Mapping Larval Connectivity for MPA-networks:
– a Swedish case-study –

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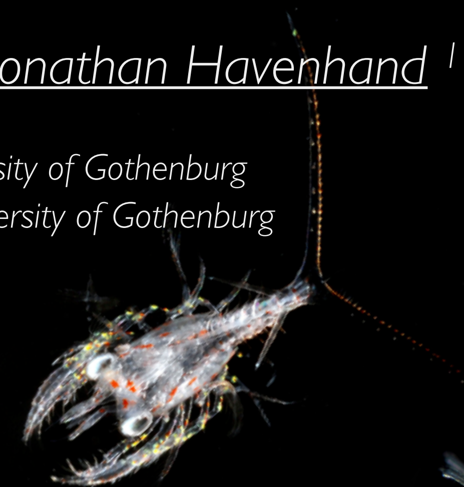
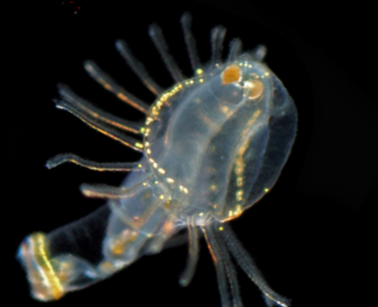


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Most marine animals have planktonic larvae


Lobster larva


Anglerfish larva


Seastar larva

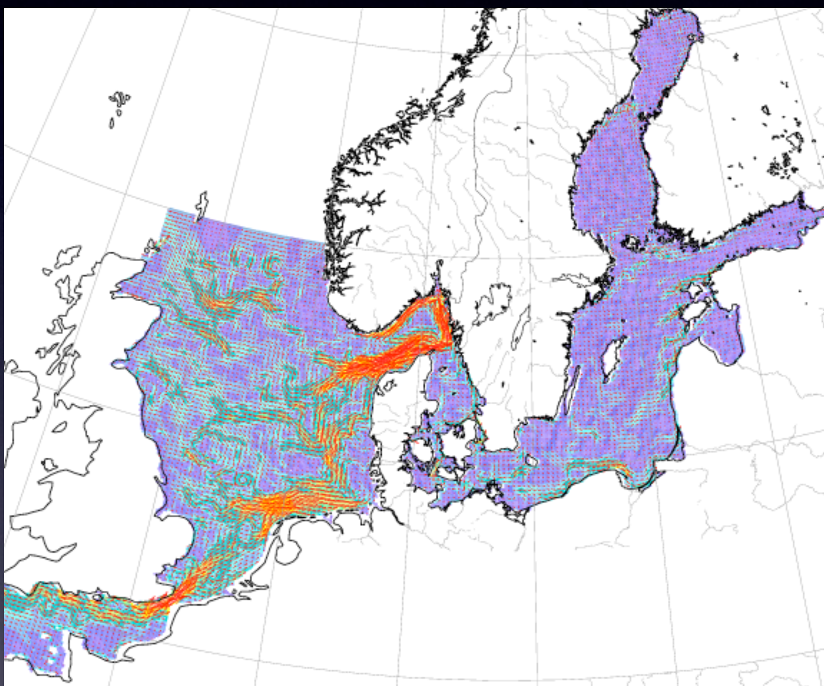

Barnacle larva


Polychaete larva

- potential for long-distance dispersal
- substantive effects on population dynamics and management

- create biophysical model
  - hydrodynamics (at relevant spatial and temporal scales)
  - larval dispersal trajectories
  - connectivity among sites (connectivity matrix)
- identify optimal MPA network (fancy mathematics)
  - *de novo*
  - as extension of existing network
- evaluate potential benefits of alternatives
- identify barriers to dispersal
  - biogeographic "units"

Biophysical modeling

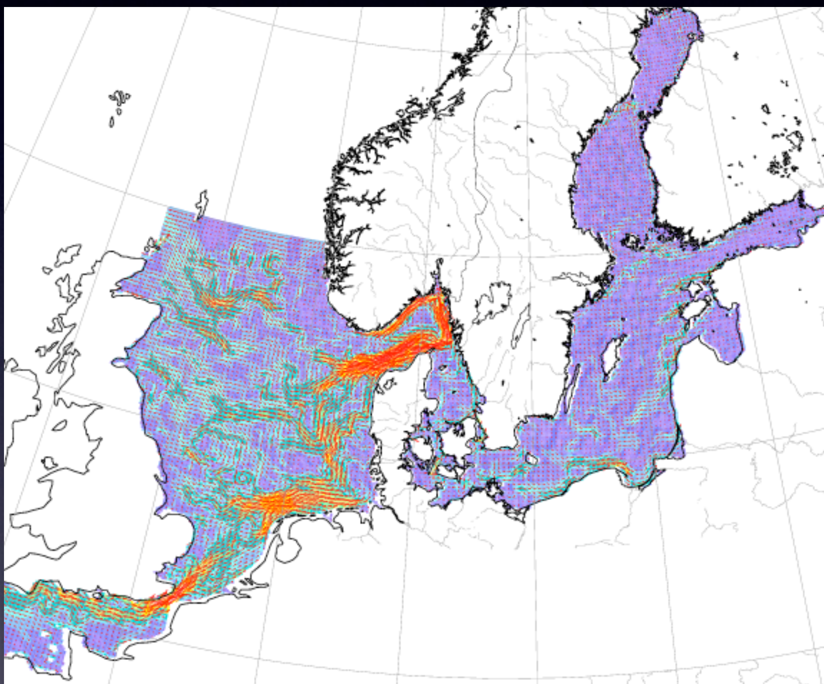


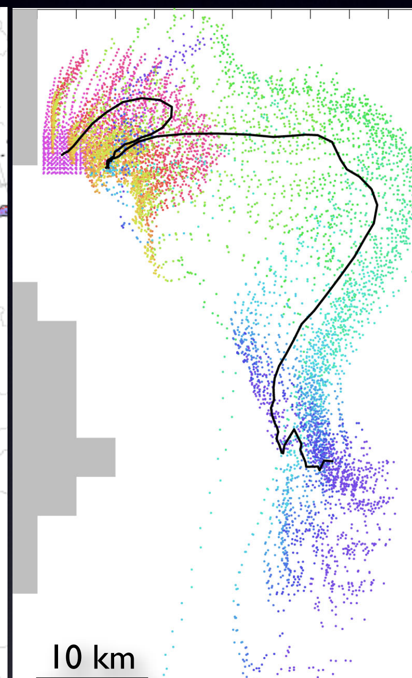
3D-circulation model

- BaltiX
  - circulation model
  - 120,000 km^2
  - grid of 2 nm x 2 nm
  - 119 depth layers

  - run for 8 years (1995-2002)
  - data every 3h
    - transport vectors, T°, salinity
  - describes circulation

Biophysical modeling



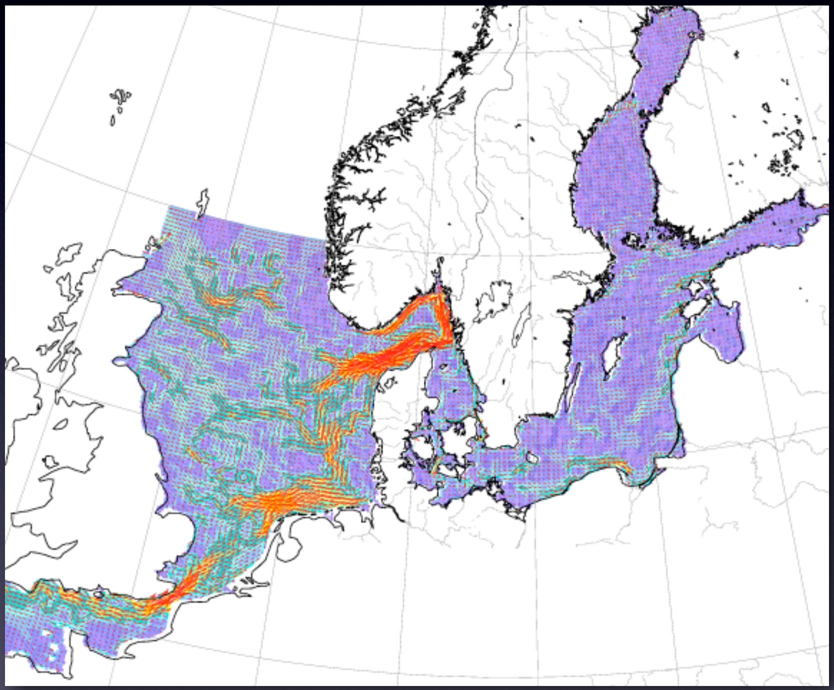


- TRACMASS model
  - uses BaltiX output "offline"
  - releases virtual larvae
    - reproductive season
    - planktonic duration
    - depth distribution
    - (no larval behaviour)
  - output:
    - start & end points

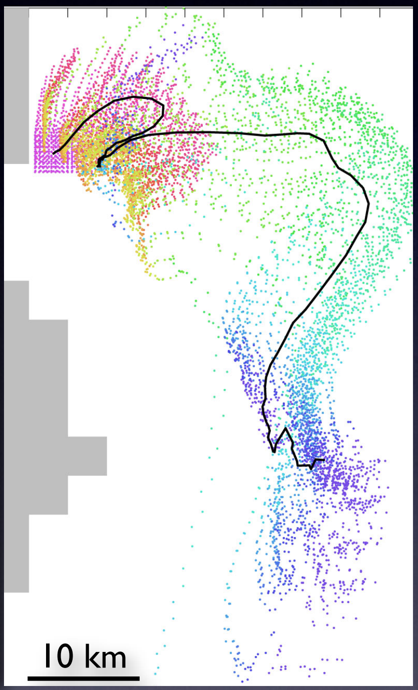
3D-circulation model

trajectory model

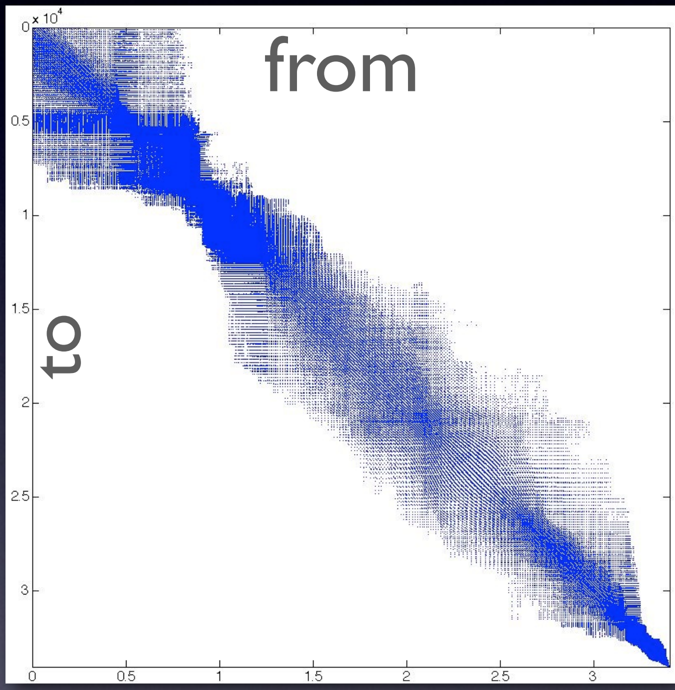
Biophysical modeling



3D-circulation model

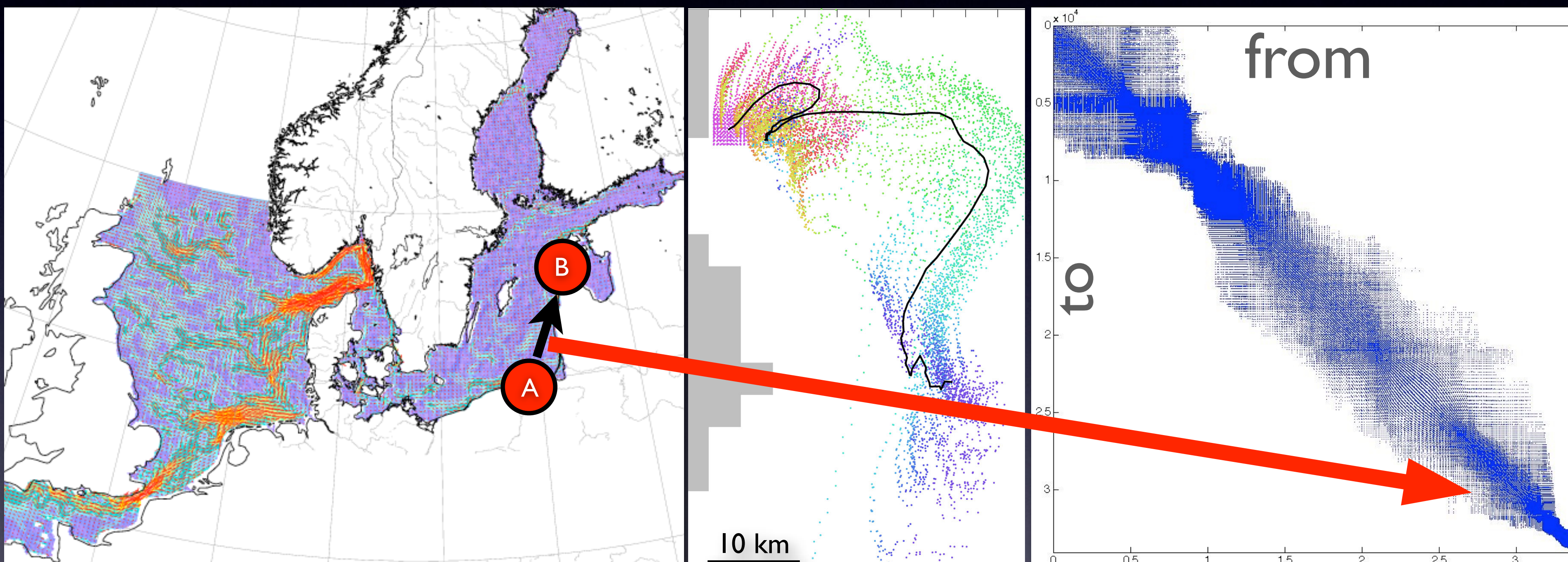


trajectory model



connectivity matrix

Biophysical modeling



3D-circulation model

trajectory model

connectivity matrix

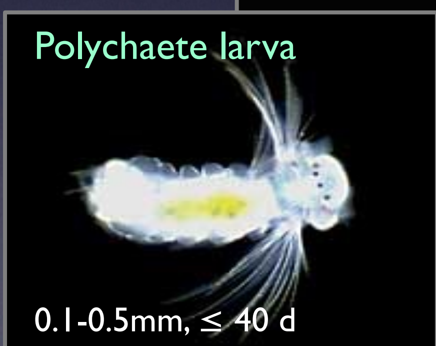
Larval dispersal is difficult to study

Larvae (and algal spores) are typically:

- small (<1 mm)
- numerous ($10^4 – 10^7$ per spawning)
- long-lived (weeks – months)
- display behaviour that can affect dispersal
- very little is known

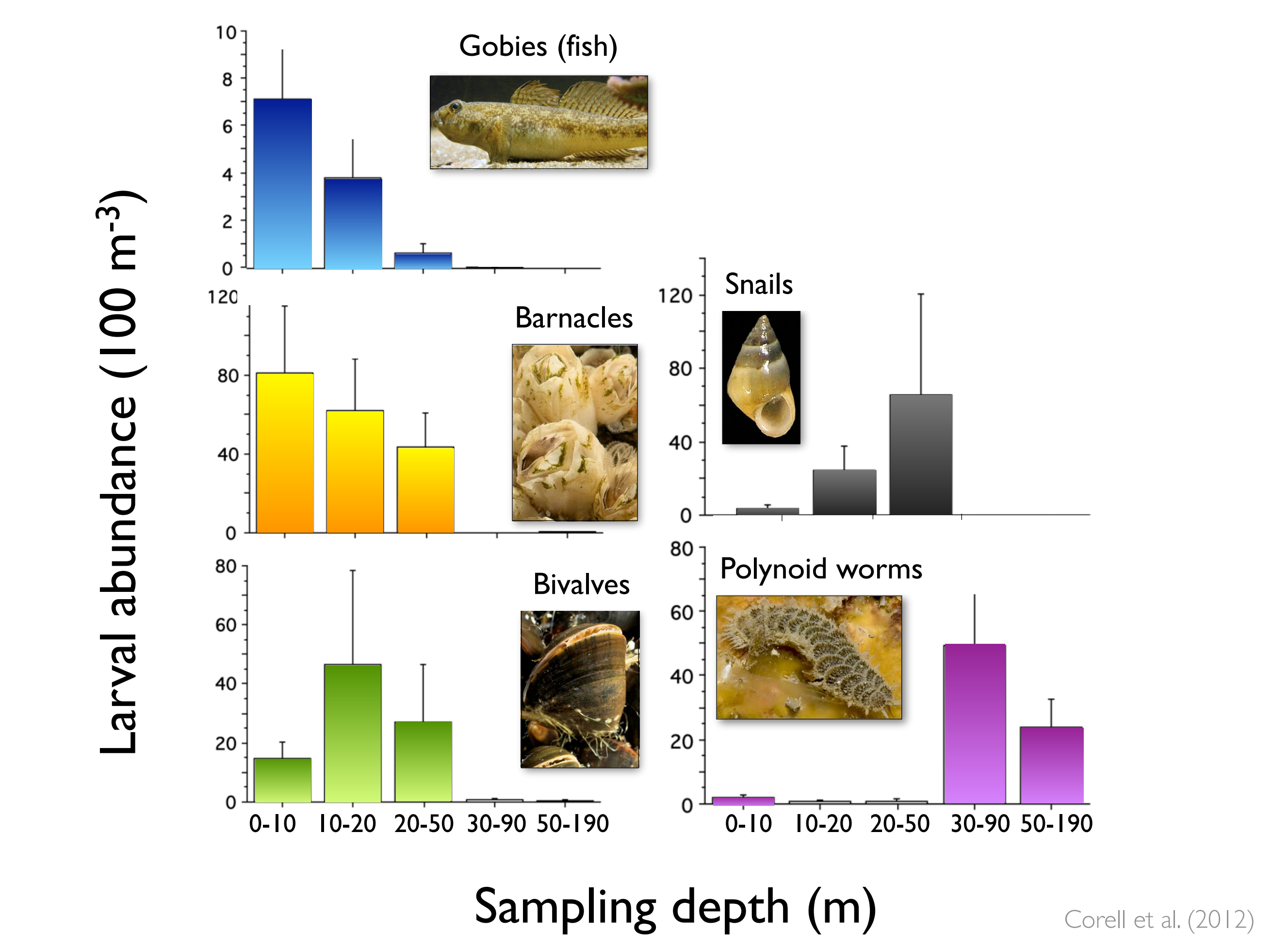
?

Most marine animals have planktonic larvae



- potential for long-distance dispersal
- substantive effects on population dynamics and management

Depth distribution of larvae



Database of larval distribution & season

Invertebrates

Phylum /Class	Order/Family	New Species/stage	n	N	Density (no. 100 m-3) Ave	SE	Depth distribution (m) 0-10 %	10-30 %	0-10 Dag (%)	0-10 Natt (%)	PLD (d)	Larval Occurrence	Larval Peak	Adult habitat Depth (m)	Substrate	Distribution
Bivalvia																
		Bivalve veliger larva	172	108	723.2	89.8	9%	86%	9%	8%	16-39 [1]	Jun-Aug	Jul	Sp.d	Sp.d	
Gastropoda																
		Gastropod veliger larva	172	128	686.0	51.5	22%	57%	14%	23%	25-42 [1]	All year	Aug	Sp.d	Sp.d	
		Nudibranchia (cf.)	172	14	17.6	0.4	46%	54%	37%	63%		Jul-Dec	Aug	> 350	H	Katt-Skag
Polychaeta		Trocophore larva	172	67	112.6	14.5	48%	37%	6%	67%	20-40 [1]	All year	Jul	Sp.d	Sp.d	
	Spionida	Spionid sp.	172	21	100.4	3.4	22%	72%	22%	0%	20-40 [1]	All year	Jan	Sp.d	Sp.d	
		Poecilochaetidae	172	12	284.3	5.7	0%	100%	0%	0%	20-40 [1]	Jul	Jul	Sp.d	Sp.d	
	Phyllodocia	Polynoidae	172	14	77.3	2.2	55%	43%	58%	0%	20-40 [1]	Mar-Jul	Mar	Sp.d	Sp.d	
Phoronida																
		Phoronid larva	172	14	14.8	0.3	32%	55%	43%	17%	11-30 [4]	Aug-Dec	Aug	0-10; 9-50	S,M,H	Katt-Skag
Bryozoa																
		Cyphonautes larva	172	27	467.5	21.0	54%	43%	51%	56%	< 1 [1]	Aug-Apr	Dec	0–42 [6]	H [6]	
Cnidaria																
		Cnidaria	172	3	18.2	0.2	0%	100%	0%	NaN	< 1 [1]	Mar-Apr	Mar	< 10 [6]	Sp.d	
Echinodermata		Echinodermata spp.	172	21	388.5	20.1	2%	98%	3%	1%		Aug	Aug			
Ophiuroidea/Echinodea		Pluteus larva	172	15	1927.0	40.6	22%	78%	3%	30%		Jul	Jul			
	Ophiurida (~11 spp.)	Ophiurid juvenile	172	30	618.6	51.2	1%	99%	0%	19%		Jul	Jul	< 350	S,M,G [4]	Katt-Skag
	Echinoida (3-4 spp.)	Echinoid juvenile	172	18	71.4	2.0	39%	61%	34%	57%	30-60 [4]	Jun-Aug	Jul	0-100; >1200	S,H	Katt-Skag
Asteroidea		Bipinnaria larva	172	16	64.6	3.2	78%	21%	81%	39%	30-60 [4]	Jun-Nov	Jun	< 900	S,M,H	Katt-Skag
		Brachiolaria larva	172	14	45.1	0.9	53%	47%	52%	55%	40-50 [4]	Jul	Jul	< 900	S,M,H	Katt-Skag
	Luididae (2 sp.)	Luidia sarsi	172	14	11.2	0.2	9%	90%	14%	0%	30-60 [4]	Oct-Apr	Mar	10-1300	S,M	Katt-Skag
Crustacea																
Cirripedia																
	Balanidae (5-7 spp.)	Naplius larva	172	77	211.8	12.8	28%	65%	32%	14%	14-28 [1]	All year	Jun	0-6; 60-300	H [6]	SW BS-Skag
		Cyprid larva	172	101	111.2	8.3	28%	63%	28%	26%	14-28 [1]	All year	Jul			
Caridea		Caridea spp. Z	330	122	18.1	2.3	24%	67%	20%	33%	30-60 [4]	All year	Jul	-	-	
	Paelmonidae (4 spp.)	Palaemon sp. Z1-2	330	24	19.2	0.5	8%	92%	2%	17%	30-60 [4]	Jul-Aug	Jul	0-10 (40)	M,H	SW BS-Skag
		Palaemon sp. Z3-5	330	74	3.9	0.2	80%	18%	66%	97%	30-60 [4]	Jul-Aug	Jul			
		Palaemon sp. PL	330	9	0.3	0.0	43%	20%	43%	46%	30-60 [4]	Jul-Aug	Jul			
	Crangonidae (2 spp.)	Crangon sp. Z1-3	330	42	2.7	0.3	8%	89%	5%	33%	30-180 [4]	Jul-Nov	Aug	0-22, 30-250	S,M [6]	SW BS-Skag
		Crangon sp. Z4-5	330	39	1.2	0.0	43%	28%	45%	59%	30-180 [4]	Jul-Nov	Aug			
		Crangon sp. PL	330	85	4.0	0.3	53%	33%	35%	62%	30-180 [4]	Jul-Nov	Aug			
		Philicheras bispinosus Z	330	8	3.1	0.0	0%	85%	0%	0%		Mar-Jul	Jun			
	Pandalidae (6 sp.)	Pand ZI-V	330	8	19.1	0.2	75%	25%	56%	93%	30-180 [4]	Jul	Jul	20-550	S,M,H	Katt-Skag
		Pandalina brevirostus Z	330	2	0.2	0.0	35%	65%	35%	NaN	30-60 [4]	Jul	Jul	10-50	S,H	Katt-Skag
	Alphaeidae (1 sp.)	Athanas nitescens (cf.) PL	330	4	0.6	0.0	94%	6%	74%	100%	~ 4 [3]	Jul	Jul	1-13	S,H	Katt-Skag
		Alphaeid Z	330	2	0.5	0.0	72%	28%	0%	100%	~ 4 [3]	Jul	Jul	1-13	S,H	Katt-Skag
	Hippolythidae(~6 sp.)	Hippolythid Z	330	11	76.7	1.0	13%	87%	0%	20%	30-60 [4]	Jul	Jul	3-30; 30-300	S,M,H	Katt-Skag
	Callianassidae (1 sp.)	Callianassa sp. Z	330	12	18.9	0.3	6%	84%	10%	0%	30-60 [4]	Jul-Sep	Sep	30-60	M,S	Skag
Thalassinidea																
	Upogeviidae (2 sp.)	Upogebia sp. Z	330	8	2.7	0.0	18%	66%	0%	47%	11-30 [4]	Jun-Aug	Jul	8-20	S,H	Katt-Skag
		Upogebia sp. PL	330	30	0.7	0.0	7%	70%	8%	8%		Jun-Aug	Jul			
	Axiidae (2 sp.)	Calocaris sp. Z	330	54	112.6	5.7	44%	40%	2%	12%		Jul-Aug	Aug	12-1070	M	Katt-Skag
Astacidae																
	Nephrodidae (2 sp.)	Nephrops norvegicus Z1-2	330	38	1.4	0.1	19%	77%	20%	8%	30-60 [4]	Mar-Oct	Jul	27-300	S,M	Katt-Skag
		Nephrops norvegicus Z3-5	330	22	1.4	0.0	12%	85%	12%	0%		Mar-Oct	Jul			
		Homarus gammarus Z1	330	1	0.2	-	100%	0%	100%	NaN	15-35 [4]	Jul	Jul	3- >30	S,H	Katt-Skag
Anomura																
	Paguridae (5-7 sp.)	Pagurid Z1-5	330	46	12.3	0.4	5%	93%	6%	0%	11-30 [4]	All year	Jun	0-470	S,M,H	Katt-Skag
		Pagurid PL	330	30	0.9	0.0	4%	90%	1%	29%		All year	Jun			
	Galatheidae (9 spp.)	Galathea sp. Z	330	42	24.3	0.8	13%	73%	4%	0%	180 [4]	Mar-Sep	Aug	10-110	S,H	Katt-Skag
		Galathea sp. PL	330	4	0.6	0.0	70%	8%	84%	0%		Mar-Sep	Aug			
		Munidopsis sp. PL	330	24	0.5	0.0	49%	51%	0%	53%		Jul	Jul			
	Porcellanidae (1 sp.)	Pisidia longicornis (cf.) Z	330	45	28.9	0.9	9%	81%	0%	0%	30 [4]	Apr-Nov	Jul	0-70	H	Katt-Skag
		Pisidia longicornis (cf.) PL	132	65	1.4	0.1	10%	63%	1%	27%		Apr-Nov	Jul			
Brachiura																
	Portunidae (7- 11 spp.)	Carcinus maenas Z1-2	330	100	21.4	1.3	30%	19%	8%	27%	40 [4]	Jun-Aug	Aug	0-40	S,M,H	Katt-Skag
		Carcinus maenas Z3-4	330	115	27.8	1.9	30%	30%	19%	29%		Jun-Aug	Aug			
		Carcinus maenas M	330	172	17.1	1.7	24%	69%	14%	36%		Jun-Aug	Aug			
		Liocarcinus navigator (cf.) Z1-2	330	29	14.9	0.3	28%	71%	27%	30%		All year	Aug	1-100; 1-450	S,M,H	Katt-Skag
		Liocarcinus navigator (cf.) Z3-5	132	18	19.2	0.6	85%	15%	29%	100%		All year	Aug			
		Liocarcinus navigator (cf.) M	330	143	1.5	0.1	67%	29%	63%	67%		All year	Aug			
		Liocarcinus depurator (cf.) Z1-2	330	17	20.2	0.5	10%	90%	6%	22%		Jul-Oct	Jul	1-100; 1-450	S,M,H	Katt-Skag
		Liocarcinus depurator (cf.) Z3-5	132	14	13.3	0.3	21%	79%	1%	34%		Jul-Oct	Jul			
		Liocarcinus depurator (cf.) M	132	61	1.0	0.1	22%	68%	5%	37%		Jul-Oct	Jul			
		Liocarcinus sp. M	330	89	2.3	0.1	36%	57%	31%	40%		Jul-Oct	Jul	0-450 [6]	S,M [6]	
		Necora puber (cf.) Z1-4	330	5	31.7	0.4	26%	74%	19%	84%	30-60 [4]	Jun-Sep	Jun	> 60	H	Katt-Skag
		Necora puber (cf.) M	132	8	10.5	0.3	11%	83%	10%	100%		Jun-Sep	Jun			
		Portunid sp. M	330	45	2.2	0.1	25%	58%	22%	40%		Jul-Aug	Jul	1-450	S,M,H	Katt-Skag
		Portunid sp. Juvenile	132	26	1.4	0.1	11%	84%	19%	10%		Jul-Aug	Jul			
	Pirimelidae	Pirimela denticulata (cf.) Z	132	16	16.3	0.5	58%	42%	11%	76%		Jul-Aug	Aug	> 180 [4]	S,M,G [4]	Katt-Skag
	Cancridae (1 sp.)	Cancer pagurus Z1-5	330	22	31.7	0.9	36%	61%	38%	1%	30-144 [4]	Jun-Sep	Jul	1-50	S,M,H	Katt-Skag
		Cancer pagurus M	330	59	2.0	0.1	19%	57%	8%	33%		Jun-Sep	Jul			
	Thiidae (1 sp.)	Thia scutella (cf.) Z1-3	330	2	4.2	0.0	0%	100%	0%	NaN		Mar-Aug	Jan	> 30 [6]	S	Katt-Skag
	Corystidae (1 sp.)	Corystes cassivelaunus Z1-3	132	7	5.9	0.1	27%	73%	10%	100%	11-30 [4]	Mar-Aug	Jun	7-90	S,M	Katt-Skag
		Corystes cassivelaunus Z4-5	330	7	10.0	0.1	34%	56%	34%	NaN		Mar-Aug	Jun			
		Corystes cassivelaunus M	330	3	0.7	0.0	0%	12%	0%	0%		Mar-Aug	Jun			
	Atelecyclidae (1 sp.)	Atelecyclus rotundatus Z1-3	330	10	11.4	0.1	57%	43%	2%	73%		Jul-Aug	Jul	< 12	S	Katt-Skag
		Atelecyclus rotundatus Z4-5	132	12	8.2	0.2	34%	66%	21%	36%		Jul-Aug	Jul			
		Atelecyclus rotundatus M	132	1	0.1	-	0%	100%	NaN	0%		Jul-Aug	Jul			
	Majidae (8 sp.)	Hyas spp. Z1-2	132	3	16.2	0.2	0%	100%	0%	0%	30-180 [4]	Mar-Jul	Jul	3-50; 12-120	S,H	Sw BS-Skag
		Hyas spp. M	330	4	6.2	0.0	0%	100%	0%	NaN		Mar-Jul	Jul			
		Macropodia rostrata M	330	3	0.5	0.0	0%	90%	0%	0%	11-30 [4]	Jul	Jul	2-86	S,M,H	Katt-Skag
		Euronyme spp. (cf.) Z1-2	330	1	37.9	0.1	0%	100%	NaN	0%		Aug	Aug	12-40;12-120	S,H	Katt-Skag
		Euronyme spp. (cf.) M	330	12	0.5	0.0	4%	27%	0%	0%		Aug	Aug			
	Pinnotheridae (1 sp.)	Pinnotheres pisum (cf.) Z	330	1	5.5	-	0%	100%	NaN	0%		Aug	Aug	5-50	S,H	Katt-Skag
	Geryonidae (1 sp.)	Geryon trispinosus (cf.) Z1-3	132	6	12.4	0.2	25%	75%	0%	100%		Jul-Aug	Jul	-	-	
	Pilumnidae (~3 spp.)	Pilumnus hurtellus (cf.) Z1	132	1	4.8	-	100%	0%	100%	NaN	30-60 [4]	Sep	Sep	> 70 [6]	H [6]	Skag
		Pilumnus hurtellus (cf.) M	330	1	1.4	-	0%	100%	NaN	0%		Sep	Sep			
	Leucosidae (2-3 sp.)	Ebalia spp. Z1-4	330	16	2.9	0.1	2%	83%	0%	0%	30-60 [4]	Jul-Sep	Jul	12-60	S,H	Katt-Skag

Fish

Order	Family	Species/stage	n	N	Density (no. 100 m-3) Ave	SE	Depth Distruibutions (m) 0-10 %	10-30 %	0-10 Day (%)	0-10 Night (%)	PLD (d)	Seasonality Larval Occur.	Larval Peak	Spawn Per. Literature	Adult Depth (m)	Habitat
Clupeiformes																
	Clupeidae	*Sprattus sprattus*	201	9	19.56	0.57	44%	56%	45%	0%		Mar-Aug	Mar	Jan-Jul	10-150	P
	Clupeidae < 10		201	68	7.46	0.87	38%	60%	39%	32%		Mar-Aug	Mar	Mar-May, Sep-Jan	> 300	P
	Clupeidae > 10		201	40	0.74	0.04	28%	70%	40%	20%		Mar-Aug	Mar	Mar-May, Sep-Jan	> 300	P
Gadiformes																
	Gadidae	*Gadus morhua*	201	5	6.78	0.09	39%	61%	39%	NaN	60-120	Mar-Apr	Apr	Jan-Jun, Oct-Dec	5-500	-
	Gadidae	*Merlangius merlangus*	201	2	3.61	0.03	79%	21%	79%	NaN		Jun	Jun	Mar-Jul	> 200	-
	Gadidae	*Raniceps raninus*	201	1	0.19	-	0%	100%	NaN	NaN		Aug	Aug	Jan-Jun, Oct-Dec	> 100	H
	Phycidae		201	3	1.50	0.01	67%	0%	100%	0%		Mar-Sep	Jun	Mar-Jul	150-300	-
	Lotidae	*Enchelyopus cimbrius*	201	14	5.28	0.11	51%	49%	52%	48%		Jun-Nov	Jun	Jan-Sep	20-250	S, M
	Merlucciidae	*Merluccius merluccius*	201	1	2.77	0.01	0%	100%	NaN	0%		Jul	Jul	Jun-Sep	100-300	-
Perciformes																
	Labridae	*Ctenolabrus rupestris*	201	31	4.34	0.20	47%	13%	68%	89%		Jun-Aug	Jul	Jun-Aug	> 20	Ve
	Labridae	*Labrus* sp.	201	6	8.70	0.13	8%	4%	68%	NaN		Jun-Jul	Jul	Jun-Aug	5-30	H
	Labridae	*Symphodus* sp.	201	7	7.57	0.14	30%	70%	49%	0%		Jun-Aug	Jul	May-Aug	5-30	H
	Ammodytidae	*Ammodytes lancea*	201	56	1.25	0.10	42%	35%	59%	35%		All year	Jul	Mar-May, Oct-Dec	0-30	S
	Callionymidae	*Callionymus* sp.	201	23	5.15	0.15	10%	70%	13%	4%		Jun-Sep	jul	Apr-Sep	> 400	-
	Callionymidae/ Carangidae		201	12	11.15	0.26	6%	70%	15%	0%		Jun-Jul	Jul	Apr-Sep	> 400	-
	Carangidae	*Trachurus trachurus*	201	31	3.65	0.30	24%	60%	13%	82%		Jul-Aug	Jul	May-Oct	> 90	P
	Carangidae		201	26	4.21	0.30	19%	64%	13%	59%		Jul-Aug	Jul	May-Sep	> 90	P
	Gobiidae	*Aphia minuta*	201	6	0.46	0.01	25%	75%	NaN	25%		Jul-Aug	Jul	May-Sep	0–10	S, M
	Gobiidae	*Crystallogobius nilssonii*	201	6	6.29	0.11	0%	85%	1%	0%		Jul-Aug	Jul	May-Sep	0–10	S, M
	Gobiidae	*Pomatoschistus* sp.	201	8	5.74	0.11	4%	96%	5%	0%		Apr-Sep	Jul	May-Sep	0–10	S, M
	Gobiidae		201	91	11.63	0.76	33%	41%	41%	38%	20–30	All year	Jul	May-Sep	0–10	S, M
	Pholidae	*Pholis gunellus*	201	1	1.79	0.01	100%	0%	100%	NaN	30	Mar	Mar	Nov-Apr	0-30	Ve
	Scombridae	*Scomber* sp.	201	4	6.06	0.07	12%	88%	16%	0%		Jun-Jul	Jun	May-Sep	> 90	P
	trachinidae	*Trachinus* sp.	201	17	8.71	0.30	62%	38%	61%	58%		Jul-Aug	Jul	Jun-Sep	5-40	S
Pleuronectiformes																
	Bothidae	*Arnoglossus laterna*	201	72	2.55	0.20	37%	61%	40%	34%		Jul-Sep	Jul	Jun-Oct	10-100	-
	Pleuronectidae		201	2	2.58	0.02	0%	31%	0%	NaN		May-Jun	May	Jan-May	10-50	S, M
	Pleuronectidae	*Buglossidium luteum*	201	66	1.28	0.08	18%	74%	10%	28%		Jun-Aug	Jul	Apr-Sep	5-20	S
	Pleuronectidae	*Hippoglossoides platessoides*	201	2	2.12	0.02	68%	32%	68%	NaN		Mar	Mar	Dec-Apr	10-400	M
	Pleuronectidae	*Limanda limanda* > 5	201	17	8.18	0.41	0%	95%	0%	0%		Mar-Jul	Apr	Mar-Jul	> 70	S
	Pleuronectidae	*Limanda limanda* ≤ 5	201	26	33.03	1.54	30%	69%	30%	5%		Mar-Jul	Apr	Mar-Jul	> 70	S
	Pleuronectidae	*Microstomus kitt*	201	2	1.49	0.01	0%	42%	0%	NaN		Jun	Jun	May-Nov	20-150	H
	Pleuronectidae	*Platichtys flesus*	201	12	10.07	0.40	86%	14%	86%	NaN		Jan-Jul	Apr	Jan-Aug	> 25	-
	Pleuronectidae	*Pleuronectes platessa*	201	1	11.23	0.06	0%	100%	NaN	0%		Jul	Jul	Jan-May	10-50	S, M
	Scophthalmidae	*Phrynorhombus norvegicus*	201	1	0.13	-	0%	0%	0%	NaN		Jul	Jul	Apr-Sep		H
	Scophthalmidae	*Psetta/Scophtalmus* sp.	201	4	3.48	0.06	1%	99%	0%	15%		Jun-Aug	Jun	Apr-Sep	20-70	S, M
	Scophthalmidae	*Zeugopterus punctatus*	201	4	1.00	0.01	0%	95%	0%	0%		Jun-Jul	Jun	Mar-Jul		H
	Soleidae	*Solea* sp.	201	5	1.30	0.02	31%	69%	31%	NaN		May-Aug	Jun	Apr-Sep	10-60	S, M
Scorpaeniformes																
	Cottidae	*Myoxocephalus* sp.	201	2	0.80	0.01	37%	63%	0%	100%		Feb-Apr	Apr	Dec-Apr	5-200	Ve
	Cottidae	*Taurulus* sp.	201	2	1.06	0.01	94%	6%	94%	NaN		Apr-Jul	Apr	Feb-Jun	5-200	Ve
	Triglidae		201	1	1.00	-	100%	0%	NaN	100%		Aug	Aug	Apr-Nov	10-150	S, M
	Cyclopteridae	*Cyclopterus lumpus*	201	1	1.83	0.01	0%	100%	NaN	0%		Sep	Sep	Feb-Jun	20-200	H
	Liparidae	*Liparis* sp.	201	2	1.21	0.01	0%	100%	0%	NaN	10-20	Jun	Jun	Jan-May, Sep-Jan	20-50	Ve
	Triglidae	*Eutriglia gurnardus*	201	6	0.87	0.02	0%	86%	0%	0%		Jul-Aug	Jul	Apr-Sep	10-150	S, M
Syngnathiformes																
	Syngnathidae	*Entelurus aequoreus*	201	4	1.38	0.02	87%	3%	0%	100%		Jul-Aug	Aug	Jun-Aug	5-100	Ve
	Syngnathidae	*Nerophis* sp.	201	1	0.19	-	100%	0%	NaN	100%		Aug	Aug	May-Oct	0–15	Ve
	Syngnathidae	*Syngnathus* sp.	201	3	0.20	0.00	63%	0%	100%	100%		Jul	Jul	Jun-Sep	0–15	Ve

Habitat legends denote type of habitat where species are found or an established preference. S=Sand, M=Mud, H=Hard Bottom/substrate, Ve= Vegetation rich bottoms, P=Pelagic, "-" indicates that preference is not known or that information was not found.

Moksnes et al. 2014. *Larval connectivity and ecological coherence of MPAs in the Kattegat-Skagerrak region.*
Swedish Institute for the Marine Environment report 2014:2

Scenarios of larval distribution & season

Larval release	PLD (d)	Depth (m)	Rocky-reef taxa	ID
April–August	10	0% 0–2	Anthozoa	B1
		20% 10–12	Crinoidea	
		40% 24–26		
		40% 48–50		
April–August	30	0% 0–2 m	Ophiurida	B2
		20% 10–12	*Galathea* sp	
		40% 24–26	*Pisidia longicornis*	
		40% 48–50	*Zeugopterus punctatus*	
April–August	30	10% 0–2 m	Echinoida	B3
		40% 10–12	Mytilidae	
		40% 24–26	*Homarus gammarus*	
		10% 48–50	*Sabella* spp.	
April–August	60	10% 0–2	Gadidae	B4
		40% 10–12	Labridae	
		40% 24–26	*Cancer pagurus*	
		10% 48–50		
April–August	30	40% 0–2	Asteroidea	B5
		30% 10–12	*Liocarcinus* sp.	
		20% 24–26		
		10% 48–50		

Jonsson et al. 2016 *Diversity & Distributions*

Scenarios of larval distribution & season

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		30% 10–12	*Liocarcinus* sp.	
		20% 24–26		
		10% 48–50		

Jonsson et al. 2016 *Diversity & Distributions*

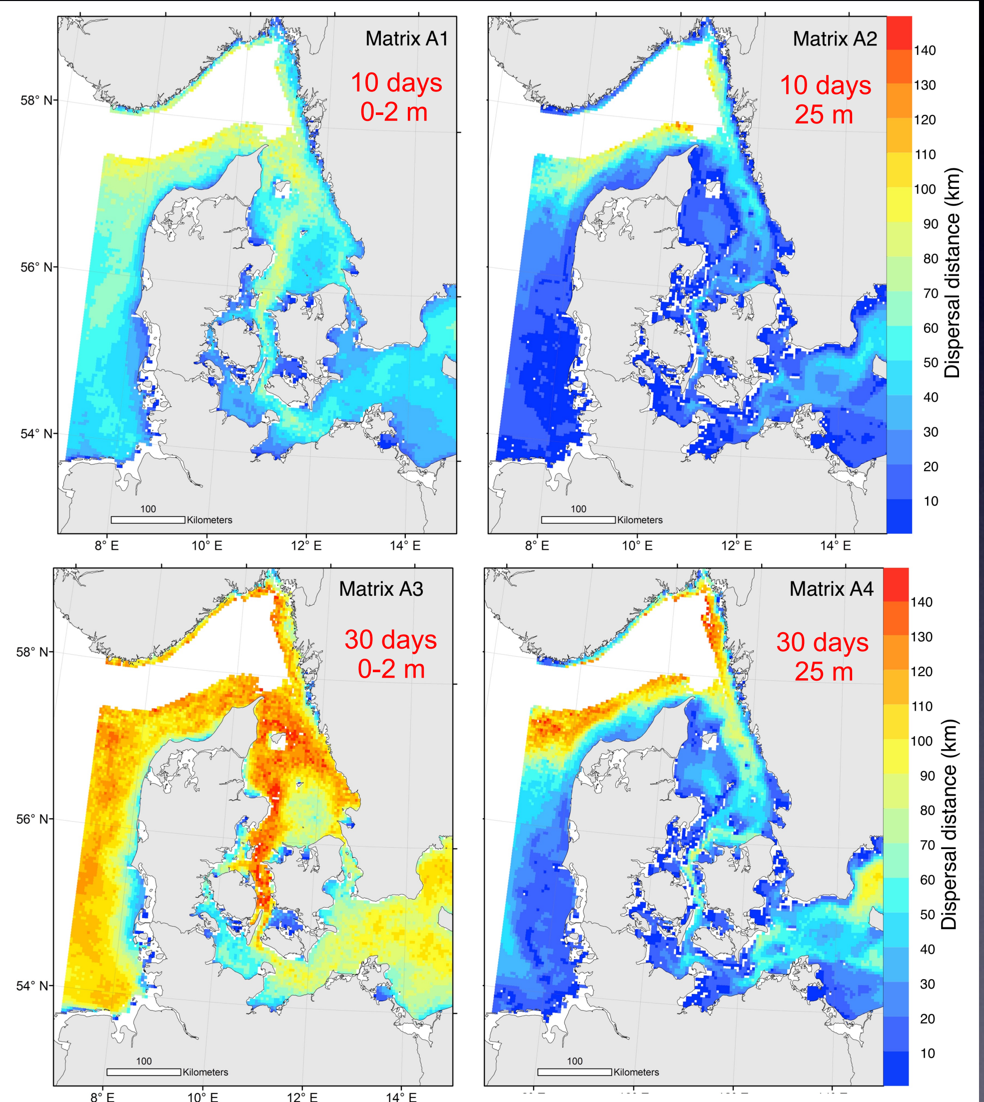
Larval release	PLD (days)	Drift depth (m)	ID
January–December	10	0–2	A1
January–December	10	24–26	A2
January–December	30	0–2	A3
January–December	30	24–26	A4

Jonsson et al. 2016 *Diversity & Distributions*

Scenarios of larval distribution & season

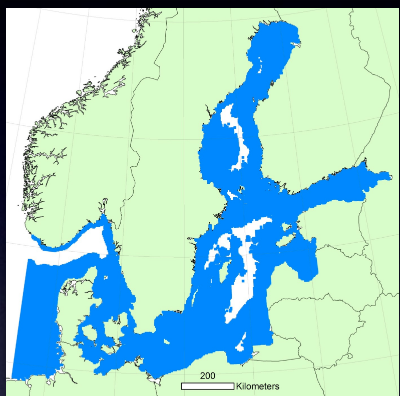
Larval dispersal under "simple scenarios":

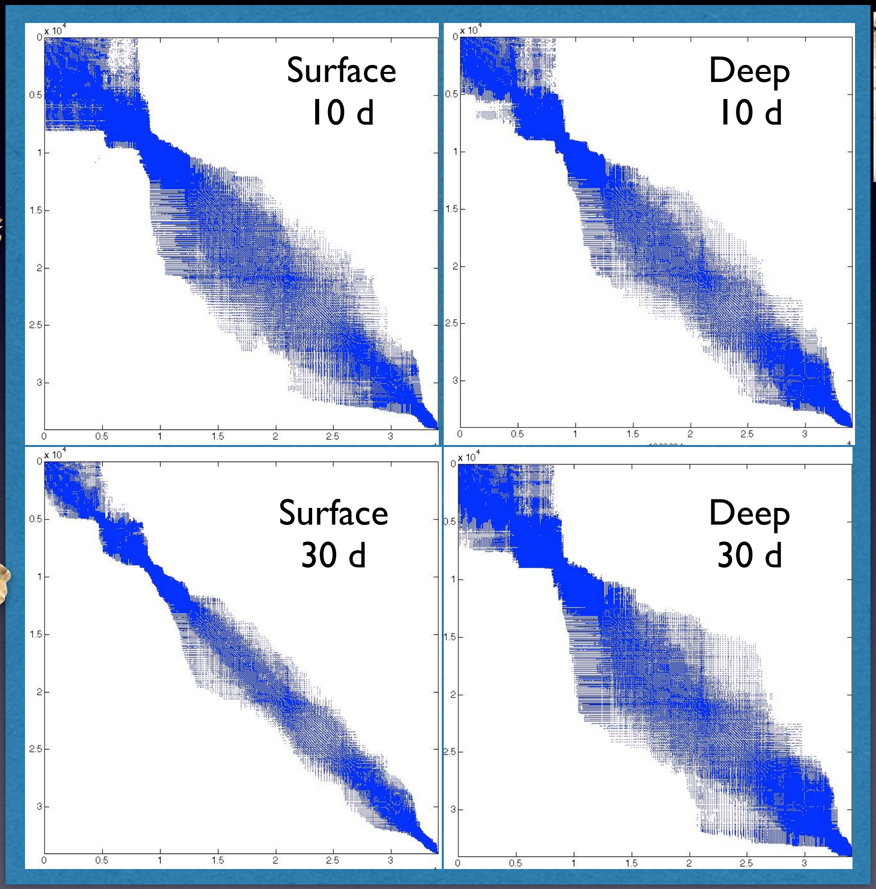
- large effects of larval duration, drift depth and release location
- typical dispersal distance is much larger than most MPA's



Jonsson et al. 2016 *Diversity & Distributions*

Connectivity matrix for each scenario

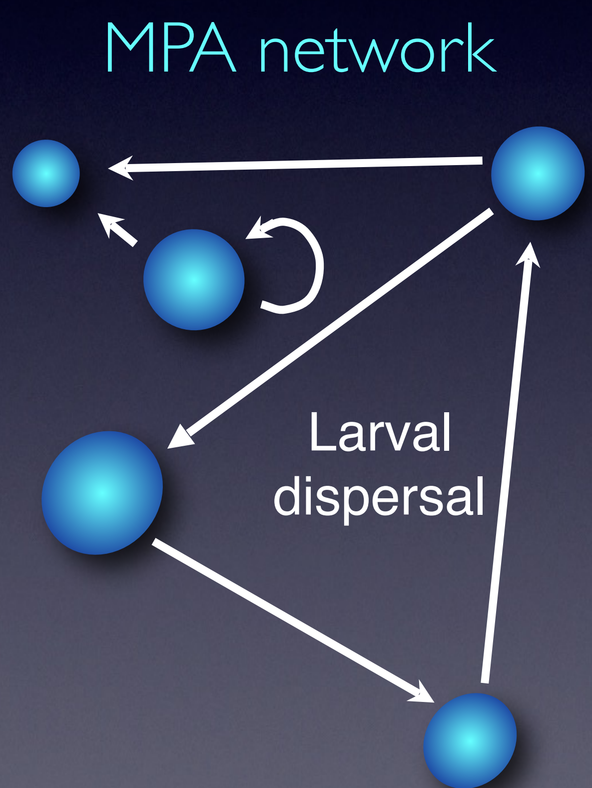




Each dispersal strategy produces a unique connectivity matrix

- create biophysical model
  - hydrodynamics (at relevant spatial and temporal scales)
  - larval dispersal trajectories
  - connectivity among sites (connectivity matrix)
- identify optimal MPA network (fancy mathematics)
  - *de novo*
  - as extension of existing network
- evaluate potential benefits of alternatives
- identify barriers to dispersal
  - biogeographic "units"

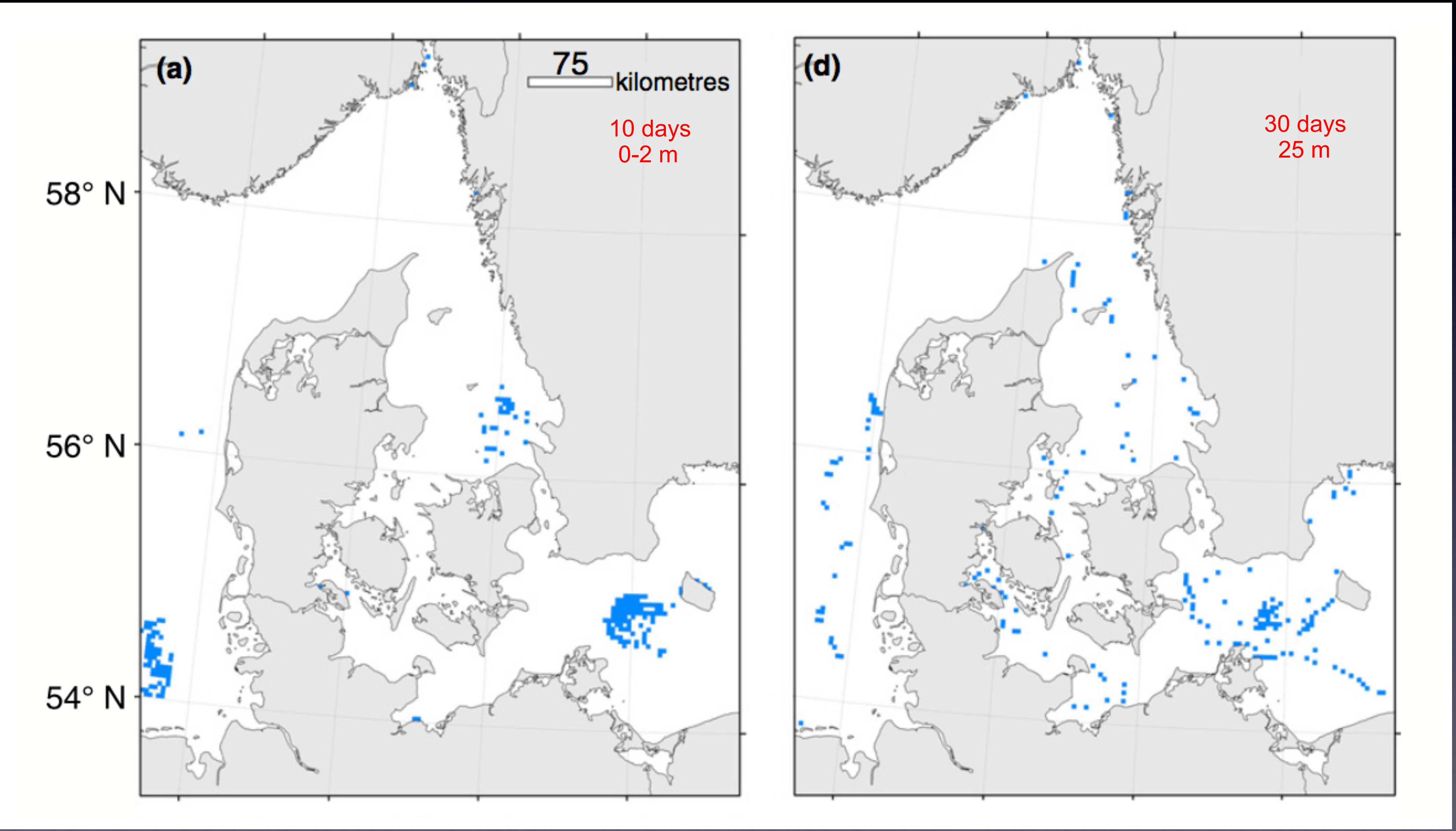
Identifying the optimal MPA-network



- "Eigenvalue Perturbation Theory"
  - selects areas that both deliver (sources) and receive (sinks) high numbers of larvae
  - identifies the optimal areas for the maximal overall connectivity
  - ranks all areas based on their contribution

Nilsson Jacobi & Jonsson. 2011. *Ecological Applications*
Jonsson et al. (2016) *Diversity and distributions*

Identifying the optimal MPA-network



Nilsson Jacobi & Jonsson. 2011. *Ecological Applications*
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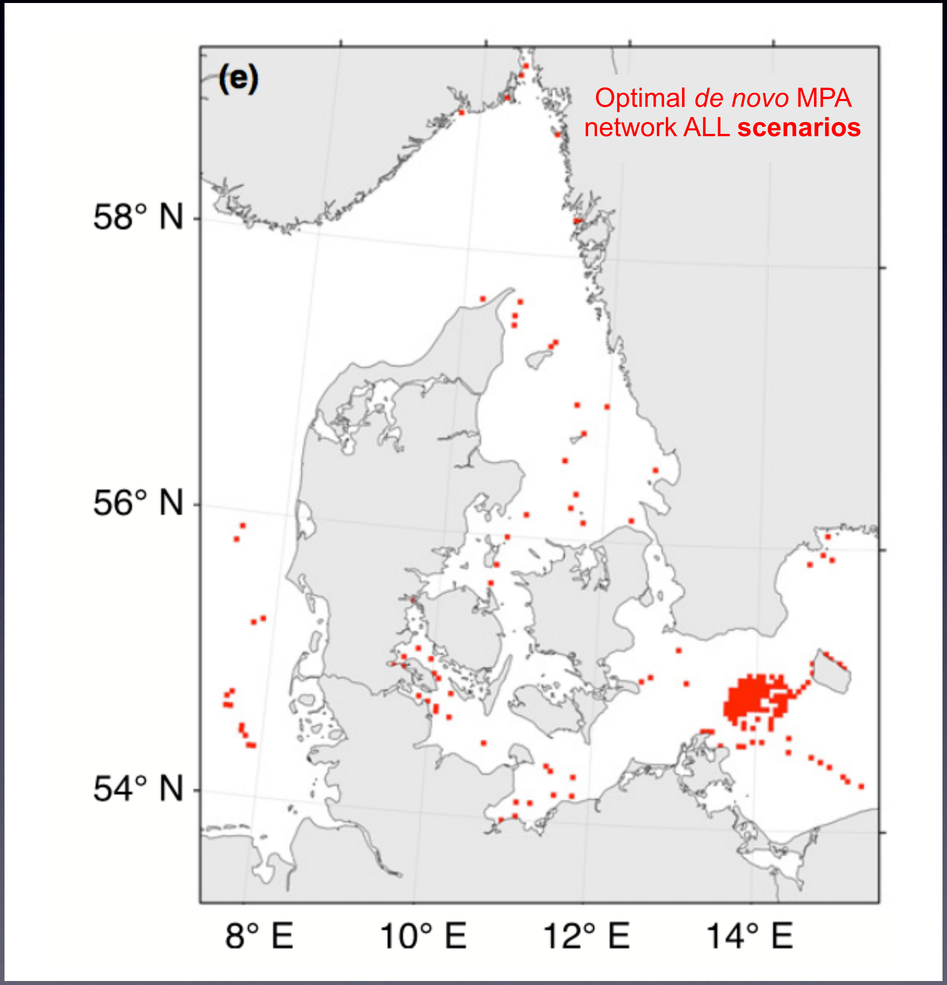
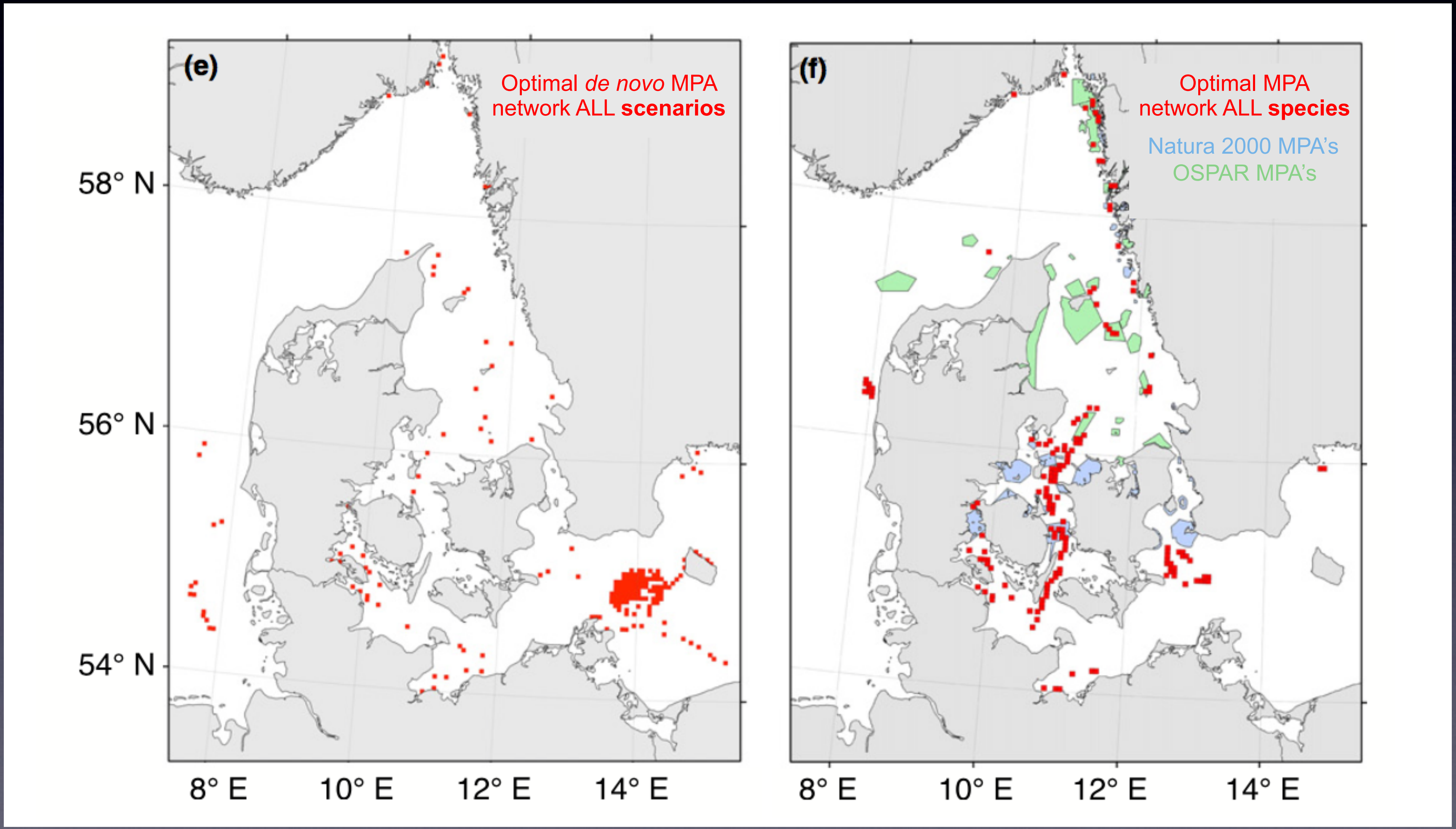
Identifying the optimal *multi-species* MPA-network



Identifying the optimal *multi-species* MPA-network



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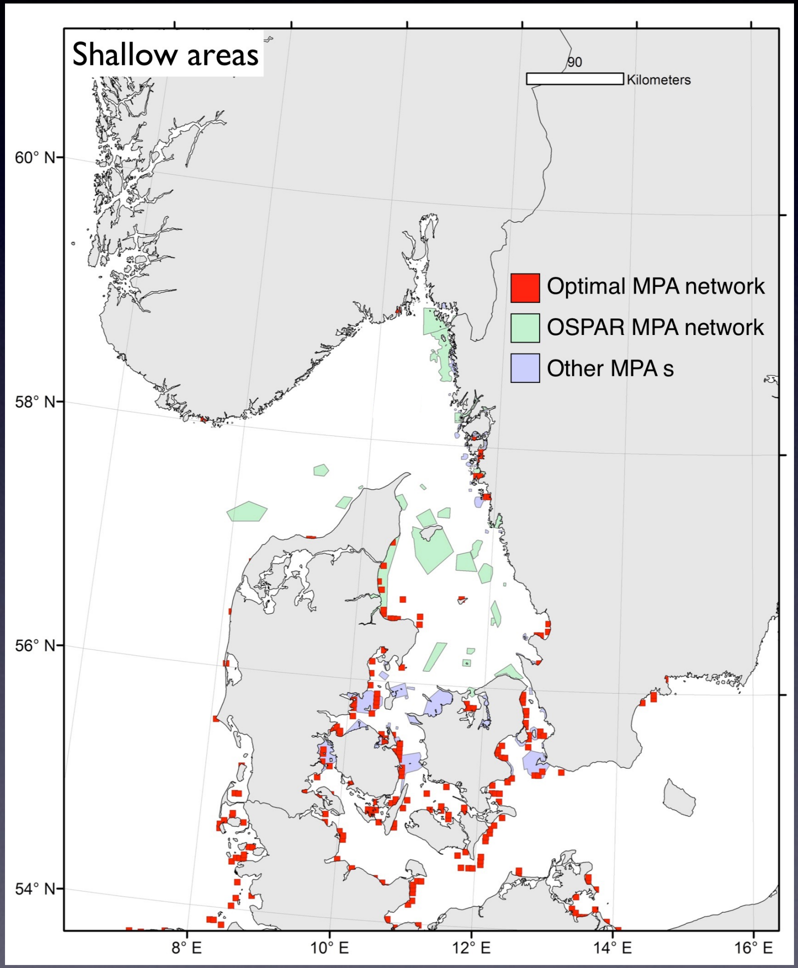
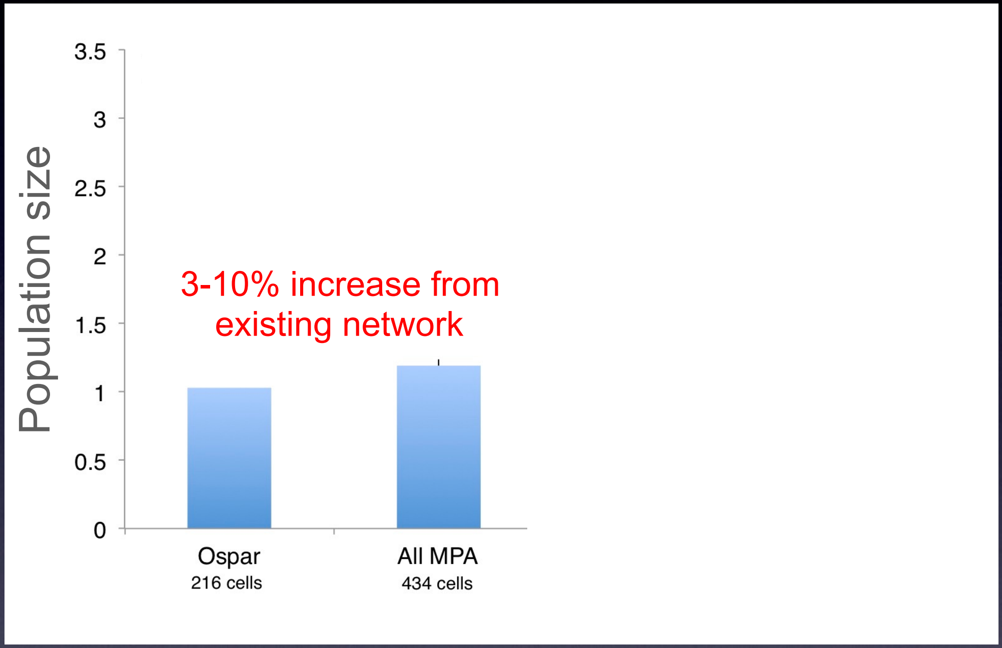
Evaluating alternate model MPA-networks

- model dispersal & growth in each meta-population
  - do this for 100 years
- simulate positive effects of MPA's
  - 20% higher growth rate
- simulate random disturbances
  - 95% reduction in population size every 8th year
- evaluate networks
  - compare size of populations after disturbance

Nilsson Jacobi & Jonsson. 2011. *Ecol. Appl.*
Jonsson et al. 2016 *Diversity and distributions*

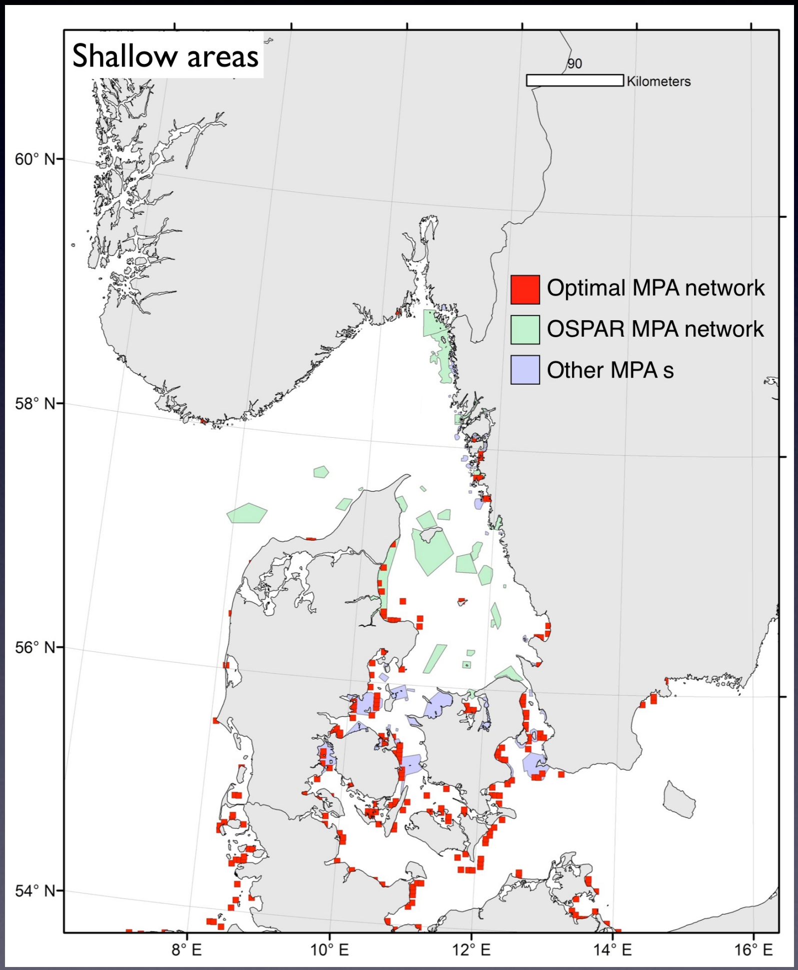
Evaluating an optimal *multi-species* MPA-network

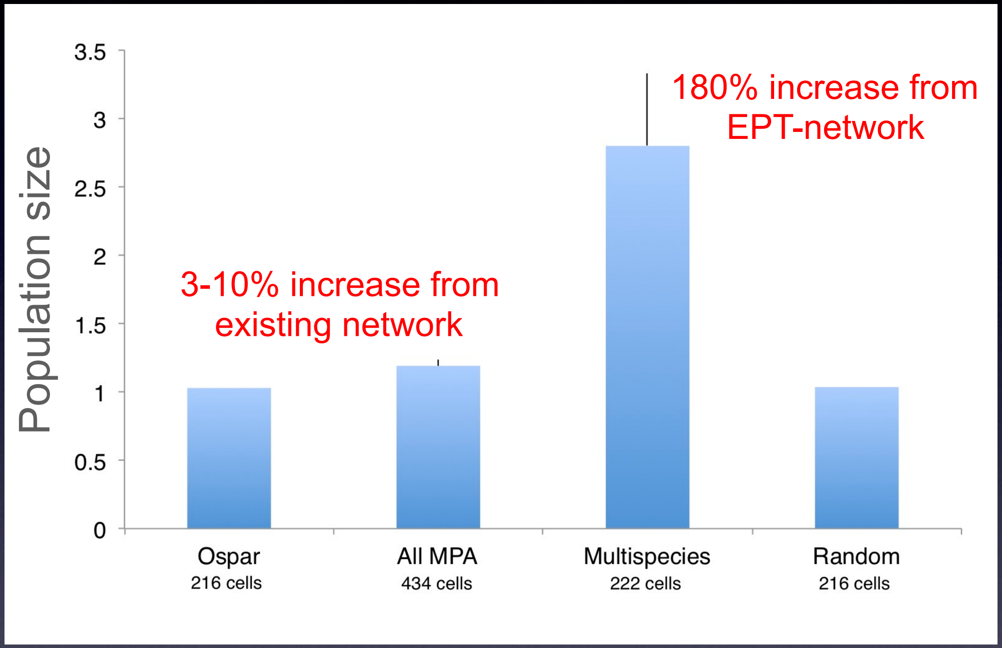




Moksnes et al. 2014. *Larval connectivity and ecological coherence of MPAs in the Kattegat-Skagerrak region.* Swedish Institute for the Marine Environment report 2014:2

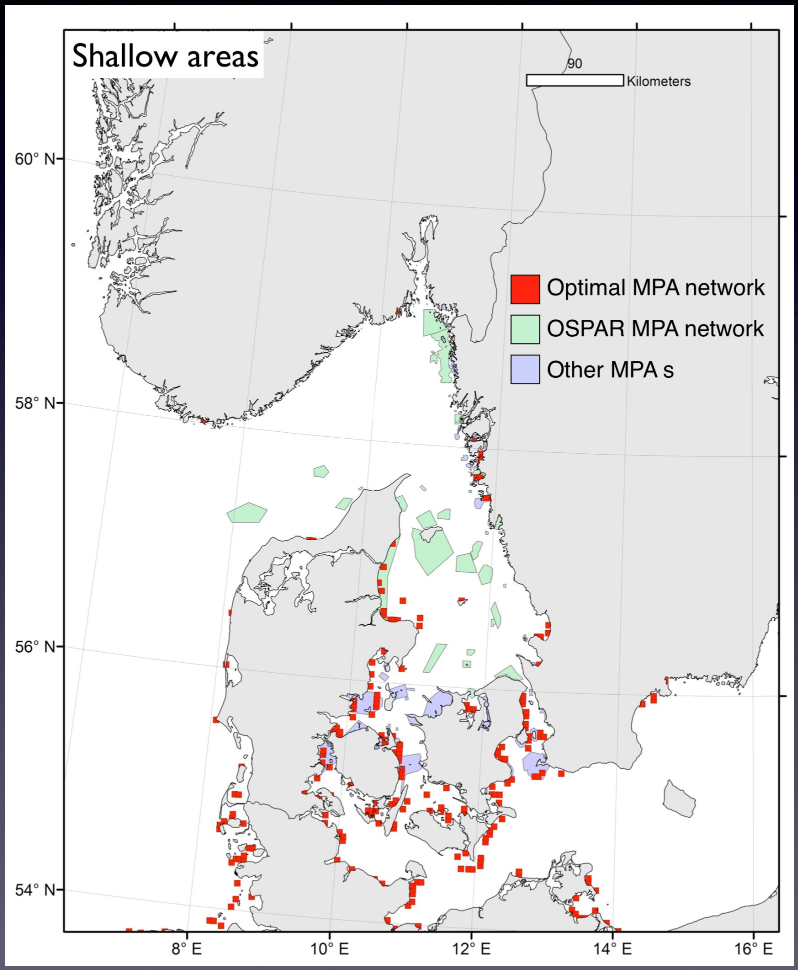
Evaluating an optimal *multi-species* MPA-network

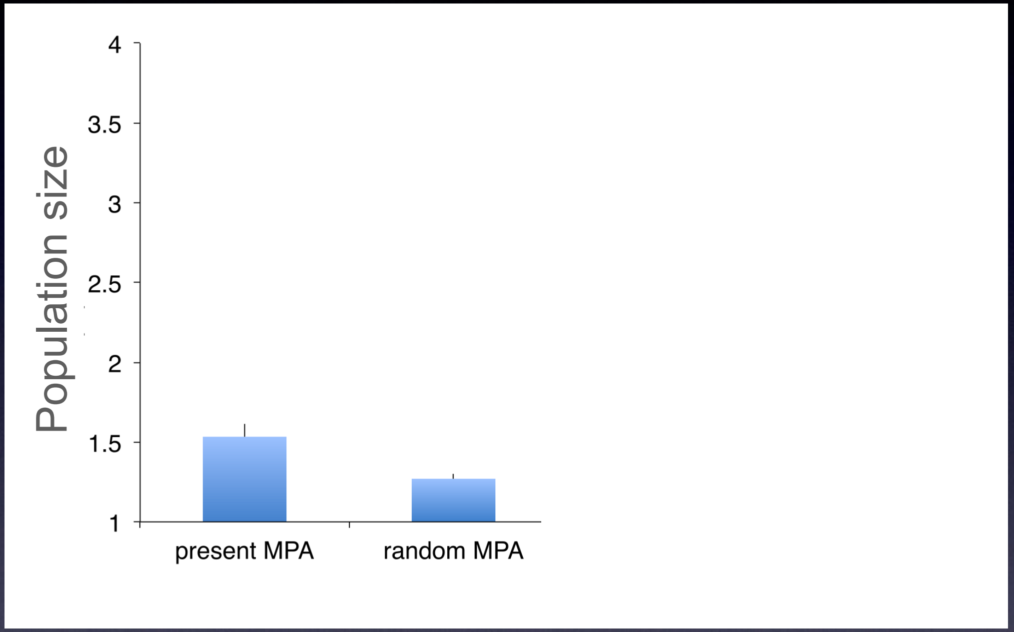




Moksnes et al. 2014. *Larval connectivity and ecological coherence of MPAs in the Kattegat-Skagerrak region.* Swedish Institute for the Marine Environment report 2014:2

Evaluating expansion of an *existing* MPA-network





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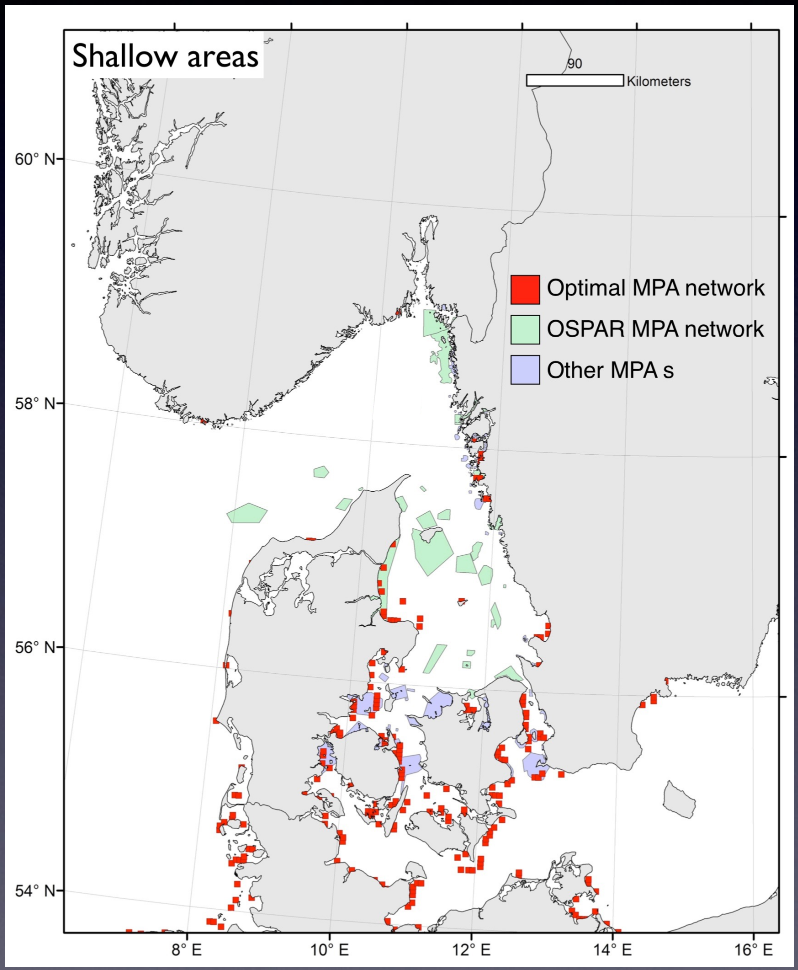

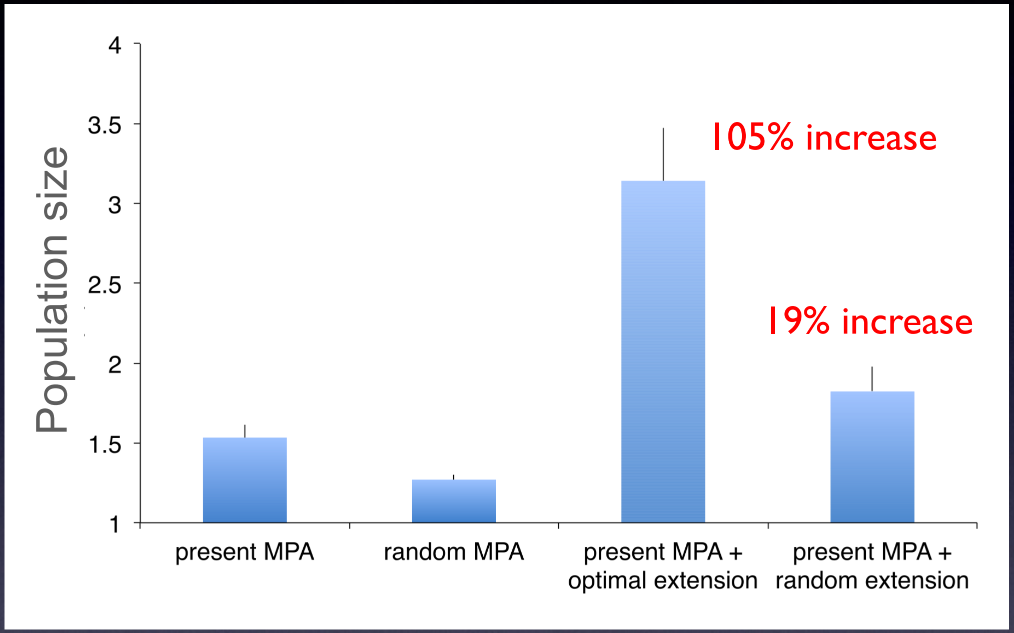

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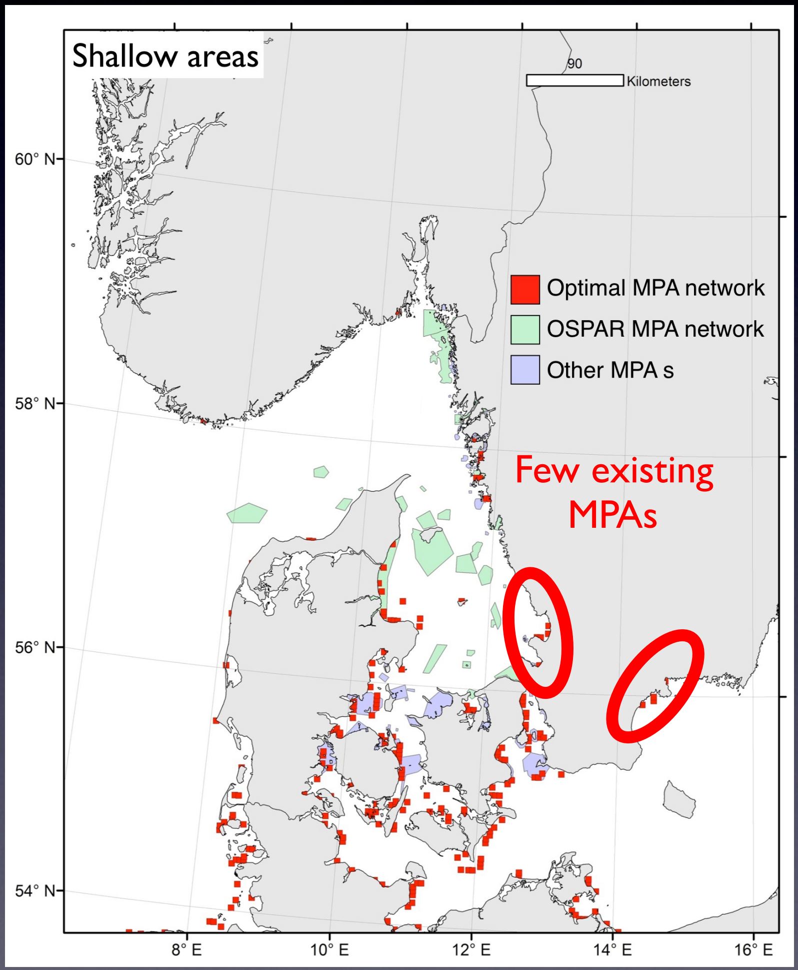

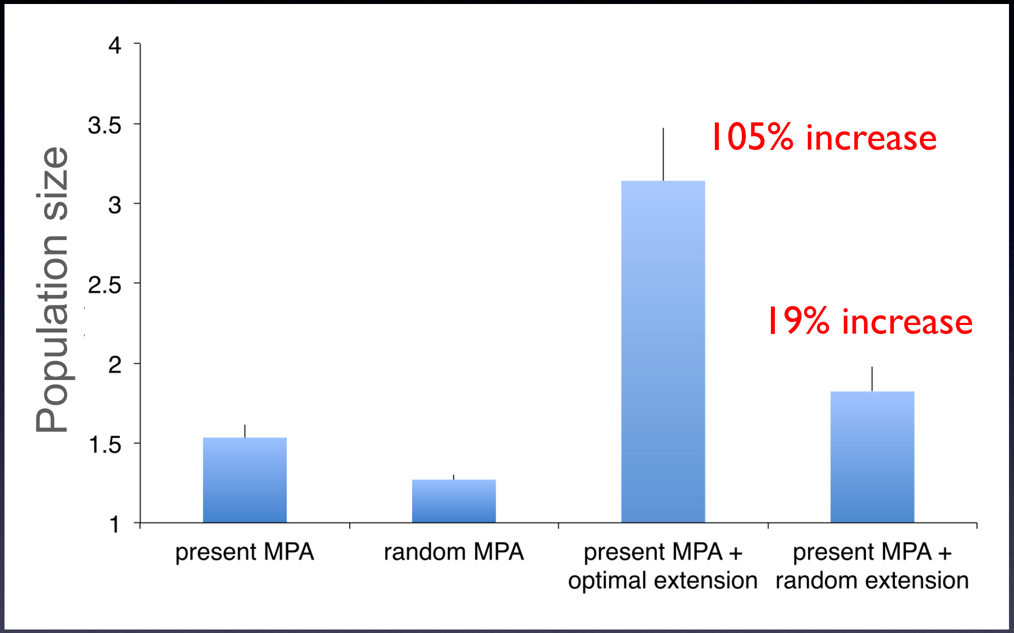

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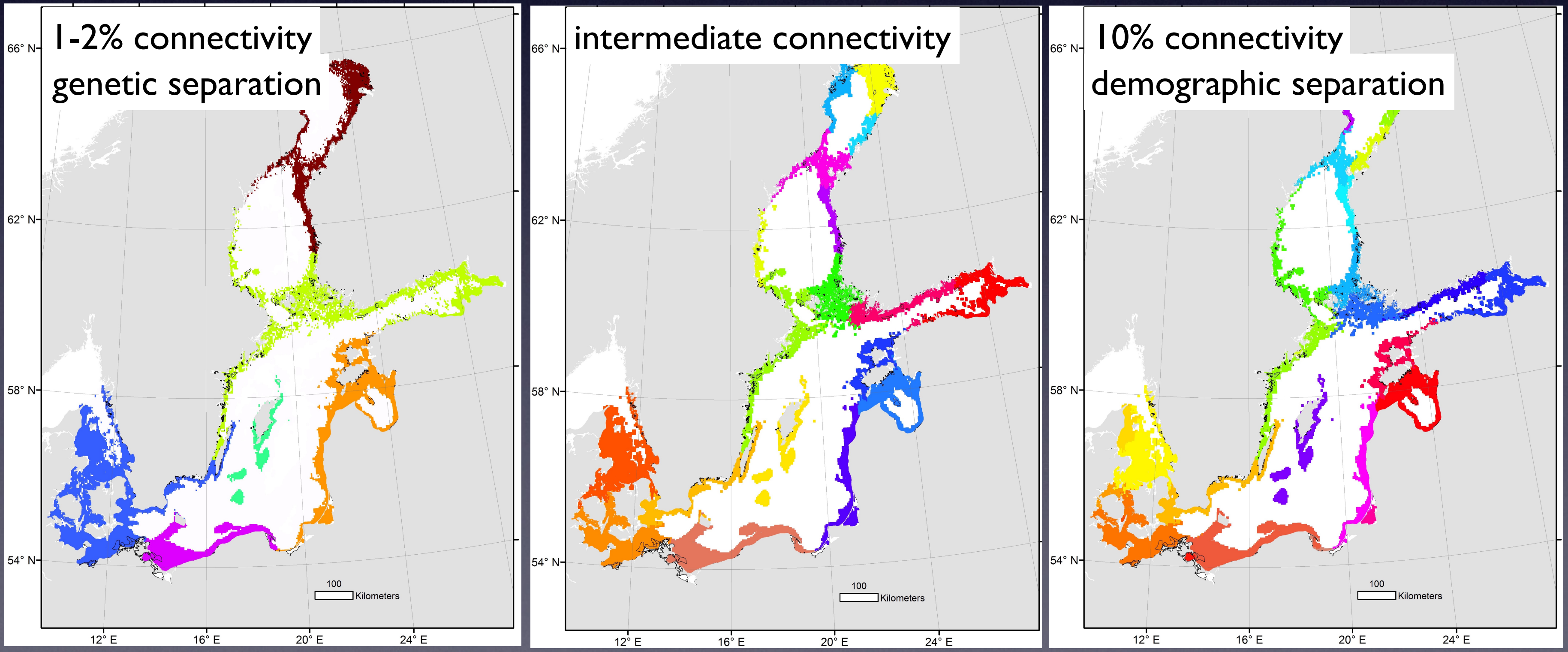
  - *de novo*
  - as addition to existing network
- evaluate potential benefits of alternatives
- identify barriers to dispersal
  - biogeographic "units"

Dispersal barriers & Management units

- 0-10 m
- 60 day duration
- dispersal at surface

- patterns vary with:
  - release depth
  - larval duration
  - dispersal profile



Limitations of the approach

- large spatial resolution (2 nm) cannot model coastal circulation well

  larval retention in bays underestimated

- species distribution data, and habitat types, are not included

  these influence locations of larval release as well as growth of populations: KEY aspect of MPA specification!

- selection only operates on larval connectivity

  habitat quality, adult dispersal, targeted fishing/disturbance also important

Conclusions

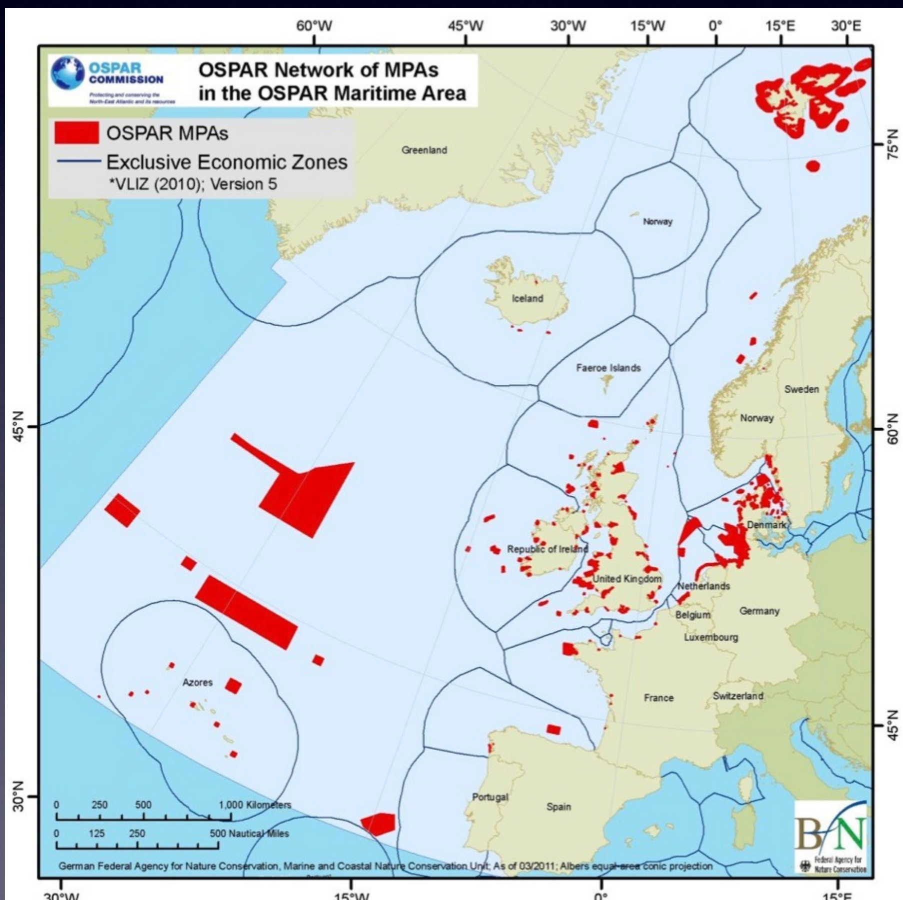
1. this is can be a very powerful tool
    - if the circulation model data are available
2. larval dispersal and connectivity vary with location and larval strategies
    - cannot be approximated with general dispersal distances
3. modeling different larval strategies can provide valuable information
4. existing MPA-networks are not optimally designed for larval connectivity
5. carefully chosen small additions (<20%) to existing networks can double population size & resilience
6. this modeling approach can identify dispersal barriers that are important for management

Thank you!

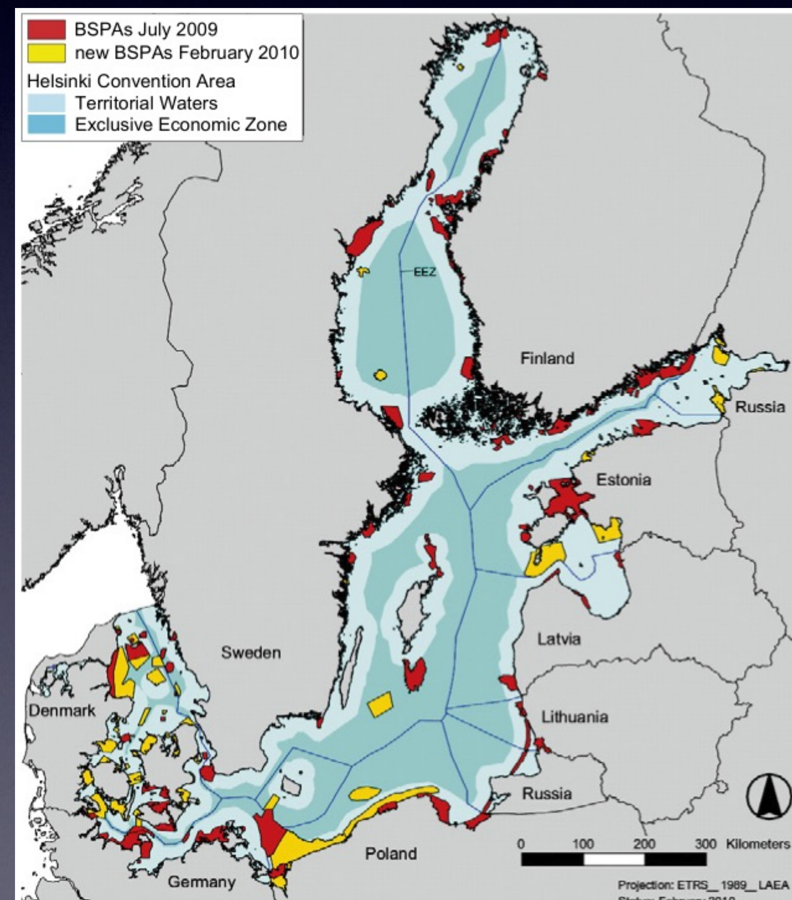
- Swedish Agency for Marine & Water Management
- Gothenburg University
- Swedish Research Council VR
- Swedish Environmental Research Council FORMAS

Networks of marine protected areas (MPAs)

North Atlantic (OSPAR)



Baltic (HELCOM)



Natura 2000 (EU)

- 3000 sites covering ~ 6% of EU territorial waters
- "Ecological Coherence"

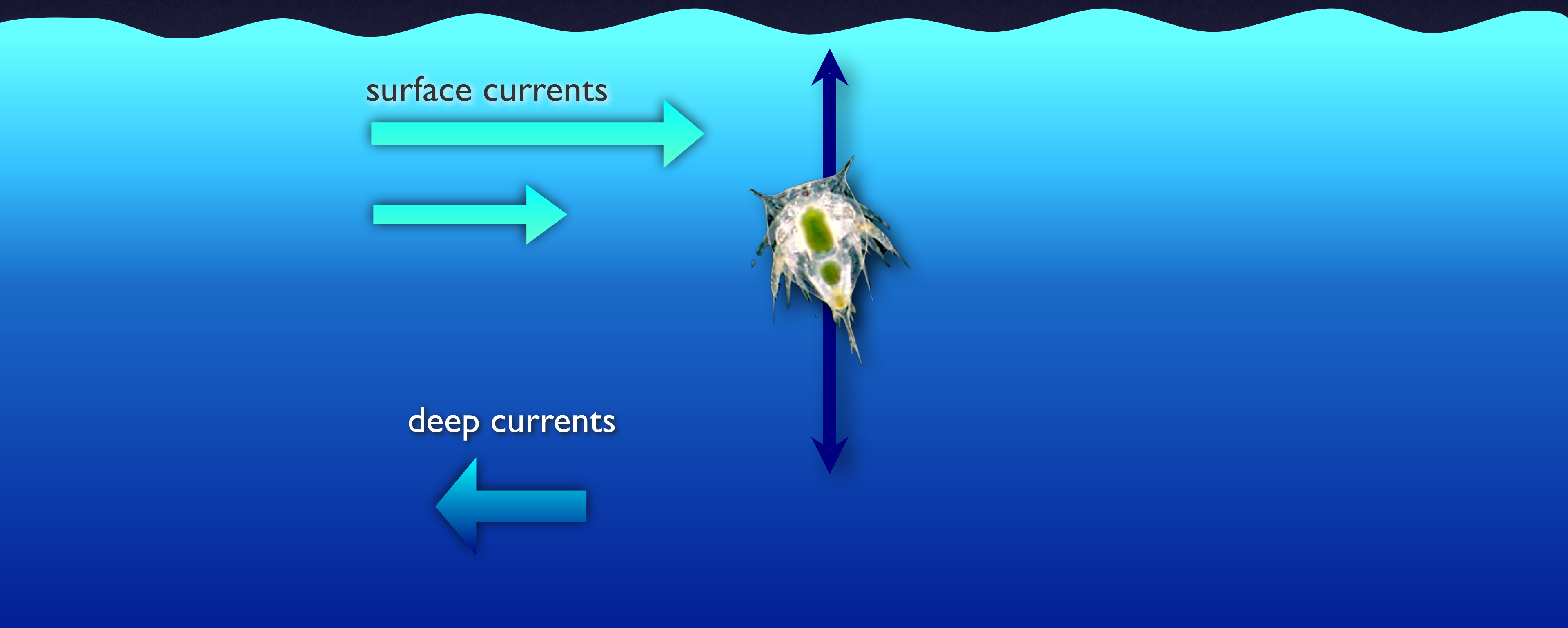
1. Adequacy
2. Representativity
3. Replication
4. Connectivity

European
Commission

Larvae interact with ocean currents

don't disperse passively

- Planktonic Larval Duration (PLD)
- dispersal depth
- spawning time

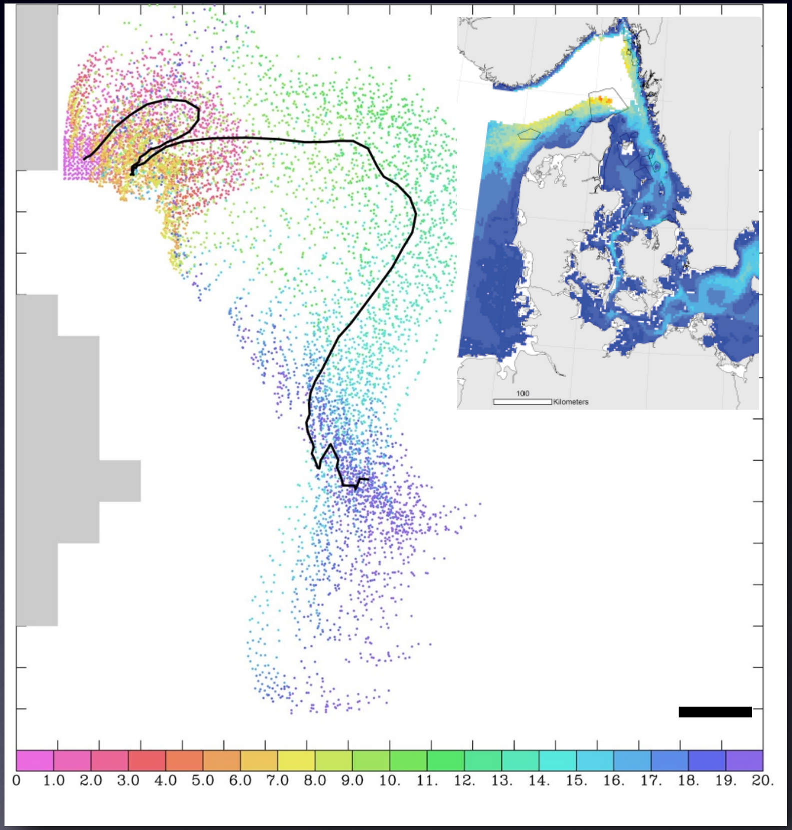


Comparison with earlier assessment of connectivity of MPA-networks

OSPAR / HELCOM	The present method
1. Only between MPAs	Between all relevant areas
2. Fixed general dispersal-distances (e.g. 250 km)	Area- and species-specific individually modeled dispersals
3. Methods to evaluate network connectivity and coherence missing	New method to identify optimal MPA-networks for multiple species (consensus networks)

Nilsson Jacobi & Jonsson. 2011. *Ecol. Appl. 21:1861-1870*
Nilsson Jacobi et al. 2012. *Ecography. 35:1004-1016*
Moksnes P-O et al. 2014. *Swedish Institute for the Marine Environment. Report no. 2014:2*
Moksnes P-O et al. 2015. *Swedish Agency for Marine and Water Management. Report. 2015:24*
Jonsson et al. 2016 *Diversity and distribution 22:161-173*

b. Particle tracking modell simulating larval dispersal (TRACMASS)



Virtual larvae released from all grid cells 0-100 m (in total 34 000 cells).

20 different larval types (drift depths, larval duration) released from all cells once per month during 8 years.

In total, 3.2 million virtual larvae modeled.

Estimates of connektivity
Connectivity matrix (probability estimates)
For each larval type

From

To

	1	2	3	4	5
1	s	e_{21}	e_{31}	e_{41}	e_{51}
2	e_{12}	s	e_{32}	e_{42}	e_{52}
3	e_{13}	e_{23}	s	e_{43}	e_{53}
4	e_{14}	e_{24}	e_{34}	s	e_{54}
5	e_{15}	e_{25}	e_{35}	e_{45}	s