TROPHIC MODELLING OF THE NORTH SEA

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Introduction

Ecopath with Ecosim methodology is a widely used tool for the quantification of food webs and analysis of ecosystem dynamics (Pauly *et al.* 2000). The approach is founded on a static description of the ecosystem represented by biomasses aggregated into ecologically functional groups. Predators and prey are linked through consumption defined by the diet composition matrix and consumption rate parameters. At present, 3 published Ecopath models exist for the North Sea. Based on 1981 year of the stomach data Christensen (1995) constructed two models representing the 1981 period; a 24 box model and 29 box model including more detailed, size based plankton groups. Mackinson (2002a), constructed a detailed historical representation of the North Sea in the 1880s which includes 49 boxes, with catch data for five different fishing fleets, and has been used in an examination of the utility of Ecosim's harvest policy analysis routine (Mackinson 2002b). The Ecopath approach provides a common platform for model development that will enable us to make comparisons of the North Sea with other marine ecosystems, particularly those surrounding the UK coast and North Atlantic.

Strategic approach to modelling the North Sea

Work to date on North Sea Ecopath models has highlighted a number of key issues that we considered deserve a more directed research effort. They include modelling structure/specification and ecological issues, specifically:

1. Model structure in relation to representing ecological linkages and management objectives;
2. Spatial representation of functional groups and their interactions;
3. Sensitivity testing and derivation of predator-prey interaction parameters.

Our aim in this study was to address the first of the issues by constructing a detailed model for 1991. We chose 1991 as the year on which to model the North Sea so that we were able to maximise the use of extensive fish diet composition data collected during the 1991 stomach sampling project (Hislop 1997), and because assessment data for the period 1991-2003 can be used in parameterising dynamic simulations used in analysing the ecosystem impacts of alternative harvest strategies. We are using this information to guide the development of the structure of the North Sea model, so that it represents a unbiased ecological perspective of the system.

The 1991 model brings together contributions from experts of relevant disciplines in its integration of diverse data sources. Our intention is to construct a model that is adequately reviewed by respected researchers such that it stands up to scientific scrutiny of international peers. This approach helps to develop the cross-science linkages that enable individual researchers to understand how their work is framed in an ecosystem context.

Progress on model construction

The wealth of information that is required to build the model includes data on biomass, consumption rates, diet composition, production rate, for each functional groups defined in the model. In addition a detailed representation of the fisheries are made by defining the fleet structure, landings, discards, fixed and operating costs, and fish prices. Not withstanding this 'basic' input information, extensive additional data are required for fitting dynamic simulations (time series of biomass, catches and effort). The present, preliminary model is one of the most detailed Ecopath models constructed.

The model structure was set to 71 functional groups including 3 mammal, 1 bird, 47 fish, 14 invertebrate, 4 autotroph, and 3 export (detritus+discard) groups (Table 1). The invertebrate, autotroph and discard groups are still under construction and not presented here. Different species either constitute single groups or are aggregated clusters of species based on information on abundance, diet, and commercial or functional importance. The commercially important target fish species were divided into juvenile and adult groups (e.g. cod, whiting, herring). Several non-target fish species, which are also commercially and/or functionally important were represented as single species or family groups (e.g. hake, dab, gurnards). Other species are included in aggregated groups based on similar taxonomic or functional characteristics e.g. large and small gadoids, large and small demersals, pelagic fish. The model was supplied with new estimates of biomass, production and consumption rates. Biomass of ~80 non-target fish species monitored by the International bottom-trawl survey, which are not subject to regular stock assessment, was estimated following the approach of Sparholt (1990). Production rates in Ecopath equal total mortality and were derived from available stock assessments, publications or estimated using empirical formulae (Table 3). Other published sources were used to derive plausible estimates of consumption rates (Tables 1, 3). The diet matrix was compiled using 1991 year of stomach data and literature sources (Tables 2 and 3). Landings were derived from the ICES fisheries statistics database and reports (ICES 2002, Mickleburgh 2003). Data on the landing and discards of 39 different fishing fleets was compiled from the 1991 Scientific Technical Committee for Fisheries data in combination with UK Fishing activity database and Trio Discards database (CEFAS) as a part of an MSc thesis (Mickleburgh 2003).

Table 1: Basic parameter values for the North Sea 1991 Ecopath model. Biomass is in thousand tonnes m^2 yr^1 rates are on a yearly basis. North Sea area assumed to be 570 000 km^2

Functional groups	Biomass	Production /biomass	Consumption/ biomass	Landings
Baleen whales	0.067	0.02	9.9	0.001
Toothed whales	0.017	0.02	17.63	
Seals	0.005	0.090	26.842	
Seabirds	0.003	0.28	216.56	
Juvenile sharks	0.003			
Spurdog	0.035	0.48	2.00	0.024
Large sharks	0.001	0.44	1.60	0.000
Small sharks	0.006	0.51	2.96	0.014
Juvenile rays	0.268	0.66	1.70	0.005
Starry ray	0.109	0.66	1.70	0.005
Thornback/Spotted ray	0.066	0.78	2.30	0.000
Cuckoo ray/Skate	0.050			0.000
Juvenile Cod	0.079	1.79	5.96	0.052
Cod (adult)	0.161	1.19	4.06	0.102
Juvenile Whiting	0.222	2.36	6.58	0.086
Whiting (adult)	0.352	0.89	5.46	0.169
Juvenile Haddock	0.284	2.54	5.39	0.056
Haddock (adult)	0.104	1.14	4.40	0.081
Juvenile Saithe	0.281	0.20	4.93	0.076
Saithe (adult)	0.191	0.68	5.13	0.129
Hake	0.033	0.82	2.20	0.003
Blue whiting	0.042	1.12	9.06	0.060
Norway pout	1.394	3.05	5.05	0.267
Other gadoids (large)	0.036	1.27	2.18	0.033
Other gadoids (small)	0.059	1.33	3.84	0.002
Monkfish	0.041	0.70	1.70	0.025
Gurnards	0.234	0.40	7.08	0.035
Juvenile herring	0.630	1.31	5.63	0.148
Herring (adult)	1.966	0.68	4.34	0.857
Sprat	0.579	1.03	5.28	0.121
Mackerel	0.100	0.80	1.40	0.023
Horse mackerel	0.579	1.64	6.51	0.223
Sandeels	3.122	2.20	5.24	1.575
Plaice	0.703	0.52	11.09	0.295
Dab	4.634	0.44	3.36	0.010
Long-rough dab	0.590	1.36	3.40	
Flounder	0.453		8.03	0.007
Sole	0.158	0.52	1.29	0.061
Lemon sole	0.305		4.32	0.005
Witch	0.082	0.90	3.00	
Turbot/brill	0.054	0.95	1.96	0.003
Megrim	0.034		12.17	0.000
Halibut	0.033	0.16	3.14	0.003
Dragonets	0.031	1.44	6.90	
Catfish (Wolf-fish)	0.017	0.48	1.70	
Large demersal fish	0.002	0.55	2.54	
Small demersal fish	0.095	1.42	3.73	
Miscellaneous pelagic fish	0.013	0.67	10.19	0.000

Table 3: Reference studies used to define model's parameters

Functional groups	Biomass	Production /biomass	Consumption/ biomass	Landings	Diet
Baleen whales	Hammond *et al.* 2002	Trites *et al.* 1999	Trites *et al.* 1999	Mickleburgh 2003	Olsen & Holst 2000
Toothed whales	Hammond *et al.* 2002	Trites *et al.* 1999	Trites *et al.* 1999		Santos *et al.* 1996, Rae 1973
Seals	ICES 2002	ICES 2002	ICES 2002		Hall *et al.* 1998, Hammond *et al.* 1994
Seabirds	ICES 2002	ICES 2002	ICES 2002		
Juvenile sharks	This study				Ellis *et al.* 1996
Spurdog	This study	FishBase 2004	Brett & Blackburn 1978	Mickleburgh 2003	Ellis *et al.* 1996
Large sharks	This study	FishBase 2004	FishBase 2004	Mickleburgh 2003	Ellis *et al.* 1996
Small sharks	This study	FishBase 2004	FishBase 2004	Mickleburgh 2003	Ellis *et al.* 1996
Juvenile rays	This study		ICES 2002	Mickleburgh 2003	Daan *et al.* 2003
Starry ray	This study	FishBase 2004	FishBase 2004	Mickleburgh 2003	Daan *et al.* 2004
Thornback/Spotted ray	This study	FishBase 2004	FishBase 2004	Mickleburgh 2003	Daan *et al.* 2005
Cuckoo ray/Skate	This study	FishBase 2004	FishBase 2004	Mickleburgh 2003	Daan *et al.* 2006
Juvenile Cod	ICES 2002	ICES 2002	Greenstreet 1996	ICES 2002	Hislop 1996
Cod (adult)	ICES 2002	ICES 2002	Greenstreet 1996	ICES 2002	Hislop 1996
Juvenile Whiting	ICES 2002	ICES 2002	Greenstreet 1996	ICES 2002	Hislop 1996
Whiting (adult)	ICES 2002	ICES 2002	Greenstreet 1996	ICES 2002	Hislop 1996
Juvenile Haddock	ICES 2002	ICES 2002	Greenstreet 1996	ICES 2002	Hislop 1996
Haddock (adult)	ICES 2002	ICES 2002	Greenstreet 1996	ICES 2002	Hislop 1996
Juvenile Saithe	ICES 2002	ICES 2002	Greenstreet 1996	ICES 2002	Hislop 1996
Saithe (adult)	ICES 2002	ICES 2002	Greenstreet 1996	ICES 2002	Hislop 1996
Hake	This study	FishBase 2004	Pauly 1989	Mickleburgh 2003	Du Buit 1996
Blue whiting	This study	FishBase 2004	FishBase 2004	Mickleburgh 2003	Bergstad 1991
Norway pout	ICES 2002	ICES 2002	Greenstreet 1996	Mickleburgh 2003	Malyshev & Ostapenko 1982
Other gadoids (large)	This study	FishBase 2004	FishBase 2004	Mickleburgh 2003	Hoines & Bergstad 1999, Bergstad 1991, Rae&Shelton 1982
Other gadoids (small)	This study	FishBase 2004	FishBase 2004	Mickleburgh 2003	Albert 1995, Armstrong 1982
Monkfish	This study	FishBase 2004	FishBase 2004	Mickleburgh 2003	Rae & Shelton 1982
Gurnards	This study		Gee & Kikkert 1993	Mickleburgh 2003	
Juvenile herring	ICES 2002	ICES 2002	Greenstreet 1996	ICES 2002	Last 1989
Herring (adult)	ICES 2002	ICES 2002	Greenstreet 1997	ICES 2002	Last 1989
Sprat	ICES 2002	ICES 2002	Greenstreet 1998	ICES 2002	De Silva 1973
Mackerel	ICES 2002	ICES 2002	Greenstreet 1999	Mickleburgh 2003	
Horse mackerel	Rueckert *et al.* 2002	Rueckert *et al.* 2003	Greenstreet 1996	Mickleburgh 2003	Greenstreet 1996
Sandeels	ICES 2002	ICES 2002	Greenstreet 1996	ICES 2002	Reay 1970
Plaice	ICES 2002		Greenstreet 1996	ICES 2002	De Clereck & Buseyne 1989
Dab	This study		Greenstreet 1996	Mickleburgh 2003	De Clereck & Tonreele 1988
Long-rough dab	This study	FishBase 2004	FishBase 2004		Ntiba & Harding 1993
Flounder	This study		Doornbos & Twisk 1984	Mickleburgh 2003	Doornbos & Twisk 1984
Sole	This study			ICES 2002	Braber & Groot 1973
Lemon sole	This study		Greenstreet 1996	Mickleburgh 2003	Rae, 1956
Witch	This study	FishBase 2004	FishBase 2004		Rae, 1969
Turbot/brill	This study	FishBase 2004	FishBase 2004	Mickleburgh 2003	Wetsteijn 1981
Megrim	This study		Du Buit 1984	Mickleburgh 2003	Du Buit 1984
Halibut	This study			Mickleburgh 2003	McIntyre, 1952
Dragonets	This study	FishBase 2004	FishBase 2004		Gibson & Ezzi 1987
Catfish (Wolf-fish)	This study	FishBase 2004	FishBase 2004		Bowman *et al.* 2000
Large demersal fish	This study	FishBase 2004	FishBase 2004		Bergstad *et al.* 2001, Bowman *et al.* 2000
Small demersal fish	This study	FishBase 2004	FishBase 2004		Ebeling & Alshuth 1989, Albert 1993, Gibson&Robb 1996
Miscellaneous pelagic fish	This study	FishBase 2004	FishBase 2004	Mickleburgh 2003	Bowman *et al.* 2000

Table 2: Fish in the diet (in %)

PREY \ PREDATOR	Tope	Juvenile sharks	Dogfish	Small sharks	Juvenile rays	Starry ray	Thornback/Spotted ray	Cuckoo ray/Skate	Juvenile Cod	Cod (adult)	Juvenile Whiting	Whiting (adult)	Juvenile Haddock	Haddock (adult)	Juvenile Saithe	Saithe (adult)	Hake	Blue whiting	Norway pout	Other gadoids (large)	Other gadoids (small)	Monkfish	Gurnards	Juvenile herring	Herring (adult)	Sprat	Mackerel	Horse mackerel	Sandeels	Plaice	Dab	Long-rough dab	Flounder	Sole	Lemon sole	Witch	Turbot/brill	Megrim	Halibut	Dragonets	Catfish (Wolf-fish)	Large demersal fish	Small demersal fish	Miscellaneous pelagic fish
Juvenile rays						0.02				0.02												0.59	0.03																					
Starry ray																																												
Thornback/Spotted ray																																												
Cuckoo ray/Skate																																												
Juvenile Cod					0.20	2.65			2.91	0.89	0.37	0.17		0.01						2.18		0.90	2.59			0.01	7.40														16.48			
Cod (adult)										1.03												0.90																				0.74		
Juvenile Whiting		0.48	2.79	0.12		3.11	1.77	1.45	2.21	4.86	0.68	4.51			0.60	0.38	2.81			4.35	0.28	9.15	8.66			0.01	27.87			0.41										28.19		43.99			
Whiting (adult)		1.92	11.17	0.58		0.43				9.47		0.13				1.89						9.15																						
Juvenile Haddock			0.57			1.28	0.31	0.41	2.30	2.13	0.87	1.36		1.09	0.21	1.52				0.32		5.15	0.67				4.33															24.53			
Haddock (adult)			0.57							2.00						0.57						5.15																						
Juvenile Saithe												0.02		0.00								0.29	0.01																						
Saithe (adult)																																													
Hake								0.06									0.66					0.59																						
Blue whiting			0.35	2.02	7.36			0.12		0.02		0.00				3.26	40.93			3.80			0.01				0.04													12.49		2.31			
Norway pout			7.32	9.30	2.08	1.05	10.41	0.13	4.72	11.48	7.02	13.30	16.89	1.02	8.98	20.54	30.89	5.70	9.08	7.62	0.04	10.32	6.44				0.82				0.47									22.14	4.33				
Other gadoids (large)															0.39																													
Other gadoids (small)	18.96	0.26	14.37	1.02	1.49	4.42	3.07	5.92	3.34	2.16	1.27	1.70	0.12	0.38	1.80	3.48	4.40			0.97	1.32		6.81				5.91	14.67			2.36									3.84	21.00	1.52		2.60		
Monkfish								0.06														0.29																						
Gurnards	9.48			0.03		0.04		0.17	0.20	0.61	0.00	0.03	0.01	0.00		0.03	0.26						0.01					0.74													0.57			7.45		
Juvenile herring	1.04	0.64	2.00			0.31	3.64	14.44	0.35	2.51	0.33	6.89		1.56	0.02	1.70	2.50			27.70		9.30	0.13				0.60	9.60		0.25											1.46			0.04		
Herring (adult)	9.38	6.28	17.61	0.54		0.79			0.20	8.82						19.71				12.38		9.30																						
Sprat		2.32	3.84	1.36		0.02	1.81		0.66	0.41	1.40	11.63		0.10		0.01	2.50			0.00	0.31	0.29	1.41				5.27	0.50												1.83	31.22			0.05	0.13	
Mackerel	14.22	1.38	7.70	0.47					1.30							0.36	15.56					5.31	0.07				0.00																		
Horse mackerel			1.82						0.08	0.28	0.16	0.91					17.01						0.12				0.55																0.95			
Sandeels		1.45	3.63	1.09	39.23	46.32	3.29	34.68	11.26	2.85	29.80	29.49	12.87	27.86	0.82	1.94				26.29	0.08	13.27	36.20				23.08			0.76		2.07								15.92	1.70	16.34		0.02	32.29	
Plaice	5.69		4.46	0.20	0.28	2.49			0.61	19.10	0.03	0.01		0.02		0.06						0.29	0.86																						
Dab	5.69	0.67	0.64	0.58	0.11	1.74		0.17	2.16	5.76	0.42	0.54	2.02	0.31		0.04						2.36	1.51								3.36									5.97			0.05	3.64	
Long-rough dab				0.21				0.12		0.37										1.35		3.54																						
Flounder					1.51	3.25		0.03			0.41	0.82	0.89	0.11	0.05	0.00											0.00																		
Sole				0.20		0.12	0.42	2.48	0.34	1.79	0.18	0.27	0.03	0.02									0.00							0.25												0.05		
Lemon sole											0.00	0.00				0.00						0.88																						
Witch			0.64			0.01		0.06	0.01	0.12	0.00	0.00		0.01								0.29	0.01				0.00																		
Turbot/brill																																													
Megrim																						0.29																						
Halibut						0.02																																						
Dragonets	10.42	0.35	2.53	1.63		0.52		7.14	1.37	1.46		0.04	0.01	0.05							2.27	0.29	2.12																	6.18	2.84		0.14	0.53	
Catfish (Wolf-fish)									0.03	0.00		0.00		0.00		0.00						0.04																				0.14		
Large demersal fish						0.02		0.12		0.00		0.03		0.01		0.00																													
Small demersal fish	2.85		1.00	0.30	0.09	0.85	4.89	0.95	2.58	1.41	2.43	1.02	0.05	0.04		0.01	1.50			0.66	1.08	3.24	0.61			0.01	0.72		0.05	3.33	11.72	1.28	0.68	0.82	15.95	0.57				6.80	3.58		
Miscellaneous pelagic fish		0.37		0.43	0.01				0.01	0.00	0.05	0.26		0.03	23.25	10.45	5.93	2.88				0.29	0.02			0.02										2.27				1.68		11.50	
fish larvae																								16.22				1.79												0.00				
fish eggs																								0.36				15.69			5.14											0.00	

Biomass estimates were compared to historical data (Sparholt, 1990; Mackinson, 2002a, Figure 1). Total fish biomass in the North Sea was estimated ~26 million tonnes by the end of the 19th century to ~10 million tonnes in 1991. The biggest change was in exploited target species e.g. gadoids (cod, haddock, saithe), mackerel, herring and flatfish. Gadoids and mackerel/horse mackerel also decreased between 1980s and 1991, but herring and some prey-fish (e.g. dab, flounder) increased in 1991 compared with 1980s (Figure 1). There was also an important decrease in cetaceans, seabirds and elasmobranchs and an increase in seals in 1991 compared to the 1880s. The biomass estimates in the 1880s model were based on scarce data and strong assumptions and should be interpreted with caution.

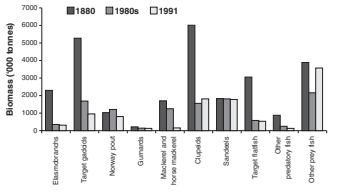

Figure 1: Comparison between fish biomass estimates in the 1880s (data from Mackinson, 2002a), 1980s (data from Sparholt, 1990) and 1991 (present study)

Future work

Development of the North Sea ecosystem model is steered by a strategic work plan for the development, scientific reviewing of parameters, sensitivity testing and application of the model (Figure 2). Future work will include temporal and spatial simulation of alternative fishing and environmental change scenarios. A specific term of reference regarding the evaluation of the North Sea model has been included in the 2005 ICES SGMSNS: "Perform a data fitting exercise using the North Sea 1991 EwE model. The fitting exercise will require input (survey CPUE) and output data (MSVPA estimated biomasses) from the updated 4M key-run (ICES 2003).

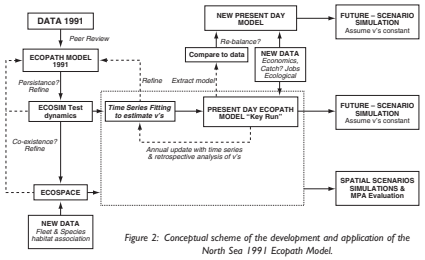

Figure 2: Conceptual scheme of the development and application of the North Sea 1991 Ecopath Model.

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