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Evaluation of Potential Sustainability of Deep-Sea Fisheries for Grenadiers (Macrouridae)[1]

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Abstract—The ability of six grenadier species from the North Atlantic, North Pacific, and Southern Ocean to sustain deep-sea fisheries is assessed. These species are captured in high amounts as bycatch and a few are taken in targeted fisheries, yet population status for most is poorly known or known for only a small portion of their range. A productivity and susceptibility analysis showed that none of the species was highly productive, which was not unexpected given their life history characteristics. While grenadiers were ranked more vulnerable than species in the northeastern Pacific groundfish fisheries, none of the investigated species was ranked as highly susceptible or heavily exploited. This result exposed several weaknesses in the PSA technique and attribute scoring. Management actions and regulations are discussed, which, if employed, might make grenadier fisheries sustainable.

Keywords: grenadier, *Albatrossia, Coryphaenoides, Macrourus*, deep-sea, fisheries, productivity, susceptibility, vulnerability, North Atlantic, North Pacific, Southern Ocean

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The increase of fisheries activity in the deep-sea, in part as a response to fully exploited or collapsed continental shelf fisheries (Morato et al., 2006), and their deeper and wider reaching impacts on populations (Bailey et al., 2009; Priede et al., 2011) and habitat (Roberts, 2002; Althaus et al., 2009) has raised the question of whether deep-sea fisheries can be sustainable (Roberts, 2002; Norse et al., 2012). Fisheries exploiting the deep-sea have occurred in many areas since the late 1960s and early 1970s (e.g., northwest Atlantic, Atkinson, 1995; northeast Atlantic, Allain et al., 2003), but exploitation has increased worldwide in the past decades (Morato et al., 2006; FAO, 2009). Beginning in 2004, the United Nations adopted a series of resolutions on deep-sea fisheries (e.g., 59/25, 61/105, 64/72), which included calls for the identification and protection of vulnerable marine ecosystems and regulation of bottom fisheries (UNGA, 2004, 2007, 2009). The Food and Agriculture Organization (FAO) adopted guidelines in 2008 to assist state and regional fisheries management organizations (RFMOs) in sustainable management of deep-sea fisheries on the high seas, in which some progress has been made, albeit not enough (Rogers and Gianni, 2010; Weaver et al., 2011; Norse et al., 2012). These regulations require RFMOs to fish both targeted and bycatch species in a sustainable manner consistent with the precautionary approach, as stated in the FAO Code of Conduct for Responsible Fisheries. The RFMOs must also prevent significant adverse impacts to vulnerable marine ecosystems (Weaver et al., 2011).

There are few groups of deep-sea fishes that attain large enough size and sufficient abundance to be of any commercial importance (Merrett and Haedrich, 1997). Of these, fishes in the family Macrouridae (grenadiers or rattails) tend to be captured in virtually all deep-sea fisheries around the world (Orlov and Iwamoto, 2008). The group consists of roughly 400 species that are globally distributed across a wide depth range (~200–7000 m; Iwamoto, 2008), hence fisheries occurring on the upper and middle continental slopes capture these species, either as bycatch (most common) or as a target, if the species are large or form dense aggregations. Many of the species in this

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Table 1. Summary of life history characteristics for six species of grenadiers

Species	Max longevity, years	Age 50% maturity	Natural mortality, M	Fecundity	*K*	*r*	Trophic level	Spawning season	Citation
Giant	58	23	0.052–0.12	35–231	0.022	0.26	4.32	All year	1, 6, 21, 35, 83
Pacific	73	20–40	0.057, 0.16	22.6–150	0.041	0.22	3.8	All year	1, 6. 20, 35, 62, 87, 92
Popeye	15–22	3–6	0.295, 0.22	17	0.13	0.66	3.66	All year	1, 6, 35, 92
Roundnose	50–72	8–14	0.076–0.2	2.5–70	0.03–0.128	0.157–0.512	3.54	All year	4, 10, 14, 18, 35, 52, 53, 59, 60, 72
Roughhead	25–28	13–16	0.043–0.2	8.5–80	0.031–0.246	0.12	4.48	All year	10, 35, 66, 67, 72
Ridge-scaled	37–42	11–13	$Z = 0.15$	15–57	0.069–0.108	–	3.75	Unknown	35, 57, 96, 97

Note: Fecundity ranges, expressed in 1000 s, may not reflect true estimates if grenadiers do not spawn annually. Age estimates were restricted to otolith-only studies. *K* is the von Bertalanffy growth coefficient and *r* refers to the intrinsic rate of population increase. Citation numbers refer to numbers in the reference list.

family are small or unpalatable, thus they are not directly marketable, but are either discarded or processed as fishmeal (Matsui et al., 1990; Iwamoto, 2008). A few fisheries have targeted grenadiers specifically (see examples below), but were incapable of sustaining high catch levels (Haedrich et al., 2001; ICES, 2011). New directed grenadier fisheries will most likely develop (e.g., Clausen, 2008; Tuponogov et al., 2008) and, if deep-sea fisheries continue to expand, their capture as bycatch will invariably continue or even increase.

The life history characteristics of grenadiers are not conducive to intensive exploitation. A review of the available information for six of the larger species indicates high longevity, low fecundity, slow growth, and late age at maturity (Table 1). Even smaller species, which are shorter-lived, have relatively slow mass-specific growth (Drazen, 2008), suggesting that they could be greatly depleted by moderate exploitation rates. They have very low metabolic rates (Drazen and Seibel, 2007) and an energy budget analysis of the Pacific grenadier *Coryphaenoides acrolepis* suggests that females may require two or more years to develop adequate energy stores to spawn (Drazen, 2008). Histological examination and time series sampling of gonads suggests a similar situation for ridge-scaled grenadier *Macrourus carinatus* in the Southern Ocean (Alekseyeva et al., 1993), giant grenadier *Albatrossia pectoralis* in the North Pacific (Tuponogov et al., 2008), and possibly roundnose grenadier *Coryphaenoides rupestris* in the northeast Atlantic (Kelly et al., 1996). This means that the fecundity estimates may actually be two times higher than realized annual reproductive output.

An important question is whether grenadiers are currently fished sustainably, including those cases where the species is taken as bycatch in fisheries for other species. A large factor inhibiting quantitative assessment of sustainability is the lack of catch statistics. When recorded in the catch, rattaiis are generally not differentiated by species, but are aggregated in an unspecified category, e.g., "grenadiers", "other fish". Data on a few grenadier species, usually the larger species (50–200 cm maximum total length), are available from some RFMOs (e.g., Gonzalez-Costas and Murua, 2008).

Here, we assess the sustainability of grenadier fisheries by focusing on six of the larger species: giant *Albatrossia pectoralis*, Pacific *Coryphaenoides acrolepis*, popeye *C. cinereus*, roundnose *C. rupestris*, roughhead *Macrourus berglax*, and ridge-scaled *M. carinatus*. First, we describe the existing fisheries and known population status for these species. To evaluate the vulnerability of grenadiers, we employ a risk analysis procedure called a productivity-susceptibility analysis—PSA (Milton, 2001; Stobutzki et al., 2001), which has recently been used to assess the vulnerability of several data-poor fish stocks (e.g., Patrick et al., 2009; Field et al., 2010). We then suggest sustainable management actions for grenadier fisheries.

Giant grenadiers *Albatrossia pectoralis* are captured in the groundfish trawl and longline fisheries operating off the west coast of North America, but all are discarded (Benson and McFarlane, 2008; Clausen, 2008; Dick and MacCall, 2010). In Alaska, grenadiers have not been part of the fishery management plans for many years, which means that no recommendations for acceptable biological catch limits, TACs, or overfishing levels are currently required (Clausen and Rodgveller, 2010). However, there have been recent suggestions to include grenadiers in the management plans as "in the fishery", which would result in active management of the species. Giant grenadiers are also not in the fisheries management plans within Canadian or the Pacific Fisheries Management Council (PFMC; pertains to US West Coast) regions. Bycatch of *A. pectoralis* can be extremely high. Amounts caught within the Alaskan management region between 1997–2010 were similar to the catch of sablefish *Anoplopoma fimbria*, a commercial species with a directed fishery (Clausen and Rodgveller, 2010). Recent gear changes in this fishery from longlines to pots may reduce the amount of giant grenadier bycatch (Clausen, 2008; Hanselman et al., 2009). Within Canadian and PFMC regions, giant grenadier is one of the top species in the bycatch in terms of catch weight (Benson and McFarlane, 2008; Dick and MacCall, 2010). Small directed fisheries were attempted by Alaskan fishermen in 1998 and 2005 (Clausen, 2008), but the extremely soft and watery flesh has limited consumer appeal (Matsui et al., 1990). Some interest exists in fisheries for livers and roe (Orlov and Tokranov, 2008). Within Alaskan waters, the current population status is not considered overfished (Clausen and Rodgveller, 2010), but their status in other areas can only be inferred from bycatch. Females generally occur shallower than males and there is concern that, due to the depths the fisheries operate, disproportionate removal of female fish is occurring, which could reduce the spawning potential of the stock (Clausen and Rodgveller, 2010). Perhaps of greater concern is the important ecological role giant grenadier are suspected to have due to their high abundance and biomass, which is higher than many important commercial species (Hoff and Britt, 2011), and importance as prey for many large sharks and whales (Clausen and Rodgveller, 2010).

Pacific grenadier *Coryphaenoides acrolepis* is considered to be a high-quality food fish and is sold as fresh or frozen fillets (Abbott, 2006); in the past, it was also taken for surimi, but other species have since replaced it (Matsui et al., 1990). Experimental longline fishing found extremely high abundance in some locations off Alaska, but Pacific grenadiers are found deeper than the depths most fisheries operate in this area, therefore, currently they are not considered at risk of overexploitation in the Alaskan region (Clausen and Rodgveller, 2010). Within Canadian waters, *C. acrolepis* is captured in both trawl and longline fisheries, particularly in the thornyhead *Sebastolobus* spp. fishery, but recent declines in effort have resulted in less bycatch (Benson and McFarlane, 2008). Pacific grenadiers were targeted off California, where catches peaked at approximately 1200 t in 1996 (Pearson et al., 2008). But, largely through restrictions on the mixed-trawl fishery off the US West Coast, fishing effort has been dramatically reduced (Abbott, 2006). The species is in the PFMC fisheries management plans, but because it is listed within the "other fish" complex, landed catch does not have to be specified to species (NWFSC, 2010). Currently, the PFMC has set a median overfishing limit, which is the yield resulting from fishing at the F_{MSY} harvest rate (the level of fishing mortality that results in the greatest yield from the fishery (Quinn and Deriso, 1999), for the grenadier complex at 1796 t (Dick and MacCall, 2010). The high abundance of *C. acrolepis* off California and the high quality of its flesh means there is potential for a directed fishery to occur again, but concerns exist over whether the species can sustain harvest (Matsui et al., 1990). Very few biomass estimates are available and those that are tend to cover only the upper portion of the species' range (e.g., Clausen and Rodgveller, 2010; Hoff and Britt, 2011). A deep-water survey (500–1600 m) off Canada's Pacific coast in 2003 found Pacific grenadier was the second most abundant species (Krishka et al., 2005). Russian investigations have also found commercially exploitable concentrations and relatively high biomass in the western Bering Sea and near the Kurils (Tuponogov et al., 2008).

Popeye grenadier *Coryphaenoides cinereus* tend to be captured more in the bottom-trawl fisheries operating around Alaska and are rarely taken by longline (Clausen and Rodgveller, 2010). The amount of reported *C. cinereus* bycatch in Canadian and the US West Coast fisheries is very low, which may be due to poor species identification (the species is difficult to distinguish from *C. acrolepis*) or their relative rarity in the southern part of their range (Benson and McFarlane, 2008; NWFSC, 2010). Biomass appears to be high in the eastern Bering Sea (Hoff and Britt, 2011), and dense concentrations have been recorded in the Sea of Okhotsk and western Bering Sea, which have the potential to attract targeted fisheries (Orlov and Iwamoto, 2008; Tuponogov et al., 2008). There are currently no management regulations for this species.

Commercial fisheries in the northwest Atlantic targeted the roundnose grenadier *C. rupestris* in the 1960s–1990s (Atkinson, 1995; Haedrich et al., 2001) and in 2008, it was listed as endangered by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC, 2008). Moratoriums are currently in place for this species within the Northwest Atlantic Fisheries Organization (NAFO) Subarea 0 and Canadian waters of Subareas 2 and 3 (DFO, 2010; NAFO, 2010), but catches in international waters adjacent to these regions are regulated primarily through mesh size regulations and closed areas for other fisheries (NAFO, 2010). Roundnose grenadier is taken as bycatch, mainly in the Greenland halibut *Reinhardtius hippoglossoides* fishery and, to a lesser extent, the deep-water shrimp fishery, with bycatch estimates ranging from 60–5400 t $year^{-1}$ since 2000 (NAFO 21A STATLANT database, www.nafo.int). Bycatch exceeding 1250 t was predicted to impede recovery of roundnose grenadier (DFO, 2010).

In the northeast Atlantic, *C. rupestris* is one of several target species in a mixed-species deep-water fishery (Lorance et al., 2008; Bensch et al., 2009) and is also taken as bycatch in other fisheries (Basson et al., 2001; Gordon et al., 2003). Catches have declined in recent years, partially as a consequence of decreased TACs for grenadier and other deep-water species, which have been in place since 2003 and are revised every second year (ICES, 2011). Furthermore, regulations such as landing and on-board observer obligations and fishing effort limits are in place for EU vessels, while minimum size limits exist in Faroes waters

(ICES, 2011). Nevertheless, high discard levels (approximately 50% by number and 30% by weight) are reported in some areas, although rates around 20% tend to be typical in most fisheries (Pawlowski and Lorance, 2009; ICES, 2010). A small target fishery existed in the Skagerrak (International Council for the Exploration of the Sea (ICES) Division IIIa) until 2007, but current landings are extremely low (<2 t; ICES, 2011). Biomass west of the British Isles was estimated to be between 15–23% (Basson et al., 2001) and ~30% of virgin biomass (Lorance et al., 2008). Within the Skagerrak, biomass is low but no formal assessment has been completed (ICES, 2011). There are concerns that *C. rupestris* populations are declining (Priede et al., 2011) and that the effects of fisheries in this area may be felt far beyond the depths of current operation (Bailey et al., 2009). However, a recent study noted biomass of *C. rupestris* has recently stabilized west of the British Isles (ICES Division VIa; Neat and Burns, 2010), likely as a result of reduced TACs and modified deep-sea fishing regulations (ICES, 2011).

The roughhead grenadier *Macrourus berglax* is principally taken as bycatch in the Greenland halibut and deep-water shrimp trawl fisheries in the northwest Atlantic (Gonzalez-Costas and Murua, 2008; NAFO, 2010), but catches have declined in recent years as a result of decreased effort for targeted species (NAFO, 2010). *M. berglax* was listed as ‘Special Concern’ by COSEWIC partially due to large declines in abundance noted in the 1980s and 1990s (Devine et al., 2006; COSEWIC, 2007). NAFO assessments show that biomass of roughhead grenadier has been increasing outside of Canadian waters since 1995 (NAFO, 2010), mainly as a result of decreased fishing mortality (Gonzalez-Costas, 2010). In the northeast Atlantic, *M. berglax* is commonly taken in the mixed deep-water fisheries (Gordon et al., 2003; ICES, 2010) and in small amounts in fisheries targeting *C. rupestris* (ICES, 2011; Durán Muñoz et al., 2012). Misidentifying roughhead catch as *C. rupestris* in the northeast Atlantic and off Greenland is an issue (Lyberth, 2009; ICES, 2011). For management purposes, roughhead grenadier is included in the ‘other species’ group in the northeast Atlantic, but there are currently no set quotas nor are vessels required to hold a Deep-water Fishing Permit to land these species (ICES, 2011). However, both catch and effort information is required to be relayed to management bodies.

Ridge-scaled grenadier *Macrourus carinatus* were targeted in the Southern Ocean by Russian trawlers from 1988–1991, but catches quickly declined within that four-year period (Laptikhovsky et al., 2008). *M. carinatus* is taken as bycatch in fisheries targeting hake *Merluccius* spp., squid *Illex* and *Loligo* spp., and Patagonian toothfish *Dissostichus eleginoides* (Laptikhovsky et al., 2008). Bycatch in the longline fishery for Patagonian toothfish can be as high as 17% of the total catch (van Wijk et al., 2003). Typically, landings are relatively low, around 1100 t annually (Laptikhovsky, 2011). A small target fishery exists in Argentine waters; catches peaked in 2008 at approximately 12000 t, but have since declined (Laptikhovsky, 2011; http://www.minagri.gob.ar/site/pesca/pesca_maritima/index.php). Biomass estimates in international waters of the Southern Ocean are high, ranging between 116000 and 212000 t, while estimates for the Falkland Islands region are around 40000 t (Laptikhovsky et al., 2008; STECF, 2010; Laptikhovsky, 2011). *Macrourus* species (not species-specific) are managed in some areas with a TAC and stipulations that if bycatch in any one haul is equal to or greater than 2 t, the vessel must not fish within 5 nautical miles of that location with that gear for 5 days (Bulman et al., 2007). Ridge-scaled grenadier is also taken as bycatch in New Zealand waters, such as in the orange roughy *Hoplostethus atlanticus* fishery, but it is not known if the species is landed nor are there any current biomass estimates (Stevens et al., 2010).

MATERIAL AND METHODS

How vulnerable are grenadiers to the effects of deep-sea fisheries? To answer this question, we conducted a Productivity-Susceptibility Analysis (PSA), which is a semi-quantitative risk assessment that is useful in data-limited situations. The approach assesses the vulnerability of a stock or species, where vulnerability, or potential to become overfished under the current fishing practices, is a function of a stock’s biological productivity (ability to sustain exploitation or recover after depletion) and susceptibility to the impact of the fishery (Stobutzki et al., 2001). The PSA technique originated in Australia in the early part of this century (Milton, 2001; Stobutzki et al., 2001, 2002), and its use has spread to the eastern North Pacific to assess the vulnerability of US fish stocks to overfishing (Patrick et al., 2009). It has subsequently been applied to California nearshore finfish species (Field et al., 2010), US West Coast (Cope et al., 2011) and Alaskan groundfish (Ormseth and Spencer, 2011), Arctic charr *Salvelinus alpinus alpinus* in Nunavut (Roux et al., 2011), and bycatch species from Atlantic tuna fisheries (Arrizabalaga et al., 2011).

The PSA technique evaluates and scores an array of productivity and susceptibility attributes for a stock, typically on a scale of 1 (low) to 3 (high). Attributes can be assigned a relative-importance weighting, which reflects the relative importance of each criterion (Stobutzki et al., 2001). Plots of the weighted average of productivity and susceptibility are then made. Stocks that score on the low end of the productivity and high end of the susceptibility scale are considered most vulnerable, while those on the high productivity/low susceptibility end are least vulnerable. A vulnerability score is calculated by measuring the Euclid-

Table 2. Productivity and susceptibility attributes used in the analysis

Productivity attribute	Susceptibility attribute—Patrick et al., 2009	Status attribute—Berkson et al., 2011
Maximum age	Areal overlap	Overall fishery exploitation based on assessed stocks
Maximum size	Geographic concentration	Presence of natural or managed refugia
Intrinsic rate of population increase, *r*	Fishery impact to essential fish habitat or habitat in general for non-targets	Schooling, aggregation, or other behaviors affecting capture
Estimated natural mortality, *M*	Seasonal migrations	Morphology affecting capture
von Bertalanffy growth coefficient, *K*	Schooling, aggregation, or other behaviors affecting capture	Natural mortality compared to dominant species in the fishery
Fecundity	Vertical overlap	Bycatch or actively targeted by the fishery
Breeding stratery	Morphology affecting capture	Rarity
Rectuitment pattern	Desirability/Value of the fishery	Value or desirability
Age at maturity	Management strategy	Trend in catches, used only when effort is stable
Mean trophic level	Fishing rate relative to *M*	
	Biomass of spawners, *SSB*, or other proxies	
	Survival after capture and release	

Table 3. Summary of current biomass and fishery information for six grenadier species

Species	Fishery type	Depths of maximum abundance	Current fishing effort, F	Biomass	Current management regime	Citation
Giant	BT, LL, BGL	400–1500	Low	High	Russia: TAC, USA: unregulated	16, 21, 55, 69, 75, 92
Pacific	BT	700–1500	Was high, now low	Russia, California: high Rest of range: unknown	Unregulated; in PFMC plans	6, 20, 21, 45, 51, 55, 62, 87, 92
Popeye	BT	400–1400	Low	Russia: high, patchy Rest of range: unknown	Russia: TAC, USA: unregulated	21, 45, 75, 92
Roundnose	BT	400–1500	NWA low, NEA high, Skagerrak low	NWA: low, moratorium NEA: 15–30% B_0 Skagerrak: unknown	NWA: Regulated (BT closed areas, moratorium), NEA: TAC	47, 59, 60
Roughhead	BT, LL	800–1500	Low	NWA: increasing NEA: unknown	NWA: unregulated NEA: catch & effort	37, 38, 47
Ridge-scaled	BT, LL	200–1000	Low	Moderate	TAC, bycatch regulations	56, 57, 96

Note: Fishery type refers to bottom trawl (BT), longline (LL) or bottom gill net (BGL). The letters in parentheses under "Current Management Regime" refer to the country, area or organization of jurisdiction: USA is the United States of America, NWA is northwest Atlantic, NEA is northeast Atlantic, NZ is New Zealand, PFMC is Pacific Fishery Management Council, and CCAMLR is the Commission for the Conservation of Antarctic Marine Living Resources. TAC is total allowable catch and B_0 is virgin biomass. Citation numbers refer to numbers in the reference list.

ean distance of the data point from the plot origin (Patrick et al., 2009).

Productivity and susceptibility were estimated using the attributes and scales outlined in Patrick et al. (2009) and also the status attributes of Berkson et al. (2011), which were designed for species that have only historical catch data (Table 2). All attributes were scored either 1 (low susceptibility or low exploitation), 2 (moderate), or 3 (high), but, similar to Patrick et al. (2009), we allowed intermediate scores (e.g., 1.5, 2.5). When a species was known to have one attribute in part of its global range but another elsewhere, scores for the areas were averaged. Evaluation of attributes were based on published data (e.g., Tables 1, 3), but where attributes were more subjective, the opinions of the coauthors, all with expertise in deep-sea fisheries or grenadier life history, were used. Several of the attributes either did not apply to the grenadiers or no information existed to evaluate the attribute. Unknown attributes can be left blank (no score),

Table 4. Data quality tiers used for evaluating productivity and susceptibility scores, based on scoring outlined in Patrick et al. (2009)

Score	Description	Example
1	Best data. Information is based on collected data for the population/area of interest	Data rich stock assessment, published literature that uses multiple methods, estimated using models (data, not theory based)
2	Adequate data. Information with limited coverage, (e.g., from part of the range, not the entire range), or not as reliable as tier 1 data	Limited temporal or spatial data, relatively old information, estimated using other data or life history characteristics, e.g., *M* estimated using Hoenig (1983) or Jensen (1996) technique
3	Limited data. Estimate with high variation and limited confidence. Estimates may be based on similar taxa or life history strategy	May be based on what is known in general or information comes from part of the global range, may be from dubious methods, or the studies are more than 30 years old. Data may be from a different population, when population structure is known, e.g., using *C. rupestris* estimates from the Skagerrak for the NW Atlantic population
4	Very limited data. Expert opinion or based on general literature review from a wide range of species	General data—not referenced
5	No data	No available information on which to base score

assigned a mean score (2), or scored as high risk, but the latter two options confound the issue of data quality with risk assessment (Patrick et al., 2009; Ormseth and Spencer, 2011). Therefore, we opted to not score unknown attributes but instead incorporate data-quality scores (see below). Attribute weightings, based on a scale of 0 (no relation) to 4 (most important), could be used, but we elected for a default weight of 2, based on the recommendation in Patrick et al. (2009). Effects of attributes were considered to be additive as this approach does not magnify the overall effect of attributes on the vulnerability score (Hobday et al., 2007; Ormseth and Spencer, 2011).

Assessing grenadiers by specific stocks was not attempted for most of the species because (1) stock structure is poorly known and data from distinct stocks were lacking, (2) we were concerned about the global vulnerability of these species, not populations within specific management areas, and (3) management areas do not define stock boundaries. *C. rupestris* is one of the few grenadiers that has had extensive investigations into its stock structure (White et al., 2010, 2011; Longmore et al., 2011); therefore it was assessed as three separate stocks: Skagerrak, northeast Atlantic, and northwest Atlantic.

Trawl and longline fisheries were analyzed separately for *A. pectoralis* and *C. acrolepis* because the data existed to analyze the effects of these fisheries separately. This eliminated the risk of obtaining high vulnerability scores when gears are combined within one assessment (Ormseth and Spencer, 2011). Productivity attributes for each species were assumed to be similar across its geographic range, unless there were population-specific data to suggest otherwise.

To provide an estimate of information uncertainty, a data-quality index was developed, based on the scoring of Patrick et al. (2009). The data used to assign scoring to productivity and susceptibility attributes were assigned a ranking of 1 (best data) to 5 (no data; Table 4). Data-quality scores were computed as the weighted average of the individual productivity and susceptibility attributes. Data were then divided into three tiers: low quality (>3.5), moderate (2–3.5); and high quality (≤2). When there were no data to assess an attribute, the data quality was scored 5, but the attribute did not receive a score; in this way, the attribute was then omitted from the vulnerability computation, but was in the overall data-quality assessment.

To determine how the productivity and susceptibility of these deep-sea species compare with various continental shelf and pelagic fisheries, means and 95% confidence intervals of productivity and susceptibility values were compared with the nearshore California groundfish species, northeast US groundfish species, and species in the Atlantic shark complex taken from Patrick et al. (2009), the elasmobranch complex from the eastern Pacific (Cope et al., 2011), and the Alaskan groundfishes (Ormseth and Spencer, 2011). All were assessed using the attributes of Patrick et al. (2009).

RESULTS AND DISCUSSION

PSA analysis. Within the six grenadier species we analyzed, none of the species was highly productive. Productivity of grenadiers ranged from 1.44 for giant grenadier to 1.89 for popeye grenadier (Table 5). Popeye grenadier stood out as the most productive species, which may be due to its smaller size, lower age at maturity, and higher intrinsic rate of population increase (*r*). No species was ranked as highly susceptible (using Patrick et al. (2009) attributes) or heavily exploited using the scoring of Berkson et al. (2011; Table 5). Susceptibility rankings were fairly similar for the species and ranged from 1.79 (ridge-scaled and Pacific grenadiers) to 2.29 (roundnose grenadier),

Table 5. Results of the PSA analysis with assessment of data quality

Species	Population or fishery	Scoring of Patrick et al. (2009)					Scoring of Berkson et al. (2011)		
		Productivity		Susceptibility		Vulnerability	Status		Vulnerability
		Attribute score	Data quality	Attribute score	Data quality		Attribute score	Data quality	
C. rupestris	NE Atlantic	1.67	2.15	2.15	1.92	1.76	2.13	2.06	1.74
C. rupestris	Skagerrak	1.67	2.00	2.29	2.42	1.86	1.75	2.22	1.53
C. rupestris	NW Atlantic	1.67	2.40	2.08	2.58	1.72	1.63	2.22	1.47
A. pectoralis	BT, global	1.44	2.00	2.04	2.33	1.87	1.83	2.11	1.76
A. pectoralis	LL, global	1.44	2.00	2.21	2.42	1.97	2.06	1.89	1.88
C. acrolepis	LL, global	1.67	2.10	2.25	2.58	1.83	2.13	2.22	1.74
C. acrolepis	BT, global	1.67	2.10	2.08	2.75	1.72	1.88	2.44	1.59
C. cinereus	Global	1.89	2.30	1.79	2.83	1.36	1.44	2.33	1.19
M. berglax	Global	1.72	2.10	1.96	2.42	1.60	1.78	1.94	1.50
M. carinatus	Global	1.63	2.45	1.79	2.33	1.59	1.94	2.06	1.67

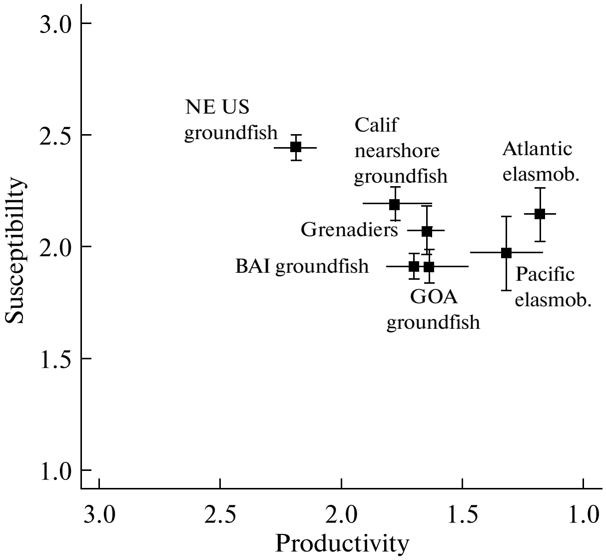
Note: Productivity and susceptibility scores applied to six grenadier species, resulting in the final assessment of their vulnerability; attributes were scored based on Patrick et al. (2009) and Berkson et al. (2011). Where data existed, populations or fisheries were assessed and scored separately. Attributes were assigned an average weight of 2. BT refers to bottom trawl and LL is longline. Data quality was scored 1 (best) to 5 (no data). Average data quality scores ≤2 were considered high quality data, between 2 and 3.5 were moderate, and ≥3.5 were considered low quality.

while status attributes ranged from 1.44 (Pacific grenadier) to 2.13 for the northeast Atlantic *C. rupestris* population and Pacific grenadier longline fishery. Pacific and giant grenadiers were more susceptible to longline fisheries than bottom trawl fisheries, which may seem counterintuitive. The main fishery that catches giant grenadier, particularly in Alaskan waters, is longline (Clausen, 2008), and both giant and Pacific grenadiers appear to be strongly attracted to the baited lines (Benson and McFarlane, 2008; Clausen and Rodgveller, 2010).

When PSA scores for grenadiers were compared to other fisheries, they were at the more vulnerable end of the plot of susceptibility and productivity scaling (Figure). Grenadiers were more productive, but as equally susceptible as the Atlantic and east Pacific elasmobranch complexes, but less susceptible than northeast US groundfishes. Previously, other studies have used PSA to assess two of the grenadier species in their relative fisheries in the northeast Pacific. Cope et al. (2011) estimated productivity and susceptibility of Pacific grenadier from the US West Coast groundfish complex to be 1.39 and 2.32, respectively, while our estimates for the global distribution were 1.67 and 2.08–2.25 (Table 5). Giant grenadiers were also assessed for the Bering Sea/Aleutian Islands (BAI) and Gulf of Alaska (GOA) areas (Ormseth and Spencer, 2011); productivity for these two Alaskan fisheries were similar to our global assessment, but we estimated susceptibility to be greater (Alaskan fisheries: 1.79, our data: 2.04, 2.21).

Equal weight was given to all productivity and susceptibility attributes. Increasing the weights of some criteria raised the susceptibility of the lowest-rated species a small amount (to as high as 2.3), but the values still did not approach those of the northeast US groundfish species group, for example. Productivity also declined slightly for all species, between 0.01 (*C. cinereus*) to 0.18 (*M. berglax*).

Our data quality scores fell mainly within the moderate-quality category for all attributes (Table 5). This was surprising, particularly as one productivity attribute, recruitment pattern, was scored 5 (no data) for all species. Many of the productivity attributes received a scoring of 2 as data existed to estimate the von Bertalanffy growth coefficient, age at maturity, *r*, or maximum age and size for at least part of the species range, which could then be expanded to the global distribution. Additionally, natural mortality had been estimated for many of the species. Susceptibility data for the northeast Atlantic roundnose grenadier population were scored as high quality because estimates of virgin spawning biomass (B_0) and fishing mortality relative to natural mortality exist for part of this population (west of the British Isles; ICES, 2011). For all other species, these two attributes received a lower-quality score. Biomass could only be inferred from relative biomass in research surveys, which often cover only a fraction of the known range or depth distribution; therefore, this attribute was scored 4 for most species. Some of the attributes were scored with high precision (score = 1) for all species and included: survival after capture, value of the fishery, fishery impacts on habitat, and management strategy for targeted



PSA results of grenadiers plotted with northeast (NE) US groundfishes, California nearshore groundfish, and Atlantic elasmobranch complex from Patrick et al. (2009), Pacific elasmobranchs from Cope et al. (2011), and the Bering Sea/Aleutian Islands (BAI) and Gulf of Alaska (GOA) groundfish complexes from Ormseth et al. (2011). Values plotted are the means ±95% confidence limits for both productivity and susceptibility scores. The lower left corner is considered least vulnerable, while the upper right is most vulnerable; 'elasmob' refers to elasmobranchs.

stocks. Survival rate for most deep-sea species is low because of expansion of the swim bladder due to pressure differences between the depth fished and the surface, or physiological stress caused by changing water temperature (Gordon, 2001). The attributes of Berkson et al. (2011) mainly assessed data-poor species relative to the status of data-rich species, therefore the data-quality scores were often higher than that of the Patrick et al. (2009) attributes.

Using the susceptibility criteria listed by Patrick et al. (2009) and, to a lesser extent Berkson et al. (2011), has exposed several issues with the attributes and scoring. For example, hyperdispersion, or if the species is known to range over a whole ocean basin, might mean that not all members of the population can be caught, resulting in a low susceptibility score. In this scheme, such low overlap with the fishery is considered to be a positive condition, when in fact it might be disadvantageous due to the inability of individuals to find mates when mature (i.e., Allee effects), especially in the face of fishing pressure. Furthermore, the attributes do not reflect the role that fishing practices might play in contributing to susceptibility for widely dispersed species that aggregate for spawning in areas that overlap with fisheries; such species receive a low susceptibility score, but may be easily found and targeted at these times. A classic example is the orange roughy spawning aggregation that forms on the flats on the northeastern edge of the Chatham Rise (Dunn et al., 2009). Another weakness is with the criterion of management strategy. If targeted stocks have catch limits and proactive accountability measures and non-target stocks are closely monitored, the attribute is given a low susceptibility score. This does not account for species that are grouped into unspecified but monitored categories nor does it consider how depleted the stock was at the time the management strategy was finally put in place. Thus, a stock that is currently at 10% of virgin biomass but is now being managed is given a lower susceptibility rating than one for which there has been little fishing and for which there is currently no management plan.

The National Marine Fisheries Service (NMFS) has modified susceptibility attributes within the PSA framework to better account for non-target species, where only catch data exist, and which bases scoring relative to what is known about assessed species within the catch complex (Berkson et al., 2011). Assessing grenadiers using this framework limits comparability with other species. Additional work is needed on developing adequate scoring for deep-sea species. For example, if a species is not targeted by the fishery but taken as bycatch, the attribute is ranked lightly exploited. But the lack of targeted fishing does not afford a species protection from fisheries, as evidenced by the high bycatches of some of these grenadier species (e.g., van Wijk et al., 2003; Clausen and Rodgveller, 2010) and the nearly 100% mortality of discards.

This analysis has shown that the PSA technique might be a useful conceptual tool for determining the relative vulnerabilities of fish species or species groups, but the method has some shortcomings that need to be considered before the tool is used for deep-sea fisheries. The productivity side of the relationship seems to be well estimated, with deep-sea and low-fecundity shallow-water species being properly placed along the productivity axis, but the susceptibility criteria need to be re-evaluated. We decided not to modify the attributes within our analysis because we were interested in determining how grenadiers compared to other groups and fisheries assessed using both the same attributes and scoring approaches. However, should the PSA technique be used for grenadiers or other deep-sea species, we suggest the following modifications to the susceptibility attributes:

(1) Vertical overlap should not be used because this does not take into consideration the negative downslope effects of fisheries on deep-sea species (e.g., Bailey et al., 2009; Priede et al., 2011).

(2) There is no attribute that describes the behavior of the fishers and fisheries. Many fishers target aggregations, either at spawning times or over special features, e.g., seamounts. Species in such situations would have high susceptibility to the impact of fisheries, which is not taken into account, while the effect on non-aggregating species is partially reflected in the areal overlap and geographical concentration attributes.

(3) The current management attribute and scoring are based largely on whether strategies are in place for targeted stocks. Grenadiers are often not targeted stocks so the strategies are not always a good indication of the effectiveness of management. Furthermore, whether management is in place does not reflect the current status of a stock, which may have already suffered great depletion. For instance, strategies are in place in the northwest Atlantic for roundnose grenadier, which is ranked low susceptibility, but that population is currently considered to be extremely low and at high risk of collapse due to activities prior to policy modification. Therefore, the current management attribute should be modified to consider the management for non-target species and should reflect the state of the population at the time of policy enactment.

Recommended sustainable management actions for grenadier fisheries. The history of overexploitation of grenadiers, their unproductive life-history characteristics, the issue of bycatch, and the potential deleterious impacts of bottom-fishing gears on vulnerable marine ecosystems (VMEs) make fisheries that include grenadiers extremely difficult to manage sustainably. However, we believe such fisheries could be sustainable given the following regulations and management actions:

(1) Given the low productivity of grenadiers (Tables 1, 5), fishing effort and fishing mortality must remain very low (with fishing mortality being much lower than natural mortality).

(2) Bycatch and discard amounts and composition must be monitored by observers and reporting must be mandatory for each species; aggregated general categories as currently used are insufficient and their use must be eliminated. Such actions are especially important, considering that in these deep-sea fisheries virtually all of the catch dies after capture (Koslow et al., 2000; Bailey et al., 2009). Knowledge of bycatch and discarding is essential for understanding the nature of the fishery impacts on grenadiers, which are typically bycatch, and for assessing populations in the future.

(3) Marine spatial planning should be considered an important element of a comprehensive strategy for achieving sustainability of grenadier fisheries and deep-sea fisheries in general. Spatial and temporal management tools, such as Marine Protected Areas (MPAs) or seasonal closures, could be particularly useful in data-poor situations such as encountered in the deep seas (FAO, 2007). Because grenadiers are part of mixed assemblages, suffer near 100% discard mortality, and have problematic catch statistics and reporting, spatial protection is likely to be more effective than reductions in allowable catch. Protected areas should be distributed throughout the distributional range of grenadier species to cover potentially distinct stocks, of which only a few have been identified (Katsarou and Naevdal, 2001; White et al., 2010). Relatively little is known about the spawning grounds and seasons of grenadiers, or the distribution, abundance, and dispersal of their larval and juvenile offspring; therefore, deciding upon the placement of spatial closures may be difficult. For data-poor species, a simple method for determining which areas to protect may be to simply choose those areas where aggregated bycatch is highest. If the protected areas are situated as to maximize the number and areal coverage of VMEs (i.e., corals), both VMEs and the entire species assemblage, of which grenadiers are a part, will be protected. These protected areas can then be used as a benchmark to compare to fished areas; time series monitoring of both closed and fished areas must be required and may provide empirical measures of r as populations in closures rebound.

(4) The uncontrolled expansion of current deep-sea bottom fishing (all gears) grounds must cease. Actions have been implemented by some RFMOs in the North Atlantic (e.g., NAFO, NEAFC; NEAFC, 2011) and CCAMLR has banned bottom trawling on the high seas in the Southern Ocean, but measures have not been implemented in the Pacific Ocean (Rogers and Gianni, 2010). In conjunction with the development of MPAs, this action would prevent fishers from moving to areas that are unstudied, may contain newly fished species, may contain more important habitats for these fishes, or may potentially contain VMEs. Such action would halt the widely recognized problem that fisheries managers are unable to keep pace with new developments in deep-sea fisheries in places heretofore unfished (Haedrich et al., 2001).

(5) Utilize a vessel monitoring system (VMS) to enforce marine spatial planning units and to truly understand the spatial distribution of fishing activity. VMS is a potentially valuable source of information on spatial and temporal patterns of fishing activity at multiple scales (Mills et al., 2007). A VMS has been successfully implemented by some nations and is mandatory for EU fishing vessels >15 m length; however, the vessels are not required to report when they are fishing, so indirect evidence (e.g., vessel speed) has to be used as a proxy (Benn et al., 2010). It is important that the system records position frequently (i.e., every 20–30 minutes) so that it can be used effectively to record the positions of fishing activities at the appropriate spatial scale for management purposes.

CONCLUSION

The extreme life-history characteristics of deep-sea species result in fisheries that mine the resource, rather than sustainably fish (Koslow el al., 2000). Currently, catch estimates from bottom-trawl fisheries on the high seas (and therefore in deep water) amount to less than 1% of the global marine catch and have a value of approximately 1% of the total global marine catch value (Sumaila et al., 2010). Although there are a few profitable examples (e.g., Garza-Gil and Varela-Lafuente, 2009), typically the low profitability of fishing deep-sea populations, especially with bottom trawls, coupled with the risk of extreme harm to populations and VMEs does not warrant continued exploitation of these habitats. As a result of our analysis of the literature on species of grenadier, we feel that the following life-history features dictate how their fisheries most likely will act over time. Grenadiers, in general, are: 1—K-selected species; 2—have boom & bust fisheries; 3—often exhibit strong population declines; 4—most likely will have long recovery times; 5—have unpredictable reproductive output and recruitment patterns; and 6—generally do not appear to have clear habitat utilization patterns. If there are to be any sustainable fisheries for these fishes, these traits need to be better understood and then included in management plans. Grenadier fisheries, and perhaps many other deep-sea fisheries, could be sustainable by implementing appropriate regulations and management actions such as those described in this paper.

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