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ECOSYSTEM IMPACTS OF ORANGE ROUGHY FISHERIES

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July 2013

Summary

This document provides background information and a perspective on the ecosystem impact of orange roughy fishing. It is not comprehensive, but intended to be indicative of current knowledge and understanding. My objective was to consider how we might best monitor the orange roughy ecosystem for signs of significant or informative change in function, and in its ability to maintain ecosystem services.

I have structured the text into sections; (1) the orange roughy ecosystem, (2) ecosystem outcome, (3) ecosystem management, and (4) ecosystem monitoring. My focus is on (1) and (2). Within these first two sections, I have kept a summary of key existing knowledge separate from a discussion of theory and research. The latter may include further detail on existing research and data sets, other pertinent findings, and ideas for research which may improve our understanding.

Orange roughy fishing has two main impacts. The first is capture of target species and by-catch, and the second is damage to the seabed by bottom trawls (including incidental mortality). I have tended to focus on the ecosystem impacts of the former. This is because of my expertise, and because bottom trawl impacts may be reduced, minimised or mitigated through reduction in the trawl footprint, whereas a Bmsy objective does, by definition, require a persistent and substantial reduction in the biomass of the target species (and potentially the closely associated by-catch).

We know quite a lot about the orange roughy and its ecosystem. Orange roughy occur in a variety of deep water habitats on the upper continental shelf. Different orange roughy life stages tend to predominate in different habitats. Orange roughy forage primarily on mesopelagic and benthopelagic fauna. The known predators of orange roughy include sharks and toothed whales. Predation of orange roughy appears to be very rare, consistent with their high longevity. The orange roughy fish community has been described, and by-catch species are known. The trophic role of many of the fish species is known. Detailed and representative catch composition and biomass data are available, for example from a time series of demersal research trawl surveys, of varying lengths, for the Challenger Plateau, Mid-East Coast, and Chatham Rise. Catch composition data are also collected by MPI observers in the commercial fishery. Substantial biological data are available for orange roughy, and for several sympatric species.

To improve our understanding, I have argued that we should research and monitor ecosystem characteristics (e.g., biodiversity) and components (e.g., functional groups or species) that are

indicative of, or directly linked to, the dynamics and maintenance of ecosystem function. These would initially focus on the functional groups containing, or directly connected to, orange roughy. They will be specific to the fishery in question. This is a simpler, and quicker, approach than pursuing the development of ecosystem simulation models. I do consider ecosystem models, but reserve their use for developing and testing management responses. Within the short-term, ecosystem statistics could be developed to inform us on ecosystem function, and would focus on aspects of niche structure, dynamics of competitors, prey and predators. The concepts behind this are:

- The importance of environment.
- Trophic relationships and function.
- Maintenance of biodiversity, focusing on ecosystem function.
- Understanding biological drivers, and the significance of these relative to environmental drivers.
- Knowing how to interpret observed changes.

In a broader context, this would also include:

- Understanding the impact of bottom trawl on benthic nutrient recycling.

As an example, a time series of research trawl surveys of the Mid-East Coast (SE coast North Island, NZ) orange roughy stock has revealed some significant changes in by-catch biomass. At the moment, interpretation of these is speculative. We need to be able to determine whether the changes are indicative of "positive" compensatory processes, meaning ecosystem function is being maintained despite the reduction in orange roughy abundance, or whether they could indicate a detrimental change and loss of productivity (the capacity to deliver ecosystem services). To determine the need and nature of a management response to this change (if any), we need to know the most likely cause, and what implications it has for productivity. To answer this, we might (1) determine the environmental limits and preference of species, (2) determine their functional role, and which other species they are functionally related to, (3) thereby advise on whether overall ecosystem function is likely to be impacted, and (4) evaluate whether environment or orange roughy fishing is the most likely cause. New analyses would be required, and some new data collection, but much of this could be achieved with existing data.

Achieving a credible ecosystem monitoring programme is undoubtedly a substantial challenge. This document provides background information. But regarding the overall objective, I consider this to be "work in progress", and I am sure some ideas could be modified, extended, or improved, after further thought.

1. The orange roughy ecosystem

Current knowledge

Orange roughy occur in a variety of deep water habitats on the upper continental shelf. The ecosystem inhabited by orange roughy is relatively constant, cold and unproductive. Orange roughy are almost always caught near the seabed (demersal), but their diet indicates they can forage some distance into the water column (benthopelagic).

Juvenile orange roughy occur most frequently on flat areas of the upper continental shelf at depths of 850–900 m (Dunn et al., 2009). As they grow, their spatial and depth distribution expands, both shallower and deeper but with a skew towards deeper water, such that by the onset of maturation, they are found in relative abundance from 850–1300 m. Whilst both juvenile and adult orange roughy may aggregate around underwater features, such as ridges, canyons, hills, and seamounts, these areas are most often used by larger fish (Branch 2001; Dunn & Devine 2010).

The flat areas of the upper continental shelf may superficially appear homogenous, but biodiversity and habitats do vary, at least over large spatial scales (Compton et al., 2013). The primary driver of this variability appears to be environmental, and therefore probably not fishing intensity (Hewitt et al., 1998; Pitcher et al., 2007; Compton et al., 2013). The habitat of features is obviously different to the flat, most notably in having more variable habitat, including exposed rock and associated benthic fauna (e.g., corals). Orange roughy aggregations around features indicate this habitat can attract high densities of fish (Branch 2001), but the value for an individual orange roughy may not be that different to the flat (Dunn & Forman 2010). Although features support large aggregations of some species, fish biodiversity is actually greater on flat areas (Tracey et al., 2004). Features are thought to support higher fish densities because of improved access to mesopelagic food resources, combined with easier access to refuges (Rowden et al., 2010). Studies of diet, and the persistence of aggregations over extensively fished features, both support this, and suggest the benthic faunal characteristic of features may not have any particular importance to orange roughy (Dunn & Forman 2010). Generalisations about features are difficult however, and seamount characteristics and associated faunal communities have been found to be highly variable and difficult to predict (Tracey et al. 2012). More recently, the importance of some submarine canyons as productive areas has been recognised (De Leo et al., 2010). Juvenile orange roughy have been found in particular abundance around the submarine canyons off the NE South Island (Kaikoura) (Dunn et al., 2009; Doonan & Dunn 2011).

The mesopelagic habitat provides the majority of the food resources to adult orange roughy (details below). Although orange roughy eggs exist temporarily in the mesopelagic habitat (Branch 2001), early juveniles appear to have a benthic orientation, with benthopelagic movements (i.e., foraging into the mesopelagic layers) increasing as orange roughy get larger (Dunn & Forman 2010). The mesopelagic habitat and communities are stratified by depth (Koubbi et al., 2011; Olivar et al., 2012), and Dunn & Forman (2010) suggested that changes in orange roughy diet with depth may reflect prey species depth stratification within the mesopelagic and bathypelagic layers. Mesopelagic waters are warmer than bottom waters, which may help to speed up the development of orange roughy eggs. Studies have indicated temperature has a role in determining the overall distribution of orange roughy (Kulka et al., 2003; Dunn et al., 2009). Temperature at depth is relatively constant, so seasonal cues to orange roughy probably come from biological factors not yet studied, or from other environmental factors such as day length (Pankhurst 1988).

Theoretical and research considerations

The functional importance of orange roughy to its ecosystem, and what we should expect following the exploitation of orange roughy, remains vague. The deep water fish community is reasonably well described, at least in terms of species composition and distribution (e.g., Anderson

et al., 1998; Tables 1 & 2). The influence of the physical environmental in determining species distribution and dynamics is well studied for shallow waters, but poorly studied in the deep sea. The few existing deep-sea studies (as far as I am aware) use statistical niche models, i.e., models predicting occurrence or abundance from environmental statistics (Holt 2009), and are predominantly for benthic fauna (e.g., Bryan & Metaxas 2007). The influence of biological interactions on species' distribution and dynamics is also poorly studied for the deep sea, and whilst we expect predation to be influential (Johnson et al., 2012), the role of competition is proving more difficult to establish (Link & Auster 2013; Dunn et al., in prep.). As a result, the nature and relative importance of environment (neutral or random processes) and biological interactions (niche processes) is not clear (Holt 2009, Wennekes et al., 2012); this is true for many species, not just the orange roughy. Nevertheless, understanding these processes and their relative importance would help us to determine how the ecosystem functions, what it is important to study and monitor, and what constitutes an informative or significant change.

Marine ecosystems have relatively high connectivity, which leads to relative high resilience, but also allows the effects of fishing to be transmitted relatively widely (Dunne et al., 2004). Some recent work suggests that, in terms of maintaining ecosystem function and productive capacity, the actual species contributing to connectivity may not matter (Rice et al., 2013; but this is not a new idea, see e.g., Johnson 2007). To determine the impact of fishing orange roughy, it would therefore be helpful to know whether orange roughy have a unique role in the ecosystem, which other species have similar functional roles (i.e., are competitors), and whether populations of these other species have compensated and are maintaining ecosystem function after orange roughy populations are reduced. It would then be useful to know the same information for major by-catch species, and for the subsequent ecosystem links. If compensatory processes have occurred, then biomass indices for these functional groups, and taxon-independent biodiversity statistics, should indicate no significant change after fishing, and we might assume that ecosystem function has not been adversely impacted. Compensatory processes should guard against potentially detrimental effects such as trophic cascades.

Orange roughy have relatively high longevity (Table 3), and accordingly a relatively low overall mortality rate (low after the egg and larval phase at least), so we might expect competitive processes to have a relatively strong role in population dynamics. Further, orange roughy are ubiquitous and often relatively abundant (see Tables 1 & 2), although as adults they may encounter limited availability of apparently preferred habitat (seamounts and other features). If these statements are correct, then the (relatively strong) competitive effects might/should be detectable, for example in density dependent demographic characteristics for orange roughy, and/or distributional and biological (fundamental and realised niche breadth) or biomass (productivity/abundance) changes amongst orange roughy competitors. It should be possible to convert such characteristics into statistics that can be monitored, and which describe the extent to which ecosystem function is being modified.

The evaluation of wider ecosystem impacts (and potential feedbacks) is far from straightforward, and requires considerable additional knowledge. This includes consideration of the impact of bottom trawl fishing on benthic biodiversity and processes. Certain species, which might be linked to orange roughy through predation, may indicate the extent to which benthic disturbance is modifying food webs and ecosystem function (e.g., benthic foraging grenadiers). Rather than attempt to fully understand benthic impacts, in the short term it may be appropriate to extend monitoring approaches (derived from similar rationale to that above) for a set of species that can be linked to particular benthic processes and productivity.

Table 1: Research trawl survey total catches by weight from a deep-water stratified random survey of the Mid-East Coast (SE North Island NZ) conducted in 2010 (Table 10 from Doonan & Dunn 2011). Excludes rocks and broken shell rubble. * catch from all species caught.

Species	Species Code	Weight (kg)	Percentage of the catch
Alfonsino		53 125.8	49.7
Orange roughy		11 801.7	11.0
Shovelnose dogfish		7 889.2	7.4
Smallscaled brown slickhead		4 740.1	4.4
Smooth oreo		4 736.4	4.4
Hoki		3 592.9	3.4
White rattail		2 329.2	2.2
Spiky oreo		2 030.8	1.9
Johnson's cod		1 368.3	1.3
Javelinfish		1 352.5	1.3
Owston's dogfish		895.4	0.8
Ribaldo		785.2	0.7
Baxter's dogfish		759.7	0.7
Serrulate rattail		621.5	0.6
Bollon's rattail		610.7	0.6
Pale ghost shark		589.7	0.6
Largescaled brown slickhead		588.0	0.6
Basketwork eel		570.4	0.5
Widenose chimaera		564.5	0.5
Leafscale gulper shark		503.7	0.5
Total catch*		106 903.8	

Table 2: Research trawl survey total catches by weight from a deep-water stratified random survey of the east Chatham Rise (off NE South Island NZ) conducted in 2007 (Appendix C of Doonan et al. 2009). Occurrence is the percentage of all tows (including tows additional to those for the trawl biomass survey) where the species was caught, and weight (kg) is the total catch from all tows. The table has been reduced to show only those species where total catch was >50 kg.

Fish, General				
ORH	Orange roughy	*Hoplostethus atlanticus*	79	23090.7
SSM	Slickhead, smallscaled brown	*Alepocephalus* sp.	40	2027.6
HJO	Johnson's cod	*Halargyreus johnsonii*	83	1805.2
SBI	Slickhead, bigscaled brown	*Alepocephalus australis*	58	1535
RIB	Ribaldo	*Mora moro*	33	722.5
BSL	Black slickhead	*Xenodermichthys copei*	29	395.4
SSO	Smooth oreo	*Pseudocyttus maculatus*	48	387.9
HOK	Hoki	*Macruronus novaezelandiae*	37	334
EPR	Robust cardinalfish	*Epigonus robustus*	55	161.7
SMC	Small-headed cod	*Lepidion microcephalus*	56	146
WOE	Warty oreo	*Allocyttus verrucosus*	27	111.5
VCO	Violet cod	*Antimora rostrata*	30	75.9
Fish, Chimaeras				
RCH	Widenosed chimaera	*Rhinochimaera pacifica*	24	214.8
LCH	Long-nosed chimaera	*Harriotta raleighana*	34	112.2
GSP	Pale ghost shark	*Hydrolagus bemisi*	26	91.9
CHP	Chimaera, brown	*Chimaera* sp	20	81.5

Fish, Marine eels				
BEE	Basketwork eel	*Diastobranchus capensis*	74	2023.6
SBK	Spineback	*Notacanthus sexspinis*	59	153.3
SCO	Swollenhead conger	*Bassanago bulbiceps*	32	95.9
HCO	Hairy conger	*Bassanago hirsutus*	33	71.4
Fish, Macrouridae				
CSU	Four-rayed rattail	*Coryphaenoides subserrulatus*	74	956.4
WHX	White rattail	*Trachyrincus aphyodes*	49	747.3
CSE	Serrulate rattail	*Coryphaenoides serrulatus*	73	551.2
CIN	Notable rattail	*Caelorinchus innotabilis*	74	377.6
CMA	Mahia rattail	*Caelorinchus matamua*	40	174.6
MCA	Ridge scaled rattail	*Macrourus carinatus*	45	173.8
CHY	Roughhead rattail	*Caelorinchus trachycarus*	40	158.2
JAV	Javelin fish	*Lepidorhynchus denticulatus*	35	144.8
CBA	Humpback rattail(slender rattail)	*Coryphaenoides dossenus*	57	128.6
Fish, Sharks & Dogfish				
SND	Shovelnose spiny dogfish	*Deania calcea*	69	5181.2
ETB	Baxters lantern dogfish	*Etmopterus baxteri*	77	750.6
CYP	Centroscymnus crepidater	*Centroscymnus crepidater*	50	558.4
SOP	Pacific sleeper shark	*Somniosus pacificus*	1	450
CYO	Smooth skin dogfish	*Centroscymnus owstoni*	38	231.5
CSQ	Centrophorus squamosus	*Centrophorus squamosus*	14	120.7
APR	Catshark	*Apristurus* spp	24	56.8

Table 3: Maximum zone count for a variety of deep-sea fishes (taken from a draft manuscript; McMillan, Neil, Dunn, et al.). Zone count typically indicates age, but this has not been validated for all species. Note some groups are missing e.g., chimaeras, and sharks, rattails, slickheads are poorly represented. Contact Peter McMillan (NIWA) for more details and data sources if required. Whilst deep-sea fauna may exhibit higher longevity on average than shallow water equivalents, high longevity in the deep sea is not ubiquitous, and orange roughy seem to be one of the longer-living species.

Common name	**Scientific name**	**Maximum zone count**	**Age source**
Orange roughy	*Hoplostethus atlanticus*	130	Doonan (1994)
Alfonsinos			
Alfonsino	*Beryx splendens*	17	Massey & Horn (1990)
Oreos			
Smooth oreo	*Pseudocyttus maculatus*	86	Doonan et al (1997)
Black oreo	*Allocyttus niger*	153	McMillan et al. (1997)
Spiky oreo	*Neocyttus rhomboidalis*	128	Smith & Stewart (1994)
Warty oreo	*Allocyttus verrucosus*	130	Stewart et al. (1995)
Merluccid cods			
Hoki	*Macruronus novaezelandiae*	20	Horn & Sullivan (1996)
Hake	*Merluccius australis*	30	Horn (1997)
Deepsea cods			
Johnson's cod	*Halargyreus johnsonii*	42	NIWA unpublished
Ribaldo	*Mora moro*	39	Sutton et al. (2010)
Morid cods			
Red cod	*Pseudophycis bachus*	5	Horn (1996)
Grenadiers, rattails			
Javelinfish	*Lepidorhynchus denticulatus*	13	Stevens et al. (2010)
Ridge scaled rattail	*Macrourus carinatus*	42	Stevens et al. (2010)
White rattail	*Trachyrincus aphyodes*	89	NIWA unpublished

Sharks			
Spiny dogfish	*Squalus acanthias*	30	Henderson et al. (2002)
Shovelnose spiny dogfish	*Deania calcea*	35	Clarke et al. (2002)
Baxter's dogfish	*Etmopterus baxteri*	26-57	Irvine et al. (2006b)
Longnose velvet dogfish	*Centroscymnus crepidater*	54	Irvine et al. (2006a)
Slickheads			
Black slickhead	*Xenodermichthys copei*	39	NIWA unpublished
Medusa fishes			
Bluenose	*Hyperoglyphe antarctica*	76	Horn et al. (2010)
White warehou	*Seriolella caerulea*	21	Horn (1999)
Silver warehou	*Seriolella punctate*	23	Horn & Sutton (1996)
Cutthroat eels			
Basketwork eel	*Diastobranchus capensis*	32	NIWA unpublished

2. Ecosystem Outcome

Current knowledge

The intended outcome is that the fishery does not cause serious or irreversible harm to the key elements of ecosystem structure and function. The key elements include key prey, predators, community composition, productivity patterns, and biodiversity. Existing knowledge of the key prey and predators is summarised in Figure 1.

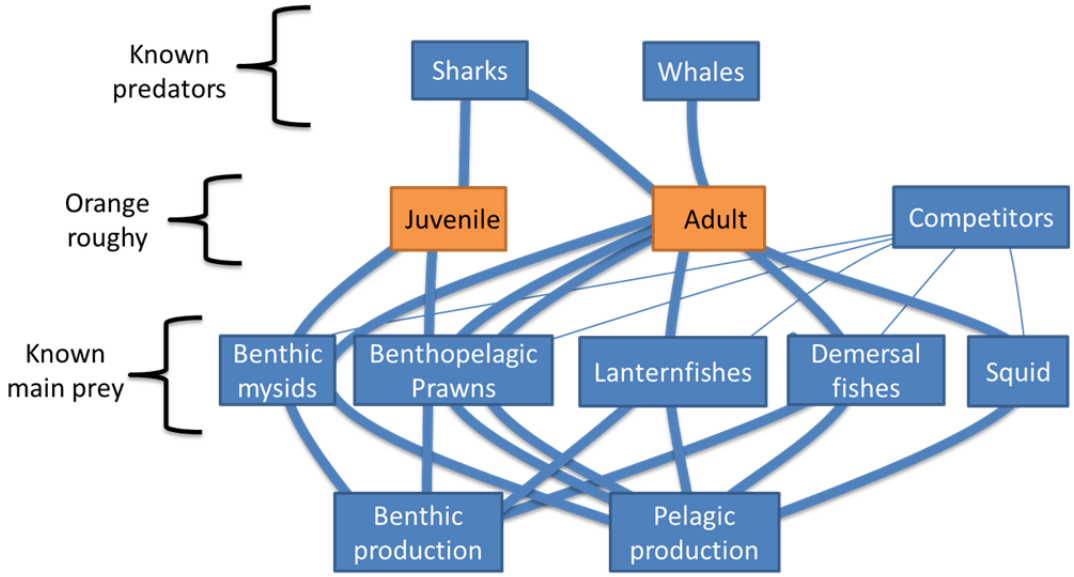

Figure 1: A simplified food web for orange roughy, as juveniles and adults. Energy flows from the bottom to the top.

Knowledge of key prey

The diet of orange roughy is known fairly well, and has been described in detail off Australia (Bulman & Koslow 1992), and off New Zealand on the Challenger Plateau and Chatham Rise (Rosecchi et al. 1988) and southeast North Island (Dunn & Forman 2011).

Further basic information on diet composition on Chatham Rise has also been published (Clark et al. 2000; Jones 2007), and extensive diet samples (over 100,000 stomachs) collected during research surveys around New Zealand have been summarised, although not analysed in any detail

(Stevens et al. 2011). Note that (at least) the Clark et al. (2000) data set and most of the Jones (2007) data set is subsumed in the data set described by Stevens et al. (2011). There are at least three other studies of orange roughy diet from elsewhere in the world (Branch 2001).

Additional to this, samples of predominantly juvenile orange roughy stomach contents have been collected during research surveys on Chatham Rise since 2010 (Darren Stevens, NIWA, unpublished).

All diet descriptions have been based upon observed stomach contents, from orange roughy greater than 10 cm standard length (SL).

Over 160 prey species or types have been identified for orange roughy (Stevens et al. 2011), and the diet is dominated by benthopelagic and mesopelagic crustaceans, fishes, and squids. Diet composition changes as orange roughy get larger, with juveniles eating more small crustaceans, and adults eating more fishes (Bulman & Koslow 1992; Rosecchi et al. 1988; Dunn & Forman 2011; Stevens et al. 2011). Research has also found changes in orange roughy diet composition can been associated with changes in depth, area, year, or water temperature (Bulman & Koslow 1992; Rosecchi et al. 1988; Dunn & Forman 2011).

Have the key prey changed?

Although there has been no long-term consistent monitoring of orange roughy diet, the diet descriptions seem to be fairly consistent, which tends to suggest no dramatic change in orange roughy diet has occurred. Bulman & Koslow (1992) reported a year effect, but only sampled two consecutive years. Clark et al. (2000) concluded no change in basic diet composition on Chatham Rise using samples from 1984–96, although samples were taken on and around the spawning grounds during the spawning season (i.e., not on feeding grounds during the feeding season). Jones (2007) described a decline in squid in the diet of orange roughy, but personally I do not find this analysis convincing (sample stratification is not corrected, nor is uncertainty taken into account).

Knowledge of key predators

There are only a few records describing orange roughy predators. There are anecdotal stories of toothed whales (sperm whales in particular) being associated with orange roughy spawning aggregations. The only scientific study I am aware of which support whales eating orange roughy is Gaskin & Cawthorn (1967), who found orange roughy were the commonest single species of fish found in the stomachs of sperm whales harvested from Cook Strait during 1963 and 1964.

Some deep-sea sharks are known to eat orange roughy. Wetherbee (2000) provides an anecdotal report of orange roughy in the stomachs of four species of deep-water shark from Chatham Rise; the species were *Etmopterus granulosus* (= *E. baxteri*), *Centroscymnus owstoni*, *Centrophorus squamosus* and *Dalatias licha*. In a detailed study, orange roughy were found to be the most important prey of *E. baxteri* off Tasmania (Hallett & Daley 2011). Pethybridge et al. (2011) found one orange roughy in the diet of 98 *E. baxteri*, and one in five *D. licha* off Tasmania. Anecdotal evidence of direct predation (i.e., not scavenging) on orange roughy is given by occasional observations of bitten orange roughy, presumably the culprit being a shark judging by the bite shape, where the orange roughy subsequently survived and actually healed. It is possible that other orange roughy do not survive the attacks, and are fully consumed. Similar bite marks are also sometimes seen on smooth oreos (Figure 2).

Figure 2: Examples of smooth oreo (*Pseudocyttus maculatus*) from Chatham Rise which have been bitten, but subsequently survived, and the wound healed (these fish were ~30 cm in length). I have seen orange roughy from Chatham Rise with similar wounds, although diet descriptions of potential predators (sharks) on Chatham Rise have not yet found orange roughy as prey. The bites are nearly always in a similar place; I recall seeing only one bite to the posterior anal region. This suggests attack usually from above and behind, or that only those attacked in this way actually survive.

Records of orange roughy being eaten by teleost (bony) fishes are extremely rare. Stevens et al. (2011) reported just one orange roughy eaten in a sample of 18 000 ling, and four eaten in a sample of nearly 106 000 orange roughy (i.e., cannibalised). Stevens et al. (2011) found no orange roughy in the diets of many potential orange roughy predators, including black oreo, alfonsino, sea perch, bluenose, stargazer, hoki, hake, smooth oreo, and barracouta. No orange roughy were found in 11 254 stomachs from 25 species sampled at 200–800 m on Chatham Rise during 2004–2007 (Dunn et al. 2009).

The rarity of data on orange roughy predation is at least consistent with the species' high longevity and low natural mortality rate. Nevertheless, the scarcity of predated orange roughy is striking, and suggests small orange roughy might have been either (a) somewhere else, or (b) rare or absent, at the time the stomach samples were collected.

Have the key predators changed?

Clark et al. (2000) reported that biomass estimates from stratified random trawl surveys of the east Chatham Rise (in the orange roughy Spawning Box) between 1984 and 1996 decreased substantially for Baxter's dogfish and Plunket's shark. Conversely, however, the biomass estimates for Shovelnose dogfish, Owston's dogfish, and longnose velvet dogfish, increased over the same period. Doonan & Dunn (2011) reported biomass estimates for sharks from stratified random trawl surveys of the Mid-east Coast in 1992–94 compared with 2010, and found a significant decline in biomass for longnose velvet dogfish, but an increase for Lucifer's dogfish, and no change for four other shark species (Table 4).

I have not seen any biomass estimates for sperm whales for the New Zealand region (only worldwide). However, whale population sizes were presumably reduced as a result of whaling during the last century.

Table 4: Biomass estimated from the Mid-east Coast research trawl survey (Table 7.3 from Doonan & Dunn 2011). For species other than orange roughy, abundances (Abd, t) and cv (%) from the 1992–94 and 2010 surveys using all relevant tows. Also shown is the mean abundance over the 1992–94 surveys, the ratio of the change between the mean 1992–94 abundance to that from 2010, and the t-test of the mean 1992–94 abundance to 2010 (coded yellow for significant at the 5% level).

Species		2010		1992		1993		1994		Ratio A2010/	Combined 92-94		t-test
Code	Common name	Abd	Cv	Abd	Cv	Abd	Cv	Abd	Cv	A92-94	Abd	Cv	
BYS	Alfonsino	182 267	100	0	0	7 120	91	9	58	7 670	2 376	91	1.0
BEE	Basketwork eel	698	11	470	16	1 120	14	755	12	89	782	8	-0.8
ETB	Baxters lantern dogfish	752	15	535	19	2 543	53	1 022	15	55	1 366	33	-1.3
CBO	Bollons rattail	1 256	43	713	34	1 191	33	995	30	130	966	19	0.5
APR	Catshark	76	20	63	26	61	29	66	22	120	63	15	0.7
CSQ	*Centrophorus squamosus*	499	24	312	23	534	36	291	25	132	379	19	0.8
CYP	*Centroscymnus crepidater*	410	11	1 698	13	2 874	63	1 018	41	22	1 863	33	-2.3
EPT	Deepsea cardinalfish	328	89	2 683	94	95	28	200	41	33	992	85	-0.7
CSU	Four-rayed rattail	406	19	238	17	347	14	265	15	143	283	9	1.5
HOK	Hoki	5 465	30	7 664	37	6 822	38	5 340	15	83	6 609	20	-0.5
JAV	Javelin fish	2 272	22	553	22	1 165	34	1 434	16	216	1 050	15	2.3
HJO	Johnson's cod	1 465	17	388	13	604	10	561	12	283	518	7	3.8
LCH	Long-nosed chimaera	418	19	261	16	340	14	367	19	130	322	10	1.1
ETL	Lucifer dogfish	38	20	10	34	17	37	17	25	263	15	19	2.9
NNA	*Nezumia namatahi*	11	20	1	58	1	33	3	43	689	2	29	4.1
CIN	Notable rattail	96	38	15	56	30	20	24	11	414	23	15	2.0
GSP	Pale ghost shark	660	8	472	23	784	24	994	32	88	750	17	-0.6
RIB	Ribaldo	972	13	763	13	901	20	758	12	120	808	9	1.1
MCA	Ridge scaled rattail	313	13	422	56	283	11	217	12	102	307	26	0.1
CTH	Roughhead rattail	147	24	0	0	0	0	0	0		0		
CSE	Serrulate rattail	558	15	275	14	356	8	313	11	177	314	6	2.8
SND	Shovelnose spiny dogfish	12 023	21	9 845	17	13 426	17	14 905	22	94	12 725	11	-0.2
SRH	Silver roughy	147	46	77	51	67	29	54	48	222	66	26	1.2
SSM	Slickhead bigscaled brown	6 223	10	5 108	15	9 079	14	4 234	11	101	6 140	8	0.1
SBI	Slickhead smallscaled brown	826	9	591	12	787	18	638	18	123	672	10	1.5
SMC	Small-headed cod	30	24	11	30	28	26	22	28	146	20	17	1.2
CYO	Smooth skin dogfish	691	15	457	17	553	22	588	21	130	533	12	1.3
SSO	Smooth oreo	7 304	58	5 822	44	2 276	37	2 047	30	216	3 382	27	0.9
SOR	Spiky oreo	2 946	36	1 520	42	2 609	53	2 009	41	144	2 046	28	0.7
TRS	*Trachyscorpia capensis*	23	27	10	46	15	29	3	51	250	9	23	2.1
WHR	Unicorn rattail	593	23	7	67	33	61	95	27	1 324	45	24	4.0
WOE	Warty oreo	536	36	780	57	343	40	160	45	125	428	37	0.4
WHX	White rattail	2 304	12	1 539	10	1 812	12	1 659	11	138	1 670	6	2.2
RCH	Widenosed chimaera	439	16	298	18	431	18	319	15	126	349	10	1.1

Knowledge of key competitors

I do not know of any single substantial ecosystem-study of diet at orange roughy depths. I know of five studies at depths of ~200–800 m (see Dunn et al., in prep.). Diet information for a wide range of species (*n* = 70) at orange roughy depths in the North Atlantic were collated by Heymanns et al. (2011), although the details of the diet data were not reported, and key competitors to orange roughy were not identified.

Black oreo are known to have a similar diet to orange roughy (Clark et al., 1989). Based on existing diet data, potential competitors for juvenile orange roughy include alfonsino, lookdown dory, Oliver's rattail, and javelinfish (Dunn et al., 2009). Potential competitors for adult orange roughy include squid, hake, hoki, Ray's bream, Owstons dogfish, longnose velvet dogfish, shovelnose dogfish, Baxter's dogfish, Lucifer's dogfish (Dunn et al., 2009, 2013). Johnson's cod is also suspected to be a competitor; I believe their diet was described (to some extent) in the North Atlantic (by Mauchline?) by I didn't have time to track this down. Trawl caught Johnson's cod have near 100% everted stomachs, effectively precluding description of diet from stomach contents.

Have key competitors changed?

Trawl survey data for Chatham Rise 1984-96 (Clark et al.,2000) and the Mid-East Coast (Table 4) indicate significant biomass changes in some orange roughy potential competitors. One of the largest changes on the Mid-east Coast was for Johnsons cod (Table 4), a species suspected to be an orange roughy competitor, and caught during targeted orange roughy fishing. The diet of other species showing significant biomass changes, including four species of grenadier (javelinfish excluded; Table 4) have been poorly described, if at all (Jones 2008; Stevens & Dunn 2011; Stevens 2012). As a result, with current knowledge the relevance of these particular changes to ecosystem dynamics (if any) and impacts of orange roughy fishing is speculative.

Community composition, productivity patterns, and biodiversity

Descriptions of community composition, productivity patterns, and biodiversity, are more common for deep sea benthos than for fishes. The focus of such research has been on quantifying and mapping biodiversity. Research has shown deep-sea benthic fauna exploit resources of both benthic and pelagic origin. There is a time series of mesopelagic biomass on Chatham Rise for depths at and around 200-800 m (O'Driscoll et al., 2011), and research on species composition and ecology of the mesopelagic layers is underway at NIWA (Matt Pinkerton and others, pers.comm.)

Benthic biodiversity surveys have shown that trawls remove exposed fauna such as corals and sponges. The implications of this, however, remain poorly known. I have often heard that corals may offer refuges and resources for juvenile fish, but evidence for this is lacking (Baillon et al., 2012). Benthic biodiversity surveys have included fished and unfished areas (e.g., Clark & Rowden 2009), but otherwise baseline data are lacking. I do not know of any "stock assessment" research to identify initial population size, and current status, of benthic fauna such as sponges and corals. Stock assessment research is also lacking for many by-catch species, but NIWA and Victoria University (VUW) both have research underway in this area (e.g., a postgraduate student at VUW is currently conducting stock assessment research for macrourids on Chatham Rise; NIWA is evaluating, and making operational, assessment methods for data-poor stocks).

Theoretical and research considerations

To go from speculation to statement, we need to know more about the role of species, and about the driving factors. Driving factors may be environmental, or biological; i.e., have some grenadiers increased in biomass because the environment has become more favourable allowing them to extend their distribution and/or abundance, or because of predation or competitive release after orange roughy or by-catch species are reduced?

There are undoubtedly more data available on the diets of deep-sea species, and greater clarity can be brought, but such a review is beyond the scope of this document. Species of particular interest may be white rattail, spiky oreo, Johnson's cod, ribaldo, Baxter's dogfish, and basketwork eel. Because of problems with stomach eversion in some of these species, alternative and/or complimentary methods might be used to improve confidence in diet descriptions, in particular where the number of samples available for analysis may be limited (e.g., fatty-acid analyses, DNA prey identification; e.g., Dunn et al., 2010; Pethybridge et al., 2011). Further research on sharks would help us to understand the importance of these predators to orange roughy dynamics (and *vice versa*).

Data sets do exist that might be used to evaluate spatial, temporal, and biological patterns in species distribution, community composition, and biodiversity, but such studies are currently lacking, or have not deliberately and usefully targeted ecosystem components that might be used to monitor the effects of orange roughy fishing. The time series of research trawl data sets from Challenger Plateau and Mid-east Coast provide data that could be used for such analyses. There is

not a consistent long-term survey series for Chatham Rise, but the inclusion of deep-water strata in the middle-depths survey (MPI; summer surveys) provides a potential data set, and monitoring tool, for the future. For the Mid-East-Coast, preliminary analyses have been done, and changes in species composition do appear to have occurred. The value of this analysis would be improved by understanding the role of each species, and another survey would increase the power and confidence in conclusions.

As far as I am aware, the only recent and potentially on-going time series of orange roughy diet samples is that on Chatham Rise from 2010 (Darren Stevens, NIWA, unpublished); to continue this would require the deep-water strata be included in the January surveys, and that there is continuing (NIWA at present) support to process the samples.

Probably the least understood component of the orange roughy ecosystem is the mesopelagic habitat and fauna. The demersal community is perhaps the easiest to study, because it is sampled during fisheries resource surveys and fishing activities. Benthic research surveys are relatively specialist, but have been much more frequent than mesopelagic surveys (Malcolm Clark or Ashley Rowden would be the best sources for further information on these surveys). NIWA is currently conducting some research on mesopelagic layers on Chatham Rise (Matt Pinkerton, Richard O'Driscoll). Monitoring of mesopelagic biomass on Chatham Rise has suggested no significant change between 2001 and 2010 (O'Driscoll et al., 2011); although this survey is predominantly at depths shallower than orange roughy, the mesopelagic resources presumably overlap (although this is supposition).

The flux of nitrate from deep water is the primary method of renewal in the ocean (rather than regeneration in surface layers). This is readily apparent as seasonal phytoplankton blooms, and high productivity in upwelling areas; areas where orange roughy are also often relatively abundant (Chatham Rise, Puysegur). To avoid ecosystem productivity being reduced, any nutrients lost from the system must be replaced by others. This is the rationale behind my thoughts on identifying and monitoring compensatory responses in the fish community (i.e., ensuring there is no net loss of function or nutrients at and directly around the orange roughy trophic level). The extent to which fishing may influence the benthic microbial activity and nutrient recycling through bottom trawl damage is beyond scope at present, but needs investigation. If benthic damage by trawls does reduce microbial activity and nutrient recycling in the deep sea, then in principle this could reduce overall production. However, even if bottom trawls did reduce benthic recycling, is, for example, bottom trawling on Chatham Rise extensive enough to have any material impact, especially when the nutrients driving primary production may come from deep subantarctic currents? There is clearly an issue of scale, and source, here. I would expect there to be some general research available on this issue (and experimental approaches could be imagined), but I have not had time to investigate.

In the longer-term, and in principle, measures to reduce, minimise, or mitigate benthic impact may help benthic processes to remain intact, despite a fishery. The trawl footprint alone may provide a measure of fishery impact on benthic processes. However, the deliberate reduction of orange roughy stocks towards Bmsy results in a permanent shift in community composition. Focusing research and monitoring around the orange roughy functional role may therefore be an important long-term objective.

3. Ecosystem management

This refers to measures in place to ensure the fishery does not pose a risk of serious or irreversible harm to ecosystem structure and function. I believe approaches discussed above do, to some extent, address the risk. Identifying limits and responses is much harder. The most obvious approach to use is simulation ecosystem modelling with management strategy evaluation (MSE).

The first step in this process would be to develop qualitative models (Figure 1 is the basis of a qualitative model). This approach can be deployed relatively quickly, readily incorporates stakeholder advice and input, provides a useful overview, and can identify key system components

and processes, trends and trade-offs. However, qualitative models lack the explicitness and accountability of quantitative approaches, and in large models the effects are very likely to become ambiguous (Fulton 2010).

Quantitative models require greater understanding and data. We probably do have enough information to start creating quantitative ecosystem models for the deep sea (Heymans et al., 2011). Nevertheless, highly complex quantitative ecosystem models are vulnerable to model misspecification in structure and parameters. Yet simplified models may under-estimate resilience. The best tool for quantitative research would, in my opinion, be ATLANTIS (Fulton et al., 2011). Research might initially test ecosystem response against a small set of pre-specified scenarios (Kaplan et al., 2012), targeting the identification of strategies to mitigate changes in each main ecosystem driver. The development of an ATLANTIS model might be a longer-term research objective, requiring a multi-disciplinary and multi-year research project. In the foreseeable future, the uncertainties in ecosystem models will still favour them as strategic, rather than tactical, tools.

4. Ecosystem monitoring

Essentially, I have argued to research and monitor ecosystem characteristics (e.g., biodiversity) and components (e.g., species) that are indicative of, or directly linked to, the dynamics and maintenance of ecosystem function. These will be specific to the fishery in question.

I have tended to discuss aspects of monitoring and data availability throughout, so I won't repeat them here. The MSC suggests that the impact of fishing on ecosystem structure is often inferred from impacts to populations, species and functional groups, and ecosystem function inferred from impacts on ecosystem processes and properties such as trophic relationships, and community resilience. I would argue that structure and function are closely linked and can be seen as the same thing, and the ideas presented above would combine to address both issues. The additional issue of monitoring and information methodology and quality is detailed and case specific, and I'm not going to address it here.

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