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The biomass-weighted proportion of South Coast-spawned sardine eggs that are simulated to be transported to the West Coast nursery area

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The average biomass-weighted proportion of eggs transported from South Coast spawning areas to the West Coast nursery based on two hydrodynamic particle-tracking individual-based models is either 0.08 or 0.177. If the number of eggs lost to the system are accounted for, these estimates increase to 0.139 and 0.325.

Introduction

The sardine population is currently assumed to consist of two stocks including cool temperate sardine located primarily to the west of Cape Agulhas and warm temperate sardine located to the west of Cape Agulhas in addition to their preferred habitat east of Cape Agulhas. The hypothesis assumes passive movement of some early-stage recruits originating from South Coast spawning to the West Coast, in addition to active movement of older sardine from the West to the South Coast (de Moor et al. 2023). A hydrodynamic particle-tracking individual-based model (IBM) that simulated the movement and fate of sardine spawning products from both West Coast and South Coast spawning regions (Miller et al. 2006) suggested that in the order of 15% of eggs spawned on the Central Agulhas Bank (CAB) and 3% of eggs spawned on the Eastern Agulhas Bank (EAB) are successfully transported to the West Coast nursery area. These successfully transported eggs and larvae are therefore potentially contributing to sardine recruitment measured on the West Coast during the annual recruit survey and under a natal homing hypothesis are more likely to move back to the South Coast as they mature.

Coetzee (2016) used sardine distribution data (biomass per stratum) estimated from November pelagic surveys to derive a biomass-weighted proportion of South Coast eggs that contribute to West Coast recruitment. At that time, it was estimated that an average of 8.3% of South Coast-spawned eggs were transported to the West Coast between 1984 and 2015.

Since then, an updated IBM (McGrath et al. 2020), which includes an extended geographical domain further east and features greater horizontal and vertical resolutions as well as more realistic wind-forcing has become available.

This document updates those earlier biomass-weighted estimates, based on the Miller et al. (2006) IBM with recent biomass data and compares those results to similarly biomass-weighted results based on the McGrath et al. (2020) IBM.

Methods

Table 1 lists the number of eggs released in each of 9 spawning areas and the number of eggs successfully transported to or retained in either the West Coast or South Coast nursery areas for both the Miller et al. (2006) IBM and the McGrath et al. (2020) IMB. Annexure A provides details of the spawning area naming conventions and locations of spawning and nursery areas.

Because the survey estimates of biomass are not split according to the same inshore/offshore spawning areas as were used by either Miller *et al*. (2006) or McGrath et al. (2020), the number of eggs released and successfully transported, or retained were summed to obtain an aggregated proportion of successfully transported eggs for the larger survey strata (Table 2).

To account for eggs lost to the system, the aggregated number of eggs successfully transported to or retained in each nursery area were renormalised, so that the proportions of eggs transported/retained from each aggregated spawning area summed to one (Table 3).

However, because the proportion of successfully transported eggs from the Central and Eastern Agulhas Bank spawning areas varied greatly (areas F and G compared to H and I in Miller et al (2006), and CAB compared to EAB in McGrath el al. (2020) and because these two spawning areas coincide with the existing November survey boundary between stratum D and E off Mossel Bay and Port Alfred, a biomass-weighted annual proportion of successfully transported eggs from the South Coast ($q_{y,s}$) to the West Coast nursery was calculated instead (Table 4) as:

$$q_{y,s} = \left(\frac{B_{y,D}}{B_{y,D} + B_{y,E}} \times q_D\right) + \left(\frac{B_{y,E}}{B_{y,D} + B_{y,E}} \times q_E\right)$$

Where $B_{y,D}$ and $B_{y,E}$ are the annual hydro-acoustic estimates of biomass obtained in stratum D and E respectively and q_D and q_E are either the original proportion or renormalised proportions of eggs transported to the West Coast nursery area from the South Coast spawning areas. For the more recent McGrath model that has a separate spawning area east of Cape St Francis (ALG), the proportions of eggs transported to the West Coast from spawning in EABin, EABoff and ALG are summed.

Results

Table 1. The numbers of eggs and proportion transported/retained (in each of the nurseries) and lost within each of the spawning areas (from Miller *et al.*, 2006 and McGrath et al., 2020).

IBM Study	Spawning Area	Eggs released	Eggs (n) transported to/retained in WC nursery	Eggs (P) transported to/retained in WC nursery	Eggs (n) transported to/retained in SC nursery	Eggs (P) transported to/retained in SC nursery	Eggs (n) lost to the system	Eggs (P) lost to the system
Miller et al. 1996	A	1441729	351092	0.244	0	0.000	1090637	0.756
	B	1861286	467263	0.251	1	0.000	1394022	0.749
	C	259595	98341	0.379	4	0.000	161250	0.621
	D	273508	108913	0.398	4	0.000	164591	0.602
	E	590546	235708	0.399	22500	0.038	332338	0.563
	F	1528492	221989	0.145	729649	0.477	576854	0.377
	G	1079128	163430	0.151	258506	0.240	657192	0.609
	H	426108	11384	0.027	271713	0.638	143011	0.336
	I	1170968	31044	0.027	669836	0.572	470088	0.401
McGrath et al. 2020	UWCin	631414	358836	0.568	0	0.000	272578	0.432
	UWCoff	1183922	768671	0.649	0	0.000	415251	0.351
	LWCin	469495	261464	0.557	0	0.000	208031	0.443
	LWCoff	696906	513503	0.737	0	0.000	183403	0.263
	WAB	1037610	609109	0.587	58	0.000	428443	0.413
	CABin	1221460	403708	0.331	388551	0.318	429201	0.351
	CABoff	1523934	513496	0.337	97962	0.064	912476	0.599
	EABin	586913	28225	0.048	421964	0.719	136724	0.233
	EABoff	452291	52186	0.115	158726	0.351	241379	0.534
	ALG	512055	19748	0.039	298192	0.582	194115	0.379

Table 2. The aggregated numbers of eggs and proportion transported/retained (in each of the nurseries) and lost within each of the major spawning areas for both IBMs.

IBM Study	Survey stratum	Spawning Area	Eggs released	Eggs (n) transported to/retained in WC nursery	Eggs (P) transported to/retained in WC nursery	Eggs (n) transported to/retained in SC nursery	Eggs (P) transported to/retained in SC nursery	Eggs (n) lost to the system	Eggs (P) lost to the system
Miller et al. 1996	A&B	A-D	3836118	1025609	0.267	9	0.000	2810500	0.733
	C	E	590546	235708	0.399	22500	0.038	332338	0.563
	D	F&G	2607620	385419	0.148[1]	988155	0.379	1234046	0.473
	E	H&I	1597076	42428	0.027[1]	941549	0.590	613099	0.384
McGrath et al. 2020	A&B	UWC&LWC	2981737	1902474	0.638	0	0.000	1079263	0.362
	C	WAB	1037610	609109	0.587	58	0.000	428443	0.413
	D	CAB	2745394	917204	0.334	486513	0.177	1341677	0.489
	E	EAB&ALG	1551259	100159	0.065	878882	0.567	572218	0.369

[1] The proportions used by Coetzee (2016) to calculate the proportion of eggs transported to the West Coast.

Table 3. The aggregated numbers of eggs and proportion transported/retained (in each of the nurseries) for each of the major spawning areas for both IBMs **after accounting for eggs lost to the system**. The proportions used are shown in grey.

IBM Study	Survey stratum	Spawning Area	Eggs released	Eggs (n) transported to/retained in WC nursery	Eggs (P) transported to/retained in WC nursery	Eggs (n) transported to/retained in SC nursery	Eggs (P) transported to/retained in SC nursery
Miller et al. 1996	A&B	A-D	3836118	1025609	1.000	9	0.000
	C	E	590546	235708	0.913	22500	0.087
	D	F&G	2607620	385419	0.281	988155	0.719
	E	H&I	1597076	42428	0.043	941549	0.957
McGrath et al. 2020	A&B	UWC&LWC	2981737	1902474	1.000	0	0.000
	C	WAB	1037610	609109	1.000	58	0.000
	D	CAB	2745394	917204	0.653	486513	0.347
	E	EAB&ALG	1551259	100159	0.102	878882	0.898

Table 4. Biomass per stratum and biomass-weighted proportion of South Coast-spawned eggs that are transported to the West Coast nursery area ($q_{y,s}$). Results are provided with and without accounting for eggs lost to the system.

						Miller	McGrath	Miller	Mc Grath
biomass per stratum						Includes eggs lost to the system		Excludes eggs lost to the system	
Year	A	B	C	D	E	$q_{y,s}$	$q_{y,s}$	$q_{y,s}$	$q_{y,s}$
1984			36453	2565	255	0.137	0.310	0.259	0.604
1985		246	23188	17997	2510	0.133	0.301	0.252	0.586
1986		9494	228736	948	81742	0.028	0.068	0.046	0.109
1987	15720	60779	17666	9926	9726	0.088	0.201	0.163	0.381
1988	26421	2806	98817	5451	1173	0.126	0.286	0.239	0.556
1989	354	23869	174105	18972	39355	0.066	0.152	0.120	0.282
1990	0	6085	242770	34184	8471	0.124	0.281	0.233	0.544
1991	13636	52860	450685	60391	26064	0.111	0.253	0.209	0.487
1992	7331	2087	238339	24654	222056	0.039	0.091	0.067	0.157
1993		93602	387220	57981	21217	0.115	0.262	0.217	0.506
1994		116077	273653	3854	154074	0.030	0.071	0.049	0.116
1995	26450	15492	322382	48914	431488	0.039	0.092	0.067	0.158
1996	4399	20385	232980	45623	226070	0.047	0.110	0.083	0.195
1997	613	185527	778696	257278	2519	0.147	0.331	0.278	0.648
1998	213055	343144	526347	185573	339209	0.069	0.160	0.127	0.297
1999	0	118053	589976	382689	544692	0.077	0.176	0.141	0.330
2000	800	576065	149365	138731	1559539	0.036	0.087	0.063	0.147
2001	40	207714	461863	947079	692904	0.097	0.220	0.180	0.421
2002	3191	11515	1170007	1073536	1999367	0.069	0.159	0.126	0.295
2003	6837	8460	1327821	684186	1536867	0.064	0.148	0.116	0.272
2004	255	17	295836	414214	1908979	0.048	0.113	0.085	0.201
2005	132	15	75458	616993	356393	0.103	0.235	0.194	0.452
2006	642	61086	116161	206842	327825	0.073	0.169	0.135	0.316
2007	677	2676	49785	21121	177941	0.039	0.093	0.068	0.161
2008	0	38	211833	25531	146678	0.045	0.105	0.078	0.184
2009	77132	38919	146124	234237	5164	0.145	0.328	0.275	0.642
2010	27972	77122	197503	58006	140891	0.062	0.143	0.112	0.263
2011	62063	1711	119051	321630	532605	0.072	0.166	0.133	0.310
2012	9409	472	176228	67660	91285	0.078	0.179	0.144	0.337
2013	0	2369	465243	84363	59787	0.098	0.222	0.182	0.425
2014	0	286	195499	175480	73234	0.112	0.255	0.211	0.491
2015	741	32157	65569	47229	217534	0.048	0.113	0.085	0.201
2016	2691	49778	130887	9239	65980	0.041	0.098	0.072	0.170
2017	0	3008	104165	28275	199355	0.042	0.098	0.073	0.171
2018	37	1579	33229	3118	52805	0.033	0.080	0.056	0.133
2019	0	67	43553	48152	96471	0.067	0.154	0.122	0.286
2020	5343	1748	44587	143263	54000	0.115	0.260	0.216	0.503
2021	No survey								
2022	142104	27734	51654	25317	322669	0.060	0.142	0.060	0.142
2023	104152	164997	139007	88809	498330	0.079	0.186	0.079	0.186
					Average	**0.077**[2]	**0.177**	**0.139**	**0.325**
					SD	0.036	0.079	0.071	0.165
					CV	0.453	0.444	0.511	0.507

[2] The equivalent estimate of what was previously used to inform movement of eggs from the south coast to the west coast. The average at that time for data up to 2015 was 0.083 .

Conclusion

Results from the updated IBM suggest an increase in the average percentage of particles released on the South Coast and transported to the West Coast compared to the previous IBM.

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Annexure A.

Spawning area naming conventions and locations of spawning and nursery areas – **Miller et al. 2006.**

Miller DCM, Moloney CL, van der Lingen CD, Lett C, Mullon C, and Field JG. 2006. Modelling the effects of physical–biological interactions and spatial variability in spawning and nursery areas on transport and retention of sardine Sardinops sagax eggs and larvae in the southern Benguela ecosystem. Journal of Marine Systems, 61: 212–229

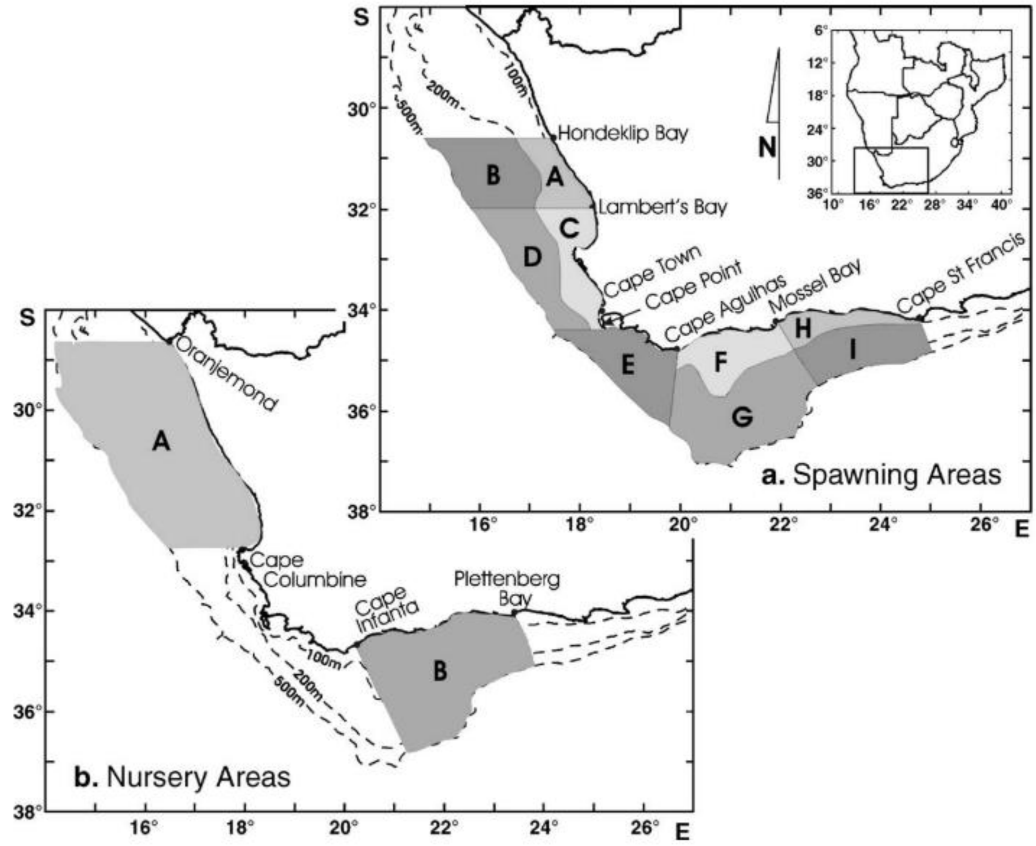

Fig. 3. (a) The nine spawning areas used in the IBM experiments. A = upper west coast inshore (UWC in), B = upper west coast offshore (UWC off), C = lower west coast inshore (LWC in), D = lower west coast offshore (LWC off), E = western Agulhas Bank (WAB), F = central Agulhas Bank inshore (CAB in), G = central Agulhas Bank offshore (CAB off), H = eastern Agulhas Bank inshore (EAB in), I = eastern Agulhas Bank offshore (EAB off). (b) The two nursery areas used in the IBM experiments. A = west coast (WC), B = south coast (SC).

Spawning area naming conventions and locations of spawning and nursery areas – **McGrath et al. 2020.**

McGrath AM, Hermes JC, Moloney CL, Roy C, Cambon G, Herbette S, van der Lingen CD. 2020. Investigating connectivity between two sardine stocks off South Africa using a high-resolution IBM: Retention and transport success of sardine eggs. Fisheries Oceanography, 29, 137-151.

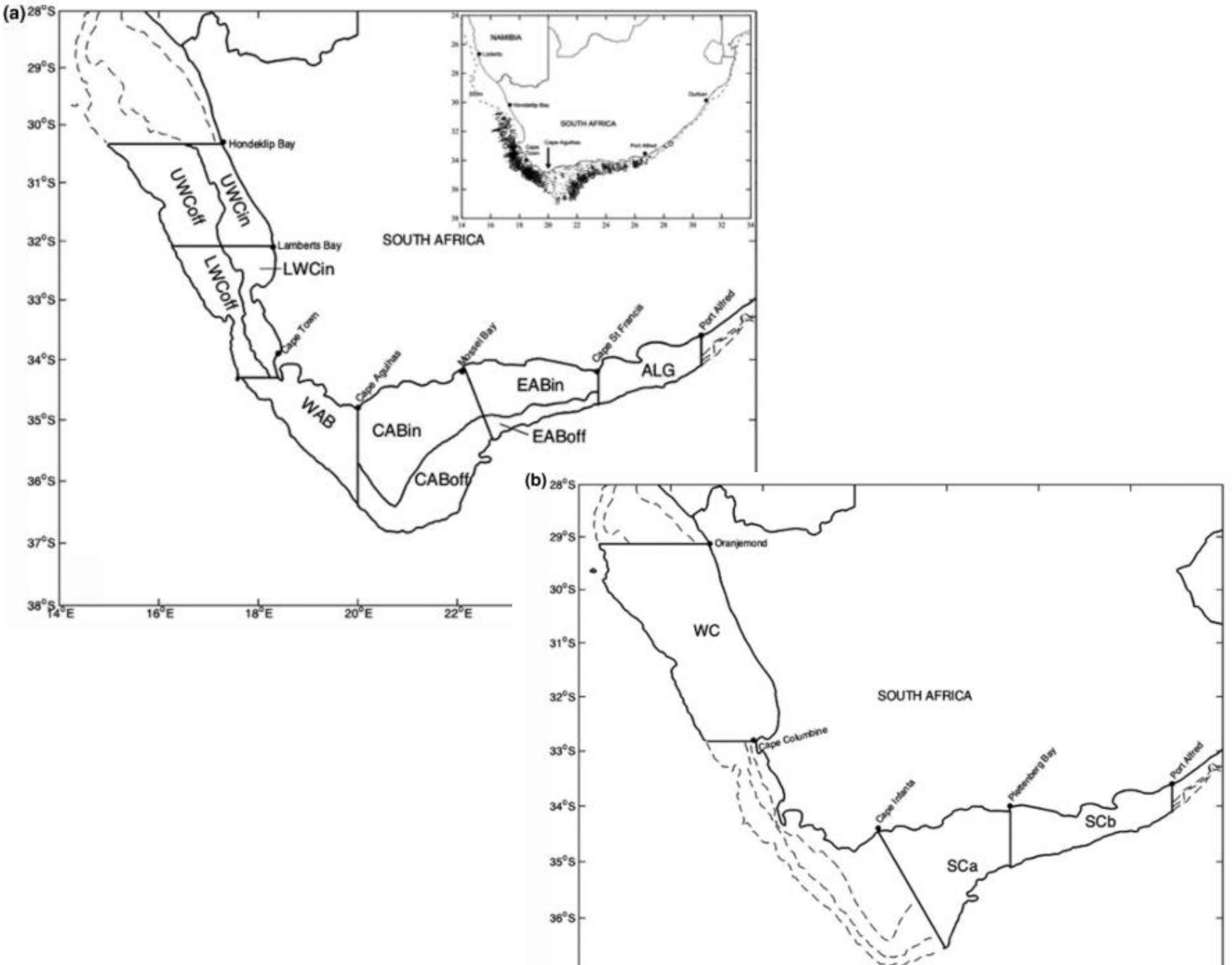

FIGURE 2 (a) The ten spawning areas defined in the IBM simulations. UWCin, upper West Coast inshore; UWCoff, upper West Coast offshore; LWCin, lower West Coast inshore; LWCoff, lower West Coast offshore; WAB, western Agulhas Bank; CABin, central Agulhas Bank inshore; CABoff, central Agulhas Bank offshore; EABin, eastern Agulhas Bank inshore; EABoff, eastern Agulhas Bank offshore; ALG, Algoa Bay. (b) The three recruitment areas defined in the IBM simulations. WC, West Coast, SCa, south-West Coast, SCb, south-east coast. The 125, 200 and 500 m isobaths are displayed by dashed lines. The insert in (a) shows the composite sardine egg density (eggs per square metre with circle diameter proportional to abundance and a maximum value of 9,193 eggs.m−1) derived from CalVET net samples collected during annual surveys conducted between Hondeklip Bay and Port Alfred from 1986 to 2010 from de Moor et al., (2017)