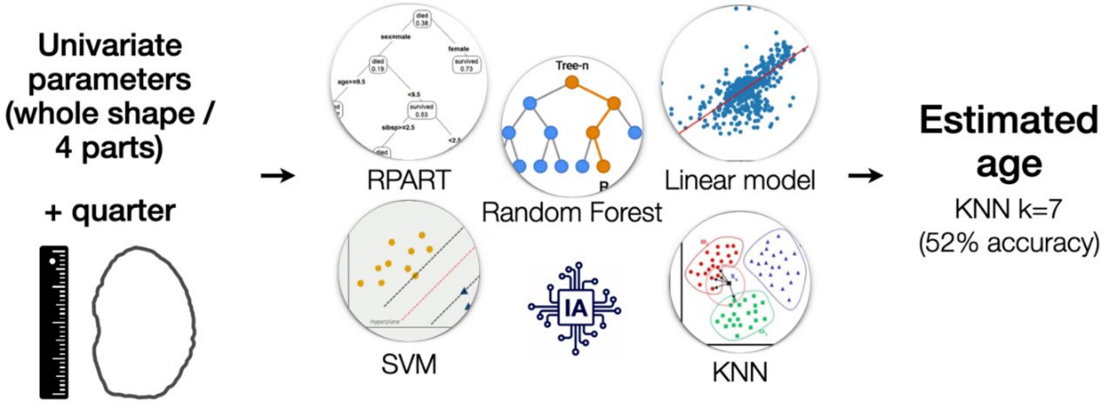

Figure 1. Summary of automated workflow.

Results show that the KNN model (k = 7) achieved the best performance, with approximately 52% accuracy within ±1 year of the true age. While the findings are promising, some variability persists, particularly in distinguishing between middle and older age classes, where ontogenic effects on otolith shape become less pronounced.

2.1.2 Automation of age estimation utilizing AI in *Solea solea* (speaker: Elli Kiourani)

Otoliths are widely used for fish age estimation and ecological studies, yet manual interpretation remains challenging, particularly for flatfish such as *Solea solea*. In this study, the potential of artificial intelligence to support automated age determination was estimated by adapting the open-source deep learning framework of Politikos *et al*. (2022). A dataset of 184 *S. solea* otolith images collected and processed at ILVO was used, with age readings conducted by experts from ILVO and Gent University providing the reference baseline. After preprocessing (resin embedding, sectioning, staining, and resolution adjustments), otolith images were trained and tested within the AI framework, with final evaluation performed on 41 samples. Model performance was modest, achieving an accuracy of 0.35, recall of 0.35, and precision of 0.19. Mean squared error (MSE) values indicated average deviations of ~1.5 years in age estimation and ~0.4 mm in length prediction. The model captured overall trends but exhibited systematic bias, with a tendency to underestimate older individuals. While the accuracy remains limited, the study demonstrates proof of concept for automated age estimation in *S. solea*. Expanding the dataset with broader representation across ages and lengths, as well as a larger dataset overall, is essential to improve model robustness. These findings highlight both the challenges and potential of integrating AI into traditional otolith analysis, supporting the development of tools such as Deep Otolith for more standardized and efficient fisheries management.

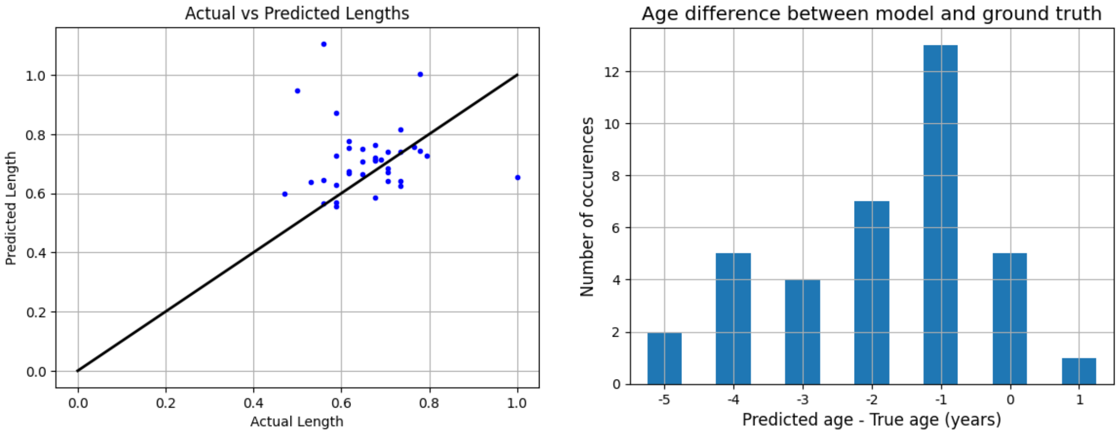

Figure 2. Length and age prediction errors (predicted – true) for *Solea solea* otoliths.

2.1.3 Age prediction based on otolith rings detection using computer vision (speaker: Mariia Tiurina)

This presentation introduced a deep learning–based method for automatic detection of annual growth rings on otolith images, with a focus on turbot (*Scophthalmus maximus*). The developed workflow utilized image recognition algorithms to identify key reference points that enable precise localization of regions of interest (ROIs)—specifically, two upper triangular sectors of the otolith. Each triangle was then processed independently to detect growth increments using a trained segmentation network, followed by post-processing steps to merge fragmented or overlapping segments.

For validation, expert annotations were collected: each otolith image was overlaid with a reading axis, and the expert manually marked visible increments directly along these axes. Model predictions were compared against the expert annotations by projecting detected points onto the same bisectors, enabling objective performance assessment. The results showed a strong agreement between the automated and expert-derived increment positions, particularly for younger individuals (age under 6). Prediction accuracy for fish age was, however limited, and the results highlight the need for large training datasets with precise age data to ground-truth age estimates based on increment detection.

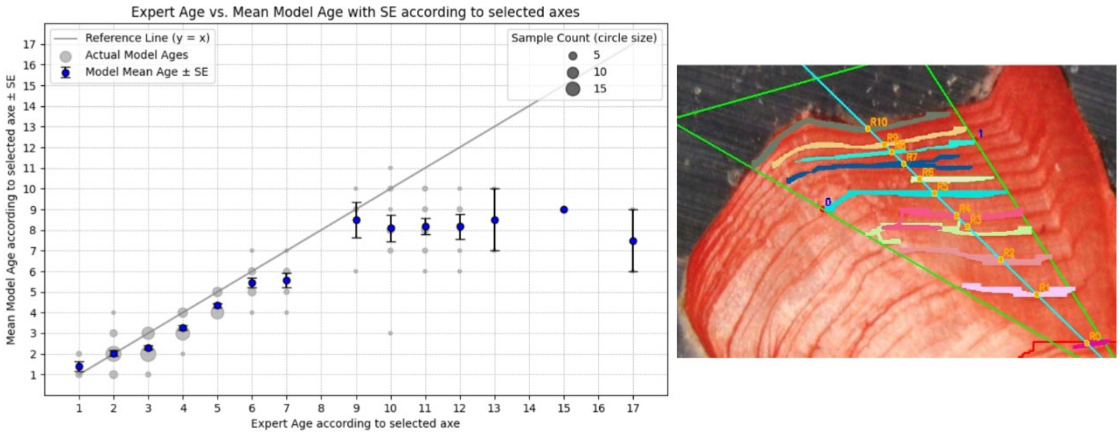

Figure 3. Age prediction errors and example identified increments in segmentation ROI.

2.1.4 Automated annotation of otoliths using an autoregressive model (speaker: Troels Bojesen)

Building on similar previous work for Atlantic cod (Bojesen *et al.*, 2023), an ongoing project for automated aging of saithe otoliths using an autoregressive approach was presented. This model is trained on separate streams of images and associated expert annotations to emulate the increment identification and tally done by expert readers. For a given image, the model constructs a sequence of spatial annotation dot probability distributions, starting from the centre of the otolith and progressing toward the edge until the sequence is stopped. From that sequence the entire age distribution of the otolith can be computed, thus not only providing a best (most likely) age assessment, but also the uncertainty associated with this through the combined probability of any other sequence length. Furthermore, by outputting images annotated with each calculated probability distributions, the autoregressive design of the model makes it possible to "peek behind the curtain" and intuitively observe the sequential process, thus rendering the method more transparent than traditional black box methods. In this initial small-scale test trained on a moderately sized dataset of around 3000 annotated otolith images, the method already showed promising results and will be further improved with new data collected in 2025 and 2026.

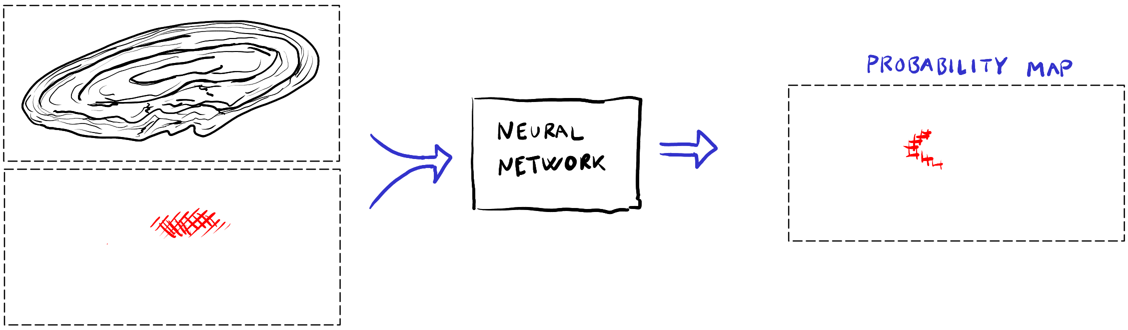

Figure 4. Graphical representation of the autoregressive model shown as an input of otolith image + probability distribution at sequence n, and associated output of probability distribution at sequence n+1.

2.2 Species and stock discrimination

2.2.1 More than classification: A multi-task AI model for herring population analysis (speaker: Krzysztof Świtek)

Accurate identification of fish stock components is essential to effective fisheries management, particularly in cases like Baltic herring, where genetic differences and environmental factors complicate fish classification. This study investigates the use of deep neural networks to differentiate stock components of Baltic herring based on otolith morphology. Otolith samples were collected from herring in the southern Baltic during scientific surveys conducted between 2021 and 2024. The study focused on distinguishing the southern (CBSC) and northern (CBNC) components of the central Baltic herring stock—traditionally classified through expert examination of key biological otolith features. To enhance efficiency and reduce reliance on manual labour, an automated system was developed for sample collection, i.e. otolith imaging and object detection. A ResNet-34 model was employed to classify herring otoliths using digital images. The model achieved relatively high classification accuracy, demonstrating strong performance in distinguishing the two stock components. Stable training and validation loss trends indicated good generalization, ensuring reliable predictions on unseen data. While classification was slightly more precise for one stock component, the overall results confirm the model's robustness in automated otolith classification. To improve interpretability, the Grad-CAM technique was applied, revealing that the model primarily focused on biologically relevant otolith features, such as edge regions and specific structural characteristics. This suggests that the neural network successfully identifies key morphological traits distinguishing the two stock components. Additionally, growth analysis using the von Bertalanffy model revealed significant differences in growth parameters between CBNC and CBSC, with CBNC exhibiting a slower growth rate. Age structure analysis further indicated that older individuals dominated CBNC compared to CBSC, another factor that may influence stock productivity. These findings emphasize the importance of distinguishing both components for accurate stock assessment and effective fisheries management.

2.2.2 Advancing three-dimensional otolith shape analysis for better fish classification (speaker: Nicolas Andrialovanirina)

Otoliths, calcified structures located in the inner ear of fish, are widely used for age determination and species identification. Beyond these functions, otolith morphology also encodes valuable information about environmental conditions, genetic background, life history traits, and ontogeny. Since otolith shape is influenced by these combined effects, understanding these sources of variation is essential to accurate biological interpretation.

However, most existing studies rely on two-dimensional (2D) images, which represent only a single projection of the otolith's inherently three-dimensional (3D) structure. This research advances beyond traditional 2D methods by employing 3D otolith imaging to more comprehensively capture external morphological features. The workflow incorporates standardized image acquisition, ensuring consistent scale, position, and orientation, followed by feature extraction using Fourier descriptors and principal component analysis (PCA). Both unsupervised and supervised machine learning techniques, including clustering and classification algorithms, are applied to categorize fish specimens.

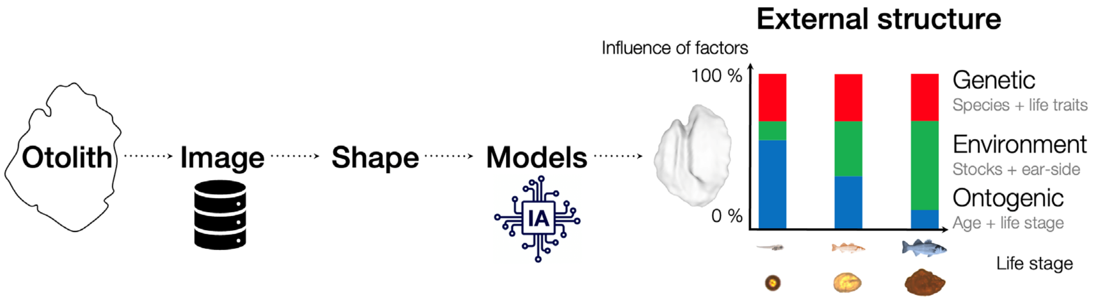

Figure 5. Illustration of 3D shape extraction and analysis workflow with expected environmental and ontogenetic drivers at different fish life stages.

The 3D analysis demonstrates suitable performance in species identification and classification based on life-history traits and ontogenic variations. It also reveals potential for distinguishing biological and ecological factors such as sex, maturity stage, and otolith laterality (left/right). A multivariate mixed-effects model found no significant asymmetry between left and right otoliths in 2D analyses but detected clear geographical differentiation. In contrast, 3D shape analysis revealed significant effects of both otolith side and geographic origin. Furthermore, hierarchical clustering and Random Forest models based on 3D data outperformed their 2D counterparts in fish stock discrimination.

While some classification challenges remain due to overlapping genetic, ontogenic, and environmental influences, the study concludes that 3D otolith shape analysis represents a major advancement in fisheries science. It provides richer and more precise morphological information, improving the accuracy of species classification, stock identification, and the understanding of life-history diversity.

2.2.3 Advances and new horizons in otolith contour analysis (speakers: Victor Tuset and Antoni Lombarte)

Since the 1980s, Fourier equations have been widely used to analyse otolith contours for identifying teleostean fish populations. Researchers quickly adopted the analysis of the resulting data, and it has provided acceptable results. However, there is a major drawback: the difficulty of understanding the morphological implications, given that Fourier harmonics represent the mathematical components that describe a shape rather than the shape itself. In the early 2000s, the introduction of Mallat's wavelet transform (WT) to the study of otolith contours on the *AFORO* website solved the problem of morphological interpretation and improved the capacity for identification using otolith contours. This is because the WT decomposes contours into scale-dependent components that capture both whole and local characteristics. However, this technique has only been used by a few teams associated with the AFORO website, and while it can be used online, the website is not designed to analyse multiple images simultaneously. The emergence of *ShapeR* made WT analysis accessible to all R environment users. On the other hand, it also has some weaknesses, such as the use of Daubechies wavelets that reduce the signal to coefficients, which do not have morphological meaning similar to elliptical Fourier analysis and therefore may hinder the morphological interpretation of the results obtained. As both systems have various weaknesses, an environment for R users is currently being developed based on the AFORO system (*AforoR GitHub*), which preserves all the details of the outline for analysis and avoids coefficients. This facilitates morphological interpretation since the different levels or scales provide more or less detail of the outline. The environment also includes some useful features, such as the ability to select the first point in all images, which allows otoliths to have different orientations (unlike previous systems) and to convert the data as semi-marks with a mark. Using this programme provides better results for phenotypic variability of interspecific and intraspecific studies. It will also help to achieve massive digitalization of otoliths and other hard structures stored in research centres, as well as the development of new classifiers based on deep neural networks.

2.2.4 Discriminating pelagic fish stocks in the Black Sea using otolith morphometrics and artificial intelligence (speaker: Ömerhan Dürrani)

Accurate stock discrimination is essential to sustainable fisheries management, particularly in transboundary systems such as the Black Sea. In our published studies, we investigated two commercially important pelagic species: Mediterranean horse mackerel (*Trachurus mediterraneus*) and European anchovy (*Engraulis encrasicolus*), which are currently managed as single stocks despite accumulating evidence of regional structuring. Morphometric analyses of body and otolith shape, using geometric morphometrics and elliptical Fourier descriptors, revealed significant spatial differentiation in both species. For *T. mediterraneus*, distinct morphological stocks and directional bilateral asymmetry in otoliths were observed, suggesting environmental stress gradients across regions. Similarly, European anchovy exhibited regional variation in body and otolith morphology, supporting the presence of multiple morphological stocks. To complement traditional morphometric approaches, a deep learning model (MobAtt-MixerNet) was developed specifically for *T. mediterraneus* otolith image classification. The model integrates MobileNet and an attention-based MLP-Mixer architecture. Trained on otolith images from different regions, it achieved relatively high classification accuracy, outperforming conventional machine learning and CNN-based methods. These results demonstrate the feasibility of AI-assisted otolith analysis for rapid and reliable stock discrimination in *T. mediterraneus*. In sum, the findings challenge the single-stock management strategy and highlight the value of integrating morphometric and AI-based tools to support region-specific, adaptive fisheries management in the Black Sea and adjacent seas.

2.3 Methodological aspects

2.3.1 Automatic detection of fish scale *circuli* using deep learning (speaker: Nora Hanson)

Teleost fish scales form distinct growth rings deposited in proportion to somatic growth in length, and are routinely used in fish ageing and growth analyses. Extraction of incremental growth data from scales is labour-intensive. We present a fully automated method to retrieve these data from fish scale images using Convolutional Neural Networks. Our pipeline of two CNNs automatically detects the center of the scale and individual growth rings (*circuli*) along multiple radials transects emanating from the center. The focus detector was trained on 725 scale images and achieved an average precision of 99%; the *circuli* detector was trained on 40 678 *circuli* annotations and achieved an average precision of 95.1%. *Circuli* detections were made with less confidence in the freshwater zone of the scale image where the growth bands are most narrowly spaced. However, the performance of the *circuli* detector was similar to that of another human labeller, highlighting the inherent ambiguity of the labelling process. The system predicts the location of scale growth rings rapidly and with high accuracy, enabling the calculation of spacings and thereby growth inferences from salmon scales. The success of our method suggests its potential for expansion to other species.

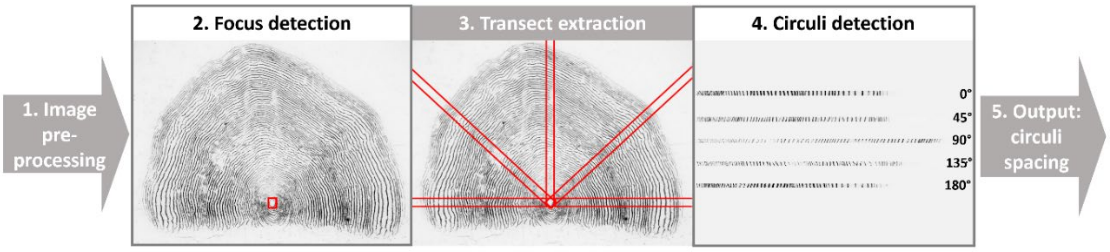

Figure 6. Illustrated workflow of the *circuli* detector algorithm

2.3.2 The AI-Workshop Initiative of the Thünen-Institute of Sea Fisheries (speaker: Arjay Cayetano)

The use of AI in the field of otolith research has grown exponentially in recent years. Multiple AI-based approaches have already been demonstrated, showing excellent performance for the task of fish age determination. As our contribution to this research area, we showed how the use of deep learning methods based on object detection and segmentation can also be an effective approach for estimating the fish age without sacrificing explainability. In the presentation, two algorithms, namely Mask R-CNN and U-Net, were highlighted, showing how the perspective of object detection and segmentation can be a good formulation of the problem/task to make it compatible with the traditional process of age reading based on manual counting of growth rings (annuli). Furthermore, the discussion points revolved around the interactive web-based application that we developed, housing the two algorithms with the goal of increasing accessibility.

More importantly, in the presentation, we elaborated that we designed the graphical interface such that it can be used as an interactive platform that allows a workflow based on continual learning. That is, the platform permits the age readers to be directly involved with the development of the AI models by allowing them to incorporate their own inputs and corrections to the AI, which can then be used in the next rounds of model training. As the next step in this direction, we conducted workshops that aimed to help the age readers get acquainted with the platform and to gauge the ease-of-use of the web-based application, not only for testing the existing AI models but also for training their own models using the ground-truth annotations that they created using an integrated annotation toolkit. The lessons learned from these workshops, along with the challenges encountered, were also tackled in the presentation. Lastly, some important points regarding the future direction of the project were also included.

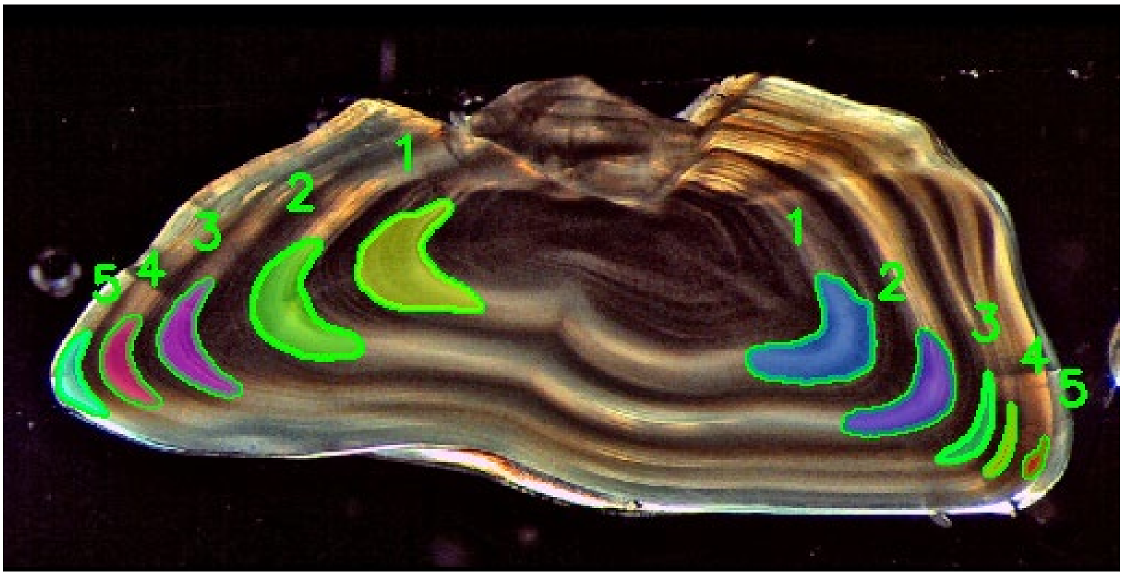

Figure 7. Example image displaying growth increments identified and masked by one of the AI models, with corresponding count

2.3.3 AI integration in SmartDots: an ILVO proof of concept (speaker: Lukas Snoeck)

A lot of research has been done in determining the age of otoliths and the detection of rings. While still far from perfect, it's already important to think about how models can be integrated so that age readers can benefit from this new technology. ILVO has been developing a pipeline that is both modular and interoperable for continuous deployment in SmartDots. This proof of concept uses new paradigms and technologies used for deployment and makes it very easy to use and release new versions. This presentation explores the different facets and technologies used for this proof of concept.

2.3.4 Investigations into the use of FT-NIR for ageing NW Atlantic fish and harp seals and for species identification (speaker: Aaron Adamack)

Several recent studies (Wedding *et al.*, 2014; Helser *et al.*, 2019a; Helser *et al.*, 2019b; Passerotti *et al.*, 2022) have shown the potential of Fourier transform, near infrared spectroscopy (FT-NIRs) as a tool for ageing fish otoliths. Work by Benson *et al.* (2020) demonstrated that FT-NIRs can be combined with classification models to identify fish species from their otoliths. The

Newfoundland and Labrador (NL) region of Fisheries and Oceans Canada (DFO) has been investigating the potential of FT-NIRs for aging Atlantic cod (*Gadus morhua*) and herring (*Clupea harengus*) otoliths, and harp seal (*Pagophilus groenlandicus*) teeth and for identifying fish species from their otoliths as a means of investigating diet composition of harp seals, with a particular focus on distinguishing between Atlantic and Greenland cod. We have also conducted pilot studies into using FT-NIRs for aging two species of flatfish (witch flounder *Glyptocephalus cynoglossus* and American plaice *Hippoglossoides platessoides*). We found (Adamack *et al.*, 2025) that FT-NIRs performed well for aging Atlantic cod otoliths (Figure 8) with linear regressions between traditional and FT-NIR ages having adjusted $R^2 = 0.91$ to 0.92 and root mean square errors (RMSE) = 0.98 to 1.02 years). A time cost analysis (Table 1) was performed comparing the time required to age 12 000 otoliths using the traditional aging method with FT-NIR aging approaches using 1 (across the entire region) or 6 calibration models (individual models for each NAFO Division) showed that the time needed to age otoliths could be reduced by 23% (6 calibration models) to 40% (1 calibration model). Examination of the potential of FT-NIRs for Atlantic herring suggests that the method has potential with adjusted R^2 for simple linear regressions between traditional and FT-NIR ages ranging from 0.8 to 0.85 while RMSE ranged from 1.13 to 1.5 years depending on how the dataset was partitioned. There was also reasonable correspondence between traditional age estimates and FT-NIR predicted ages from harp seal premolars with adjusted R^2 ranging from 0.83 to 0.90, however RMSE was somewhat high at ~3.5 – 4 years. The method did not perform well for the flatfish where adjusted R^2s were low or the relationships had concerning patterns. Our investigations of FT-NIR to identify fish species from freshly collected otoliths were promising. Using support vector machines, we had greater than 95% accuracy in determining species ID of otoliths given the set of 10 species we analysed. Determining whether or not an otolith came from a Greenland cod, our precision was greater than 90% with a near 0 misclassification rate of identifying Atlantic cod as Greenland cod using soft-independent modelling of class analogies (SIMCA) Determining whether or not an otolith came from an Atlantic cod, our precision was greater than 95% with a near 0 misclassification rate of identifying Greenland cod as Atlantic cod using partial least squares discriminant analysis. Collectively, our results show that FT-NIR has great potential for aging fish otoliths and seal teeth, but the performance of the method clearly varies across species.

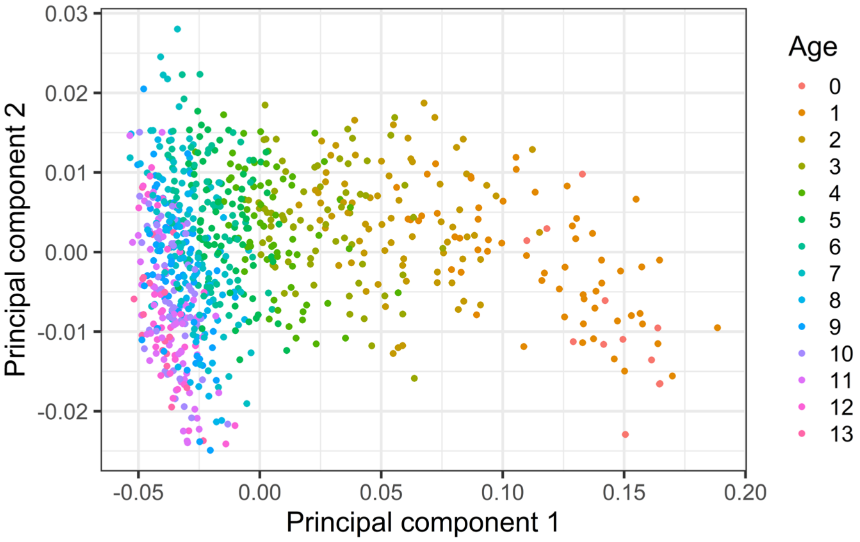

Figure 8. Principal component plot of the first two principal components of Atlantic cod FT-NIR spectra coloured by age class. Cod were sampled from NAFO Divisions 2J, 3K, 3L, 3N, 3O, and 3Ps.

2.3.5 3D Otolith images database augmentation: 3D DCGAN Completion and Generation of Broken 3D Objects from a Reduced Datasets (speaker: Emilie Poisson-Caillault)

The generation and completion of 3D objects is a transformative challenge in computer vision. Our study explores Generative Adversarial Networks (GANs) for generating and completing fractured 3D scanned objects. Our approach leverages Deep 3D Convolutional GANs (DCGANs) to generate high-quality 3D models and reconstruct incomplete or damaged objects. By training DCGANs on latent vectors, we enable realistic 3D shape generation and completion of partial objects. Additionally, we evaluate the model's ability to recognize and fill holes of varying sizes and compare its performance against existing methods. Quantitative and qualitative results highlight the effectiveness of the proposed DCGAN in handling small datasets, processing complex 3D data, and generating coherent, biologically plausible structures (Figure 9).

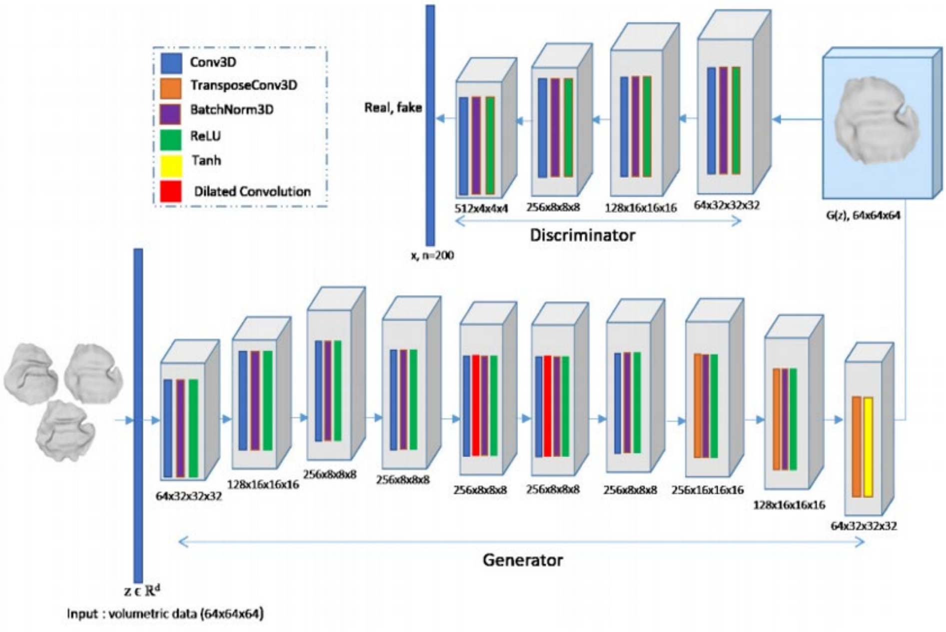

Figure 9. Illustration of proposed architecture for DCGAN.

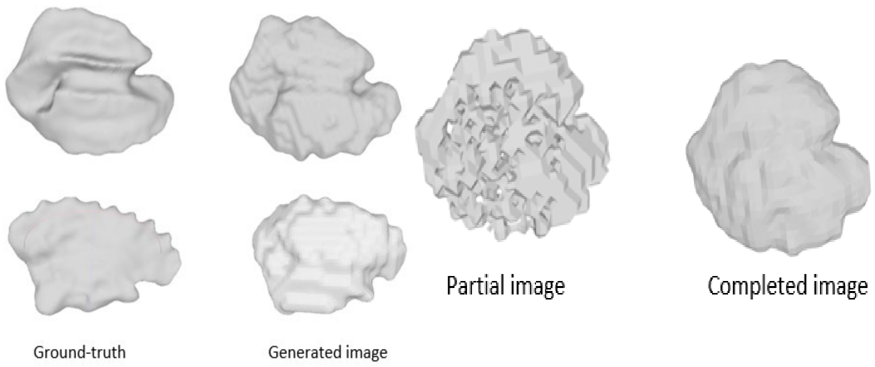

Figure 10. example images from this framework generated from a striped red mullet (*Mullus barbatus*) otolith dataset containing 691 images.

The effects of the percentage of removed points on the completion accuracy of 3D objects (Otoliths, Chairs, and Airplanes) were evaluated using three metrics such as Chamfer Distance (CD), Hausdorff Distance (HD), and Earth Mover's Distance (EMD).

Table 1. Completion results on test database (up to 70% removed voxel)

Category	Model	CD	HD	EMD	PRR
Airplane	3DGAN	46.7	72.8	84.0	77.2
	RaGANs	41.2	71.3	81.1	85.7
	DCGAN (ours)	**27.1**	**67.6**	**65.5**	**94.9**
Chair	3DGAN	43.2	76.0	80.4	82.5
	RaGANs	41.1	73.2	79.6	84.4
	DCGAN (ours)	**26**	**65.4**	**61.2**	**95**
Otolith	3DGAN	54.8	94.1	81.9	80
	RaGANs	52.6	87.6	79.1	82.3
	DCGAN (ours)	**41.7**	**82.1**	**69.4**	**94**

The code and data supporting this work are publicly available at: https://github.com/yahya-hamdi-lab/3D-DCGAN

3 Review the cost and benefits of presented methods

Discussions during the second half of the workshop focused on the potential costs and benefits from developing automated methods for calcified structure analysis. Earlier publications on this question highlighted the practical bottleneck tied to sample collection, often at sea, and sample processing (varying costs depending on structure type and preparation method), two incompressible steps that must occur before automated image analyses can be conducted. However, given the quantity collected around the world every year and associated costs for processing and age reading, automation of specific steps could still provide significant advantages.

New approaches such a deep learning method get their efficiency from the amount of data that can be analysed and outputted in bulk: the training and tuning will always be a net additional effort, but the algorithms could still yield improved efficiency once the appropriate level of accuracy and confidence are reached. With the example of individual age estimation from otolith sections, the collection and preparation of samples would be the exact same as needed for traditional expert-based reading, but a trained algorithm could generate overnight thousands of readings within a single "run" on the entire image collection, while experts would use weeks. External information extracted from these images together with age, such as individual growth histories or stock-specific morphology to aid in stock identification, could also motivate the development of such automated methods to extract a large amount of data within a single processing.

Additionally, the participants agreed that, while calcified structures are regularly analysed as part of research projects and published articles, the sheer number of samples collected for aging and assessment purposes every year means that a majority of those will be rapidly archived and not used further. The most promising automation methods, such a deep-learning approaches on digital images, may therefore also benefit scientific advances by shifting resources to allow for more digitalization and provide new tools for their large-scale analysis. One key motivation for digitizing as much material as possible is that environment and conditions change through time, and how it will affect fish ecology and biology will be recorded in these calcified structures. Automated methods in combination with large digital repositories may therefore provide a powerful tool to not only produce large amount of biological data more efficiently, but also ensure any biological change through time can be corroborated and quantify.

3.1 Cost–benefits of each method

3.1.1 Shape analysis

Traditionally, otolith shape analysis has been conducted in 2D using contour analysis and mathematical deconstructions such as Fourier harmonics or wavelets, more rarely with manual landmarks. As presented throughout the workshop, these methods aren't necessarily appropriate in all cases and may also show significant limitations in providing anything beyond wider group differences across suspected populations or species. The recent advances in 3D shape analysis, which fully captures the otolith in all directions, are showing promising results but are currently limited in their wider scale applicability by their costs.

For example, when Fourier harmonics were used to reconstruct the 3D average shape of the otolith (Andrialovanirina *et al.*, 2024), results showed a greater accuracy at disentangling stocks and/or species identification (Mahé *et al.*, 2025). However, this 3D approach also required potentially costly equipment with the need for trained technicians (i.e. a microCT tomograph), extra time costs associated with acquiring the image scan and process it, then the 3D decomposition with Fourier harmonics proved more time consuming than the direct 2D approach from digital contour images (30 minutes for 10 otoliths of red mullet).

While the method is promising it may not yet be fit large-scale automated approaches. However, considering the overlap between digital images for aging and for shape analysis, there may be considerable room for automation and improvement of the "classical" 2D shape decomposition, with the added need to address current shortcomings in shape analysis and its interpretation.

3.1.2 FT-NIRS

Fourier-transform near-infrared spectroscopy (FT-NIRS) has recently been used for rapid, non-destructive estimates of annual age in several fish species from scans of various tissues, including otoliths (Basilone *et al.*, 2024; Adamack *et al.*, 2025). A recent study also compared the time-costs effectiveness of FT-NIRS compared to traditional approaches for ageing 12 000 cod otoliths (Adamack *et al.*, 2025; Table 2).

Table 2. Comparison of the time-costs for ageing 12 000 otoliths for three scenarios: the existing method, FT-NIRS ageing with one overall calibration model for all NAFO Divisions, and FT-NIR ageing with individual calibration models for each NAFO Div. Total time required for the method is the sum of the times required for each step in the ageing process.

	Existing method	FT-NIRS / combined NAFO	FT-NIRS / ind. NAFO
Otoliths aged by counting annuli	12 000	200	1200
Otoliths aged compared current method (%)	NA	1.67	10
Otoliths scanned using FT-NIRS	NA	12 000	12 000
Time required to age otoliths by counting annuli (days)	150	5.33	32
FT-NIRS scanning time (days)	0	48	48
FT-NIRS cleaning time (days)	0	43	43
Total time required (days)	150	96.33	123
Time cost savings (%)	NA	40	23

With the ongoing development and test of portable models that could provide enough spectral resolution to be bought on board research vessels, FT-NIRS could be a promising method for ageing large numbers of individuals even directly at sea. As shown in section 1, other uses such as species identification can also be done with spectral data collected using FT-NIRS, as long as the machine learning side is properly trained. One of the main drawbacks with the method for now is the lack of cross-validity with known biological variables: while the spectral data seem to be accurate at classifying individuals, the processes behind it are still opaque.

3.1.3 AI-assisted approaches to ageing

Several AI-assisted approaches were presented and discussed during the workshop, with different cost and benefits. For example, traditional regressions such as CNNs require minimal input besides the picture and target variable (most often age alone), and may therefore be easier to scale up. However, they are limited in interpretability and trustability by the black-box nature of their processes, giving little to no control over the output. In the case of a biologically relevant and validated feature such as age estimated from growth counts, this can pose serious issues to their adoptability at a larger scale in the context of fisheries assessment.

Multiple such pilot studies have been conducted in the last few years (see for example Martinsen *et al.*, 2022; Moen *et al.*, 2018; Moen *et al.*, 2023; Politikos *et al.*, 2021; Vabø *et al.*, 2021), and in most cases seem to show similar patterns where accuracy is satisfying at younger ages but starts to deteriorate for the adults, eventually showing increasingly low correlation with expert age estimates. While attempts have been made to highlight areas and features of the image that weigh most in the predictions, it seems traditional unguided regressions consistently fail at identifying growth zones and instead use various size metrics which correlate well enough at the younger and more numerous ages, but become increasingly inaccurate for older individuals. This is not surprising considering fish and otolith growth are intrinsically related and, since younger fish grow at faster rates, the morphometry of their otoliths is likely to change more significantly between each age. The growth of older fish, especially those who have fully matured, will on the other hand be reduced in favour of energy investment into body weight and gonad production, and changes in otolith growth and morphology are therefore likely to be much less significant from one age to another.

A promising alternative to those black-box approaches are methods using expert annotations and object identification to "force" the algorithm to learn to identify and count the target otolith or scale features. For example, mask R-CNNs in an interactive web platform allow continuous learning from the experts, as they can adjust and correct physical masks used to detect and segment growth rings. Iterative approaches using images and annotation coordinates in tandem are also promising, as they emulate the sequential nature of growth ring counts from experts. Those methods are much better at providing verifiable and trustable outputs, as each individual is not only given a single age estimate but also visual outputs (e.g. an annotated image) and confidence intervals (i.e. probability distributions for ages). Developing and packaging such approaches in already widespread software for age reading could be the key to provide enough training material across species and stocks, while consistently involving experts in the process. This concept of an assist AI is currently tested in the ILVO internal SmartDots API. The idea is to propose AI readings to each age exchange which experts can use as guidance or sanity check.

In all cases, such approaches are currently limited by the availability and cost of training materials, more so for guided methods. As highlighted by Fisher and Hunter (2018), a large portion of the time dedicated to collecting, processing and ageing an otolith or a scale is incompressible and not part the automation loop targeted by AI approaches. Fish need to be collected at sea, the otoliths processed and prepared, then the age estimated. Many institutes still work with broken otoliths read directly under binoculars, meaning that any training for AI also requires the additional steps of embedding, sectioning, photographing and annotating before it can be used in training. Even if some fish groups such as pelagic or flatfish may be easier as the otoliths often are read whole and already routinely photographed, this represents a net extra effort.

That said, there are still arguments in favour. First, there's an increasing push for digitalization of age reading structures, as it increases quality assessment of age reading and allows for much more biological information than individual age to be extracted and analysed (growth, life history, population, etc). AI-driven automation is likely to come as a complimentary by-product from this digitalization. Additionally, while the resources involved in AI training will always be higher than traditional ageing on an individual basis, automation can "recover" those investments in the sheer scalability of their outputs. For example, similar to the FT-NIR table presented above, a reader may currently use multiple months to read a few thousand otoliths of a given species. With a high-performance algorithm available, a fraction of this time would be needed to prepare and digitalize the material, but the ages (and other desired biological information) could be produced in a single run of the script overnight. This scalability makes AI-automation promising, as even a 50/50 split between samples read respectively by the expert readers and the algorithm could represent significant time savings for the most numerous species that can be read in the tens of thousands yearly.

4 Best practices for the transparent and reproducible implementation of automated methods

During the workshop, it was agreed that, rather than developing precise guidelines for acquisition equipment and parameters, which would be impractical given the range of techniques and procedures adopted by different laboratories across the world, quality standards and guidelines are most desirable to ensure that material is widely usable and transferable. For image acquisition, such guidelines are available through the SmartDots platform and form a solid foundation for future efforts for digitizing large number of samples and training automated algorithms. This will require adding all metadata referring to the sample and the image, such as preparation and acquisition methods, as well as developing tools to identify and process a "raw" image to a desired standard (Table 3).

Table 3. Example sources of differences between otolith images with proposed solutions (Andrialovanirina et al., 2023).

Source of bias	Potential differences	Methodological steps to standardize
Otolith presentation	Whole / Broken / overlapped otoliths / pairs of otoliths / left or right otoliths	Sorting (with several groups with different characteristics)
Preparation method	Otolith in water / burnt otolith / otolith embedded in resin	Sorting (with several groups with different characteristics)
Light type	Transmitted light / Reflected light	Sorting (with several groups with different characteristics)
Acquisition system	Scanner / Binocular microscope / High-resolution microscope	1. Greyscale image / 2. Count and cut otolith image: resizing / 3. Oriented image : binarized image
Light intensity	Various exposures	1. Greyscale image / 3. Oriented image: binarized image
Contrast of image	Depends on readers and camera	1. Greyscale image / 3. Oriented image: binarized image
Color channel	RGB / Greyscale	1. Greyscale image / 3. Oriented image: binarized image
Number of otoliths	Left otolith / Right otolith / Both otoliths	2. Count and cut otolith image: cutting and mirror effect
Magnification	From 1x to 100x	2. Count and cut otolith image: resizing
Ratio of otolith to image size	Percentage from 10 to 95%	2. Count and cut otolith image: resizing
Image resolution	Between 658 and 1432 pixel/cm	2. Count and cut otolith image: resizing
Orientation of longest axis	Orientation from 0 to 360 degrees	3. Oriented image: main axis alignment
Format of image	jpg / png / raw / tiff	Save in single format

Similarly, it will be essential to document and standardize algorithms. For all algorithms, experts could have the same pipeline of data standardization or feature extraction if they use one or use one that is recommended or already validated by the community. If possible, all data and scripts used in training must be available for reproducibility and transparency. For all models, experts can provide the parameters and metrics used for model optimization and performance evaluation, which will be needed to compare inter-model performances and assess the quality of new developments. With such standardization, it will also be easier to use transfer learning to teach new data to existing models. A more detailed set of guidelines will be developed as part of WGBIOP ToR C and may be available in the corresponding 2025 report.

5 Target species and future pathways for developing a collaborative framework

5.1 Identifying species of highest interest

The idea of a collaborative pilot project was discussed throughout the workshop, particularly in light of the current costs of developing successful automation approaches. Because the same task is done across all species and stocks (i.e. counting rings), with some extra layer of complexity in the sense of their biological interpretation, a single push toward a specific set of species or stocks where most data are available could yield a successful algorithm on which to form the basis of more dedicated project through transfer leaning and other such methods.

During WKETAC, the subgroups worked on identifying the most promising target species or stocks in terms of available data and scientific/economic/ecological interest, as well as formulating a collaborative project framework that could help develop open data initiatives to strengthen and successfully adopt automated approaches. Because accuracy and repeatability are crucial, the species of highest interest that were identified were primarily species with a high reading confidence and well-understood biological processes and biomineralization patterns. While age information is central to the quantitative assessment of many species across the world, inter-expert agreement is often found to be lower than ideally expected, especially when multiple laboratories and institutes are compared. ICES run events compiled in SmartDots that provide a convenient overview of those agreement levels for many species, and in most cases with a temporal dimension, as new age reading workshops are compiled for the same stock ahead of a benchmark.

Overall, these species and structures were highlighted as the most promising:

1. Atlantic cod (*Gadus morhua*), otoliths

Atlantic cod is a historically important fishery in the North Atlantic, and one of the longest and most studied wild fish species in the world. It is widespread from the eastern American and Canadian coast to the Subarctic waters of the Barents Sea to the east, with multiple populations found in Greenland, Iceland, Norway, the Irish and Celtic Seas, the North Sea, and even the Baltic. While many of these stocks have been drastically reduced during the second half of the 20th century, they remain of high economic and ecological importance and represent a significant proportion of all otoliths and biological data collected in those areas.

While its geographic spread is associated with significant differences in growth and life history between populations, age reading of cod remains consistent across those (except for the eastern Baltic), and large amounts of training material can be easily accessed. One challenge with cod otoliths is that the creation of digital age reading images requires embedding and thin-sectioning to reveal growth zones, which can be a costly time investment without large-throughput laboratories, and has therefore led many countries to keep ageing cod using a visual estimation of manually broken otoliths, which is not compatible with automation approaches. On the other hand, cod has the added benefit of loosely sharing otolith shapes and growth patterns with other demersal gadoids such as haddock (*Melanogrammus æglefinnus*), saithe (*Pollachius virens*) or pollack (*Pollachius pollachius*), which are all economically important and significantly sampled species. This means that the potential for a successful transfer learning from a cod algorithm to those is high.

2. Atlantic salmon (*Salmo salar*), scales

Like Atlantic cod, the Atlantic salmon is a historically important resource with a widespread distribution in the North Atlantic that has experienced significant stock fluctuation. Owing to its anadromous life cycle, salmon is studied, and age read using scales instead of otoliths as they easily mark the transitions between freshwater and marine environments. These scales can either be directly imaged, or imprints can be made and photographed, which provides a higher quality at the cost of additional processing time.

3. Small pelagics, otoliths

Pelagic species like herring (*Clupea harengus*), mackerel (*Scomber scombrus*) or capelin (*Mallotus villosus*) are also economically and ecologically important species with a long history of fishing, and are therefore well sampled throughout their range for research and assessment purposes. An additional advantage is that their otoliths are small and easily stored in large numbers, and are also read whole directly under a microscope. This makes the processing time between collection and digital imaging minimal, and significantly increases the potential for a semi-automated, high-throughput solution to produce large numbers of images in little time. However, this same storage solution can prove challenging for digital images, as the solution used to cover the otoliths can often turn opaque or damaged in appearance, significantly reducing the quality of the image and the associated annotations and training data for an eventual automated algorithm.

4. Other species, otoliths

Several other species were highlighted, primarily because they are currently being investigated in pilot projects for age reading automation in several institutes. These species include, for example, various flatfish of commercial interest, such as plaice (*Pleuronectes platessa*) or smaller commercial gadoids, such as blue whiting (*Micromesistius poutassou*), and may be interesting to consider as they are usually collected in relatively large numbers for ageing purposes, and may be processed and imaged with little to no extra preparation.

In most of the cases above, the existence of biologically and geographically distinct units within each species was another criterion of interest, as any automated approach to their analysis could, beyond age reading, also integrate shape and other metrics capable of differentiating individuals coming from different populations.

5.2 Development of a collaborative framework

Discussions during the second half of WKETAC focused on bringing together the various experts and institutions currently involved in relevant automation initiatives to develop a collaborative framework. This was highlighted as one of the key outcomes from the workshop, as the various presentations and discussions confirmed the need for larger datasets and standards that could only be achieved through international collaboration.

In the last few years, similar projects have been submitted but ultimately not financed across different funding calls, usually due to mismatching scientific goals. To ensure a successful application, it was concluded that these previous proposals could be used as a basis and reworked in an upcoming draft with a stronger emphasis on scientific output and data governance. Because automated methods will require a large amount of curated training data, such a proposal could take the form of an international, open-access repository with both a public-facing work package (i.e. standardized stored pictures and metadata from various fish species and populations) and a scientific pilot work package (i.e. an attempt at automation on a specific data-rich species). Such proposals would share similarities with existing collaborative scientific repositories, such as:

- Darwin Tree of Life: a collaborative public repository of genome sequences from organisms found in Britain and Ireland.
- SMarTaR-ID: a standardized marine taxon reference image collection.
- BioTIME: a global database of biodiversity time-series.

The main idea would be to provide a queryable, standardized and FAIR platform on which to host and reference large digital archives of calcified structures used for ageing and other purposes, to be maintained, enriched and used collaboratively. This would provide a much-needed repository for experts and institutes to develop automated methods, while encouraging transparency and exchange. A "pilot" study within the wider project could focus on a singular species of stock of high interest to develop and test a functional automated algorithm, which could form the basis of more targeted initiatives on other species. Source code, methodological considerations and version control for each of those could then be hosted and catalogued together with the digital archive, to provide fully transparent algorithms to be developed and shared.

A project in this direction would also have a strong circular relationship with existing platforms within ICES, such as the SmartDots software and the new SMART4SAM project, which will add to it a reference collection and training module, and will investigate how to export age reading uncertainty from workshops directly into assessment. For example, international age reading events could query a digital archive for images that fit their exact criteria (species, stock, area, ages…), then build the exchange from there. Then, through the integration of an existing automated algorithm for this species, could add an "unbiased", automated set of age estimates and annotations to those from human readers as a comparison. Finally, the resulting age error matrix could be fine-tuned and added to related assessment models.

To successfully develop such a pilot study will require both a high level of image standardization and a thorough storage of associate meta data. While general quality guidelines like those developed by WGSMART are a good starting point, when the acquisition of images is realized by several laboratories under different formats or qualities, it will be essential to standardize them before storage and analysis. These meta data will, in turn, require the use of standardized and targeted vocabulary. This kind of pipeline from sample collection to image, storage and analysis already exists across different institutions, and may be used as basis for developing a collaborative repository (Figure 11). Standardized processing tools and scripts have also been developed to process raw images into digital standards. For example, Andrialovanirina *et al.* (2023) proposed a set of R scripts to transform otolith images into multiple morphological databases, using a combination of alignment, contour detection, segmentation, and image processing (Figure 12). A collaborative repository should provide clear image quality and metadata guidelines for submitted content, but could then integrate its own standardized processing algorithm to ensure the final stored and publicly available images are similar.

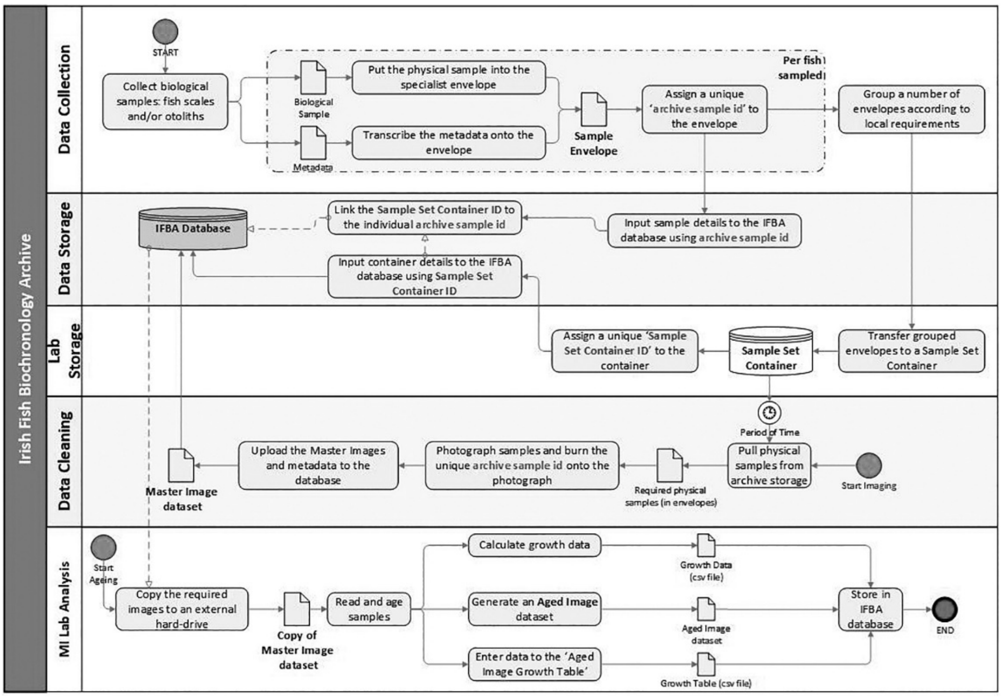

Figure 11. Collection and standardization process for salmon scales within the Irish institute (Tray *et al.,* 2020).

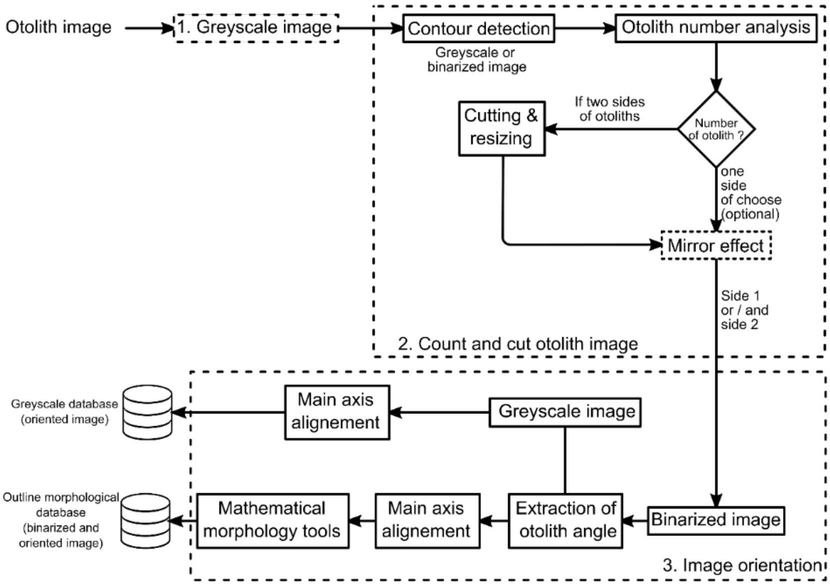

Figure 12. Processing scripts developed for otolith images by Andrialovanirina *et al.* (2023).

6 Conclusions

WKETAC highlighted the increasing interest and development of new methods and technologies to utilize biological information stored in calcified structures, as well as the inherent need for a more collaborative approach to offset the time and monetary costs of developing, training, calibrating and adopting those methods at an adequate level of quality.

By bringing together a diverse panel of participants from across the ICES network and the wider marine community, WKETAC achieved several crucial steps:

- It brought together experts in both fish biology, calcified structures and emerging technologies/machine learning, providing crucial knowledge of a broad range of aspects and allowing them to form an informal network for knowledge exchange.
- It identified the most promising set of methods and target species or populations.
- It laid the foundation for a targeted collaborative initiative to allow for more transparent and shareable data, and collectively increase the potential and quality of emerging automation methods.

Its natural continuation will be to formalize those discussions and findings into a collaborative pilot project that can utilize the network created during the workshop. While this initiative's scope will be beyond that of ICES alone, it will have significant ramifications with ongoing ICES work across multiple WGs and WKs such as WGSMART, WGMLEARN, WGBIOP and WKAAII.

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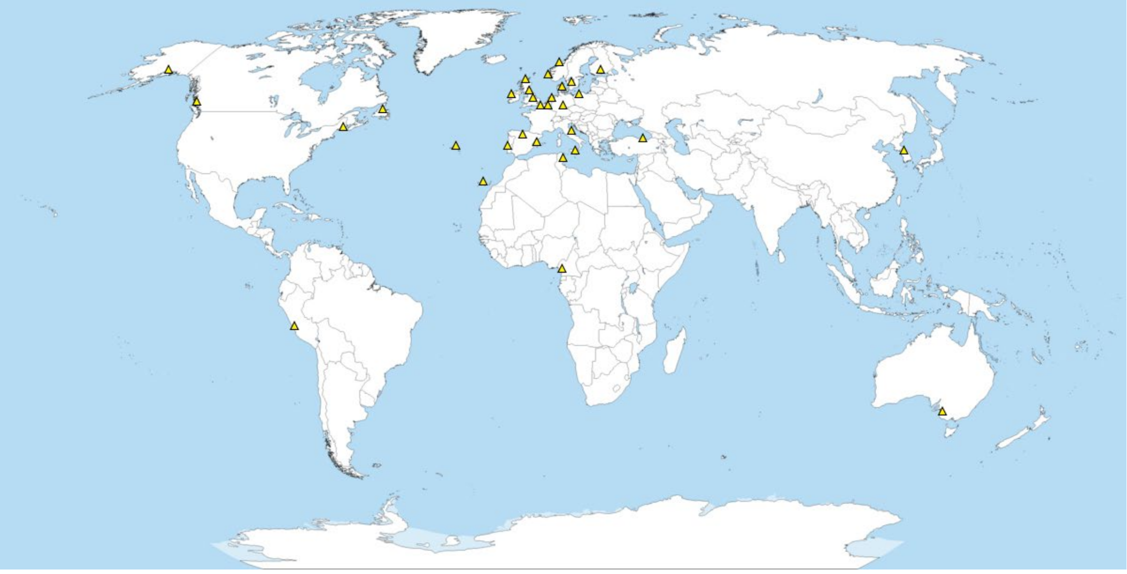
Annex 1: List of participants

Over 70 experts from institutes and universities across the world attended WKETAC.



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Annex 2: Resolutions

WKETAC - Workshop on emerging methods and technologies for the automated analysis of calcified structures

Approved on 13 November 2025 *Workshop*

2024/WK/DSTSG13 The Workshop on emerging methods and technologies for the automated analysis of calcified structures (WKETAC), chaired by Côme Denechaud (Norway), and Kélig Mahé (France) will work on ToRs and generate deliverables as listed below.

	Meeting Date(s)	Venue	Report Deadline
2025	2 October - 3 October	Boulogne-sur-Mer, France	30 December 2025

ToR	Description	Background	Science Plan Codes	Year	Expected Deliverables
a	Review automated technologies and methods for extracting biological information from fish calcified structures (such as otoliths, scales or spines) to derive individual data on age, life history and species or stock identification.	Emerging technologies and methods are transforming the collection and analysis of biological data, but their quick development across many parallel actors makes identifying and implementing them within fish stock assessment challenging. Calcified structures like otoliths and scales are a fundamental component of this assessment as they provide individual age and other biological parameters, and it is therefore essential that any emerging method of interest is properly understood and tested to ensure the quality and validity of the data it provides. It is timely and necessary to assess the portfolio of emerging methods and technologies of relevance, review and compare their costs, benefits and limitations, and use this information to provide guidelines and best practices.	4.1, 4.2	2025	To be addressed in final report.
b	Compare the performance and limitations of emerging analytical methods (deep learning, supervised/unsupervised classifiers, 2D/3D imaging, computer vision).	(See ToR a Background)	4.1, 4.2	2025	To be addressed in final report.
c	Assess the costs and		4.1, 4.2	2025	

	benefits of implementing emerging automated methods in parallel with current practices.			
d	Develop a list of interest species and stocks to be targeted for pilot studies implementing automated methods within the EU Data Collection Framework.	4.1, 4.2	2025	List of species.
e	Create a set of guidelines and best practices to be adopted for the transparent and reproducible implementation of automated methods, following the generic ToRs provided by WGBIOP.	4.1, 4.2	2025	Development of guidelines and best practices, following generic Terms of Reference provided by WGBIOP.

Scientific Justification

Emerging technologies and methods are transforming the collection and analysis of biological data, but their quick development across many parallel actors makes identifying and implementing them within fish stock assessment challenging. Calcified structures like otoliths and scales are a fundamental component of this assessment as they provide individual age and other biological parameters, and it is therefore essential that any emerging method of interest is properly understood and tested to ensure the quality and validity of the data it provides. It is timely and necessary to assess the portfolio of emerging methods and technologies of relevance, review and compare their costs, benefits and limitations, and use this information to provide guidelines and best practices. This is the first workshop focused on a horizon scanning of emerging methods to get biological information from fish calcified structures. It has many ramifications across the fields of age estimation, stomach content analysis for diet studies, and species and stock identification, which are all central elements of ICES science and advice production. The workshop will be of interest to scientists involved with fish biology (in particular those already involved in assessment and biological working groups within ICES) and computer analysis. It will also interest actors involved in the development and implementation of these technologies, such as computing experts working directly with the development of AI and computer vision.

Resource Requirements

None

Linkages to other ICES Committees or Groups

SIMWG, WGBIOP, WGMLEARN

Linkages to other Organizations

EC, RCGs