

Alma Mater Studiorum Università di Bologna
Archivio istituzionale della ricerca

New perspectives on Eastern Baltic cod movement patterns from historical and contemporary tagging data

This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

Published Version:

New perspectives on Eastern Baltic cod movement patterns from historical and contemporary tagging data / Mion, M; Griffiths, CA; Bartolino, V; Haase, S; Hilvarsson, A; Hüsey, K; Krüger-Johnsen, M; Krumme, U; Lundgreen, RBC; Lövgren, J; McQueen, K; Plikshs, M; Radtke, K; Raitaniemi, J; Casini, M. - In: MARINE ECOLOGY PROGRESS SERIES. - ISSN 0171-8630. - STAMPA. - 689:(2022), pp. 109-126. [10.3354/meps14047]

Availability:

This version is available at: <https://hdl.handle.net/11585/886682> since: 2022-05-21

Published:

DOI: <http://doi.org/10.3354/meps14047>

Terms of use:

Some rights reserved. The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

This item was downloaded from IRIS Università di Bologna (<https://cris.unibo.it/>).
When citing, please refer to the published version.

(Article begins on next page)

This is the final peer-reviewed accepted manuscript of:

Mion, M; Griffiths, CA; Bartolino, V; Haase, S; Hilvarsson, A; Hüsey, K; Krüger-Johnsen, M; Krumme, U; Lundgreen, RBC; Lövgren, J; McQueen, K; Plikshs, M; Radtke, K; Raitaniemi, J; Casini, M: *New perspectives on Eastern Baltic cod movement patterns from historical and contemporary tagging data*

MARINE ECOLOGY PROGRESS SERIES vol. 689 ISSN 0171-8630

DOI: 10.3354/meps14047

The final published version is available online at:

<https://dx.doi.org/10.3354/meps14047>

Terms of use:

Some rights reserved. The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

This item was downloaded from IRIS Università di Bologna (<https://cris.unibo.it/>)

When citing, please refer to the published version.

1 New perspectives on Eastern Baltic cod movement patterns from
2 historical and contemporary tagging data
3

4 Monica Mion^{1*}, Christopher A. Griffiths^{1,2,3}, Valerio Bartolino¹, Stefanie Haase⁴, Annelie Hil-
5 varsson¹, Karin Hüsey⁵, Maria Krüger-Johnsen⁵, Uwe Krumme⁴, Regitze Benedicte Carlstedt
6 Lundgreen⁵, Johan Lövgren¹, Kate McQueen^{4,6}, Maris Plikshs⁷, Krzysztof Radtke⁸, Jari Raitaniemi⁹,
7 Michele Casini^{1,10}.

8
9 ¹Swedish University of Agricultural Sciences, Department of Aquatic Resources, Turistgatan 5,
10 45330 Lysekil, Sweden.

11 ²University of Sheffield, Department of Animal and Plant Sciences, Western Bank, Sheffield, S10
12 2TN, UK.

13 ³Centre for Environment Fisheries and Aquaculture Science, Lowestoft, NR33 0HT, UK.

14 ⁴Thünen Institute of Baltic Sea Fisheries, Alter Hafen Süd 2, 18069 Rostock, Germany.

15 ⁵Technical University of Denmark, National Institute of Aquatic Resources, Kemitorvet, DK - 2800
16 Kgs. Lyngby, Denmark.

17 ⁶Institute of Marine Research, P.O. Box 1870 Nordnes, 5817 Bergen, Norway.

18 ⁷Fish Resource Research Department, Institute of Food Safety, Animal Health and Environment, 3
19 Lejupes Street, LV-1076 Riga, Latvia.

20 ⁸National Marine Fisheries Research Institute, Ul. Kołłątaja 1, 81-332 Gdynia, Poland.

21 ⁹Natural Resources Institute Finland, Luke, Itäinen Pitkätatu 4 A, FI-20520 Turku, Finland.

22 ¹⁰University of Bologna, Department of Biological, Geological and Environmental Sciences, Via
23 Selmi 3, 40126 Bologna, Italy.

24
25 *corresponding author e-mail: monica.mion@slu.se
26
27
28

30 Abstract

31 Knowledge of the movement patterns and area utilisation of commercially important fish stocks is critical to management. The Eastern Baltic cod (*Gadus morhua*) has been one of the most commercially
32 and ecologically important stocks in the Baltic Sea but is currently one of the most severely impacted
33 fish stocks in Europe. During the last two decades, this stock has experienced drastic decreases in population size, distributional range, individual growth, and body condition, all of which could have affected the stock's movements between different areas of the Baltic Sea.
36

37 In this study, we investigated the seasonal movement patterns of Eastern Baltic cod by re-analysing
38 historical tagging data collected by the countries surrounding the Baltic Sea (1955-1988), and compared
39 historical patterns with contemporary data from a recent international tagging experiment (2016-2019).
40 Our re-analyses of historical data showed the presence of different movement behaviours, resident and
41 seasonally migratory, with larger distances moved by cod released in the northern and central Baltic
42 areas compared to cod released in the southern Baltic areas. Furthermore, trends from the recent tagging
43 experiment indicate a persistent resident strategy in the southern Baltic area.

44 These findings present additional information on general movement patterns and area utilisation of
45 Eastern Baltic cod that could inform future management actions and aid stock recovery.

46

47 *Keywords:* Baltic Sea, *Gadus morhua*, fish movement, mark-recapture, historical data, home range,
48 kernel density estimation, generalized additive model

49

50 1. Introduction

51 Fish often undertake regular migrations between areas of feeding and spawning in order to maximize
52 the benefits available from certain habitats for a particular activity or life-stage (Metcalf, 2006). As a
53 consequence, knowledge of migration and dispersal behaviour, termed “movement patterns”, is funda-
54 mental for managing commercially fished populations, especially in areas where population mixing
55 takes place (Rose & Rowe 2015, Neat et al. 2014, Zemeckis et al. 2014), where environmental condi-
56 tions are subject to change (Drinkwater 2005, 2015, Engelhard et al. 2014) or where ontogenetic move-
57 ments generate marked differences in the spatial distribution of different age groups.

58 One of the most widely applied methods to study the movements of wild animals is to use individual
59 markers. Particularly, conventional tagging experiments, which provide information on release and re-
60 capture positions, and are used for investigating broad-scale patterns such as area of utilisation and
61 movement patterns of individuals (e.g., Righton & Metcalfe 2019).

62 The movements of Atlantic cod (*Gadus morhua*) have been studied extensively with tagging experi-
63 ments (Robichaud & Rose 2004). Cod migratory behaviour has been shown to vary markedly with
64 respect to area, season, and major environmental factors (Pálsson & Thorsteinsson 2003). Cod of the
65 same population may adopt different migration routes between areas and their speed of travel can vary
66 considerably during and between journeys (Righton & Metcalfe 2019). Differences in migratory strat-
67 egies have also been identified, with some cod remaining relatively stationary, while others redistribute
68 over vast spatial distances that exceed 1000 km (Robichaud & Rose 2004). Cod migratory patterns
69 therefore appear to be complex and there are cases where populations of predominantly migratory and
70 predominantly sedentary cod overlap in certain areas and at certain times of the year (e.g., cod at the
71 Lofoten Islands, Nordeide 1998).

72 Baltic Sea cod inhabit an area that differs from most of the other areas where the species is found. The
73 Baltic Sea is, in fact, one of the largest brackish areas in the world, where severe changes in biotic and
74 environmental conditions have occurred in the past hundred years (Reusch et al. 2018). Two genetically
75 distinct cod populations are present in this area: the western Baltic cod (WBC) stock in ICES subdivi-
76 sions (SD) 22-24, and the Eastern Baltic cod (EBC) stock in SD 24-32 (Fig.1) with mixing of the two
77 stocks occurring in SD 24 (Hüssy et al. 2016, ICES 2021).

78 In this extreme environment, the EBC have uniquely adapted to survive and successfully reproduce in
79 the low salinity and low oxygen conditions of the eastern Baltic Sea (Andersen et al. 2009, Nissling et
80 al. 1994), experiencing temperatures and salinities at the upper and lower tolerance limits of Atlantic
81 cod, respectively (Köster et al. 2005, Mackenzie et al. 2007). Historically, cod have been one of the
82 most important commercial species in the Baltic Sea (Bagge et al. 1994; ICES 2014) and, as a major
83 piscivorous fish, play an important structuring role in the ecosystem (Casini et al. 2009). However, the
84 EBC stock is currently one of the most severely threatened fish stocks in Europe (ICES 2020) and since
85 2019 the scientific advice has recommended a complete closure of the EBC fishery (ICES 2021).

86 The EBC stock size has changed considerably, with a peak in the early 1980s (ca. 200,000 tonnes) and
87 a subsequent decline (Eero et al. 2015). Concurrent with the decline in stock size, a number of changes
88 have been observed in the EBC stock, which include reduced body condition, maturation at a smaller
89 size, shift in the timing of peak spawning, reduced growth, increased parasite infestation and thiamine
90 deficiency (Eero et al. 2015, Mion et al. 2021, Engelhardt et al. 2020, Horbowy et al. 2016). After the
91 late 1980s, the decline in cod abundance was also accompanied by a spatial contraction of the stock,
92 primarily to the southern Baltic Sea (SD 25) (Eero et al. 2012, Bartolino et al. 2017, Orio et al. 2019,
93 Wieland et al. 2000). This contraction has been linked to different biotic and abiotic conditions, which
94 caused some areas to become “cod hostile” (Möllmann et al. 2009, Casini et al. 2009). In fact, in the
95 last 40 years, the extent of hypoxic areas in the Baltic Sea has increased 5-fold (Carstensen et al. 2014,
96 Meier et al. 2018). In addition, since the mid-1980s, the hydrographic conditions in the eastern spawn-
97 ing areas (in SDs 26 and 28) were thought to be no longer suitable for survival of cod eggs, and SD 25
98 is now considered the only area supporting successful reproduction of EBC (Köster et al. 2017, Fig.1).
99 All of these dramatic changes in the marine environment, biology and distribution of the EBC stock
100 may have resulted in changes in the movement patterns of the stock.

101 Extensive conventional tagging experiments were conducted from the 1950s to the 1980s to study the
102 movement patterns of cod in the Baltic Sea and adjacent areas. The results of these historical tagging
103 experiments have been summarised by a number of authors (Aro 1989, 2002, Bagge & Steffensen 1989,
104 Robichaud & Rose 2004). Briefly, these studies showed that both sedentary and migratory behaviours
105 were present in the EBC stock and that generally EBC exhibited strong migratory tendencies towards
106 the southern Baltic. However, these studies only presented a description of the general movements,
107 rather than a quantitative analysis, and a comparison with contemporary data in light of the deteriorated
108 situation of the EBC stock is lacking.

109 In the studies of Mion et al. 2020, 2021, data from most of these historical tagging experiments, together
110 with recent tagging experiments carried out in the southern Baltic Sea in 2016-2019, were digitised and
111 collated for the first time in a unique database. This database provides a perfect opportunity to reanalyse
112 historical data and investigate how the movement patterns of EBC may have changed through time. To
113 achieve this quantitatively, kernel density estimation and generalized additive models were used to ex-
114 plore seasonal movement patterns and area utilisation of EBC in different areas of the Baltic Sea. Based
115 on previous research (Aro 1989, 2002, Bagge & Steffensen 1989, Robichaud & Rose 2004), we hy-
116 pothesise that during the historic period EBC will exhibit both migratory and sedentary movement strat-
117 egies, with distance travelled and area utilisation varying based on release area. Conversely, in the con-
118 temporary data, we might expect that changing biotic and abiotic conditions in the northern and central
119 Baltic, as well as contractions in the spatial distribution of EBC towards the south, may have impacted
120 movement rates and area utilisation. Consequently, we hypothesise that recently tagged EBC will show
121 a greater utilisation of southern areas, as northern and central areas are no longer suitable for spawning
122 and are now considered “cod hostile”. Any changes in movement patterns or area utilisation of EBC

123 could impact the level of mixing with the WBC stock in the southern Baltic, with potential implications
124 for management and future stock recovery.

125 2. Materials & Methods

126 Data from historical cod tagging experiments performed between the 1950s and 1980s covering the
127 main historical distribution area of the EBC stock (SDs 24-32), and the more recent TABACOD dataset
128 (2016-2019) covering the main current distribution area of the EBC stock (SDs 24-26), were extracted
129 from the database compiled in Mion et al. (2020, 2021). All records were quality checked for movement
130 analyses, selecting only the records where release and recapture dates and geographical positions as
131 well as total body length measurements at release ($Length_{rl}$, cm) were present. Any recaptures of cod
132 that occurred within 30 days of release were excluded. This was to ensure that all cod in this study had
133 sufficient time to recover from the tagging procedure and move to different areas following release. A
134 summary of the different tagging procedures and detailed information on releases and recaptures for
135 these datasets can be found in Mion et al. (2020, 2021) and Hüsey et al. (2020).

136 2.1 Historical data

137 In total, there were 6,798 records suitable for movement analyses. Each record consisted of release and
138 recapture dates and geographical positions (Fig. 2, S1a) as well as measurements of $Length_{rl}$ (Fig. S1c).
139 Tagging efforts were focused in SDs 24-32 (Fig. 2, S2) and the recaptures were mainly reported by
140 commercial fishers from their catches. The precision of the reported recapture locations varied largely
141 between fishers. When only a location name was given (e.g., 4 nm south-east of Dueodde lighthouse),
142 a geographical position was assigned as precisely as possible. In some cases, historical maps of the
143 tagging experiments were used to confirm the position of a particular location name (an example is
144 provided in Fig. 3).

145 Records for tagged cod spanned the mid-1950s to the 1980s, with 65% of cod recaptured during the
146 1970s (Fig. S1a). Cod were released year-round, but with reduced effort in quarter 3 (July-September).
147 Tagging effort was likely reduced in the warmer months of quarter 3 as the thermocline is more pro-
148 nounced and less tolerated by cod during the tag and release process (Otterlind 1984, Table S1a).

149 Tagging effort varied in space and time. In the southern Baltic areas, in particular the Bornholm basin
150 (SD 25), tagging occurred throughout the historical period, whereas in the central and northern Baltic
151 areas, tagging effort was more concentrated in certain time periods (Fig. S2).

152 The time between release and recapture (days at liberty, DAL) ranged between 30 and 3,928 days (me-
153 dian: 174 days; Fig S1b). The historical dataset consisted of a mix of adults and juveniles with a $Length_{rl}$
154 range from 17 to 98 cm (median: 40 cm; Fig. S1c; size at sexual maturation in the historical period was

155 45 to 50 cm for females and 37 to 41 cm for males; Cardinale & Modin, 1999). The return rate (i.e., the
156 % of tagged cod that were recaptured and returned to the research institutes) was on average 11.8%
157 (Mion et al. 2021).

158 2.2 Contemporary data

159 The contemporary dataset consists of 301 records suitable for movement analyses from the TABACOD
160 project (Hüssy et al. 2020), spanning the years 2016 to 2019. Again, each record consisted of release
161 and recapture dates and geographical positions (Fig. 2, S1a) as well as measurements of $Length_{ri}$. Cod
162 were released year-round, but with limited numbers in quarter 3 (Table S1b). Tagging efforts were
163 concentrated in SDs 24-26 (Fig. 2), covering the main current distribution area of the stock (Orio et al.
164 2019). The contemporary dataset consisted mainly of adults with a $Length_{ri}$ range from 18 to 55 cm
165 (median: 39 cm; current size at sexual maturation is 19 cm; Köster et al. 2017; Fig. S1c). DAL ranged
166 between 30 and 927 days (median: 220 days) (Fig. S1b). The return rate of tagged cod from the TABA-
167 COD project was 1.5% (Mion et al. 2021).

168 2.3 Analyses of fish movement

169 Due to changes in the main distribution of the Baltic Sea cod stock (Orio et al. 2019 and references
170 therein), the spatial coverage differed by dataset (Fig. 1). The historical data contained records spanning
171 almost the entire Baltic Sea (SDs 24-32), whereas the contemporary dataset contained records restricted
172 to the southern Baltic Sea (SDs 24-26) where cod concentrate nowadays.

173 To assess seasonal differences in movement patterns, records were divided into two recapture seasons:
174 spawning and feeding. For the historical dataset, the spawning season was defined as January to June,
175 which includes the main spawning season and a period of migration to and from the spawning grounds
176 (Aro 1989, Wieland et al. 2000), whereas the feeding season was defined as July to December (Aro
177 1989). Since the 1990s, a shift in the timing of peak spawning towards the summer has occurred (Wie-
178 land et al. 2000, Bleil & Oeberst 2004); therefore, the spawning season for the contemporary dataset
179 was defined as April to September, while the feeding season was defined as October to March.

180 Average values and coefficient of variation (CV; calculated as standard deviation divided by mean) for
181 distance travelled by cod in km (d) were estimated for each SD of release (SD_{ri}) and for each season. d
182 was calculated as the great-circle distance (i.e., geodesic distance) between release and recapture loca-
183 tions using the function `dism()` in the package “geosphere” in R (Fig. 4). All analyses were conducted
184 in R using the R version 4.0.2 (R Core Team 2020).

185 2.3.1 Kernel Density Estimation

186 Kernel Density Estimation (KDE) was used to describe the main distributional areas of EBC tagged in
187 different SD_{rl} . Assuming a homogenous fishing effort, this analysis provides a visualisation of the prob-
188 ability of recapturing a tagged individual in a given location (Worton, 1987), conditional on the group-
189 ing factors applied (SD_{rl} , season of recapture and time period) and the constraints of the data ($DAL >$
190 30 days). All KDEs were calculated assuming a bivariate normal kernel using the kernel probability
191 density function from the `adehabitatHR` package (Calenge 2015) in R. A detailed description of this
192 approach can be found in Calenge (2015) and Griffiths (2019) and has been previous used to describe
193 the area utilisation of Atlantic cod in the Gulf of Maine (Dean et al. 2014) and in the waters surrounding
194 the United Kingdom (Righton et al. 2007; Neat et al. 2014). For clarity, the default ‘reference band-
195 width’ approach was used to estimate the smoothing parameter h for each KDE. Moreover, as is com-
196 mon in the movement ecology literature, the 95% and 50% probability contours were extracted from
197 each KDE and assumed to represent the population’s 2-dimensional “home range” and “core area”,
198 respectively (Worton 1989, Seaman & Powell 1996, Sólmundsson et al. 2015). Home range identifies
199 the area occupied by the majority of cod in their normal activities of spawning and feeding, and the core
200 area identifies the most intensively used areas within an animal’s home range (Burt 1943, Powell 2000).

201 For each SD_{rl} , KDEs were estimated separately for the EBC spawning and feeding recapture seasons.
202 Due to possible mixing of stocks (EBC and WBC) in SD 24 and the fact that some cod released in SD
203 24 might belong to the WBC stock, a sensitivity analysis was conducted to estimate KDEs for the WBC
204 spawning (i.e. December to April which includes the main spawning season and a period of migration
205 to and from the spawning ground; Hüsey 2011) and feeding seasons (defined as May to November).
206 This analysis showed that the estimated KDEs from the WBC feeding and spawning seasons were sim-
207 ilar to the estimated KDEs from the EBC feeding and spawning seasons, both for historical and con-
208 temporary datasets (Fig. S3). In addition, for the contemporary data, genetic and otolith shape analyses
209 revealed that $\sim 80\%$ of the recaptured cod released in SD 24 belonged to the EBC stock, highlighting
210 a higher presence of EBC in the recaptures (Hüsey et al. 2020).

211 The size (km^2) of the home ranges and core areas for each SD_{rl} and season were calculated in ArcMAP
212 (v.10.4.1). In addition, in the southern Baltic Sea, the area of home range overlap (%) and core area
213 overlap (%) between historical and contemporary datasets were also calculated for each SD_{rl} .

214 2.3.2 Generalized additive models (GAMs)

215 For the KDE analyses, records were grouped into seasons without taking into account the effects of
216 DAL on d (e.g., cod that were at liberty for two months were considered alongside cod that were at
217 liberty for two years). Previous studies on North Atlantic cod stocks described a linear relationship
218 between d and DAL for some groups, while for other groups a non-linear relationship linked to season-
219 ality was found (Rogers et al. 2014, Espeland et al. 2008). Therefore, to further explore the seasonal

220 movement patterns of EBC, generalized additive models (GAMs), with a restricted maximum likeli-
221 hood approach (Wood 2006), were applied to the relationship between d and DAL . Our prior expectation
222 was that the relationship between d and DAL would be affected by cod release location. Thus, d would
223 change according to the proximity of SD_{rl} to spawning and feeding areas (e.g., with shorter d for cod
224 recaptured during the spawning period and released in an area closer to the spawning ground). $Length_{rl}$
225 was included as an additional explanatory variable to assess possible effects of fish size and ontogeny
226 on d .

227 The GAM model was formulated as follows:

$$228 \quad d = \alpha + s(DAL:SD_{rl}) + Length_{rl} + \varepsilon \quad (2)$$

229

230
231 where α is the intercept, s is the thin plate smoothing spline function (Wood, 2003) and ε an error term.
232 An interaction was used between the continuous variable DAL and the factor SD_{rl} to assess possible
233 seasonal differences in d between SD_{rl} .

234 Due to the low number of recaptures for the contemporary dataset, the GAM was performed only with
235 the historical dataset. To analyse the shape of the relationship between d and DAL , two separate models
236 were fitted to data with release dates from quarter 2 (April – June; spawning period) and from quarter
237 4 (October – December; feeding period). Preselection of the quarter of release and treatment of DAL as
238 a continuous variable allowed us to capture possible effects of seasonality (movements between spawn-
239 ing and feeding grounds) on d . A gamma distribution with a logarithmic link function was used for the
240 GAMs because it best represented the distribution of d .

241 To improve consistency and representation of the datasets, the GAMs were fitted to restricted data.
242 Only cod with a DAL between 30 and 550 days and a $Length_{rl}$ between 25 and 70 cm ($n = 1,202$ for cod
243 released in quarter 2; $n = 1,981$ for cod released in quarter 4) were considered. To avoid taking the log
244 of zero, all zero distances were given the value of the lowest observed distance (~ 1 km). All GAMs
245 were implemented using the “mgcv” library in R (Wood 2006). Model fit was assessed by visual in-
246 spection of the residuals (see Fig. S4).

247 3. Results

248 The average d for cod released in the southern Baltic area (SDs 24-26) was ~ 80 km for both historical
249 and contemporary datasets, and for both recapture seasons (Fig. 5). In the historical dataset, seasonal
250 patterns in average d were observed. In particular, cod released in the northern and central Baltic Sea
251 (SDs 27-32) exhibited greater d during the spawning season compared to the feeding season (Fig. 5;
252 average d of 235 km and 135 km, respectively). In addition, for the northern areas (SDs 29 and 30) the
253 variation in d was higher than in the southern SDs in both the historical and contemporary datasets (Fig.
254 5; Table S2).

3.1 Movement patterns in the spawning season with Kernel Density Estimation

In the historical dataset, cod released in the southern Baltic areas (SDs 24-26), were mostly recaptured in the same SD of release, however, some variation was observed (Table 1; Fig. 6). For example, core areas of cod released in SD 26 and SD 24 extended into SD 25 during the spawning season. Similarly, cod released in SD 24 had a home range during the spawning season that extended in a western direction into SD 21. Moreover, cod released in SD 25 had a home range that extended in an eastern direction into SD 26.

In the contemporary dataset, recaptures during the spawning season mostly occurred in the same SD of release (Fig. 7; Table 1). These findings are consistent with the historical dataset from the southern Baltic areas with high home range overlaps of ~ 50 % (Fig. 8; Table 2). However, some differences between the datasets occurred in the southern Baltic area. In the contemporary dataset, core areas and home ranges in SD 24 and 25 occurred in close proximity to Bornholm Island on the boundary between the two SDs (Fig. 8), while in the historical dataset the home range extended towards the western or eastern direction depending on if cod were released in SD 24 or 25, respectively. In addition, cod released in SD 26 had two core spawning areas in the historical period, (SD 25 and 26) while in the contemporary dataset cod were mainly recaptured in SD 26 (Fig. 8). In the historical dataset, recaptures during the spawning season of cod released in the northern and central areas (SDs 27-32) were mainly found in SD 25 and to some extent in SD 26, or in the SD of release (Fig. 6; Table 1). One exception to this pattern occurred in SD 32, where cod were found to have core area and home range within SD 32.

3.2 Movement patterns in the feeding season with Kernel Density Estimation

In general, both home ranges and core areas during the feeding season were similar to the home ranges and core areas detected during the spawning season, irrespective of the dataset (Fig. 6 and 7; Table 2). In the historical dataset, there was a general trend of recapture close to the area of release, albeit some notable exceptions were observed. For example, cod released in SD 29 had core feeding areas that were limited to the northern Baltic, while in the spawning season a core area was also detected in the southern Baltic. Cod released in SD 26 had a core feeding area in SD 26, and an extended home range, which spanned SD 25, SD 26 and SD 28.2. During the feeding season of cod released in the southern Baltic areas, the overlap in core areas and home ranges between historical and contemporary datasets was higher than in the spawning season (Fig. 8; Table 2). This high overlap was especially true for cod released in SD 24 (home range overlap ~91 %) but less so in SDs 25 and 26 (home range overlap ~55 % and 78 %, respectively; Table 2). Visually, foraging areas appeared to be constricted in the contemporary period (Fig. 8).

288 3.3 Movement patterns with Generalised Additive Models

289 GAM models applied to the historical dataset for cod released in quarter 2 and 4 explained 15.5 % and
290 15.7 % of the deviance of the overall model, respectively (see Tables S3 and S4 for model summaries).
291 For cod released in quarter 2 (spawning period) in SD 24, 26, 29 and 32, *DAL* had no significant effect
292 on the distance between release and recapture positions, while for cod released in SD 25, 27 and 28.2
293 the effect was significant showing that *d* slightly increased over time and reached an asymptote (Table
294 S3, Fig. S5). For cod released in quarter 4 (feeding period) for most of the *SD_{ri}* the *DAL* had a significant
295 effect on *d* (Table S4, Fig. S6). In particular, a positive, almost linear effect of *DAL* on *d* was found for
296 cod released in SD 25 and 29. In comparison, cod released in SD 24, 26, 27 and 28.2 displayed a positive
297 nonlinear relationship between *DAL* and *d*, whereby *d* increased to a point but then declined to a mini-
298 mum at around 300 to 350 *DAL*, and then increased thereafter (Table S4, Fig. S6). There was no signif-
299 icant effect of *DAL* on *d* for cod released in SD 32 (Table S4, Fig. S6).

300 A significant positive nearly linear effect of *Length_{ri}* on *d* was found for cod released both in quarter 2
301 and 4, with cod displaying an increase in *d* with increasing body size (Tables S3 and S4, Fig. S5 and
302 S6). Therefore, larger cod tended to be recaptured at more distant locations, whereas smaller cod tended
303 to be recaptured closer to the point of release.

304 4. Discussion

305 The re-analysis of historical tagging data combined with contemporary data enabled the description of
306 movement patterns and area utilisation of EBC for both time periods. In agreement with our expecta-
307 tions, this study has shown that in the historical period, cod released in the central and northern area of
308 the Baltic generally travelled greater distances than cod released in the southern Baltic. Furthermore,
309 data from the recent tagging experiment indicated that the historical movement patterns in the southern
310 Baltic have been generally maintained over time. The results from the kernel density estimation analysis
311 confirmed the patterns described in previous research (Aro 1989, 2002, Bagge & Steffensen 1989, Ro-
312 bichaud & Rose 2004), highlighting two types of movement behaviours for EBC: sedentary (i.e. cod
313 recaptured year-round within the area of release) and migratory (i.e. cod covering larger distances,
314 probably linked to spawning in areas separated from the feeding grounds).

315 The data show that management boundaries between SD 24 and 25 are crossed all year round, both in
316 the historical and in the contemporary period. However, this study also suggests that the percentage of
317 cod released in SD 25 and recaptured in SD 24 has increased in the recent period. In the historical
318 period, 6 % and 7 % of cod released in SD 25 were recaptured in SD 24 during the spawning and feeding
319 seasons, respectively. On the other hand, in the recent period 30 % and 41 % of cod released in SD 25
320 were recaptured in SD 24 during the spawning and feeding seasons, respectively. These findings suggest

321 that the use of SD 24 by EBC has increased in the recent period, an observation that supports our ex-
322 pectations on higher utilisation of southern areas and could result in an increased likelihood of mixing
323 between EBC and WBC in SD 24. There can be limitations to the use of tagging data to quantify the
324 degree of mixing in different areas and these need to be acknowledged. For instance, differences in
325 tagging location might influence the likelihood of recapture in a different area from that of release. In
326 fact, in the recent tagging experiment, cod in SD 25 were mainly tagged in proximity to the border with
327 SD 24, thus potentially increasing the possibility of cod released in SD 25 being recaptured in SD 24.
328 However, these results are in line with recent increases in the occurrence of EBC in SD 24, as estimated
329 by shape analysis of archived otoliths (Hüssy et al. 2016). The KDE analysis results also support this
330 finding. In the historical period, during the spawning season, core areas suggested that cod released in
331 SDs 24 and 25 were mainly recaptured in the Arkona Basin (i.e. spawning area of WBC), and in the
332 Bornholm Basin (i.e. main spawning area for the EBC), respectively. The bimodal core areas observed
333 for cod released in SD 26 indicate utilisation of both the Bornholm Basin and Gdansk Deep as the main
334 spawning areas, with cod likely moving between the two. In the contemporary period, the home ranges
335 were similar to the historical period, although core areas of cod released in SDs 24 and 25 were con-
336 centrated around Bornholm Island (SDs 24 and 25) during the spawning season, whilst in the past, core
337 areas concentrated mainly in the respective area of release. Since EBC currently inhabit also SD 24
338 (Hüssy et al. 2016), these results could add evidence that, contrary to historical assumptions (Bagge et
339 al. 1994), EBC spawn in the Arkona Sea as shown by Hüssy et al. 2016 and Hemmer-Hansen et al.
340 2019.

341 Recaptures from the historical period indicate long distance movements from the northern and central
342 Baltic towards the southern Baltic, which are probably linked to spawning in the Bornholm basin, (i.e.
343 the main EBC spawning area). These movements are not observed in the contemporary dataset, as in-
344 dividuals appear to remain in the south. As recent tagging was only conducted in the south, no clear
345 conclusions on changes in movement rates of EBC, or a loss of his migratory pathway to the north can
346 be made. Thus, further work will be needed to test our hypothesis around changes in movement rates
347 of EBC, in particular, there is a need to tag EBC in northern and central areas.

348 One interesting finding during the historical period is the presence of sedentary groups in the northern
349 and central Baltic. A year-round resident population in the northern Baltic could be explained by the
350 presence of juveniles (i.e. individuals that have not reached sexual maturity) that do not participate in a
351 spawning migration. In fact, GAM results suggested that smaller fish tended to be recovered at locations
352 closer to their release positions than larger cod. However, 56 % of cod that stayed in this area had a
353 length at release that exceeded the average length at maturation (i.e. 40 cm), indicating that individuals
354 with sedentary behaviour also included adults. In addition, fish species are thought to skip spawning
355 when in low body condition as they may lack the necessary energetic reserves to successfully migrate
356 or spawn (Jørgensen et al. 2006). Due to the low salinity, fertilisation of the eggs was deemed impossi-
357 ble in the Åland Sea and further north. Previously, it was assumed that recruitment to these northern

358 areas took place mostly through larval drift and the passive transport of young cod at times of strong
359 influxes of water from the south (Otterlind 1983, 1984), rather than recruitment from a local population
360 (Hinrichsen et al. 2017). However, spawning events have previously been observed in the Åland Sea
361 (Otterlind 1976, Vallin et al. 1999), suggesting the presence of a locally reproducing population.

362 Some active migration northward of young cod can probably take place, although migration of cod from
363 the central and southern parts of the Baltic proper to the Åland Sea was negligible according to the
364 historical tagging results. Due to biological problems (i.e., high tagging mortality of smaller fish), it
365 was not possible to effectively tag cod smaller than 20 cm in total length, therefore, northern active
366 migration of young cod could have been missed in the historical period. More information is needed on
367 oceanographic processes, larval drift and possible active adult migration towards the Åland Sea to un-
368 derstand the possible connectivity between these areas. Preliminary results indicate that some individ-
369 uals from the Åland Sea have higher successful fertilisation at lower salinities compared to cod from
370 the Gotland and Bornholm areas (Bergström et al. unpublished). Thus, although the results of our study
371 for the northern Baltic area are restricted to the historical period, they could contribute evidence to the
372 presence of a sub-population of cod that remain and spawn in the Åland Sea. Preliminary genetic studies
373 showed some level of separation, although not very distinct, of cod in this area (Bergström et al. un-
374 published). Further genetic studies are needed to confirm the possible presence of a resident population
375 in the area of the Åland Sea.

376 For cod released in SD 32 (Gulf of Finland), home range analyses indicate a year-round spatial distinc-
377 tion from the home ranges of cod released in other Baltic areas. These cod are found to exhibit a sed-
378 entary behaviour and are recaptured mainly in SD 32 during both feeding and spawning seasons. How-
379 ever, in other studies the migration of adult cod southwards was evident and linked to spawning (Aro
380 & Sjöblom 1983, Otterlind, 1985). These differences are likely due to the fact that in the present study
381 tagging experiments in SD 32 were limited compared to previous evaluations. This is because the pre-
382 sent study does not include transportation experiments of marked cod to other locations (Aro & Sjöblom
383 1983, Otterlind 1985). Further work to digitise additional historical records from this area would be
384 required to examine this discrepancy.

385 Generalized additive models were used to account for the effect of *DAL* on the movement patterns of
386 cod during the historical period. Different patterns were found for cod released during the spawning or
387 feeding periods, probably linked to the proximity to spawning grounds and presence of differing be-
388 havioural strategies (i.e. sedentary and migratory). Cod released during the spawning period (quarter 2)
389 in SDs 25, 26 and 28.2 were potentially already in proximity to EBC spawning grounds, while cod
390 released in SD 24 were in proximity to one of the WBC spawning grounds (Bleil & Oeberst 2002). The
391 results indicate that cod released during the spawning period in SDs 24, 26, 29 and 32 were recaptured
392 closer to positions of release all year round. These findings suggest that these cod were sedentary, prob-
393 ably spawning in the area of release or not participating in a spawning migration (e.g. cod released

394 during spawning period in SD 29). For cod released during the spawning period in SDs 25, 27 and 28.2,
395 the distance between release and recapture positions increased through time, suggesting that cod moved
396 away from the area of release but did not necessarily return.

397 Cod released during the feeding period (quarter 4) in SDs 24, 26, 27 and 28.2 showed approximately
398 an annual pattern in the distance moved from the release. The presence of this relationship between d
399 and DAL indicates that cod moved away from the area of release, probably to reach spawning grounds,
400 and then returned a year later, suggesting homing behaviour to both feeding and spawning areas. Cod
401 released in SDs 25 and 29 during the feeding period moved away from the area of release but did not
402 appear to return.

403 In a true migratory population, a clear cyclical signal would be expected as individuals move away and
404 return. This is lacking in some areas, and this could be due to the presence of different movement
405 behaviours, as indicated by the KDE analysis of the historical dataset. Since conventional tagging data
406 consist of only two positions, release and recapture, GAM may have low power when describing tem-
407 poral cyclic patterns of migration, especially when a mix of behaviours is present (Espeland et al. 2008).
408 Individuals that alternate between spawning and feeding seasons, as well as those that display sedentary
409 behaviour, would obscure this pattern (Espeland et al. 2008).

410 Our findings, using quantitative methods to re-analyse historical tagging data combined with contem-
411 porary data, provide additional information on general movement patterns between different areas of
412 the Baltic Sea. However, caution is advised regarding some limitations of our analysis. Unfortunately,
413 as is the case for many historical tagging studies, there is a lack of spatially-resolved fisheries effort
414 data. Historical catch data does show lower catches in the northern Baltic Sea compared to the south.
415 This could have prevented a full detection of a northward migration of cod due to a lower probability
416 of recapture in the northern Baltic Sea. In addition, if fishing effort is higher in one area (e.g. SD 24)
417 compared to others, it might explain any lack of change in the movements of tagged cod. Further work
418 is needed to account for spatio-temporal patterns in fishing effort within our analysis, which might result
419 in an overrepresentation of some recapture locations (Wright et al. 2006). In addition, conventional
420 mark-recapture data are restricted to information on release and recapture but nothing is known about
421 movement between these two points. Application of dynamic migration models may enhance our
422 knowledge of movements on a smaller time scale. Data-storage tags also offer an advanced method for
423 gathering high-resolution data on demersal fish movements in both the horizontal and vertical dimen-
424 sion (Griffiths et al. 2018) and allow behaviour to be related to the physical environment (Patterson et
425 al. 2009). Combining results from conventional tagging data with fine-scale movement patterns of in-
426 dividual cod would facilitate further study on migration and how it might be related to changes in the
427 environment.

428 Failure to incorporate information on the meta-population dynamics of marine fishes in fishery man-
429 agement risks the depletion of local sub-populations that may eventually contribute to stock collapse
430 (Hilborn et al. 2003; Kritzer & Sale 2004; Heath et al. 2008, Neat et al. 2014). Our study suggests that

431 possible meta-populations in the Baltic Sea (e.g. northern and southern Baltic cod) may have existed in
432 the historical period with individuals experiencing different patterns of movement. This means that cod
433 from different areas of the Baltic may have experienced different salinity, oxygen and temperature con-
434 ditions (Mion et al., 2021). The applied implications of this are that the removal of individuals in one
435 area could be more costly than in other areas, therefore a spatial adjustment of exploitation strategies,
436 such as the setting of a maximum sustainable yield for each spatial unit, may be required to ensure
437 sustainable harvesting (Holmes et al. 2014). Future management of fisheries, especially where meta-
438 populations exist or where mixing between different stocks occur, should implement the use of tagging
439 data in area-based assessment models (e.g. Stock Synthesis; Methot & Wetzel, 2013) to provide a more
440 reliable estimation of stock status.

441 Our results show that re-analysing historical conventional tagging data can still provide important in-
442 sights on movement patterns and area utilisation that can be readily compared with contemporary data.
443 In doing so, the biological knowledge of a stock, or multiple stocks, is increased, which could inform
444 future management actions.

445 5. Acknowledgements

446 We are grateful to all the fishers, anglers and technical staff involved in data entering, tagging, collec-
447 tion and processing of the samples used in this study and to Alessandro Orio (SLU) for R advice. This
448 study was funded by BalticSea2020 (<http://balticsea2020.org>) through the project “Tagging Baltic Cod”
449 (TABACOD). We also thank the Swedish Agency for Marine and Water Management for financing the
450 compilation of the Swedish data.

451 6. References

- 452 Andersen Ø, Wetten OF, De Rosa MC, Andre C, Carelli Alinovi C, Colafranceschi M, Brix O,
453 Colosimo A (2009) Haemoglobin polymorphisms affect the oxygen-binding properties in Atlantic
454 cod populations. *Proc Royal Soc B* 276:833–841, <https://doi.org/10.1098/rspb.2008.1529>.
- 455 Aro E (1989) A review of fish migration patterns in the Baltic. *Rapports et Procès-verbaux des Réunions*
456 *du Conseil International pour l’Exploration de la Mer* 190:72–96
- 457 Aro E (2002) Fish migration studies in the Baltic Sea - a historical review. *ICES J Mar Sci* 215:361-
458 370
- 459 Aro E & Sjöblom V (1983) Cod off the coast of Finland in 1974-82. *ICES CM* 1983/J: 25, 17 pp.
- 460 Bagge O & Steffensen E (1989) Stock identification of demersal fish in the Baltic. *Rapports et Procès-*
461 *verbaux des Réunions du Conseil International pour l’Exploration de la Mer* 190: 3–16
- 462 Bagge O, Thurow F, Steffensen E, Bay J (1994) The Baltic cod. *Dana* 10:1–28
- 463 Bartolino V, Tian H, Bergström U, Jounela P, Aro E, Dieterich C, et al. (2017) Spatio-temporal dy-
464 namics of a fish predator: Density-dependent and hydrographic effects on Baltic Sea cod population.
465 *PLoS ONE* 12(2):e0172004, <https://doi.org/10.1371/journal.pone.0172004>

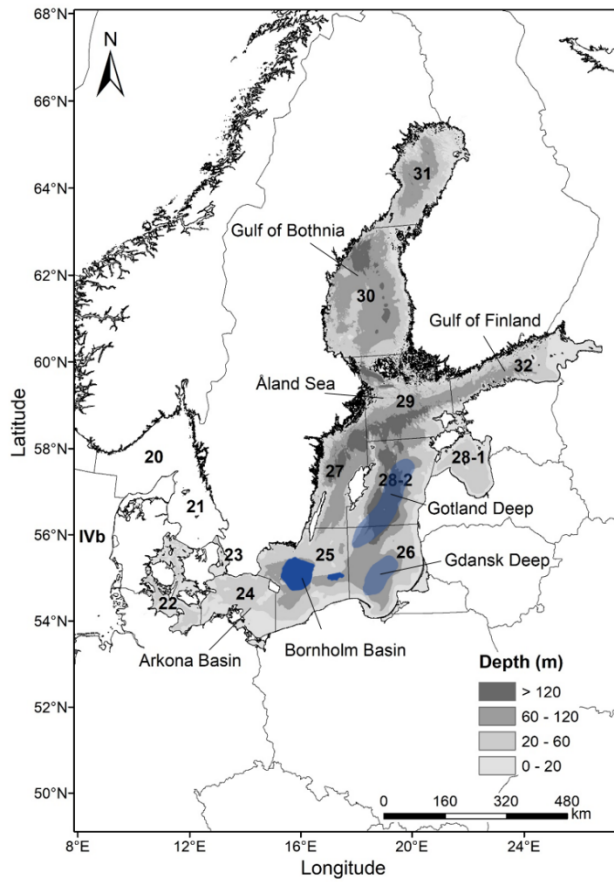
- 466 Bleil M & Oeberst R (2002) Spawning areas of the cod stock in the western Baltic Sea and minimum
467 length at maturity. Arch fish mar res 49:243-258
- 468 Bolle LJ, Hunter E, Rijnsdorp AD et al. (2005) Do tagging experiments tell the truth? Using electronic
469 tags to evaluate conventional tagging data. ICES J Mar Sci 62:236–246
- 470 Burt WH (1943) Territoriality and home range concepts as applied to mammals. J Mammal 24:346–352
- 471 Calenge C (2015). Home Range Estimation in R: The adehabitatHR Package. R Package Version 0.3.23
- 472 Cardinale M & Modin J (1999) Changes in size-at-maturity of Baltic cod (*Gadus morhua*) during a
473 period of large variations in stock size and environmental conditions. Fish Res 41:285–295
- 474 Cardinale M & Svedäng H (2011) The beauty of simplicity in science: Baltic cod stock improves rapidly
475 in a ‘cod hostile’ ecosystem state. MEPS 425:297-301. <https://doi.org/10.3354/meps09098>
- 476 Carstensen J, Andersen JH, Gustafsson BG, Conley DJ (2014) Deoxygenation of the Baltic Sea during
477 the last century. Proc Natl Acad Sci U S A 111:5628–5633
- 478 Casini M, Hjelm J, Molinero JC, Lövgren J, Cardinale M, Bartolino V, Belgrano A, Kornilovs G (2009)
479 Trophic cascades promote threshold-like shifts in pelagic marine ecosystems. Proc Natl Acad Sci
480 USA 106:197–202
- 481 Dean MJ, Hoffman WS, Zemeckis DR, Armstrong MP (2014) Fine-scale diel and gender-based patterns
482 in behaviour of Atlantic cod (*Gadus morhua*) on a spawning ground in the Western Gulf of Maine.
483 ICES. J. Mar. Sci. 71(6): 1474–1489.
- 484 Drinkwater K (2005) The response of Atlantic cod (*Gadus morhua*) to future climate change. ICES J
485 Mar Sci 62:1327–1337
- 486 Drinkwater K (2015) Comparison of the response of Atlantic cod (*Gadus morhua*) in the high-latitude
487 regions of the North Atlantic during the warm periods of the 1920s–1960s and the 1990s–2000s.
488 Deep Sea Res Part II Top Stud Oceanogr 56:2087–2096
- 489 Eero M, Hjelm J, Behrens J, Buchmann K, Cardinale M, Casini M, Gasyukov P, Holmgren N, Horbowy
490 J, Hüsey K, Kirkegaard E (2015) Eastern Baltic cod in distress: biological changes and challenges
491 for stock assessment. ICES J Mar Sci 72(8):2180–2186
- 492 Eero M, Vinther M, Haslob H, Huwer B, Casini M, Storr-Poulsen M, Köster FW (2012) Spatial man-
493 agement of marine resources can enhance the recovery of predators and avoid local depletion of
494 forage fish. Conserv Lett 5:486–492
- 495 Engelhard GH, Righton DA, Pinnegar JK (2014) Climate change and fishing: a century of shifting
496 distribution in North Sea cod. Glob Chang Biol 20:2473–2483
- 497 Engelhardt J, Frisell O, Gustavsson H, Hansson T, Sjöberg R, Collier TK, Balk L (2020) Severe thia-
498 mine deficiency in eastern Baltic cod (*Gadus morhua*). PLoS One 15(1):e0227201,
499 <https://doi.org/10.1371/journal.pone.0227201>
- 500 Espeland SH, Olsen EM, Knutsen H. et al. (2008) New perspectives on fish movement: kernel and
501 GAM smoothers applied to a century of tagging data on coastal Atlantic cod. MEPS 372:231–241.
- 502 Griffiths CA (2019) Using electronic tagging data to investigate the individual-, population-and com-
503 munity-level consequences of movement in free-roaming marine fish. Doctoral dissertation, Univer-
504 sity of Sheffield and University of Tasmania.
- 505 Griffiths CA, Patterson T, Blanchard J, Righton D, Wright S, Pitchford J, Blackwell P (2018) Scaling
506 marine fish movement behaviour from individuals to populations. Ecol Evol 8:10.1002/ece3.4223

- 507 Heath MR, Kunzlik PA, Gallego A, Holmes SJ, Wright PJ (2008) A model of meta-population dynam-
508 ics for North Sea and West of Scotland cod—the dynamic consequences of natal fidelity. *Fish Res*
509 93:92–116
- 510 Hemmer-Hansen J, Hüsey K, Baktoft H, Huwer B, Bekkevold D, Haslob H, et al. (2019) Genetic anal-
511 yses reveal complex dynamics within a marine fish management area. *Evol Appl* 12:830–844
- 512 Hilborn R., Quinn TP, Schindler DE, Rogers DE (2003) Biocomplexity and fisheries sustainability.
513 *PNAS* 100:6564–6568.
- 514 Hinrichsen HH, von Dewitz B, Lehmann A, Bergstrom U, Hussy K (2017) Spatio-temporal dynamics
515 of cod nursery areas in the Baltic Sea. *Prog Oceanogr* 155:28–40,
516 <https://doi.org/10.1016/j.pocean.2017.05.007>
- 517 Horbowy J, Podolska M, Nadolna-Altyn K (2016) Increasing occurrence of anisakid nematodes in the
518 liver of cod (*Gadus morhua*) from the Baltic Sea: Does infection affect the condition and mortality
519 of fish? *Fish Res* 179:98–103
- 520 Hüsey K (2011). Review of western Baltic cod (*Gadus morhua*) recruitment dynamics. *ICES J Mar Sci*
521 68:1459–1471
- 522 Hüsey K, Hinrichsen HH, Eero M, Mosegaard H, Hemmer-Hansen J, Lehmann A, Lundgaard LS (2016)
523 Spatio-temporal trends in stock mixing of eastern and western Baltic cod in the Arkona Basin and
524 the implications for recruitment. *ICES J Mar Sci* 73(2):293–303,
525 <https://doi.org/10.1093/icesjms/fsv227>
- 526 Hüsey K, Casini M, Haase S, Hilvarsson A, Horbowy J, Krüger-Johnsen M, Krumme U, Limburg K,
527 McQueen K, Mion M, Olesen HJ, Radtke K (2020) Tagging Baltic Cod – TABACOD. Eastern Baltic
528 cod: Solving the ageing and stock assessment problems with combined state-of-the-art tagging meth-
529 ods. DTU Aqua Report no. 368-2020. National Institute of Aquatic Resources, Technical University
530 of Denmark. 64 pp. + appendices
- 531 ICES (2014) Report of the Baltic Fisheries Assessment Working Group (WGBFAS), 310 April 2014,
532 ICES HQ, Copenhagen, Denmark. ICES CM 2014/ACOM:10. 919 pp
- 533 ICES (2020) Baltic Fisheries Assessment Working Group (WGBFAS). *ICES Scientific Reports*. 2:45.
534 632 pp. <https://doi.org/10.17895/ices.pub.6024>
- 535 ICES (2021) Cod (*Gadus morhua*) in subdivisions 24–32, eastern Baltic stock (eastern Baltic Sea). In
536 Report of the ICES Advisory Committee. *ICES Advice* 2021, cod.27.24-32,
537 <https://doi.org/10.17895/ices.advice.7745>
- 538 Jørgensen C, Dunlop ES, Opdal AF, Fiksen Ø (2008) The evolution of spawning migrations: state de-
539 pendence and fishing-induced changes. *Ecology* 89(12):3436–3448
- 540 Kritzer JP & Sale PF (2004) Metapopulation ecology in the sea: from Levins' model to marine ecology
541 and fisheries science. *Fish Fish* 5:131–140.
- 542 Köster F, Möllmann C, Hinrichsen H, Wieland K, Tomkiewicz J, Kraus G, Voss R, Makarchouk A,
543 Mackenzie B, Stjohn M (2005) Baltic cod recruitment – the impact of climate variability on key
544 processes. *ICES J Mar Sci* 62:1408–1425, <https://doi.org/10.1016/j.icesjms.2005.05.004>
- 545 Köster FW, Huwer B, Hinrichsen HH, Neumann V, Makarchouk A, Eero M, Dewitz BV et al. (2017)
546 Eastern Baltic cod recruitment revisited—dynamics and impacting factors. *ICES J Mar Sci* 74:3–19
- 547 Mackenzie BR, Gislason H, Möllmann C, Köster FW (2007) Impact of 21st century climate change on
548 the Baltic Sea fish community and fisheries. *Glob Chang Biol* 13:1348–1367,
549 <https://doi.org/10.1111/j.1365-2486.2007.01369.x>

- 550 Meier HEM, Eilola K, Almroth-Rosell E, Schimanke S, Kniebusch M, Höglund A, Pemberton P, Liu
551 Y, Väli G, Saraiva S (2018) Disentangling the impact of nutrient load and climate changes on Baltic
552 Sea hypoxia and eutrophication since 1850. *Clim Dyn* 1–22
- 553 Metcalfe JD (2006) Fish population structuring in the North Sea: understanding processes and mecha-
554 nisms from studies of the movements of adults. *J Fish Biol* 69:48-65
- 555 Methot RD & Wetzel CR (2013) Stock synthesis: a biological and statistical framework for fish stock
556 assessment and fishery management. *Fish Res* 142:86–99.
557 <https://doi.org/10.1016/j.fishres.2012.10.012>
- 558 Mion M, Hilvarsson A, Hüsey K, Krumme U, Krüger-Johnsen M, McQueen K, Mohamed E, Motyka
559 R, Orio A, Plikshs M, Radtke K, Casini M (2020) Historical growth of Eastern Baltic cod (*Gadus*
560 *morhua*): Setting a baseline with international tagging data. *Fish Res* 223:105442,
561 <https://doi.org/10.1016/j.fishres.2019.105442>
- 562 Mion M, Haase S, Hemmer-Hansen J, Hilvarsson A, Hüsey K, Krüger-Johnsen M, Krumme U,
563 McQueen K, Plikshs M, Radtke K, Schade FM, Vitale F, Casini M (2021) Multidecadal changes in
564 fish growth rates estimated from tagging data: A case study from the Eastern Baltic cod (*Gadus*
565 *morhua*, Gadidae). *Fish Fish*, <https://doi.org/10.1111/faf.12527>
- 566 Möllmann C, Diekmann R, Müller-Karulis B, Kornilovs G, Plikshs M, Axe P (2009) Reorganization
567 of a large marine ecosystem due to atmospheric and anthropogenic pressure: a discontinuous regime
568 shift in the Central Baltic Sea. *Glob Chang Biol* 15:1377–1393
- 569 Neat FC, Bendall V, Berx B, et al. (2014) Movement of Atlantic cod around the British Isles: implica-
570 tions for finer scale stock management. *J Appl Ecol* 51:1564–1574, doi: 10.1111/1365-2664.12343
571 (2014).
- 572 Nissling A, Kryvi, Vallin L (1994) Variation in egg buoyancy of Baltic cod *Gadus morhua* and its
573 implications for egg survival in prevailing conditions in the Baltic Sea. *MEPS* 110:67–74,
574 <https://doi.org/10.3354/meps110067>
- 575 Nordeide JT (1998) Coastal cod and Northeast Arctic cod – do they mingle at the spawning grounds in
576 Lofoten? *Sarsia* 83:373–379
- 577 Orio A, Bergström U, Florin AB, Lehmann A, Šics I, Casini M (2019) Spatial contraction of demersal
578 fish populations in a large marine ecosystem. *J Biogeogr* 46:633–645,
579 <https://doi.org/10.1111/jbi.13510>.
- 580 Otterlind G (1976) Fish stocks and fish migration in the Baltic Sea environment. *Ambio Special Report*
581 4:89-101.
- 582 Otterlind G (1983) Torsken och Bottenhavet. *Yrkesfiskaren* 7(1):10-11.
- 583 Otterlind G (1984) Cod migration and transplantation experiments. *ICES CM* 1984/J: 13. 6 pp.
- 584 Otterlind G (1985) Cod migration and transplantation experiments in the Baltic. *J Appl Ichthyol* 1(1):3-
585 16
- 586 Pálsson OK & Thorsteinsson V (2003) Migration patterns, ambient temperature, and growth of Ice-
587 landic cod (*Gadus morhua*): evidence from storage tag data. *Can J Fish Aquat Sci* 60:1409–1423,
588 doi: 10.1139/f03-117.
- 589 Patterson TA, Basson M, Bravington MV, Gunn JS (2009) Classifying Movement Behaviour in Rela-
590 tion to Environmental Conditions Using Hidden Markov Models. *Journal of Animal Ecology*,
591 78(6):1113–1123. <http://www.jstor.org/stable/40405875>
- 592 Powell RA (2000) Animal home ranges and territories and home range estimators. In: *Research Tech-*
593 *niques in Animal Ecology: Controversies and Consequences* (Eds L. Boitani and T.H. Fuller). Co-
594 lumbia University, New York, USA, pp. 65–110.

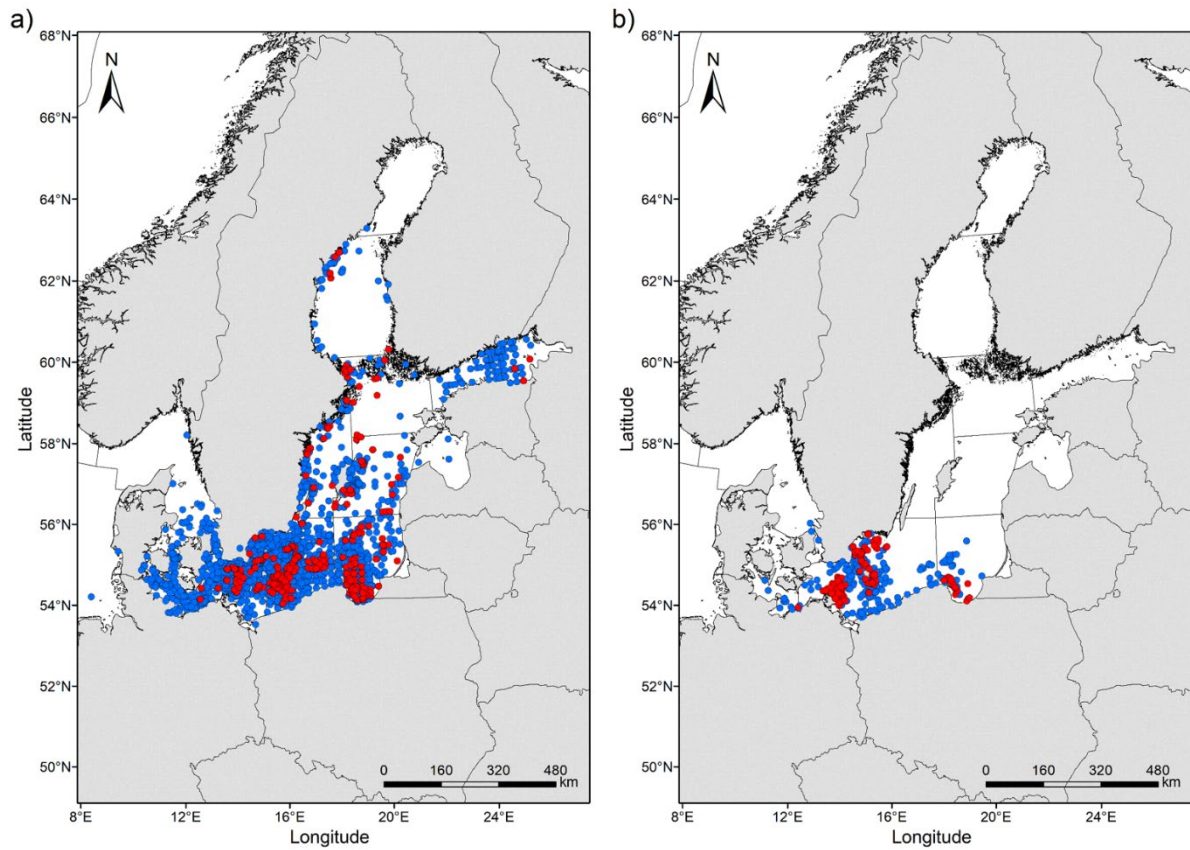
- 595 R Core Team (2020) R: A language and environment for statistical computing. [https://www.r-pro-](https://www.r-project.org/)
596 [ject.org/](https://www.r-project.org/)
- 597 Reusch TBH, Dierking J, Andersson H, Bonsdorff E, Carstensen J, Casini M, Czajkowski M, Hasler B,
598 Hinsby K, Hyytiäinen K, Johannesson K, Jomaa S, Jormalainen V, Kuosa H, Kurland S, Laikre L,
599 MacKenzie BR, Margonski P, Melzner F, Oesterwind D, Ojaveer H, Refsgaard JC, Sandström A,
600 Schwarz G, Tonderski K, Winder M & Zandersen M (2018). The Baltic Sea as a time machine for
601 the future coastal ocean. *Sci Adv* 4(5):eaar8195, <https://doi.org/10.1126/sciadv.aar8195>
- 602 Righton D & Metcalfe J (2019) Migration. In: *Atlantic cod. A Bio-Ecology*. John Wiley & Sons Ltd,
603 pp 169–218
- 604 Rijnsdorp AD & Pastoors MA (1995) Modelling the spatial dynamics of fisheries of North Sea plaice
605 (*Pleuronectes platessa* L.) based on tagging data. *ICES J Mar Sci* 52:963–980
- 606 Robichaud D & Rose GA (2004) Migratory behaviour and range in Atlantic cod: inference from a
607 century of tagging. *Fish Fish* 5:185–214
- 608 Rogers LA, Olsen EM, Knutsen H, Stenseth NC (2014) Habitat effects on population connectivity in a
609 coastal seascape. *MEPS* 511:153–163
- 610 Rose GA & Rowe S (2015) Northern cod comeback. *Can J Fish Aquat Sci* 72:1789–1798
- 611 Seaman DE & Powell RA (1996) An evaluation of the accuracy of kernel density estimators for home
612 range analysis. *Ecology* 77:2075–2085
- 613 Sólmundsson J, Jónsdóttir IG, Björnsson B, Ragnarsson SA, Tómasson GG, Thorsteinsson V (2015)
614 Home ranges and spatial segregation of cod *Gadus morhua* spawning components. *MEPS* 520:217–
615 233
- 616 Vallin L, Nissling A, Westin L (1999) Potential factors influencing reproductive success of Baltic cod,
617 *Gadus morhua*: A review. *Ambio* 28:92–99
- 618 Wieland K, Jarre-Teichmann A, Horbowa K (2000) Changes in the timing of spawning of Baltic cod:
619 possible causes and implications for recruitment. *ICES J Mar Sci* 57:452–464
- 620 Wood SN (2003) Thin-plate regression splines. *J R Stat Soc B* 65:95–114, doi:10.1111/1467-
621 9868.00374
- 622 Wood SN (2006) *Generalized Additive Models: An Introduction with R*. Journal of Statistical Software,
623 16. CRC/Chapman and Hall, Boca Raton, Florida. [http://www.jstat soft.org/](http://www.jstatsoft.org/)
- 624 Worton BJ (1989) Kernel methods for estimating the utilization distribution in home-range studies.
625 *Ecology* 70:164–168
- 626 Wright PJ, Galley E, Gibb IM, Neat FC (2006) Fidelity of adult cod to spawning grounds in Scottish
627 waters. *Fish Res* 77:148–158
- 628 Zemeckis DR, Martins D, Kerr LA, Cadrin SX (2014) Stock identification of Atlantic cod (*Gadus*
629 *morhua*) in US waters: an interdisciplinary approach. *ICES J Mar Sci* 71:1490–1506
- 630

631 Figures



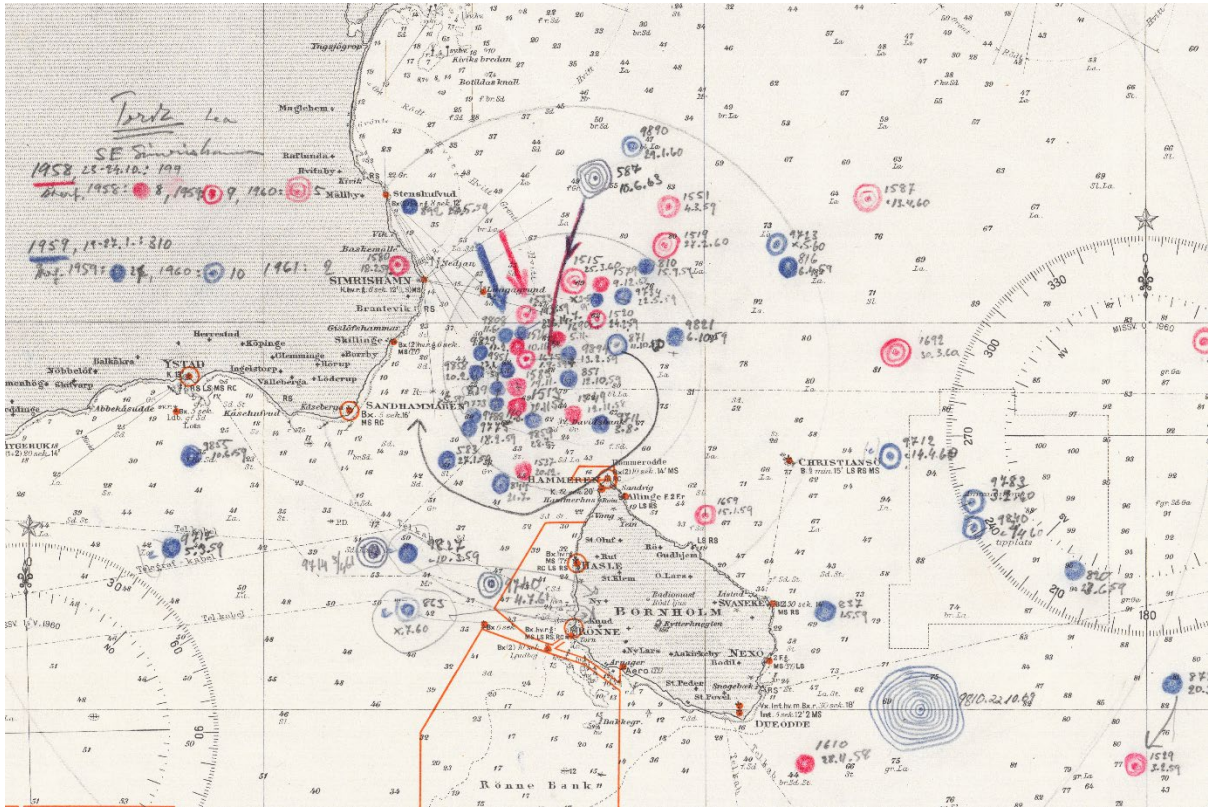
632

633 *Figure 1.* Map of the Baltic Sea with ICES subdivisions. The former spawning grounds of the Gotland
634 Deep and Gdansk Deep are shaded in blue, while the active spawning ground of the Bornholm Basin
635 is marked in blue (Modified after Cardinale and Svedäng, 2011).



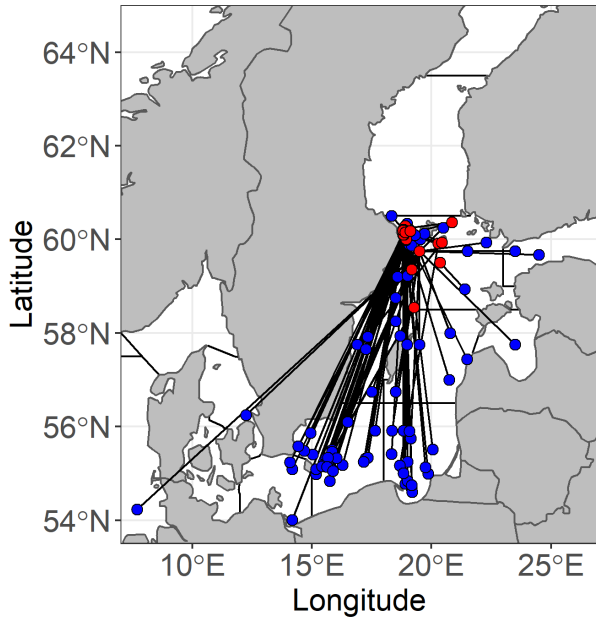
636

637 *Figure 2.* Map of the Baltic Sea with release positions (red dots) and recapture positions (blue dots)
 638 for the historical (a) and the contemporary tagging experiments (b). See Figure 1 for a map of the Bal-
 639 tic Sea with ICES subdivisions.

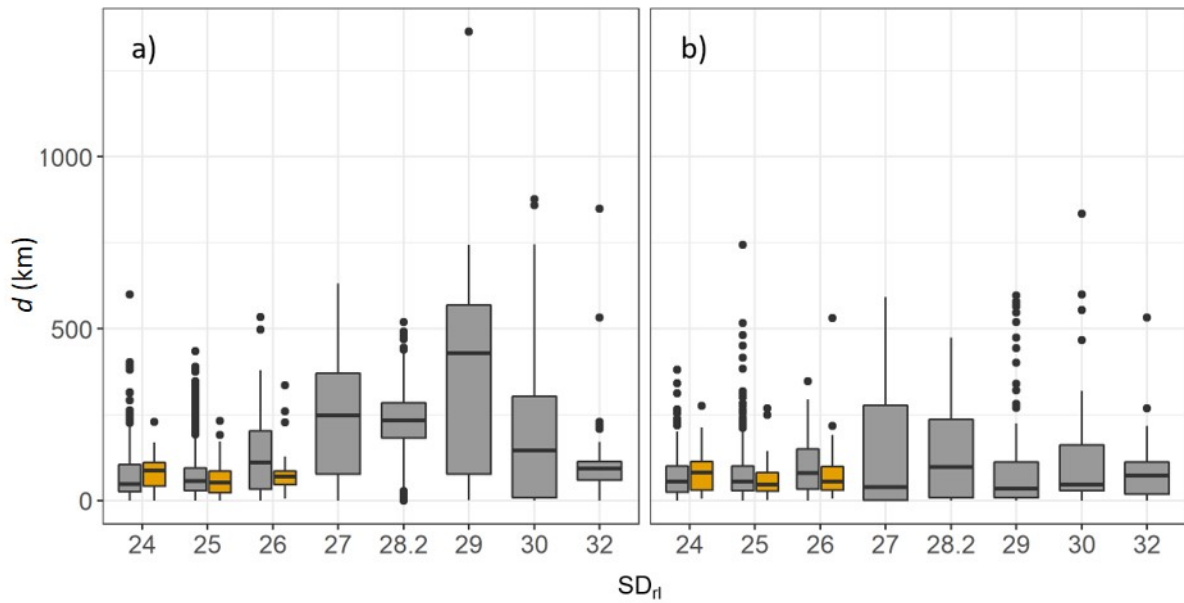


641

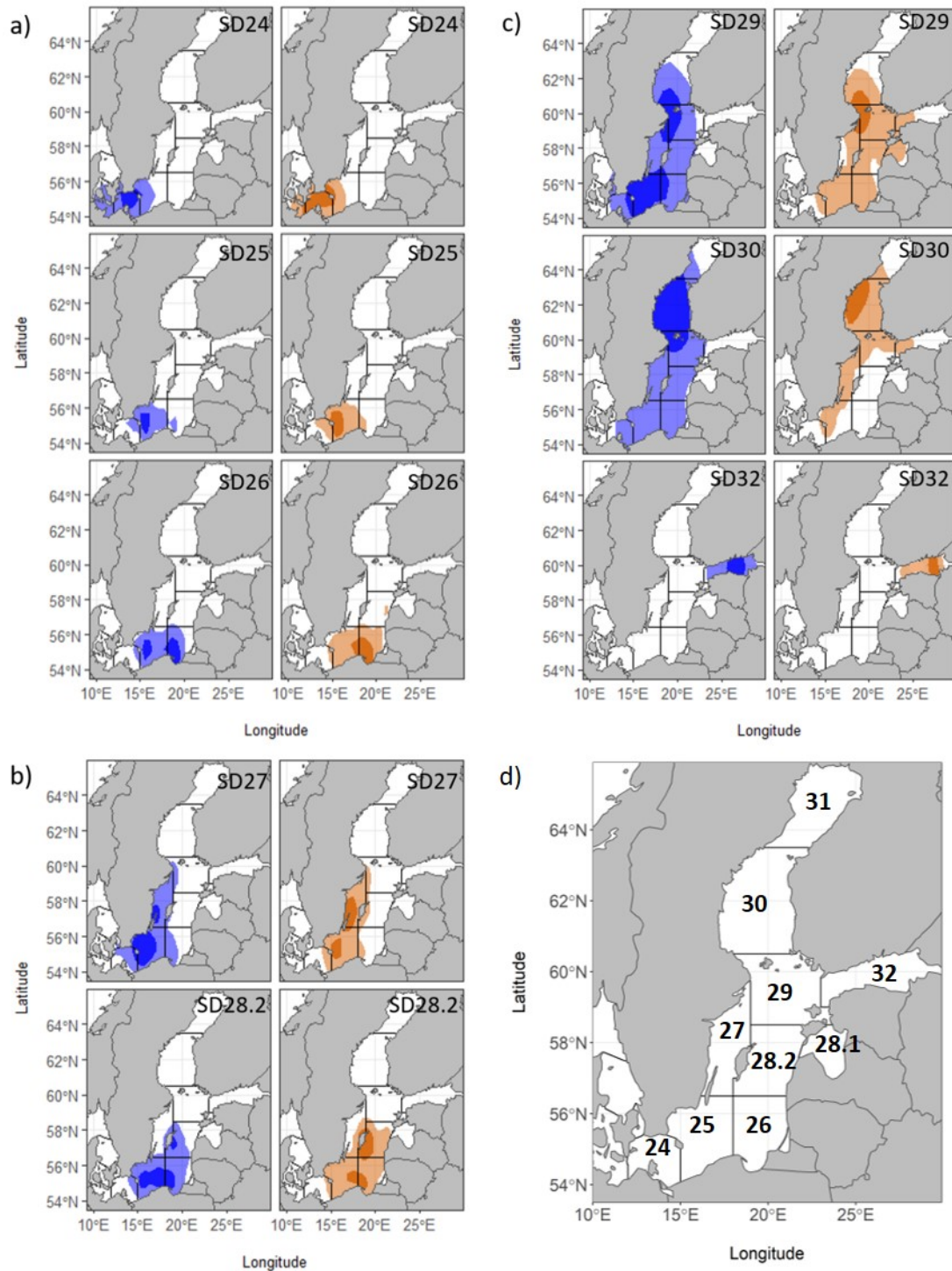
642 *Figure 3.* Example of an historical map visualising Swedish tagging experiments carried out in 1958
643 (red) and 1959 (blue) in the Baltic Sea (nearby Bornholm Island). Arrows indicate the release and dots
644 the recapture locations of cod. Filled dots represent cod that were recaptured within a year of release,
645 while additional years (>1) from release are represented as circles surrounding a recapture location. For
646 example, in the bottom right of the map, a cod is recaptured after 10 years and its recapture location is
647 illustrated as a blue dot surrounded by nine circles.



648 *Figure 4.* Example of straight-line trajectories (black lines) between release (red dots) and recapture
 649 (blue dots) positions for fish released in SD 29 (Åland Sea) during the historical tagging experiments.
 650



651
 652 *Figure 5.* Box plots of the distance between release and recapture (d) during spawning (a) and feeding
 653 (b) seasons by subdivision of release (SD_{r_i}) for the historical (grey) and contemporary (orange) peri-
 654 ods. Spawning and feeding seasons are assigned based on recapture time. Thick line: median; box:
 655 25th and 75th percentiles; whiskers: 1.5 times the interquartile range; black dots: outliers).



656

657 *Figure 6.* Maps showing the 95% kernel home ranges (shaded colour) and 50% kernel core areas (bold
 658 colour) for each subdivision (SD) of release written on the top right corner of each map in the southern
 659 (a), central (b) and northern (c) Baltic areas for the historical dataset. d) Map of the Baltic Sea with
 660 ICES subdivisions. Data shown are for cod recaptured during the spawning season (January to June;
 661 blue, left panels) and the feeding season (July to December; orange, right panels).

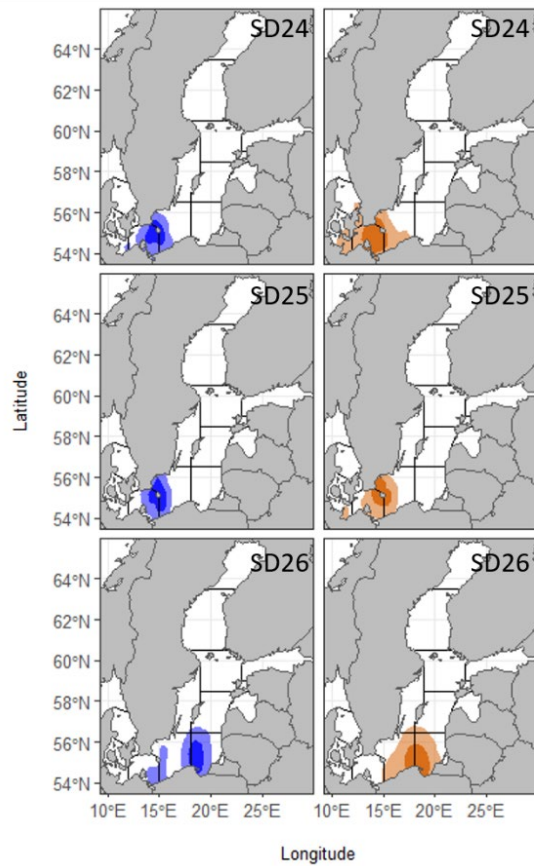


Figure 7. a) Maps showing the 95% kernel home ranges (shaded colour) and 50% kernel core areas (bold colour) for each subdivision (SD) of release written on the top right corner of each map for the contemporary dataset. Data shown are for cod recaptured during the spawning season (April to September; blue, left panels) and the feeding season (October to March; orange, right panels). See Figure 6d for a map of the Baltic Sea with ICES subdivisions.

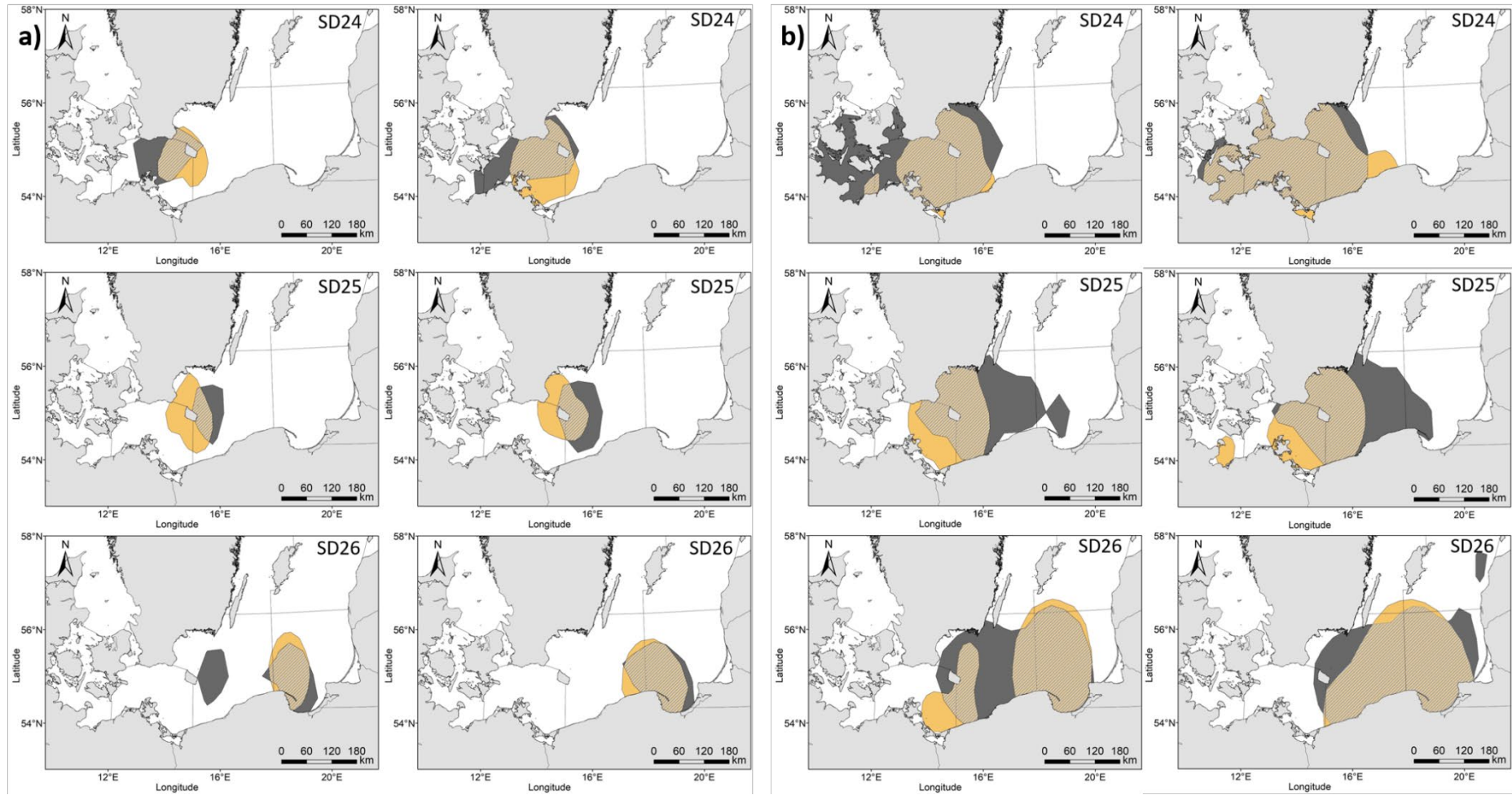


Figure 8. Overlap between the historical (grey) and contemporary (orange) data for cod recaptured during the spawning season (left panels) and the feeding season (right panels). The 50% kernel core areas are shown in panel (a) and the 95% kernel home ranges are shown in panel (b) for cod tagged in subdivision (SD; written in bold) 24, 25 and 26. See Figure 6d for a map of the Baltic Sea with ICES subdivisions.

Table 1. Percentage and total number (in brackets) of cod recaptured by subdivision of release (SD_{rl}) and subdivision of recapture (SD_{rc}) during the spawning and feeding seasons for the historical and contemporary (Contemp) datasets. Percentage and total number of recaptures in the same SD_{rl} are in bold.

a)		Spawning													
		SD_{rc}													
Dataset	SD_{rl}	IVb	20	21	22	23	24	25	26	27	28	29	30	31	32
Historical	24	0.1 (1)	1.5 (11)		16.1 (119)	1.4 (10)	61.6 (458)	18.4 (137)	0.5 (4)		0.4 (3)				
	25		0.3 (6)		1.0 (18)	0.2 (4)	6.0 (111)	87.6 (1622)	4.7 (86)	0.1 (1)	0.2 (3)				
	26				0.3 (2)		2.9 (21)	43.6 (317)	52.4 (381)	0.1 (1)	0.7 (5)				
	27		0.5 (1)		0.5 (1)	0.5 (1)	3.6 (8)	63.4 (140)	4.1 (9)	27.2 (60)		0.5 (1)			
	28					0.1 (1)	1.4 (11)	52.9 (427)	27.2 (220)	0.4 (3)	18.1 (146)				
	29	1.0 (1)	1.0 (1)				3.03 (3)	32.3 (32)	13.11 (13)	8.1 (8)	9.1 (9)	32.4 (32)			
	30							9.1 (2)	9.1 (2)	4.6 (1)		22.7 (5)	54.6 (12)		
	32							2.5(4)	2.47 (4)						
Contemp.	24				2.1 (2)		54.3 (51)	43.7 (41)							
	25					1.9 (1)	29.6 (16)	66.7 (36)	1.9 (1)						
	26						4 (1)	20 (5)	76 (19)						

b)		Feeding													
		SD_{rc}													
Dateset	SD_{rl}	IVb	20	21	22	23	24	25	26	27	28	29	30	31	32
Historical	24	0.3 (1)	1.2 (4)		13.2 (43)	2.8 (9)	54.8 (178)	26.5 (86)	1.2 (4)						
	25		0.3 (2)		0.4 (3)	0.1 (1)	7.0 (50)	85.8 (609)	5.1 (35)	0.7 (5)	0.6 (4)		0.1 (1)		
	26						0.7 (2)	33.5 (90)	61.0 (164)		4.9 (18)				
	27				0.5 (1)		0.5 (1)	34.6 (72)	1.4 (3)	61.1 (127)	1.0 (2)	1.0 (2)			
	28							27.5 (101)	16.6 (61)	1.6 (6)	54.2 (199)				
	29							7.4 (5)	7.4 (5)	2.9 (2)	4.4 (3)	73.5 (50)	1.5 (1)		2.9 (2)
	30							2.2 (1)		4.4 (2)		8.9 (4)	80.0 (36)	2.2 (1)	2.2 (1)
	32								1.7 (3)		0.6 (1)				
Contemp.	24			3.7 (2)	9.3 (5)		63.0 (34)	24.0 (13)							
	25				4.5 (2)		40.9 (18)	54.5 (24)							
	26				3.3 (1)			30.0 (9)	66.7 (20)						

Table 2. 95% kernel density estimation (KDE) home ranges (x1000 km²) and 50% KDE core areas (x1000 km²) for the historical and contemporary datasets during the spawning and feeding seasons by subdivision of release (SD_{rl}). Spatial overlap between historical and contemporary data is reported in %.

KDE 50 %					
Season	SD_{rl}	Historical (km ²)	Contemporary (km ²)	Overlap (km ²)	Historical overlaps Contemporary %
Spawning	24	12.7	11.4	6.9	54.4
	25	7.8	13.1	3.8	48.5
	26	19.4	12.8	10.2	52.5
	27	31.4			
	28	29.2			
	29	93.5			
	30	78.5			
	32	12			
Feeding	24	21.7	20.9	13.8	63.5
	25	13.5	12.6	6.2	45.9
	26	18	18.3	15.9	88.0
	27	21.9			
	28	25.5			
	29	21.7			
	30	24.6			
	32	7.1			
KDE 95 %					
Season	SD_{rl}	Historical (km ²)	Contemporary (km ²)	Overlap (km ²)	Historical overlaps Contemporary %
Spawning	24	61.6	35.5	34.6	56.2
	25	48.4	32.8	24.6	50.7
	26	69.6	55	45.8	65.8
	27	94.9			
	28	88.7			
	29	240.3			
	30	264.9			
	32	28.2			
Feeding	24	57.8	57.8	52.4	90.6
	25	56	40.5	30.9	55.2
	26	75.9	62.6	58.8	77.5
	27	77.7			
	28	113.2			
	29	200.1			
	30	113.8			
	32	21.1			