



Journal of Fish Biology (2012) **80**, 886–893

doi:10.1111/j.1095-8649.2012.03226.x, available online at wileyonlinelibrary.com

Early life migration patterns of Baltic Sea pike *Esox lucius*

M. ROHTLA*†‡, M. VETEMAA*, K. URTSON§ AND A. SOESOO§

**Estonian Marine Institute, University of Tartu, Vanemuise 46A, 51014 Tartu, Estonia,*
†*Institute of Ecology and Earth Sciences, University of Tartu, Vanemuise 46, 51014 Tartu,*
Estonia and §Institute of Geology, Tallinn University of Technology, Ehitajate 5,
19086 Tallinn, Estonia

(Received 18 August 2011, Accepted 10 January 2012)

This study investigated the movement patterns of Baltic Sea pike *Esox lucius* in Matsalu Bay, Estonia, using otolith microchemistry. Migration patterns of *E. lucius* were remarkably diverse, but distinct groups were evident. Of the *E. lucius* analysed ($n = 28$), 82% hatched in fresh water and 74% of them left this biotope during the first growth season.

© 2012 The Authors

Journal of Fish Biology © 2012 The Fisheries Society of the British Isles

Key words: anadromous; Estonia; first migration; Matsalu Bay; otolith microchemistry.

The Baltic Sea is one of the largest brackish water ecosystems in the world. Pike *Esox lucius* L. 1758 is amongst the many freshwater species which use brackish waters as feeding grounds and undertake anadromous spawning migrations to fresh water (Müller & Berg, 1982). *Esox lucius* is a commercially and recreationally important piscivorous keystone species in many aquatic food webs (Craig, 1996). Over recent decades, however, *E. lucius* stocks around the Baltic Sea have declined drastically (Lehtonen *et al.*, 2009; Jørgensen *et al.*, 2010). In the Väinameri area (west Estonian Archipelago Sea), commercial *E. lucius* catches have dropped from a mean of *c.* 70 t year⁻¹ in the 1970s and 1980s to 20 t year⁻¹ in the 1990s and 10 t year⁻¹ in the 2000s (Estonian Ministry of Agriculture; www.agri.ee). The most influential factors behind this decline are thought to be eutrophication, climate change and overfishing, which in combination have produced cascading ecosystem effects in coastal and pelagic communities (Möllmann *et al.*, 2008; Ljunggren *et al.*, 2010). As a result, large predatory fishes have declined generating a shift from a predator (cod *Gadus morhua* L. 1758, perch *Perca fluviatilis* L. 1758 and *E. lucius*) dominated food web to a prey (clupeids, cyprinids and sticklebacks) dominated food web (Lehtonen *et al.*, 2009; Ljunggren *et al.*, 2010).

One way to improve the current stock situation and to achieve management goals for water quality is to facilitate the processes involved in re-establishing a predator

‡Author to whom correspondence should be addressed. Tel.: +372 53945308; email: mehisi.rohtla@ut.ee

dominated food web (Eriksson *et al.*, 2009; Engstedt *et al.*, 2010). In the coastal and freshwater habitats, much can be done by protecting the most productive spawning and nursery grounds or restoring the old ones. For that, movement patterns and habitat preferences of the species must be known. Such information can be obtained using the chemical constituent of otoliths (Campana, 1999). The use of strontium to calcium ratio (Sr:Ca) has proved to be a worthwhile application in many fish migration studies (Elsdon *et al.*, 2008). The reconstructions are based on the chemical differences between distinct water masses (mostly between fresh and sea-water) and that those differences are reflected in the otolith. Sr:Ca in the water is usually positively correlated with the ambient salinity and also with Sr:Ca in the otolith (Secor & Rooker, 2000). In some freshwater habitats, however, Sr:Ca may be equal to or exceed the seawater values (Kraus & Secor, 2004). Therefore, it is vital to understand the variability of water chemistry. Using the chemical information in the otolith and coupling that with age data allows researchers to investigate fish movements in different temporal and spatial scales (Limburg *et al.*, 2001; Halden & Friedrich, 2008).

The aim of this study was to use otolith Sr:Ca and age data to investigate the early life migrations and the diversity of migration patterns of a facultatively anadromous Baltic Sea *E. lucius* population. Specifically, it was hypothesized that: (1) most of the anadromous *E. lucius* abandon fresh water at the end of the first growing season (*i.e.* late autumn) or later and (2) migration patterns are relatively uniform.

Esox lucius ($n = 55$) were collected from Matsalu Bay in the eastern Baltic Sea, Estonia ($58^{\circ} 45' N$; $23^{\circ} 42' E$), during 2009 spawning season using fyke nets and gillnets. All fish were collected as a part of a national fish monitoring programme and killed immediately after capture by severing the central nervous system. Matsalu Bay is the only true delta estuary in the eastern Baltic Sea, and it has a relatively long (*c.* 15 km) salinity gradient increasing from east (0.0–0.5) to west (5.0–6.0) (Porgasaar & Simm, 1985). For all fish, total length (L_T) was measured and sex determined by visual examination of gonads. Sagittal otoliths were obtained for chemical analyses and age determination. Additionally, scales, metapterygoid bone and cleithra were taken from each individual to aid age determination. For the backcalculation of *E. lucius* L_T at first freshwater exit, metapterygoid bones ($n = 683$) collected during the regular national fish monitoring programme in Matsalu Bay (2003–2007 and 2009–2010) were used to investigate the relationship between *E. lucius* L_T and the L_T of the metapterygoid bone (L_{TM}). To ensure that Sr in the water is positively correlated with salinity, water samples from various sites were also collected. Each sample was filtered (0.45 μm) and acidified to pH 2 with nitric acid for later analysis.

Twenty-eight otoliths were chosen for the microchemical analysis. Criteria of selection was based on: (1) the readability of the annuli, in order to enhance the coupling between age and Sr:Ca data and (2) the fish sex, to ensure a sample with an almost equal sex ratio. For the chemical analysis and also for the age determination procedure, one sagittal otolith from each fish was affixed sulcus side to a standard microscope slide with Crystalbond 509 adhesive. Otoliths were ground in the sagittal plane until the core was vaguely visible using abrasive paper with grit size P1200 and final polishing was done using P4000. Otoliths were then analysed with laser ablation inductively coupled plasma mass spectrometry (ICPMS; Durrant & Ward, 2005). The instrumentation consisted of a New Wave UP-213 nm Nd:YAG laser unit (New Wave

Research, Inc.; www.new-wave.com) coupled with X Series II quadrupole ICPMS device (Thermo Fisher Scientific Inc.; www.thermoscientific.com). Data were collected for the isotopes ^{86}Sr and ^{43}Ca of which the latter was used as the internal standard. The laser was pulsed at the repetition rate of 10 Hz and at a scan speed of $1 \mu\text{m s}^{-1}$ with a beam diameter of *c.* 40 μm . In order to minimize fractionation effects, material was collected with a traverse of *c.* 60 μm (along the annulus). Argon was used as a carrier gas. In order to remove surface contamination, pre-ablation of the sample was performed before the main ablation pass. To investigate the postulated hypotheses, 15–20 ablations per otolith were done. In most of the otoliths, the first ablation was always from the core (the mother peak value; Engstedt *et al.*, 2010), followed by five ablations from the first growth season. The core value represents mother's elemental contribution to the developing egg, and it depends on the environment (*e.g.* fresh or seawater) the mother inhabited during vitellogenesis (Kalish, 1990). The rest of the ablations were taken from the following transparent and opaque zones. The Sr quantification in otoliths was achieved by external calibration using NIST 610 and 612 glass standards. Quality control (*i.e.* test of analytical reproducibility) was done with CAL-S limestone (CRPG) pressed powder pellet. Water samples were analysed using X Series II ICPMS device coupled with CETAC ASX100 autosampler (CETAC Technologies Inc.; www.cetac.com). The Sr quantification in the water was achieved by external calibration using Claritas PPT multi-element standards CLMS-1 and CLMS-2 (SPEX CertiPrep Inc; www.spexcertiprep.com). Quality control was done with National Institute of Standards and Technology water standard 1643e (NIST; www.nist.gov).

Sr:Ca profiles were allocated into different migratory groups using the commonly used visual grouping method (Zlokovitz *et al.*, 2003; Shiao *et al.*, 2006). This was done based upon the range and central tendency of Sr:Ca profiles and overall qualitative similarities (Secor, 1999; Elsdon *et al.*, 2008).

The age of *E. lucius* from the 2009 sample ($n = 55$) ranged from 3 to 9 years, with a mean \pm s.d. of 6.2 ± 1.3 years. The relationship between L_T and L_{TM} was polynomial and the equation used for backcalculation was: $L_T = -27.18 + 63.27 L_{TM} - 0.95 L_{TM}^2$ ($r^2 = 0.98$, $F_{2,680} = 15297$, $P < 0.001$). The Sr concentrations in the water samples increased from fresh water (*c.* 0.045 mg l^{-1}) to brackish water (*c.* 1.3 mg l^{-1}). The constantly low Sr:Ca values of two freshwater collected *E. lucius* (Fig. 1, numbers 8 and 55) were used to define the freshwater threshold as 0.5×10^{-3} (mean + 1 s.d.; Katayama *et al.*, 2000). The threshold value was further authenticated by the fact that 81% of all the other analysed *E. lucius* ($n = 26$, excluding the freshwater residents) had a Sr:Ca value $< 0.5 \times 10^{-3}$ just next to the core (Fig. 1). This means that 82% of the *E. lucius* analysed hatched in fresh water.

Individual Sr:Ca profiles were diverse, but six distinct groups (Fig. 1) were identified: (1) freshwater residents ($n = 2$), (2) precocious fast migrants ($n = 9$), (3) precocious slow migrants ($n = 4$), (4) late migrants ($n = 4$), (5) precocious Matsalu Bay residents ($n = 4$) and (6) brackish-water recruits ($n = 5$). Precocious migration of freshwater-born individuals ($n = 17$) started at the mean estimated age of 2.8 ± 1.0 months and the mean estimated L_T of 81 ± 40 mm. This means that of all the freshwater-hatched individuals, 74% left that biotope during the first growth season.

The main result of this study is that the migration patterns of Matsalu Bay-living Baltic Sea *E. lucius* are remarkably diverse. This has never been reported

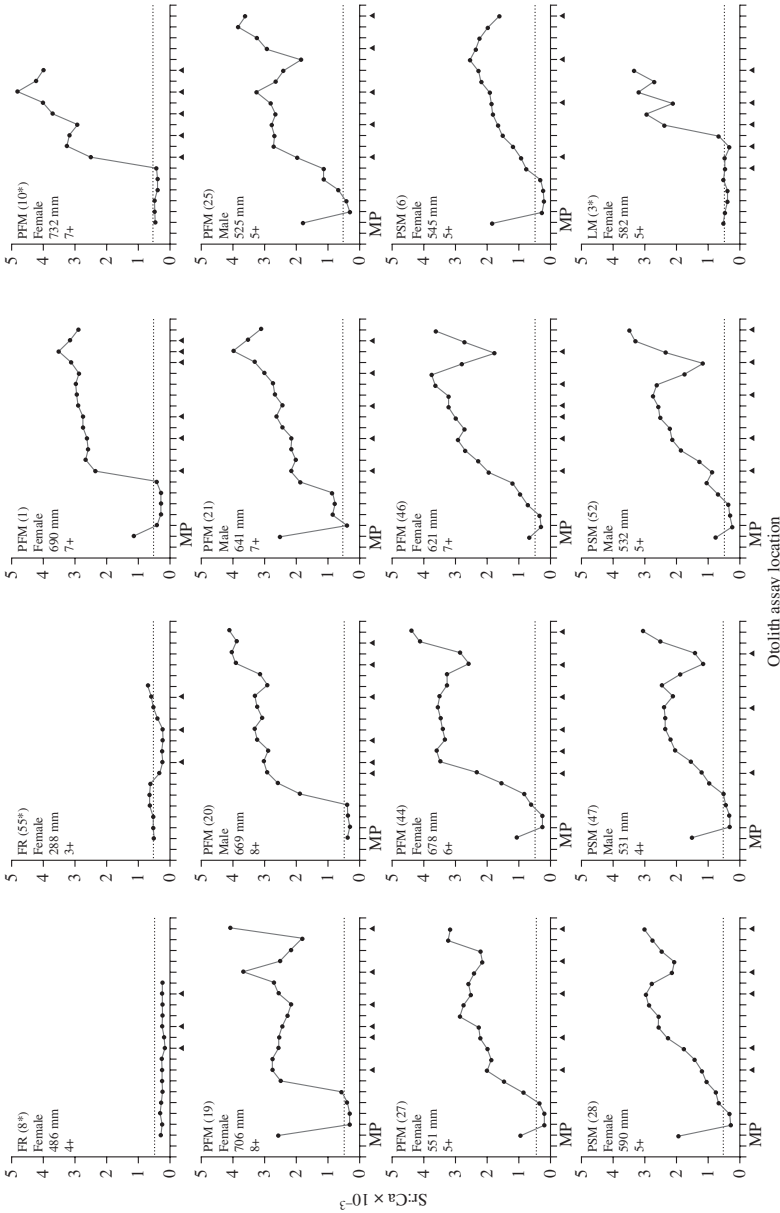


FIG. 1. Sr:Ca profiles of the *Esox lucius* analysed. FR, freshwater resident; PFM, precocious fast migrant; PSM, precocious slow migrant; LM, late migrant; MR, Matsalu Bay resident; BR, brackish water recruit. Pike identification number, sex, total length and age (years) are also given. ▲, the annulus. MP, mother peak, representing mother's elemental contribution to the developing egg. * behind the identification number denotes the individuals whose mother peak values were not measured., Sr:Ca threshold of 0.5×10^{-3} .

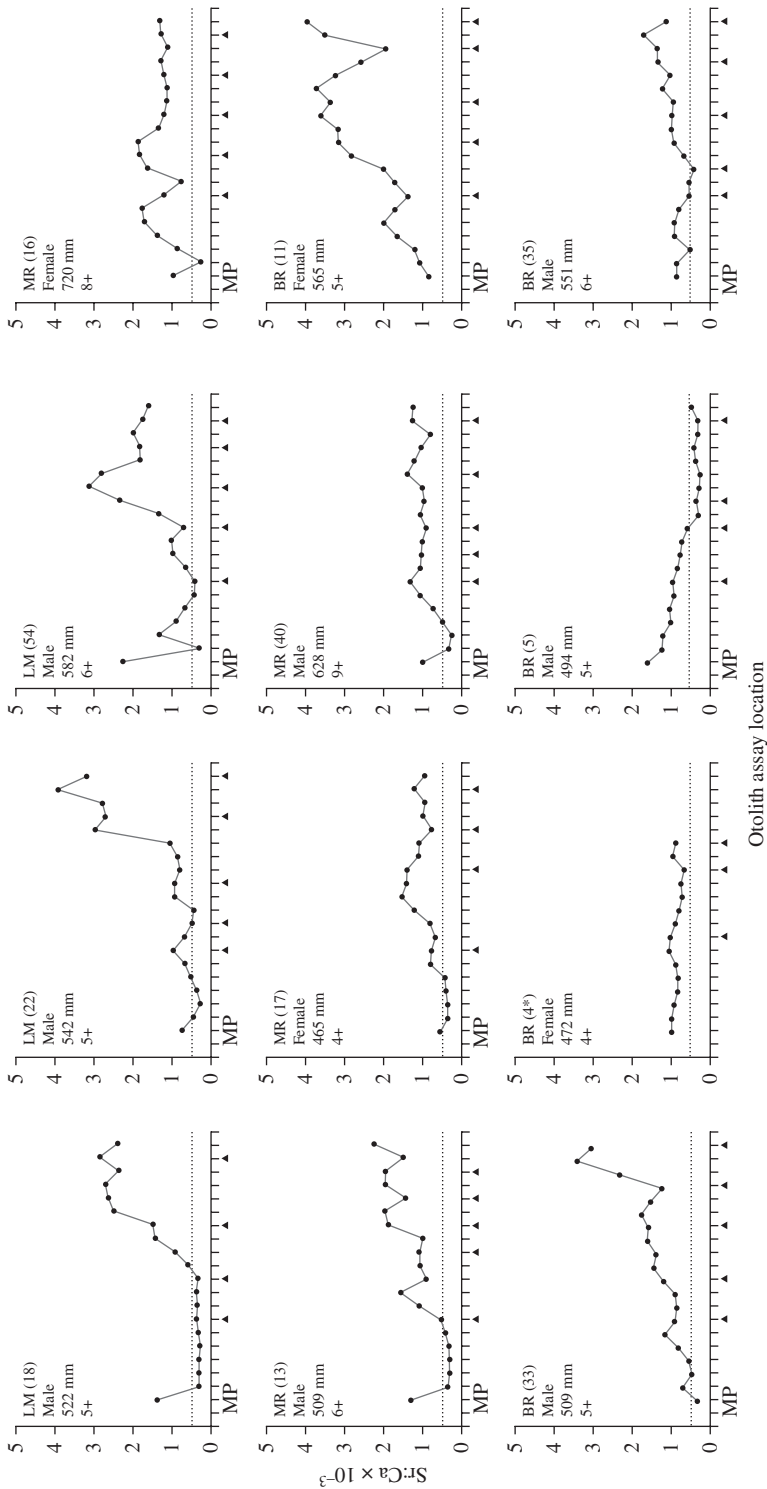


FIG. 1. Continued

for *E. lucius*. Different groups of *E. lucius* were detected, and they all differed from each other in respect of migration pattern, hatch environment or age and L_T at first migration (Fig. 1). These results add to the studies which have shown that the life-history strategies of many species are more complex than previously assumed (Limburg *et al.*, 2001; Zlokovitz *et al.*, 2003; Shiao *et al.*, 2006).

The most intriguing question regarding the different migratory groups is the difference between the precocious fast migrants (PFM) and the precocious slow migrants (PSM) (Fig. 1). It seems that the PFMs have migrated towards the higher salinities in a greater pace than the PSMs as shown by a fast increase in their otolith Sr:Ca. By contrast, the Sr:Ca profiles of PSMs show a rather slow increase in otolith Sr:Ca which seemingly point to a slower movement towards the higher salinities. One possible explanation for this may be individual osmoregulatory abilities as the length of the acclimatization period to cope with increasing salinities may vary between individual fish. It has been shown that the salinity tolerance of pikeperch *Sander lucioperca* (L. 1758) is increased by acclimatization periods in low salinity areas (Brown *et al.*, 2001) and same has been proposed to hold true for *E. lucius* (Jacobsen *et al.*, 2007). Additionally, adaptive variation in traits such as salinity tolerance may exist in Baltic Sea *E. lucius* (Jørgensen *et al.*, 2010). It is also possible that acclimatization occurred not in the context of salinity but rather as a behavioural trait during the first seaward migration (*e.g.* temporary settlement due to food or habitat abundance). A completely different explanation may be that all or some of the PFMs have descended straight to the high salinity area (*i.e.* they did not experience the increasing salinity gradient of Matsalu Bay like PSMs did), meaning that these fish did not hatch in the estuary area of Matsalu Bay. This goes especially for PFMs with extremely abrupt rise in Sr:Ca (*e.g.* *E. lucius* number 1 and 19, Fig. 1), and it could potentially mean that different freshwater bodies draining straight into Väinameri (*i.e.* salinities of 5–6) also contribute to the spawning stock of Matsalu Bay. This hypothesis is supported by the results of Westin & Limburg (2002) who reported similar *E. lucius* Sr:Ca profiles from a Gotland stream draining straight into salinities of 6–7. Matsalu Bay estuary area, however, is probably the largest *E. lucius* spawning site in the region and there is also strong evidence for natal homing in Baltic Sea *E. lucius* (O. Engstedt, pers. comm.). Therefore, it is likely that the majority of PFMs hatched in the estuary area and not in some coastal stream or river.

A total of 82% of the analysed *E. lucius* hatched in fresh water. This is no surprise, as the inner part (*i.e.* the estuary area) of Matsalu Bay is well known as productive spawning and nursery ground for *E. lucius* (Vetemaa *et al.*, 2006). Engstedt *et al.* (2010), however, reported that only 46% of the *E. lucius* from the Swedish coast were recruited from freshwater habitats. Although this may be a slight underestimation, as also stressed by the authors, the differences between two studies would still be significant. It is possible that the disparity in reported results may exist due to different sampling areas, Engstedt *et al.* (2010) sampled *E. lucius* from the sea (*i.e.* salinities > 5) where the proportion of brackish water spawning *E. lucius* may be higher, while this study aimed to sample only the anadromous, and thus, freshwater spawning *E. lucius*. In addition, the study systems are also completely different (small rivers *v.* relatively large estuary). All this corroborates the notion of Engstedt *et al.* (2010) that the importance of freshwater spawning varies greatly among Baltic Sea *E. lucius* and it most probably depends on the system and specific area investigated.

Most of the freshwater-born individuals left fresh water unexpectedly early in terms of age and L_T achieved. Although this phenomenon, in general, has been documented earlier in other studies (Johnson & Müller, 1978; Engstedt *et al.*, 2010), it has never been recorded in estuaries and linked to the age of the fish. Previous studies have concentrated on small coastal rivers, and therefore, the early seaward migration is comprehensible as such rivers cannot sustain high numbers of young-of-the-year *E. lucius* (Müller, 1986). Presumably, this is not the case in this study because space and food in the almost freshwater inner part of the Matsalu Bay and estuary is plentiful (Vetemaa *et al.*, 2006). Regarding the achieved L_T at first seaward migration of precocious individuals, the results of this study are similar to the result obtained by Johnson & Müller (1978) and Engstedt *et al.* (2010), although the habitats investigated are completely different.

This research was financed by the Estonian state-financed project SF0180005s10. M.R. received support from Estonian Science Foundation grant 8281. We thank L. Saks and two anonymous reviewers for their constructive comments to this manuscript.

References

- Brown, J. A., Moore, W. M. & Quabius, E. S. (2001). Physiological effects of saline waters on zander. *Journal of Fish Biology* **59**, 1544–1555.
- Campana, S. E. (1999). Chemistry and composition of fish otoliths: pathways, mechanisms, and applications. *Marine Ecology Progress Series* **188**, 263–297.
- Craig, J. F. (1996). *Pike: Biology and Exploitation*. London: Chapman & Hall.
- Durrant, S. F. & Ward, N. I. (2005). Recent biological and environmental applications of laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). *Journal of Analytical Atomic Spectrometry* **20**, 821–829.
- Elsdon, T. S., Wells, B. K., Campana, S. E., Gillanders, B. M., Jones, C. M., Limburg, K. E., Secor, D. H., Thorrold, S. R. & Walther, B. D. (2008). Otolith chemistry to describe movements and life-history measurements of fishes: hypotheses, assumptions, limitations, and inferences using five methods. *Oceanography and Marine Biology: An Annual Review* **46**, 297–330.
- Engstedt, O., Stenroth, P., Larsson, P., Ljunggren, L. & Elfman, M. (2010). Assessment of natal origin of pike (*Esox lucius*) in the Baltic Sea using Sr:Ca in otoliths. *Environmental Biology of Fishes* **89**, 547–555.
- Eriksson, B. K., Ljunggren, L., Sandström, A., Johansson, G., Mattila, J., Rubach, A., Råberg, S. & Snickars, M. (2009). Declines in predatory fish promote bloom-forming macroalgae. *Ecological Applications* **19**, 1975–1988.
- Halden, N. M. & Friedrich, L. A. (2008). Trace-element distributions in fish otoliths: natural markers of life histories, environmental conditions and exposure to tailings effluence. *Mineralogical Magazine* **72**, 593–605.
- Jacobsen, L., Skov, C., Koed, A. & Berg, S. (2007). Short-term salinity tolerance of northern pike, *Esox lucius*, fry, related to temperature and size. *Fisheries Management and Ecology* **14**, 303–308.
- Johnson, T. & Müller, K. (1978). Migration of juvenile pike, *Esox lucius* L., from a coastal stream to the northern part of the Bothnian Sea. *Aquilo Seriological Zoologica* **18**, 57–61.
- Jørgensen, A. T., Hansen, B. W., Vismann, B., Jacobsen, L., Skov, C., Berg, S. & Bekkevold, D. (2010). High salinity tolerance in eggs and fry of a brackish *Esox lucius* population. *Fisheries Management and Ecology* **17**, 554–560.
- Kalish, J. M. (1990). Use of otolith microchemistry to distinguish the progeny of sympatric anadromous and non-anadromous salmonids. *Fishery Bulletin* **88**, 657–666.
- Katayama, S., Radtke, R. L., Omori, M. & Shafer, D. J. (2000). Coexistence of anadromous and resident life history styles of pond smelt, *Hypomesus nipponensis*, in Lake Ogawara,

- Japan, as determined by analyses of otolith structure and strontium:calcium ratios. *Environmental Biology of Fishes* **58**, 195–201.
- Kraus, R. T. & Secor, D. H. (2004). Incorporation of strontium into otoliths of an estuarine fish. *Journal of Experimental Marine Biology and Ecology* **302**, 85–106.
- Lehtonen, H., Leskinen, E., Selen, R. & Reinikainen, M. (2009). Potential reasons for the changes in the abundance of pike, *Esox lucius*, in the western Gulf of Finland, 1939–2007. *Fisheries Management and Ecology* **16**, 484–491.
- Limburg, K. E., Landergren, P., Westin, L., Elfman, M. & Kristiansson, P. (2001). Flexible modes of anadromy in Baltic sea trout: making the most of marginal spawning streams. *Journal of Fish Biology* **59**, 682–695.
- Ljunggren, L., Sandström, A., Bergström, U., Mattila, J., Lappalainen, A., Johansson, G., Sundblad, G., Casini, M., Kaljuste, O. & Eriksson, B. K. (2010). Recruitment failure of coastal predatory fish in the Baltic Sea coincident with an offshore ecosystem regime shift. *ICES Journal of Marine Science* **67**, 1587–1595.
- Möllmann, C., Müller-Karulis, B., Kornilovs, G. & St John, M. A. (2008). Effects of climate and overfishing on zooplankton dynamics and ecosystem structure: regime shifts, trophic cascade, and feedback loops in a simple ecosystem. *ICES Journal of Marine Science* **65**, 302–310.
- Müller, K. (1986). Seasonal anadromous migration of the pike (*Esox lucius* L.) in coastal areas of the northern Bothnian Sea. *Archiv für Hydrobiologie* **107**, 315–330.
- Müller, K. & Berg, E. (1982). Spring migration of some anadromous freshwater fish species in the northern Bothnian Sea. *Hydrobiologia* **96**, 161–168.
- Porgasaar, V. & Simm, H. (1985). Matsalu lahe hüdrokeemiline režiim. In *Matsalu - rahvusvahelise tähtsusega märgala* (Kumari, E., ed.), pp. 26–35. Tallinn: Valgus.
- Secor, D. H. (1999). Specifying divergent migrations in the concept of stock: the contingent hypothesis. *Fisheries Research* **43**, 13–34.
- Secor, D. H. & Rooker, J. R. (2000). Is otolith strontium a useful scalar of life cycles in estuarine fishes? *Fisheries Research* **46**, 359–371.
- Shiao, J. C., Ložys, L., Iizuka, Y. & Tzeng, W. N. (2006). Migratory patterns and contribution of stocking to the population of European eel in Lithuanian waters as indicated by otolith Sr:Ca ratios. *Journal of Fish Biology* **69**, 749–769.
- Vetemaa, M., Eschbaum, R., Verliin, A., Albert, A., Eero, M., Lillemägi, R., Pihlak, M. & Saat, T. (2006). Annual and seasonal dynamics of fish in the brackish-water Matsalu Bay, Estonia. *Ecology of Freshwater Fish* **15**, 211–220.
- Westin, L. & Limburg, K. E. (2002). Newly discovered reproductive isolation reveals sympatric populations of *Esox lucius* in the Baltic. *Journal of Fish Biology* **61**, 1647–1652.
- Zlokovitz, E. R., Secor, D. H. & Piccoli, P. M. (2003). Patterns of migration in Hudson River striped bass as determined by otolith microchemistry. *Fisheries Research* **63**, 245–259.