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Assessment of a simple hydroacoustic system for the mapping of macrophytes in extremely shallow and turbid lagoon

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ABSTRACT

In this study, we focused on relatively inexpensive and commonly used fishermen class sonar in order to test its ability to detect stands of charophytes and other groups of submerged angiosperms in the shallow and turbid waters of the Curonian Lagoon. Based on the length of macrophytes, height thresholds (20 and 30 cm) were established in order to distinguish charophytes from submerged angiosperms in obtained echograms. The echograms were visually analysed by two experts. We successfully discriminated 3 echofeatures (bare bottom, stands of charophytes and submerged angiosperms), whereas angiosperms from different morphology groups could not be distinguished. Below 1 m depth, the stands of charophytes and submerged angiosperms were clearly distinguished, thus their maximum colonization depth could be delineated. The accuracy of the discrimination could be reduced by free-drifting mats of filamentous algae, resulting in the overestimation of charophytes. Our approach can be useful for the mapping of monospecific stands of submerged vegetation and could be an important additional tool for macrophyte monitoring and water quality assessment in shallow and turbid waterbodies.

1. Introduction

Shallow coastal waters and estuaries usually are strongly impacted by human-induced eutrophication. In such conditions submerged macrophytes are often replaced by faster growing benthic macroalgae and phytoplankton (Duarte, 1995), and maximum colonization depth of macrophytes is decreased due to reduced light climate near a bottom (Dennison et al., 1993). For this reason, species composition, distribution and abundance of submerged macrophytes are generally considered as water quality indicators under Water Framework Directive (WFD, 2000/60/EC). For example, charophytes are generally considered important indicators of good ecological status in the coastal waters (*e.g.* Schubert and Blindow, 2003; Selig et al., 2007; Hansen and Snickars, 2014).

Established manual techniques for characterising and monitoring aquatic vegetation are both time consuming and labour-intensive, and generate observations of very limited spatial extent (Winfield et al., 2007). Such methods as aerial surveys or underwater camera systems provide relatively large-scale assessments of spatial patterns of macrophytes but are highly dependent on water clarity, roughness of water surface and cloud cover (Madsen, 1993; Hewitt et al., 2004). Hydroacoustic techniques are less dependent on environmental conditions and provide rapid, extensive and spatial referenced data (Winfield et al., 2007). Therefore, this approach receives an increasing attention for the assessment of macrophyte communities. Despite several successful applications of hydroacoustics in the detection and qualitative characterisation of macrophytes (*e.g.* Xu et al., 2013), there are still limitations (Mielck et al., 2014). For instance, sonars cannot clearly reflect small morphological features of macrophytes, prohibiting the identification to species level even for relatively large kelps (Bajjouk et al., 2015).

Fishermen class sonars differ in their technical characteristics, but usually provide side scan sonar data and depth in a single beam-like manner. Although few manufacturers offer proprietary software packages, such as EcoSAV from BioSonic, that are specifically designed to measure plant height, areal coverage and density of macrophytes (Winfield et al., 2007), these solutions are not available for majority of sonar systems. Nonetheless, these characteristics can be estimated manually from echograms, where vegetation is generally visible as a contiguous vertical echo return immediately above the bottom (Depew et al., 2009). Based on the height of echofeatures, the dominant growth form in a stand can be identified (Fortin et al., 1993). For instance, charophytes are usually

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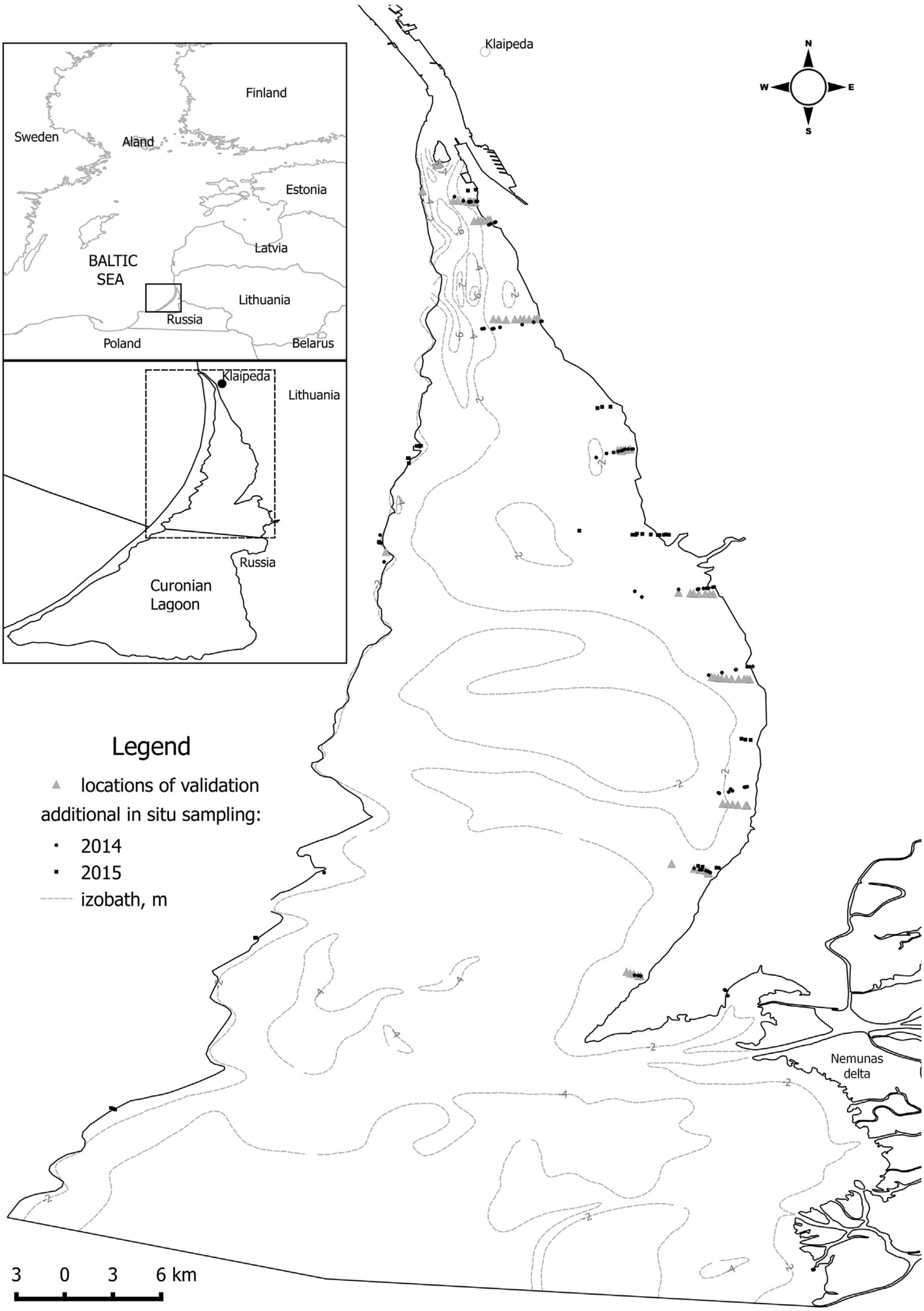

Fig. 1. The study area with sampling locations by rake and sonar in the Curonian Lagoon, 2014 and 2015.

shorter than submerged angiosperms (*e.g.* Winfield et al., 2007), especially in waterbodies with monospecific and stratified stands (*e.g.* Abukawa et al., 2013).

In this study we focused on relatively inexpensive and commonly used fishermen class sonar in order to test its ability to discriminate different morphological groups of macrophytes (including charophytes) and their distribution in shallow and tur-

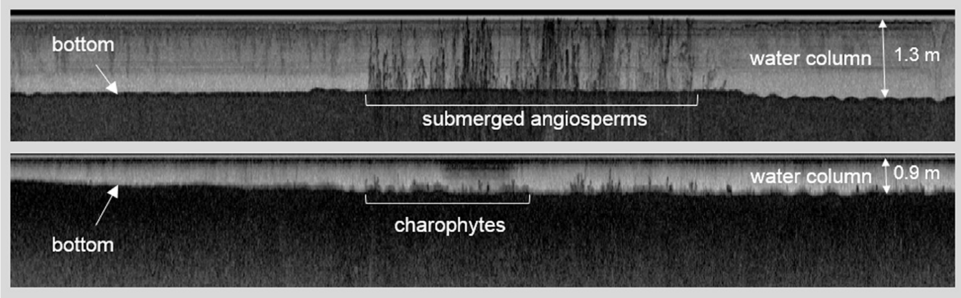

Fig. 2. The acoustic features that could be derived from the echograms (200 kHz channel): charophytes (lower image) and submerged angiosperms (upper image).

bid waters of the hyper-eutrophic Curonian Lagoon. Firstly, we sampled submerged macrophytes and measured their lengths to set thresholds for discrimination of different morphological groups. Secondly, we performed hydroacoustic surveys in parallel with *in situ* sampling of macrophytes. In relation to defined length thresholds, we visually analysed echograms to distinguish different echofeatures and validated them with *in situ* data. Finally, we estimated the accuracy of agreement between hydroacoustic data and *in situ* measurements depending on the variability associated with visual analysis by two experts, different depths and the presence of algal mats.

2. Materials and methods

2.1. Study area

The Curonian Lagoon is a large, shallow water body (total area 1584 km^2, mean depth 3.8 m) located along the south-eastern coast of the Baltic Sea (Fig. 1). The Klaipeda Strait provides the only connection to the Baltic Sea, while in the eastern part the Nemunas River (one of the largest rivers in the Baltic region) is entering the lagoon. The mixing of fresh and brackish water masses creates spatially and temporally unstable gradients with salinity ranging from 0 to 7 PSU (Dailidienė and Davulienė, 2008). During elevated discharge, the northern part of the lagoon is typically defined as a transitional riverine-like system with a mixing of brackish, lagoon and riverine waters (Ferrarin et al., 2008). The southern part is more lacustrine and characterized by a relatively closed water circulation with lower current velocities, where the wind is the main driving factor.

The Curonian Lagoon is a naturally productive water basin (Gasiūnaitė et al., 2008) and is considered as eutrophic or hyper-eutrophic. The shallow, weakly stratified lagoon remains very turbid throughout the year due to solids (mainly sand and silt) being resuspended as a result of water mixing caused by local winds and intensive primary production (Galkus, 2003). The mean Secchi depth is ca. 0.6 m and varies from 0.3 to 2.2 m (Gasiūnaitė et al., 2008). The luxuriant vegetation of both emergent and submerged macrophytes are mostly confined in the upper littoral zone (Sinkevičienė, 2004).

2.2. Sampling and length measurements of macrophytes

The sampling of submerged macrophytes was performed in July 2014 (14 transects with 93 locations of sampling), in August and September 2015 (5 transects with 37 locations of sampling). Macrophyte species were sampled by tossing a double-headed rake attached to a line. Semi quantitative abundance was assessed using the Braun-Blanquet scale. At least 8 specimens of charophytes and 16 of submerged angiosperms were selected in each 4 depth zones (<0.25 m, 0.25–0.5 m, 0.51–1.0 m, >1 m) for their length measurements. The lengths of macrophytes were pooled into 4 groups according to their characteristic morphological features (whorls charophytes, narrow-leaf pondweeds, broad-leaf pondweeds and pinnate whorls milfoil) in order to set thresholds for the discrimination of these groups in echograms.

2.3. Collection of hydroacoustic data

The survey was conducted in the beginning of September 2014, when submerged macrophytes are generally fully developed (Z. Sinkevičienė, pers. obs.). The collection of hydroacoustic data was done from a small boat (length 6 m, draft 0.3 m) equipped with the fishermen class Hummibird 898c SI Combo sonar with XHS 9 HDSI 180 T transducer. This system is able to work at 200/83/455/800/50 kHz frequencies and has 2.5 inch target separation capabilities. The sonar head was mounted on the back of the boat, 0.4 m below the water surface. The sonar operates with simultaneous dual single-beam frequencies (200/455 kHz) and records side scan data with 2D imaging. Hydroacoustic data was collected moving at a speed of ca. 4 km h^{-1} in 11 transects perpendicular to the shore, within 0.3–4 m depth, thus covering photic zone that extends up to 2.5 m (D. Vaičiūtė, unpublished). The system was not equipped with motion reference unit; therefore, only those seg-

Table 1
Relative frequency, maximum abundance and depth distribution of submerged macrophyte taxa (classified according to their morphology) recorded *in situ* in the Curonian Lagoon in July–September 2014 and 2015.

taxa	leaf morphology	relative frequency, %	max abundance & depth range, m	max depth, m
Cladophora spp.	filaments	36	5 (0.5–1.0)	1.70
Chara baltica	whorls	4	2 (0.5–0.7)	0.75
C. contraria	whorls	66	5 (0.5–1.5)	1.90
C. aspera	whorls	31	5 (0.5–1.0)	1.70
Nitellopsis obtusa	whorls	19	2 (0.9–1.0)	1.60
Tolypella nidifica	whorls	4	1 (1.0–1.2)	1.25
Myriophyllum spicatum	pinnate whorls	10	1 (0.5–0.8)	1.80
Zannichellia palustris	narrow-leaf	13	1 (0.7–1.5)	1.50
Potamogeton rutilus	narrow-leaf	18	3 (1.2–1.6)	1.80
P. pectinatus	narrow-leaf	30	4 (0.5–1.2)	1.40
P. perfoliatus	broad-leaf	45	4 (0.5–1.4)	1.50

Table 2
Length of charophytes and submerged angiosperms pooled into groups according to morphology (Table 1) in different depths of the Curonian Lagoon in July–September 2014 and 2015. The length of green filamentous algae (*Cladophora* spp.) was not estimated as they were growing as epiphytes or drifting unattached near the bottom. Data presents means ± standard deviation.

Depth, m	Length, cm			
	whorls charophytes	pinnate whorls milfoil	narrow-leaf pondweeds	broad-leaf pondweeds
0–0.25	16.0 ± 8.5	17.5 ± 10.6	18.6 ± 7.3	32.0 ± 23.6
0.26–0.5	16.9 ± 8.8	46.0 ± 22.5	26.6 ± 8.9	38.9 ± 20.8
0.51–1.0	20.0 ± 8.3	86.7 ± 32.1	35.6 ± 12.4	86.8 ± 54.9
>1.0	19.1 ± 8.4		29.8 ± 5.4	70.2 ± 57.4

ments of echograms, where actual bottom position was apparent, were analysed.

The analysis of hydroacoustic data was performed manually using HumViewer 86 software, which provides simultaneous view for both data channels (200 kHz and 455 kHz). The occurrence of echofeatures was assessed within ca. 15 m distance in 79 random segments of the echograms (Fig. 2). The echofeatures corresponding to morphological groups of macrophytes were distinguished according to the thresholds derived from *in situ* length measurements (Table 2). The height of echofeatures was estimated using length/distance measurement tool with the accuracy of 0.1 m. The bare bottom was considered where no apparent echofeatures were visible in echograms.

Two experts (A and B) independently analysed hydroacoustic data in order to evaluate the bias associated with visual assessment. The systematic disagreements between estimates of both experts were identified and reassessed.

2.4. Ground truthing

In order to validate echofeatures with four morphological groups of macrophytes, *in situ* sampling of submerged aquatic plants was conducted in parallel to hydroacoustic transects. The bottom was dredged along the drift track for ca. 15 m distance with a double-headed rake attached to a line and sometimes inspected by snorkelling. The samples were brought to the laboratory for detailed species identification and length measurements (except *Cladophora* genus). The maximum colonization depth of submerged vegetation was determined from the real time echograms and ground truthed by snorkelling and line.

2.5. Statistical analysis

Significant differences in mean lengths of 4 morphological groups of macrophytes at each depth intervals (<0.25 m, 0.25–0.5 m, 0.51–1.0 m, >1 m) were determined by nonparametric multiple contrast effects based on global rankings, computed with a Tukey-type test, using “nparcomp” package (Konietschke et al., 2015) in R 3.2.0 (R Core Team, 2015).

The correspondence of echofeatures with *in situ* samples was assessed in terms of visual analysis by two experts, presence of algal mats and depth intervals; 3 accuracy measures were used: sensitivity, specificity and area under the receiver operating characteristic curve (AUC). These parameters describe the fractions of echofeatures (presence and absence) that are classified correctly. The sensitivity describes the fraction of presences derived from echograms that actually occurred *in situ*. The specificity describes the fraction of absences (*i.e.* bare bottom) derived from echograms that actually were absent *in situ*. AUC is an effective and combined measure of sensitivity and specificity for assessing the inherent validity of classification (Kummar and Indrawn, 2011), where AUC = 1 means that the classification is perfect, AUC = 0.5 means the chance discrimination, while AUC = 0 means incorrectly classified all presences and absences. All these measures were calculated using “PresenceAbsence” package (Freeman and Moisen, 2008) in R.

Depending on data properties, statistical hypothesis on estimates (*i.e.* means of AUC and maximum colonization depth of macrophytes) were tested using several parametric statistical methods (one-way analysis of variance and Tukey’s honest significant difference test) and Wilcoxon rank sum test in R.

The effect of epiphytes or near bottom free-floating mats (mainly formed by *Cladophora* spp.) to the accuracy of classification of charophytes and submerged angiosperms was tested. Welch two sample *t*-test was performed with samples including and excluding filamentous green algae.

3. Results

3.1. Species composition, abundance and length thresholds

In total, 11 submerged macrophyte taxa were identified and classified to five morphological groups (Table 1). The first morphological group characterized by whorls was represented by 5 species of charophytes, where *Chara aspera* and *C. contraria* were the most abundant. The second group characterized by pinnate whorls consisted of only one species *Myriophyllum spicatum*. The third group characterized by narrow-leaf submerged angiosperms was dominated by *Stuckenia pectinata* and *Potamogeton rutilus*. The fourth (broad-leaf submerged angiosperms) and fifth (filamentous) groups were represented by a single taxa, *P. perfoliatus* and *Cladophora* spp. respectively.

The mean length of 4 morphological groups of macrophytes did not statistically significantly (nonparametric Tukey-type contrast $p > 0.05$) differ at 0–0.25 m depth (Table 2), thus hydroacoustic data was not further analysed in this depth range. At greater depth, the mean length of charophytes (the first morphological group) was significantly (nonparametric Tukey-type contrast $p < 0.01$) lower than the length of other groups characterized by pinnate whorls, narrow-leaf and broad-leaf submerged angiosperms. In this respect, echofeatures were reclassified into two groups (charophytes and submerged angiosperms). The mean length of charophytes at different depths ranged from 16 ± 8 (±standard deviation) to 20 ± 8 cm, therefore two thresholds (20 and 30 cm) were set to discriminate these two groups (Fig. 2). Since the discrimination accuracy of echofeatures did not significantly differ with both thresholds, the results below are given using only 20 cm threshold.

3.2. Accuracy of visual assessment

The agreement between charophytes discriminated from the echograms and *in situ* measurements was higher than chance for both experts (mean AUC = 0.63). The discrimination of charophytes between two experts was similar (Fig. 3): relatively high accuracy of presences (mean sensitivity > 91%) and low accuracy of absences (mean specificity < 37%). The mean ranks of AUC did not significantly ($V = 3.5$, $p = 0.1$) differ between the experts.

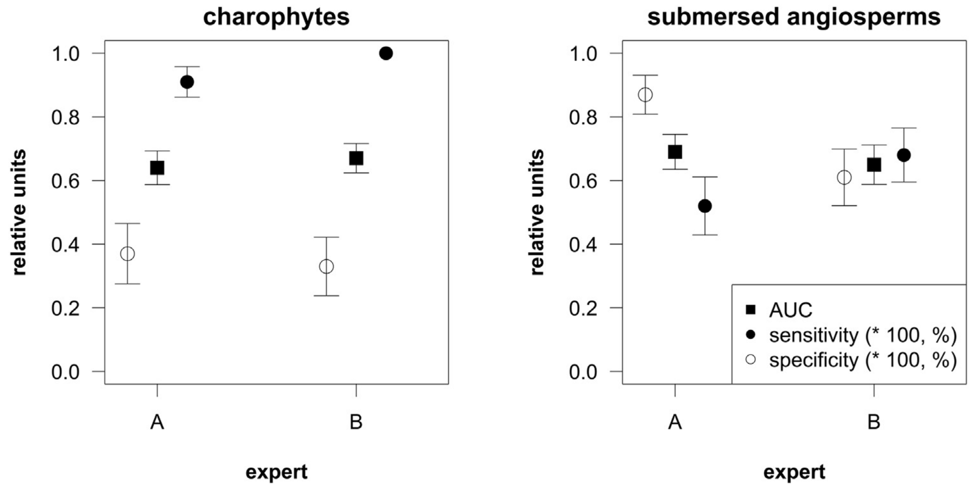

Fig. 3. The accuracy of classification of charophytes and submerged angiosperms from the echograms by two experts (A and B) and *in situ* measurements. Accuracy measures: area under the ROC curve (AUC), sensitivity and specificity. Data presents means ± standard deviation.

The correspondence between submerged angiosperms classified from the echograms and *in situ* measurements was higher than chance (mean AUC = 0.65). The mean sensitivity and specificity of both experts were higher than 50%; however, there was some disagreement in the classification. Expert A resulted in relatively lower accuracy of presences and higher accuracy of absences (respectively, mean sensitivity = 52% and specificity = 87%) than expert B (respectively, mean sensitivity = 68% and specificity = 61%). The mean ranks of AUC significantly (V = 18, $p < 0.01$) differed between the experts. After intercalibration between both experts, general agreements (mean AUC) of both groups of macrophytes (Fig. 4, A) did not significantly (respectively, F = 0.19, df = 2, $p > 0.05$ and

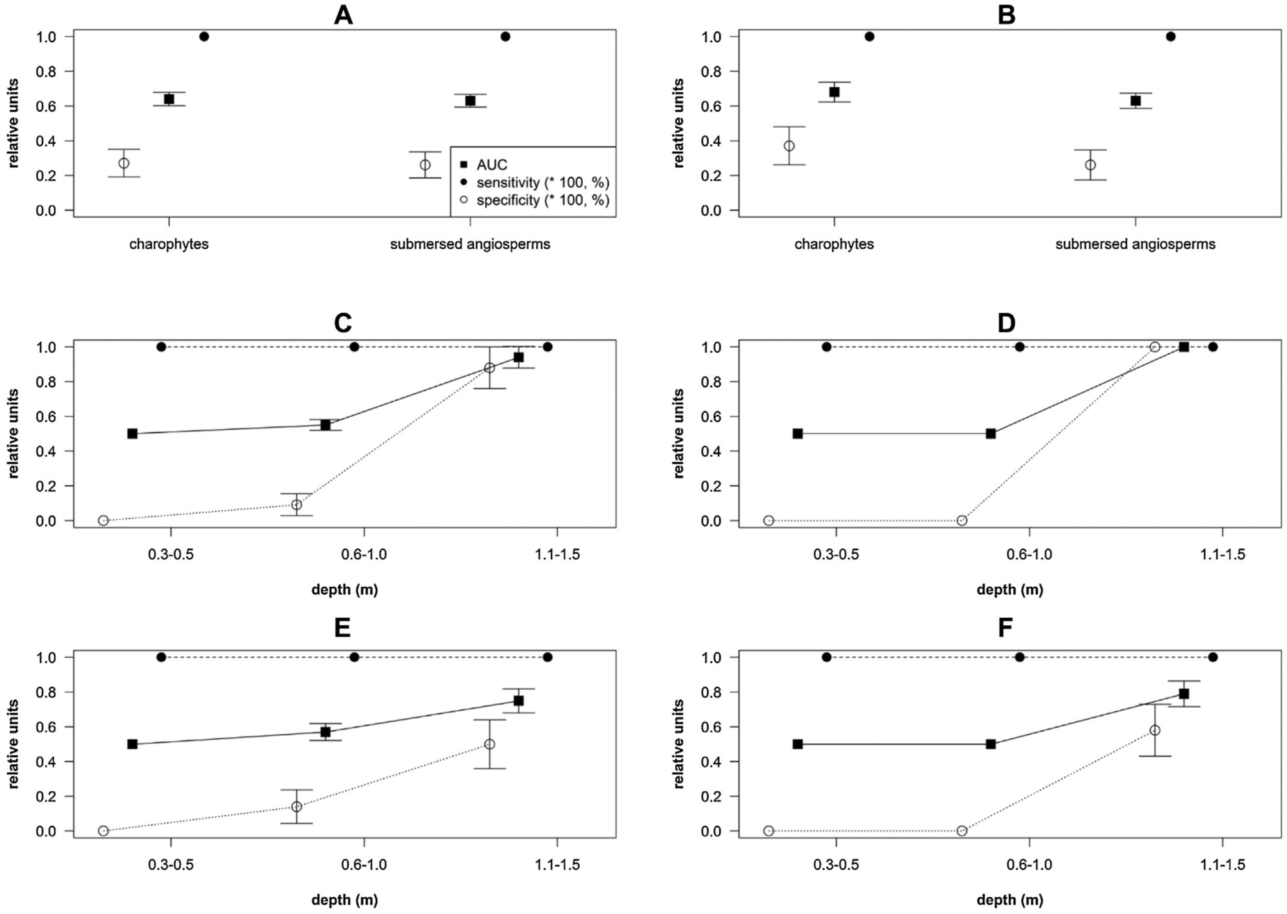

Fig. 4. The accuracy of classification of charophytes and submerged angiosperms from the echograms and *in situ* measurements after intercalibration of experts within 0.3–1.5 m depth (A and B) and separately charophytes (C and D) and submerged angiosperms (E and F) in different depths. B, D and F—after removing ground truthing stations, where filamentous green algae (*Cladophora* spp.) occurred (26). The accuracy measures: area under the ROC curve (AUC), sensitivity and specificity. Data presents means ± standard deviation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$F = 0.001$, $df = 2$, $p > 0.05$) differ compared to the estimates before intercalibration (Fig. 3). The visual assessment of both experts resulted in slight underestimation of the maximum colonisation depth of charophytes and submerged angiosperms (0.6–1.4 m) than measured *in situ* (0.7–1.9 m). After the intercalibration, the depth limits became identical (0.7–1.9 m).

3.3. *Effect of depth and algal mats*

The correspondence between charophytes classified from the echograms and *in situ* measurements significantly ($F = 603.03$, $df = 2$, $p < 0.01$) differed within the depth zones (Fig. 4, C). In shallow areas (≤ 1 m) the discrimination of charophytes was close to random (mean AUC = 0.5–0.55) and significantly (Tukey's HSD $p < 0.01$) lower than in deeper areas (>1 m), where it was relatively high (mean AUC = 0.89). The accuracy of charophytes absences displayed similar pattern: in shallow areas it was relatively low (mean specificity = 0–9%), whereas deeper it was relatively high (mean specificity = 78%). The accuracy of charophytes presences was 100% within the depth zones.

Similarly to charophytes, the correspondence between submerged angiosperms classified from the echograms and *in situ* measurements also significantly ($F = 132.93$, $df = 2$, $p < 0.01$) differed within the depth zones (Fig. 4, D). In shallow areas the discrimination of submerged angiosperms was close to random (mean AUC = 0.5–0.57) and significantly (Tukey's HSD $p < 0.01$) lower than in deeper areas (>1 m), where it was moderate (mean AUC = 0.73). The accuracy of absences was relatively low (mean specificity < 47%) and increased along the depth. The accuracy of submerged angiosperms presences was 100% within the depth zones.

The exclusion of samples with filamentous green algae resulted in significant increase in general agreement (mean AUC) between classification of charophytes and submerged angiosperms (respectively, $t = 7.50$, $df = 110$, $p < 0.01$ and $t = 5.54$, $df = 131$, $p < 0.01$) (Fig. 4, B). This was evident in deep areas (Fig. 4, E and F), where absences of both macrophyte groups were better determined (mean specificity = 88% and 54%).

4. Discussion

The mapping of aquatic vegetation in extremely shallow and turbid environments requires specific approaches, since the use of optically based remote methods (underwater video, aerial and satellite imagery) is very limited (Madsen, 1993; and references therein). Survey class hydroacoustic equipment is generally designed for greater depths; therefore, its application in ecosystems such as the Curonian lagoon is not efficient. The development of high frequency hydroacoustic equipment, such as acoustic Doppler current profiler (Waren and Peteterson, 2007) or imaging sonars operating in mHz range (Xu et al., 2013) can enhance the detection of macrophytes, however such devices are not widely available and often require special skills to operate. On another hand, relatively inexpensive and simple fishermen class sonars are widely available and may offer new possibilities for researchers, such as the assessment of aquatic plant abundance patterns and community dominance (Valley et al., 2015). They can be easily mounted on very small boats, do not require complicated configuration and calibration, hence can be operated by personnel relatively inexperienced in hydroacoustic technologies.

In our study, macrophytes from *in situ* sampling were categorized according to their morphological features, which were expected to be visible in echograms. However, we failed to distinguish them most likely due to low horizontal target separation capability (ca. 5 cm) of the sonar and too fine structure of macrophytes (*e.g.* the mean length of *Potamogeton perfoliatus* leaves was 4 ± 1 cm). Nevertheless, we obtained fairly good quality data at extremely shallow depths (0.3–2 m) for the discrimination between vegetated and bare bottoms, charophytes and submerged angiosperms (according length measurements) and the detection of their maximum colonization depth. The results of discrimination depended on several factors such as the length thresholds for groups of macrophytes, their depth distribution and variability in visual assessment.

4.1. *Length thresholds for groups of macrophytes*

The hydroacoustic mapping was performed in the beginning of September, assuming that submerged vegetation is fully formed. According to *in situ* data the mean length of dominant charophytes and submerged angiosperms increased from July to September (respectively for charophytes: from 20 to 23 cm and submerged angiosperms: from 41 to 73 cm) in <1 m depth. Nevertheless, the means did not significantly differ among the months (respectively for charophytes: $F = 1.95$, $df = 2$, $p > 0.05$ and submerged angiosperms: $F = 3.24$, $df = 2$, $p > 0.05$), showing that selected thresholds (20 and 30 cm) could be used during the whole period. This well agrees with the time recommended for macrophyte monitoring *(e.g.* Madsen, 1993), while Farrell et al. (2013) successfully identified watermilfoil (*Myriophyllum spicatum*) with hydroacoustics from middle of July to August. Furthermore, during these months most of submerged angiosperms flower above the water and since their stems tend to straighten up from the bottom towards the surface it should improve the discrimination of echofeatures.

In our approach, there is a slight methodological disagreement between *in situ* samples (length measurements) and echograms (height measurements). For instance, the mean length of dominant charophytes in some cases was higher than selected threshold for the discrimination of echofeatures. However, this could be disregarded as the lengths were measured after the macrophytes were removed from the water and stretched out, whereas charophytes do not form fully upright stands underwater. In particular, the length of *Chara contraria* specimens often exceeded 20 cm (up to 46 cm), however due to their weakly encrusted and partly ecorticated thalli (subgymnophyllous form) their stands were flattened to the bottom and did not exceed the selected threshold (pers. obs.). To avoid the underestimation of longer charophytes, the higher threshold of 30 cm was tested; however, the difference in accuracy of discrimination was insignificant compared with the results of 20 cm threshold. Finally, the thresholds used in this study were also successfully applied in discrimination between the stands of charophytes and submerged angiosperms in several hydroacoustic transects performed in August and September 2015, supporting its consistent performance and application in the Curonian Lagoon.

4.2. *Depth distribution of macrophytes*

Fortin et al. (1993) could successfully distinguish three phytoacoustic facies corresponding to dominant growth forms (*Potamogeton, Vallisneria* and *Nitella*), showing that hydroacoustic methods are best applicable for relatively homogeneous aquatic plant communities. In the Curonian Lagoon, however, dominant macrophyte species were overlapping at less than 1 m depths (Table 2), what reduced the accuracy of discrimination of echofeatures in the upper littoral part (Fig. 4). Additionally, we compared the classification accuracy between monospecific stands of charophytes and mixed stands. The discrimination was significantly ($t = 5.44$, $df = 22$, $p < 0.01$) lower in the latter case (respectively, AUC = 0.54 ± 0.03 and AUC = 0.67 ± 0.11), showing that monospecific stands were more accurately distinguished. However, the

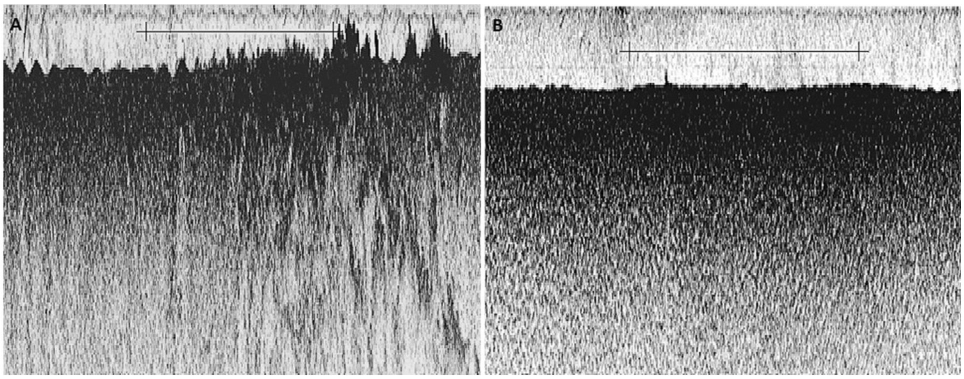

Fig. 5. The snapshots of echograms (200 kHz channel), where common mistakes occurred when classifying charophytes and submerged angiosperms: (A) charophytes classified as present, whereas submerged angiosperms could be missed since they are on the edge of validation transect, which is indicated by 15 m distance bar (ca 0.3 m above the bottom) from the ground truthing point on the left side; (B) solitary plants could be sometimes missed or interpreted as artefacts of noise.

specificity was relatively low (33%) since in transects without charophytes (especially in the western part of the Curonian Lagoon) narrow-leaf pondweeds (mainly *Stuckenia pectinata*) formed not fully upright stands, which were falsely classified as charophytes in the echograms. Similarly, at depths below 1 m the mats of filamentous algae were mistaken for charophytes that resulted in 10% accuracy decrease for the discrimination of macrophyte groups.

Only few macrophyte species (mainly submerged plants) occur in the lower part of the photic zone, forming uniform stands stratified along the depth gradient in order to avoid shading in reduced light climate (Bornette and Puijalon, 2011; and references therein). Thus, hydroacoustic methods could enhance the discrimination in the lower littoral, especially if species differ morphologically (Xu et al., 2013). In example, Abukawa et al. (2013) distinguished stands of *Potamogeton* and *Chara*, which were restricted to shallow and greater depths respectively. However, it was not entirely the case in the Curonian Lagoon, where stands of *Potamogeton* and charophytes were present in the whole photic zone. This is consistent to the patterns observed in very turbid lakes (mean Secchi disc <1 m over the vegetation season) in Denmark (Middelboe and Markager, 1997). Nevertheless, we resulted in excellent discrimination of the stands dominated by charophytes and submerged angiosperms below 1 m depth (Fig. 4). Both macrophyte groups were growing close to each other without evident overlap, probably due to shading by taller and large-leaved pondweeds. Moreover, these relatively monospecific stands were clearly distinguished in the echograms, since the mean length of *Potamogeton* plants (ca. 60 cm) was threefold higher than the mean length of charophytes (Table 2). These results show that our approach could be successfully applied for the delineation of maximum colonization depth of macrophytes, which is used as an indicator by many European countries (HELCOM, 2013). Therefore, the tested hydroacoustic method can supplement macrophyte monitoring, development and testing of indicators based on aquatic vegetation in other shallow and turbid lagoons or lakes.

4.3. *Visual assessment by experts*

Methods of manual hydroacoustic data analysis for the discrimination of biological and physical characteristics on the sea bottom have a long history, and already proved their effectiveness (Brown et al., 2002; Nitsche et al., 2004). However, to a certain level they are subject to human bias, especially when benthic features are not easily detected. In this study, two experts produced slightly different results from the same data set. The highest disagreement occurred in the detection of submerged angiosperms in echograms (Fig. 3), particularly the mismatch was determined in places, where ground truthing segment was close (up to 10 m) to the transition from stands of charophytes to submerged angiosperms (Fig. 5, A). In such cases, one expert recorded only the presence of charophytes, strictly following the protocol, while another expert considered nearby vegetation, thus adding the presence of submerged angiosperms. Monospecific stands of charophytes were well distinguished by both experts; however, in locations with low occurrence of charophytes one of the experts occasionally missed single specimens (Fig. 5, B). Despite these mistakes, the bias of visual assessment was relatively low, especially for the maximum colonization depth of charophytes and submerged angiosperms. Moreover, both experts complemented each other by their visual analysis and specific findings in the echograms (*e.g.* the occurrence of single plants, acoustic noise and artefacts, changes in the texture of sediments), what is very important for a manual assessment.

The manual analysis of echograms can become very tedious task in long acoustic transects with hetero-specific stands of macrophytes, thus automatic or semi-automatic visual assessment methods can be applied. However, they are mainly restricted to commercial software (*e.g.* Echoview, BioBase) and in case different sonars were used, the standardization of hydroacoustic systems and the signal processing approach would be necessary before using such methods as an assessment tool (Radomski and Holbrook, 2015).

5. Conclusions and perspectives

We found the potential in the use of a simple fishermen class hydroacoustic system for the detection of bare bottom and stands dominated by fully developed charophytes or submerged angiosperms in extremely shallow and turbid lagoon. The successful discrimination of echofeatures was based on differences in their height, whereas macrophytes with different morphology could not be distinguished. We could precisely separate the stands of charophytes from submerged angiosperms bellow 1 m depth due to higher difference in their lengths and more monospecific stands than in shallow part of the littoral, where application of the sonar was limited. Since we were able to discriminate stands of charophytes and their maximum colonization depth, which are generally considered as water quality indicators, the use of simple hydroacoustic method could be a very important additional tool for macrophyte mapping, monitoring and ecological status assessment according to the WFD. Although this study aimed to discriminate stands of submerged vegetation to echofeatures, we clearly see the potential for their quantitative estimation and the development of automatic or semi-automatic assessment methods that can use data from different sonars.

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References

Abukawa, K., Yamamuro, M., Kikvidze, Z., Asada, A., Xu, C., Sugimoto, K., 2013. Assessing the biomass and distribution of submerged aquatic vegetation using multibeam echosounding in Lake Towada, Japan. Limnology 14 (1), 39–42, http://dx.doi.org/10.1007/s10201-012-0383-7.

Bajjouk, T., Rochette, S., Laurans, M., Ehrhold, A., Hamdi, A., Le Niliot, P., 2015. Multi-approach mapping to help spatial planning and management of the kelp species *L. digitata* and *L. hyperborea*: case study of the Molène Archipelago, Brittany. J. Sea Res. 100, 2–21, http://dx.doi.org/10.1016/j.seares.2015.04.004.

Bornette, G., Puijalon, S., 2011. Response of aquatic plants to abiotic factors: a review 2011. Aquat. Sci. 73, 1–14, http://dx.doi.org/10.1007/s00027-010-0162-7.

Brown, C.J., Cooper, K.M., Meadows, W.J., Limpenny, D.S., Rees, H.L., 2002. Small scale mapping of seabed assemblages in the eastern English Channel using sidescan sonar and remote sampling techniques. Estuar. Coast. Shelf Sci. 54, 263–278, http://dx.doi.org/10.1006/ecss.2001.0841.

Dailidienė, I., Davulienė, L., 2008. Salinity trend and variation in the Baltic Sea near the Lithuanian coast and in the Curonian Lagoon in 1984–2005. J. Mar. Syst. 74, 20–29, http://dx.doi.org/10.1016/j.jmarsys.2008.01.014.

Dennison, W.C., Orth, R.J., Moore, K.A., Stevenson, J.C., Carter, V., Kollar, S., Bergstrom, P.W., Batiuk, R.A., 1993. Assessing water quality with submersed aquatic vegetation. Bioscience 43, 86–94, http://dx.doi.org/10.2307/1311969.

Depew, D.C., Stevens, A.W., Smith, R.E.H., Hecky, R.E., 2009. Detection and characterization of benthic filamentous algal stands (*Cladophora* sp.) on rocky substrata using a high-frequency echosounder. Limnol. Oceanogr. Methods 7, 693–705, http://dx.doi.org/10.4319/lom.2009.7.693.

Duarte, C.M., 1995. Submerged aquatic vegetation in relation to different nutrient regimes. Ophelia 41, 87–112, http://dx.doi.org/10.1080/00785236.1995.10422039.

Farrell, J.L., Harrison, J.P., Eichler, L.W., Sutherland, J.W., Nierzwicki-Bauer, S.A., Boylen, C.W., 2013. Identification of Eurasian watermilfoil using hydroacoustics. J. Aquat. Plant Manag. 51, 15–21.

Ferrarin, C., Razinkovas, A., Gulbinskas, S., Umgiesser, G., Bliudžiute, L., 2008. Hydraulic regime-based zonation scheme of the Curonian Lagoon. Hydrobiologia 611 (1), 133–146, http://dx.doi.org/10.1007/s10750-008-9454-5.

Fortin, G., Saint-Cyr, L., LeClerc, M., 1993. Distribution of submersed macrophytes by echo-sounder tracings in Lake Saint-Pierre, Quebec. J. Aquat. Plant Manag. 31, 232–240.

Freeman, E.A., Moisen, G., 2008. Presence absence: an R package for presence-absence model analysis. J. Stat. Softw. 23 (11), 1–31, http://dx.doi.org/10.18637/jss.v023.i11.

Galkus, A., 2003. Summer water circulation and spatial turbidity dynamics in the Lithuanian waters of Curonian Lagoon and Baltic Sea. Chron. Geogr. 36 (2), 48–60 (in Lithuanian, with English summary).

Gasiūnaitė, Z.R., Daunys, D., Olenin, S., Razinkovas, A., 2008. The Curonian Lagoon. In: Schiewer, U. (Ed.), Ecology of Baltic Coastal Waters. Ecological Studies 197. Springer-Verlag Berlin Heidelberg, Berlin, pp. 197–216, http://dx.doi.org/10.1007/978-3-540-73524-3.

HELCOM, 2013. HELCOM core indicators: final report of the HELCOM CORESET project. Balt. Sea Environ. Proc. 13, 1–71.

Hansen, J.P., Snickars, M., 2014. Applying macrophyte community indicators to assess anthropogenic pressures on shallow soft bottoms. Hydrobiologia 738, 171–189, http://dx.doi.org/10.1007/s10750-014-1928-z.

Hewitt, J.E., Thrush, S.F., Legendre, P., Funnell, G.A., Ellis, J., Morrison, M., 2004. Mapping of marine soft-sediment communities: integrated sampling for ecological interpretation. Ecol. Appl. 14, 1203–1216, http://dx.doi.org/10.1890/03-5177.

Konietschke, F., Placzek, M., Schaarschmidt, F., Hothorn, L.A., 2015. nparcomp: an R software package for nonparametric multiple comparisons and simultaneous confidence intervals. J. Stat. Softw. 64 (9), 1–17 http://www.jstatsoft.org/v64/i09/.

Kummar, R., Indrawn, A., 2011. Receiver operating characteristic (ROC) curve for medical researchers. Indian Pediatr. 48, 277–289.

Madsen, J.D., 1993. Biomass techniques for monitoring and assessing control of aquatic vegetation. Lake Reserv. Manag. 7, 141–154, http://dx.doi.org/10.1080/07438149309354266.

Middelboe, A.L., Markager, S., 1997. Depth limits and minimum light requirements of freshwater macrophytes. Freshw. Biol. 37, 553–568, http://dx.doi.org/10.1046/j.1365-2427.1997.00183.x.

Mielck, F., Bartsch, I., Hass, H.C., Wölfl, A.C., Bürk, D., Betzler, C., 2014. Predicting spatial kelp abundance in shallow coastal waters using the acoustic ground discrimination system RoxAnn. Estuar. Coast. Shelf Sci. 143, 1–11, http://dx.doi.org/10.1016/j.ecss.2014.03.016.

Nitsche, F.O., Bell, R., Carbotte, S.M., Ryan, W.B.F., Flood, R., 2004. Process-related classification of acoustic data from the Hudson River Estuary. Mar. Geol. 209, 131–145, http://dx.doi.org/10.1016/j.margeo.2004.05.023.

R Core Team. (2015). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Radomski, P., Holbrook, B.V., 2015. A comparison of two hydroacoustic methods for estimating submerged macrophyte distribution and abundance: a cautionary note. J. Aquat. Plant Manag. 53, 151–159.

Schubert, H., Blindow, I. (Eds.), 2003. Charophytes of the Baltic Sea. The Baltic Marine Biologists Publication 19, Gantner Verlag, Ruggell.

Selig, U., Eggert, A., Schories, D., Schubert, M., Blümel, M., Schubert, H., 2007. Ecological classification of macroalgae and angiosperm communities of inner coastal waters in the Southern Baltic Sea. Ecol. Indic. 7, 665–678, http://dx.doi.org/10.1016/j.ecolind.2006.07.006.

Sinkevičienė, Z., 2004. Charophyta of the Curonian Lagoon. Bot. Lith. 10 (1), 33–57.

Valley, R., Dustin, D., Nawrocki, J., Lauenstein, M., Johnson, M., Jones, K.D., 2015. Combining hydroacoustic and point-intercept survey methods to assess aquatic plant species abundance patterns and community dominance. J. Aquat. Plant Manag. 53, 121–129.

Winfield, I., Onoufriou, C., O'Connell, M., Godlewska, M., Ward, R., Brown, A., Yallop, M., 2007. Assessment in two shallow lakes of a hydroacoustic system for surveying aquatic macrophytes. Hydrobiologia 584, 111–119, http://dx.doi.org/10.1007/s10750-007-0612-y.

Xu, C., Mizuno, K., Asada, A., Abukawa, K., Yamamuro, M., 2013. 3D-view generation and species classification of aquatic plants using acoustic images. J. Mar. Acoust. Soc. Jpn. 40 (1), 1–13, http://dx.doi.org/10.3135/jmasj.40.14.