

Validation of otolith $\delta^{18}\text{O}$ values as effective natural tags for shelf-scale geolocation of migrating fish

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Table S1. Expected otolith $\delta^{18}\text{O}$ signatures (mean \pm SD in ‰) at monthly, seasonal (LA/EW, LW/ES, LS/ES and LS/EA) and annual (year) scales, over the full distribution range (global) or in each area frequented over the course of the year. At each spatio-temporal scale, the number of daily temperature/salinity observations extracted from the 1997, 1998 and 1999 datasets and used for $\delta^{18}\text{O}$ calculations is given in brackets (*italics*). EC: English Channel; SNS: Southern North Sea; WNS: Western North Sea; CNS: Central North Sea; ENS: Eastern North Sea; NNS: Northern North Sea.

	EC	SNS	WNS	CNS	ENS	NNS	global
year	1.29 \pm 0.80 (<i>N = 5 475</i>)	1.25 \pm 0.98 (<i>N = 17 520</i>)	1.71 \pm 1.07 (<i>N = 15 330</i>)	1.61 \pm 0.90 (<i>N = 27 375</i>)	1.32 \pm 0.77 (<i>N = 26 280</i>)	2.18 \pm 0.53 (<i>N = 44 895</i>)	1.69 \pm 0.91 (<i>N = 136 875</i>)
LA/EW	1.61 \pm 0.49 (<i>N = 1 380</i>)	1.76 \pm 0.51 (<i>N = 4 416</i>)	2.07 \pm 0.57 (<i>N = 3 864</i>)	2.03 \pm 0.50 (<i>N = 6 900</i>)	1.82 \pm 0.39 (<i>N = 6 624</i>)	2.17 \pm 0.35 (<i>N = 11 316</i>)	1.99 \pm 0.49 (<i>N = 34 500</i>)
LW/ES	2.22 \pm 0.15 (<i>N = 1 335</i>)	2.30 \pm 0.30 (<i>N = 4 272</i>)	2.51 \pm 0.46 (<i>N = 3 738</i>)	2.57 \pm 0.22 (<i>N = 6 675</i>)	2.36 \pm 0.17 (<i>N = 6 408</i>)	2.69 \pm 0.12 (<i>N = 10 947</i>)	2.51 \pm 0.31 (<i>N = 33 375</i>)
LS/ES	1.13 \pm 0.46 (<i>N = 1 380</i>)	0.85 \pm 0.65 (<i>N = 4 416</i>)	1.44 \pm 0.88 (<i>N = 3 864</i>)	1.36 \pm 0.63 (<i>N = 6 900</i>)	1.03 \pm 0.56 (<i>N = 6 624</i>)	2.22 \pm 0.36 (<i>N = 11 316</i>)	1.51 \pm 0.80 (<i>N = 34 500</i>)
LS/EA	0.23 \pm 0.21 (<i>N = 1 380</i>)	0.10 \pm 0.46 (<i>N = 4 416</i>)	0.83 \pm 0.61 (<i>N = 3 864</i>)	0.50 \pm 0.45 (<i>N = 6 900</i>)	0.10 \pm 0.52 (<i>N = 6 624</i>)	1.67 \pm 0.57 (<i>N = 11 316</i>)	0.78 \pm 0.85 (<i>N = 34 500</i>)
November	1.07 \pm 0.21 (<i>N = 450</i>)	1.19 \pm 0.29 (<i>N = 1 440</i>)	1.63 \pm 0.35 (<i>N = 1 260</i>)	1.47 \pm 0.32 (<i>N = 2 250</i>)	1.19 \pm 0.25 (<i>N = 2 160</i>)	1.80 \pm 0.28 (<i>N = 3 690</i>)	1.49 \pm 0.40 (<i>N = 11 250</i>)
December	1.67 \pm 0.19 (<i>N = 465</i>)	1.83 \pm 0.22 (<i>N = 1 488</i>)	2.14 \pm 0.31 (<i>N = 1 302</i>)	2.11 \pm 0.27 (<i>N = 2 325</i>)	1.92 \pm 0.20 (<i>N = 2 232</i>)	2.20 \pm 0.17 (<i>N = 3 813</i>)	2.05 \pm 0.28 (<i>N = 11 625</i>)
January	2.09 \pm 0.20 (<i>N = 465</i>)	2.25 \pm 0.27 (<i>N = 1 488</i>)	2.42 \pm 0.32 (<i>N = 1 302</i>)	2.49 \pm 0.22 (<i>N = 2 325</i>)	2.33 \pm 0.18 (<i>N = 2 232</i>)	2.51 \pm 0.15 (<i>N = 3 813</i>)	2.41 \pm 0.25 (<i>N = 11 625</i>)
February	2.35 \pm 0.12 (<i>N = 420</i>)	2.50 \pm 0.21 (<i>N = 1 344</i>)	2.61 \pm 0.30 (<i>N = 1 176</i>)	2.70 \pm 0.15 (<i>N = 2 100</i>)	2.54 \pm 0.14 (<i>N = 2 016</i>)	2.70 \pm 0.13 (<i>N = 3 444</i>)	2.62 \pm 0.21 (<i>N = 10 500</i>)
March	2.26 \pm 0.07 (<i>N = 465</i>)	2.36 \pm 0.21 (<i>N = 1 488</i>)	2.57 \pm 0.41 (<i>N = 1 302</i>)	2.63 \pm 0.16 (<i>N = 2 325</i>)	2.44 \pm 0.10 (<i>N = 2 232</i>)	2.73 \pm 0.10 (<i>N = 3 813</i>)	2.57 \pm 0.26 (<i>N = 11 625</i>)
April	2.05 \pm 0.08 (<i>N = 450</i>)	2.06 \pm 0.27 (<i>N = 1 440</i>)	2.34 \pm 0.51 (<i>N = 1 260</i>)	2.37 \pm 0.20 (<i>N = 2 250</i>)	2.12 \pm 0.12 (<i>N = 2 160</i>)	2.63 \pm 0.09 (<i>N = 3 690</i>)	2.35 \pm 0.35 (<i>N = 11 250</i>)
May	1.65 \pm 0.16 (<i>N = 465</i>)	1.49 \pm 0.38 (<i>N = 1 488</i>)	1.93 \pm 0.61 (<i>N = 1 302</i>)	1.91 \pm 0.33 (<i>N = 2 325</i>)	1.65 \pm 0.26 (<i>N = 2 232</i>)	2.44 \pm 0.16 (<i>N = 3 813</i>)	1.97 \pm 0.50 (<i>N = 11 625</i>)
June	1.12 \pm 0.18 (<i>N = 450</i>)	0.80 \pm 0.42 (<i>N = 1 440</i>)	1.42 \pm 0.76 (<i>N = 1 260</i>)	1.37 \pm 0.45 (<i>N = 2 250</i>)	1.02 \pm 0.39 (<i>N = 2 160</i>)	2.23 \pm 0.28 (<i>N = 3 690</i>)	1.51 \pm 0.71 (<i>N = 11 250</i>)
July	0.62 \pm 0.19 (<i>N = 465</i>)	0.27 \pm 0.43 (<i>N = 1 488</i>)	0.98 \pm 0.79 (<i>N = 1 302</i>)	0.81 \pm 0.50 (<i>N = 2 325</i>)	0.41 \pm 0.51 (<i>N = 2 232</i>)	1.99 \pm 0.43 (<i>N = 3 813</i>)	1.06 \pm 0.87 (<i>N = 11 625</i>)
August	0.20 \pm 0.13 (<i>N = 465</i>)	-0.12 \pm 0.41 (<i>N = 1 488</i>)	0.69 \pm 0.72 (<i>N = 1 302</i>)	0.41 \pm 0.49 (<i>N = 2 325</i>)	0.01 \pm 0.57 (<i>N = 2 232</i>)	1.79 \pm 0.54 (<i>N = 3 813</i>)	0.74 \pm 0.95 (<i>N = 11 625</i>)
September	0.08 \pm 0.11 (<i>N = 450</i>)	-0.05 \pm 0.37 (<i>N = 1 440</i>)	0.70 \pm 0.53 (<i>N = 1 260</i>)	0.31 \pm 0.37 (<i>N = 2 250</i>)	-0.14 \pm 0.51 (<i>N = 2 160</i>)	1.62 \pm 0.62 (<i>N = 3 690</i>)	0.64 \pm 0.88 (<i>N = 11 250</i>)
October	0.42 \pm 0.19 (<i>N = 465</i>)	0.47 \pm 0.33 (<i>N = 1 488</i>)	1.09 \pm 0.41 (<i>N = 1 302</i>)	0.77 \pm 0.33 (<i>N = 2 325</i>)	0.42 \pm 0.36 (<i>N = 2 232</i>)	1.60 \pm 0.53 (<i>N = 3 813</i>)	0.96 \pm 0.65 (<i>N = 11 625</i>)

Table S2 – Results of the two-way (month \times sub-stock) unbalanced PERM ANOVA on predicted monthly $\delta^{18}\text{O}$ values (A) and results of the Mann-Whitney-Wilcoxon post-hoc tests among (B) pairs of sub-stocks for each month and (C) pairs of months for each of the 3 sub-stocks (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

(A)

	Df	MeanSq	F-stat	N.perm	P.param	Pr(>F)
Month	11	19.55	342.90	999	1.120e-246	***
Sub-stock	2	32.98	578.35	999	2.560e-139	***
Month \times sub-stock	22	1.63	28.51	999	5.971e-78	***
Residuals	585	0.06	NA	NA	NA	NA

(B) The cells in grey indicate months when differences of $\delta^{18}\text{O}$ values are significant among all three sub-stocks.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A \neq B	*	***	***	***	***	***	***	***	***	***	***	***
A \neq C	***	**	***	***	***	***	***	***	**	***	**	ns
B \neq C	ns	ns	ns	*	ns	ns	ns	*	**	***	ns	*

(C) The cells in grey indicate month pairs for which $\delta^{18}\text{O}$ values differ significantly irrespective of the sub-stock (A, B or C).

A	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Jan		***	***	*	ns	***	***	***	***	***	***	***
Feb			ns	***	***	***	***	***	***	***	***	***
Mar				***	***	***	***	***	***	***	***	***
Apr					*	***	***	***	***	***	***	***
May						ns	***	***	***	***	***	***
Jun							ns	*	***	***	***	ns
Jul								ns	ns	ns	*	ns
Aug									ns	ns	ns	ns
Sep										ns	ns	***
Oct											ns	***
Nov												***
Dec												

B	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Jan		ns	ns	ns	***	***	***	**	**	***	***	***
Feb			ns	**	**	***	***	**	**	***	***	***
Mar				*	***	***	***	***	***	***	***	***
Apr					ns	**	***	***	***	***	***	ns
May						ns	**	*	*	**	ns	ns
Jun							ns	*	*	**	ns	***
Jul								ns	ns	ns	ns	***
Aug									ns	ns	*	***
Sep										*	*	***
Oct											**	***
Nov												***
Dec												

C	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Jan		**	**	ns	***	***	***	***	***	***	***	ns
Feb			ns	***	***	*	**	**	*	***	**	*
Mar				**	***	***	***	***	**	***	***	***
Apr					***	***	***	***	***	***	***	**
May						***	***	***	**	***	***	ns
Jun							**	**	ns	ns	ns	*
Jul								ns	ns	ns	***	**
Aug									ns	*	***	**
Sep										ns	ns	*
Oct											ns	**
Nov												**
Dec												

Table S3 - Results of the two-way (season \times sub-stock) unbalanced PERM ANOVA on predicted seasonal $\delta^{18}\text{O}$ values (A) and results of the Mann-Whitney-Wilcoxon post-hoc tests among (B) pairs of sub-stocks for each season and (C) pairs of seasons for each of the 3 sub-stocks (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$). Seasons: LW/ES = late winter/early spring, LS/ES = late spring/early summer, LS/EA = late summer/early autumn and LA/EW = late autumn/early winter.

(A)

	Df	MeanSq	F-stat	N.perm	P.param	Pr (>F)
Season	3	50.76	416.39	999	4.87 e-147	***
Sub-stock	2	30.53	250.45	999	4.21 e-80	***
Season \times sub-stock	6	4.05	33.19	999	1.12 e-34	**
Residuals	609	0.12	-	-	-	-

(B) Grey columns indicate seasons when $\delta^{18}\text{O}$ value differences are significant among all three sub-stocks.

	LW/ES	LS/ES	LS/EA	LA/EW
A \neq B	***	***	***	**
A \neq C	***	***	***	*
B \neq C	ns	ns	**	ns

(C) For each sub-stock (A, B and C), the grey cells indicate season pairs for which $\delta^{18}\text{O}$ values differ significantly.

		A				B				C			
		LW/ES	LS/ES	LS/EA	LA/EW	LW/ES	LS/ES	LS/EA	LA/EW	LW/ES	LS/ES	LS/EA	LA/EW
A	LW/ES		***	***	***	***	***	***	***	***	***	***	***
	LS/ES			***	ns	ns	***	***	**	ns	***	***	**
	LS/EA				***	***	ns	***	ns	***	ns	***	*
	LA/EW					ns	***	***	**	**	***	***	*
B	LW/ES						***	***	***	ns	***	***	**
	LS/ES							***	***	***	ns	**	***
	LS/EA								***	***	***	**	***
	LA/EW									***	***	***	ns
C	LW/ES										***	***	**
	LS/ES											***	**
	LS/EA												***
	LA/EW												

Table S4 - Results from the two-way (season \times sub-stock) unbalanced PERM ANOVA on observed seasonal $\delta^{18}\text{O}$ values (A) and results of the Mann-Whitney-Wilcoxon post-hoc tests among (B) pairs of sub-stocks for each season and (C) pairs of seasons for each of the 3 sub-stocks (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$). Seasons: LW/ES = late winter/early spring, LS/ES = late spring/early summer, LS/EA = late summer/early autumn and LA/EW = late autumn/early winter.

(A)

	Df	MeanSq	F-stat	N.perm	P.param	Pr (>F)
Season	3	8.51	82.29	999	1.85 e-27	***
Sub-stock	2	10.73	103.71	999	1.37 e-25	***
Season \times sub-stock	6	0.25	2.43	999	3.06 e-02	0.02
Residuals	105	0.10	-	-	-	-

(B) Grey columns indicate seasons when $\delta^{18}\text{O}$ value differences are significant among all three sub-stocks.

	LW/ES	LS/ES	LS/EA	LA/EW
A \neq B	***	***	***	*
A \neq C	***	***	***	*
B \neq C	ns	ns	***	ns

(C) For each sub-stock (A, B and C), the grey cells indicate season pairs for which $\delta^{18}\text{O}$ values differ significantly.

		A				B				C			
		LW/ES	LS/ES	LS/EA	LA/EW	LW/ES	LS/ES	LS/EA	LA/EW	LW/ES	LS/ES	LS/EA	LA/EW
A	LW/ES		***	***	***	***	***	***	***	***	***	***	***
	LS/ES			***	ns	ns	***	***	***	*	***	***	**
	LS/EA				***	***	*	***	*	***	ns	***	*
	LA/EW					ns	***	***	*	*	***	***	*
B	LW/ES						***	***	***	ns	***	***	**
	LS/ES							***	***	***	ns	*	***
	LS/EA								***	***	***	***	***
	LA/EW									***	***	***	ns
C	LW/ES										***	***	***
	LS/ES											***	***
	LS/EA												***
	LA/EW												