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Indicators, impacts and recovery of temperate deepwater marine ecosystems following fishing disturbance

Indicateurs, répercussions et rétablissement des écosystèmes marins tempérés en eau profonde à la suite de perturbations causées par la pêche

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ABSTRACT

This Research Document was prepared to support discussions related to specific terms of reference (ToR objective 2 and 5a) outlined for the National Science Advisory Process Concerning Corals, Sponges, and Hydrothermal Vents in Canadian Waters (DFO 2010):

> **2.** Based on available information, and to the extent possible, provide advice on the susceptibility of corals, sponges, and hydrothermal vents to fishing impacts as well as their potential for recovery once impacted.
>
> **5a.** When indicators (e.g. spatial extent, abundance, species richness, rareness, etc...) of the ecological function served by corals, sponges, and hydrothermal vents are used, discuss the strengths and weaknesses of these indicators.

We identified primary literature on the impacts of anthropogenic disturbances in temperate deepwater marine ecosystems and their recovery following disturbance. Our search returned 545 papers published from 2000-2009, and 46 of these satisfied our initial screening criteria, notably empirical studies that included a spatial or temporal reference for quantitatively measuring ecosystem responses to anthropogenic activities. Our review did not focus exclusively on impacts of fishing on coral and sponge taxa; we extracted relevant but sparse data on corals and sponges from our database to address ToR objective 2. None of the studies we reviewed addressed hydrothermal vents. To address ToR objective 5a, we summarized the suite of indicators that authors used to measure the responses of populations, communities and ecosystems to anthropogenic disturbances. Across studies, approximately 250 variables were measured to evaluate impacts, and these variables related primarily to the state of invertebrate and vertebrate populations, community structure, ecosystem function, environmental conditions, fisheries, and other threats. Preliminary analysis of published studies indicates that coral and sponge taxa are, on average, more susceptible to fishing impacts than other invertebrate or vertebrate taxa. Compared to reference states, abundances of corals and sponges were 1-57% and 20-91% lower in sites following a single disturbance event. In areas that were repeatedly disturbed, coral and sponge abundances were 19-100% (median = 88.8%) and 22-100% (median = 98.3%) lower compared to reference states. Of sponges and corals that were not removed through fishing, the proportion of dead or damaged organisms following trawling ranged from 23-100% for corals, and 14-67% for sponges. While some studies reported signs of sponge recovery following disturbance (e.g. repair, regrowth, recruitment), few studies provided quantitative or qualitative evidence of coral recovery. However, most (83%) of the studies we reviewed lasted no more than 1 year following disturbance, which made it difficult to quantify the tempo and magnitude of coral and sponge recovery.

RÉSUMÉ

Ce document de recherche a été préparé pour appuyer les discussions liées aux cadres de référence (objectifs 2 et 5a du cadre de référence) décrits précisément dans le cadre du Processus national de consultation scientifique concernant les coraux, les éponges et les griffons hydrothermaux dans les eaux canadiennes (MPO 2010) :

> **2.** Selon les renseignements disponibles, et dans la mesure du possible, formuler un avis sur la susceptibilité des coraux, des éponges et des griffons hydrothermaux aux effets de la pêche, de même que la possibilité qu'ils se rétablissent une fois touchés;
>
> **5a.** Lorsque les indicateurs (p. ex. l'étendue spatiale, l'abondance, la diversité des espèces, la rareté) de la fonction écologique servie par les coraux, les éponges et les griffons hydrothermaux sont utilisés, discuter les points forts et les points faibles de ces indicateurs.

Nous avons identifié les publications principales portant sur les répercussions des perturbations anthropiques dans les écosystèmes marins tempérés en eau profonde et leur rétablissement à la suite des perturbations. Notre recherche a permis d'obtenir 545 articles publiés entre 2000 et 2009, dont 46 correspondaient à nos critères de recherche initiaux, notamment les études empiriques qui comprennent une référence spatiale ou temporelle pour la mesure quantitative des réactions de l'écosystème aux activités anthropiques. Notre examen ne se concentrait pas uniquement sur les répercussions de la pêche sur les taxons de coraux et d'éponges; nous avons extrait de notre base des données pertinentes mais peu nombreuses sur les coraux et les éponges pour l'objectif 2 du cadre de référence. Aucune des études que nous avons examinées ne se penchait sur les griffons hydrothermaux. Pour l'objectif 5a du cadre de référence, nous avons résumé la série d'indicateurs utilisés par les auteurs pour mesurer les réponses des populations, des collectivités et des écosystèmes aux perturbations anthropiques. Dans toutes les études, environ 250 variables ont été mesurées pour évaluer les répercussions, et ces variables étaient principalement associées à l'état des populations d'invertébrés et de vertébrés, à la structure des communautés, aux fonctions des écosystèmes, aux conditions environnementales, aux pêches et à d'autres menaces. L'analyse préliminaire des études publiées indique que les taxons de coraux et d'éponges sont, en moyenne, plus à risque de subir les répercussions de la pêche que les taxons des autres invertébrés ou vertébrés. En comparaison aux états de référence, l'abondance des coraux et des éponges était inférieure de 1 à 57 % et de 20 à 91 % dans les sites à la suite d'un seul événement de perturbations. Dans les zones qui étaient perturbées à répétition, l'abondance des coraux et des éponges était inférieure de 19 à 100 % (médiane = 88,8 %) et de 22 à 100 % (médiane = 98,3 %) par rapport aux états de référence. Des éponges et des coraux qui n'étaient pas prélevés par la pêche, la proportion des organismes morts ou endommagés à la suite du chalutage se situait entre 23 et 100 % pour les coraux et entre 14 et 67 % pour les éponges. Alors que quelques études ont démontré des signes de rétablissement pour les éponges à la suite des perturbations (p. ex. réparation, repousse, recrutement), peu d'études ont fourni des preuves quantitatives ou qualitatives de rétablissement pour le corail. Toutefois, la plupart (83 %) des études examinées n'ont pas duré plus d'un an suivant les perturbations, ce qui rend difficilement quantifiables la vitesse et l'ampleur du rétablissement des coraux et des éponges.

INTRODUCTION

International guidelines for management of deepwater fisheries in the high seas define a vulnerable marine ecosystem (VME) as one likely to show a substantial negative response to disturbance (FAO 2008). The same guidelines define a serious adverse impact (SAI) as a disturbance that causes impacts to populations or communities that are not reversed within two generations or 20 years (FAO 2008). As part of Canada's International Governance Strategy, Fisheries and Oceans Canada is carrying out scientific research to identify VMEs and to inform decisions on managing human activities to prevent serious adverse impacts to VMEs in the high seas.

Serious adverse impacts may be caused by use of demersal fishing gears such as trawls, seines, longlines, traps, and gillnets, or by activities related to aquaculture, urbanization, log-handling, oil and gas development and deployment of gas pipelines and communication cables (*NOAA*, 2009). Disturbance caused by bottom trawling is among the most widespread human impacts in marine ecosystems (Hiddink et al. 2007), with more than 50% of many shelf sea beds fished annually (Watling & Norse 1998; Hall-Spencer et al. 2002). Trawling activity has increased over the last 40 years (Cryer et al. 2002), and some temperate ecosystems are trawled several times per year (Auster et al. 1996; Jennings et al. 2002). While a single localized disturbance event may have a relatively minor influence on ecosystem structure and function, cumulative effects may lead to long term changes in the structure and function of benthic ecosystems (Collie et al. 1997; Wassenberg et al. 2002). Indeed, fished areas can exhibit lower abundance, biomass, productivity, habitat complexity, and species diversity (Asch and Collie 2008), as well as shifts in community structure (Auster and Link 2009).

One approach to identifying VMEs and the activities that could lead to SAIs, according to FAO's (2008) definition, involves quantifying the timing and magnitude of marine ecosystem responses to, and recovery from, different kinds of disturbance. In literature on marine ecosystems, recovery and recovery potential are assessed using a broad range of indicators, including, as examples, changes in relative abundance (McClanahan 2000; Lotze et al. 2006) and species composition (Auster and Link 2009), recruitment dynamics (Perkol-Finkel and Airoldi 2010), and tissue repair and regrowth in the case of corals and sponges (Freese 2001; Maier 2008).

While the abundance of some species groups increases in response to moderate amounts of fishing disturbance, communities dominated by corals and sponges are considered to be among the most sensitive to demersal fishing due in part to the slow growth rates (e.g. 1.6-2.3 cm yr^{-1}, Andrews et al. 2002; Andrews et al. 2009), long lifespans (tens to thousands of years, Andrews et al. 2002; Hall-Spencer et al. 2002; Andrews et al. 2009), sedentary habit, and emergent physical structure of these bio-engineers (Boutillier et al. 2010). Indeed, studies report that corals and sponges are more abundant in unfished areas than in similar areas that have been fished (e.g. Clark and Rowden 2009). Where coral (and sponge) abundance is lower, there is also lower species diversity as well as lower densities and catches of fish (Fossa et al. 2002; Koenig et al. 2005). However, few studies quantify the impacts of fishing on corals and sponges or their potential for recovery following disturbance.

Here we provide an overview of published data on the relative susceptibility of coral and sponge assemblages to fishing impacts and their potential for recovery following disturbance. Results are based on preliminary analysis of studies identified in a systematic review of literature on the effects of fishing disturbance on temperate deepwater marine ecosystems. Specifically, the review objectives were to (1) summarize indicators that have been used to monitor and measure the initial response of deepwater marine ecosystems to different kinds of anthropogenic disturbance, (2) quantify the relative responses of corals and sponges to disturbance, and (3) characterize the timing and magnitude of recovery following disturbance. We discuss preliminary results in the context of the terms of reference outlined for the National

Science Advisory Process Concerning Corals, Sponges, and Hydrothermal Vents in Canadian Waters (DFO 2010), specifically in relation to the following two terms of reference:

> **2.** Based on available information, and to the extent possible, provide advice on the susceptibility of corals, sponges, and hydrothermal vents to fishing impacts as well as their potential for recovery once impacted.
>
> **5a.** When indicators (e.g. spatial extent, abundance, species richness, rareness, etc.) of the ecological function served by corals, sponges, and hydrothermal vents are used, discuss the strengths and weaknesses of these indicators.

Impact to and recovery of populations, communities and ecosystems can be defined in multiple ways. DFO (2010) defines impacts as the degree to which an activity results in changes to a population, community or ecosystem relative to a specified benchmark state. Here, we specify the benchmark state as the state prior to current fishing events, i.e. impact is measured as the degree to which a fishing event or regime results in changes to a benthic population, community or ecosystem from its state prior to the fishing events. We use this benchmark state because it allows us to quantify impacts in all areas regardless of the history of fishing. We define recovery as a complete return of the benthic attribute to the state from which a current fishery perturbed it, as proposed in DFO (2010).

METHODS

We reviewed published literature on ecosystem response to and recovery from fishing and other anthropogenic impacts by applying systematic search methods (Roberts et al. 2006) to the online science citation index databases ISI Web of Science (available at http://isiwebofknowledge.com/) and Scopus (available at www.scopus.com). Our search was constrained to the time period between January 1999 and August 2009. To obtain articles addressing temperate marine ecosystem response and recovery following particular types of disturbances, we used the following keyword term combination:

> "Topic=(marine OR deep* OR cold-water OR pelagic OR benth*) AND (ecosystem*) AND (trawl* OR fishing OR fisher* OR oil OR gas OR dredg*) AND (recover* OR vulnerab*)"

From these search results, a subset of articles was selected for data extraction and further analysis. We selected only those studies reporting measured ecosystem responses to seafloor disturbance (including bottom trawling, dredging, and oil or gas exploration), or those studying the effects of overexploitation of marine resources, excluding studies that were strictly conceptual or theoretical in nature, as well as those that did not present original empirical data (e.g. reviews, editorials). We also focussed initially on studies in the north Pacific and Atlantic Oceans, given their greater relevance to Canadian marine ecosystems. However, studies focusing on intertidal or nearshore coastal ecosystems (e.g. rocky intertidal, tropical coral reefs, kelp forests) were excluded because the focus of our review was on ecosystems in the high seas. Additional key studies were identified through the list of referenced papers in the selected literature. Although corals and sponges were not the sole focus of this review, we extracted data on response and recovery of these taxa in preparation for the National Science Advisory Process Concerning Corals, Sponges, and Hydrothermal Vents in Canadian Waters (DFO 2010). No studies investigating the effects of fishing disturbance on or around hydrothermal vents were identified using our literature search criteria.

A key criterion for inclusion of papers in our review was a comparison of response and recovery against one or more adequate and representative reference sites (spatial control) or reference states (temporal control). Temporal and/or spatial controls often served as references against which disturbed sites were compared to determine the magnitude of impact and trajectory of recovery following disturbance. In a few studies (e.g. de Juan et al. 1997), previously undisturbed reference sites were unavailable and disturbed sites were compared to reference sites that had remained undisturbed for some period of time (e.g. 10-27 years). These previously disturbed reference sites may still have been undergoing recovery at the time surveys were carried out. Nevertheless, we include these types of studies in our preliminary analyses due to limited literature on this topic, and because trends in ecosystem responses and recovery were consistent with those reported in studies that include previously undisturbed sites as references. For simplicity, we refer to both temporal and spatial controls as reference states throughout the remainder of this document.

For each study included in our review, we recorded any available information on approximately 250 variables, including those relating to populations, communities, ecosystems, and disturbance regime. Because impacts and recovery potential are likely to be influenced by the type of gear used, as well as the frequency, spatial extent, and intensity of fishing disturbance (Boutillier et al. 2010), we report results from studies of single disturbance events and studies of cumulative impacts and recovery in repeatedly disturbed sites separately. For all studies, we recorded the time elapsed since the disturbance, the types of indicators used to measure ecosystem response and recovery, and any quantitative values of the measured indicators in disturbed and undisturbed sites. When sufficient quantitative data were available, we calculated initial response and recovery using percent changes (increase or decrease) as well as the log-ratio of the measured indicator between disturbed and undisturbed states:

$$\ln\left(\frac{I_{disturbed}}{I_{reference}}\right)$$

where $I_{disturbed}$ was the indicator value in the disturbed site, and $I_{reference}$ was the value in the reference state. Log-ratios measure the magnitude and direction of change in indicators, and their unitless values can be compared among different kinds of indicators. A log-ratio of 0 represents no change in the measured indicator, while a ratio of 1 represents a 2.7-fold increase, a ratio of 2 represents a 7.4-fold increase, and so on. Negative log-ratios denote declines in the value of an indicator. A log-ratio of -0.5 corresponds to a 39% reduction, while a log-ratio of -1.0 corresponds to a 63% reduction, and so on.

In this document, we focus on comparing measures of species abundance, species richness, and species diversity because these continuous variables were among the most commonly reported indicators and amenable to comparisons across studies. Our definitions are consistent with those outlined in DFO (2010), where species richness refers to the total number of taxa, and species diversity is a composite measure of both the number and relative abundances of taxa.

One of the key limitations in our review related to taxonomic resolution. The authors of many studies were unable to distinguish some taxa, including corals and sponges (e.g. Freese 1999). For simplicity, and due to limited data, we pooled results for all corals and all sponges, respectively, in the following analyses. We discuss results from individual studies of corals and sponges in more detail, and summarize data on the incidences of physical damage to corals and sponges and observations on repair and regrowth.

RESULTS

The search criteria returned 357 articles in Web of Science and 414 articles in Scopus for a total of 545 citations published from 2000-2009, excluding duplicates common to both search databases. Of these 545 articles, 268 (49%) were strictly conceptual or theoretical (e.g. modelling) studies, 213 (39%) were empirical studies, and 64 (11%) were reviews or meta-analyses. Only the empirical studies provided quantitative datasets that were suitable for our analyses. Of these empirical studies, 46 papers described ecosystem and disturbance types relevant to VMEs. An additional 23 articles cited in these papers met our search criteria and were also included in our review (e.g. Sainsbury et al. 1997). Our literature review was still underway at the time this document was prepared; here we report an overview of results extracted from 41 papers listed in Appendix 1.

Most studies (55.4%) surveyed ecosystems using non-destructive sampling methods including acoustics, still photographs and ROV-mounted, net-mounted, or towed-camera video. Other studies used trawl surveys (10.8%), grab samples (13.5%), or other fishing gears (20.2%) including dredges, and traps.

The most common types of disturbance examined in the reviewed studies were bottom trawling (79%), dredging (9%), or disturbance from static fishing gears including pots, traps, anchored nets and long-lines (2%). Most studies included in our review focused on temperate marine ecosystems ranging in depths from approximately 50 – 200m, but we reviewed one study at 10m, and 5 studies at depths >500m. Studies were located primarily in the Northwest (29%) or Northeast Atlantic Ocean (24%), and the Northeast Pacific Ocean (20%). None of the studies in our review focused on hydrothermal vents.

Indicators of ecosystem impacts and recovery

The suites of measured indicators varied among studies and according to study objectives and focal taxa. Indicators used to measure the initial ecosystem responses to fishing impacts related primarily to abundance, community structure, ecosystem function, and incidences of damage to structural species, including corals and sponges (Appendix 2). Species abundance was commonly measured in units of density, % cover, or biomass, and several indices of species diversity were reported across studies. Studies also included indices of the magnitude and frequency of fishing impacts, and commonly described gear type(s), tow area, trawl footprint and density of gouges, frequency of fishing, proportion of total area fished, or catch rates (Appendix 3). In addition, studies reported details on the physical and oceanographic aspects of ecosystems (Appendix 4) and the life history traits of select species; in many cases, ecosystem responses were related to those potential physical and biological covariates of susceptibility.

The indicators used to measure the magnitude and timing of recovery generally related to abundance, community structure, ecosystem function, habitat structure, and physical damage (Appendices 2). Indices of abundance included number and density of individuals, biomass, % cover, and catch rates. Indices of community structure included measures of community similarity, community size structure, trophic structure, and more commonly, measures of species richness and diversity. Studies also measured indices of productivity, species interaction strength, sediment structure, the % incidence of damage to corals and sponges, and the % incidence of regrowth in sponges.

Indicators specifically related to corals and sponges included number, density, % cover of live or dead individuals or colonies, estimated volume of missing coral colonies, % structural species removed, biomass, catch per unit effort, and frequencies of damage, displacement, necrosis, repair, or regrowth (Appendix 2).

Susceptibility of corals and sponges

Across all studies, most taxa were less abundant in sites that had recently been disturbed or that were subject to repeated anthropogenic disturbances. The relative abundances of corals and sponges were lower in disturbed areas compared to reference states (i.e. all log-ratios < 0) in all studies that monitored these taxa, whether the disturbance was the result of a single event (Fig. 1) or repeated activities (Fig. 2). Most other invertebrate taxa and fishes also had lower abundance in disturbed sites, although 27.8% (86/309 records) of these taxa had greater relative abundance in disturbed sites.

The declines in abundance associated with disturbance were generally greater among corals and sponges than among other invertebrate taxa. Median coral abundance was 69% lower in sites subjected to one or more disturbances than in reference states, while median sponge abundance was 55% lower in disturbed sites. By contrast, the median relative abundance of other invertebrate taxa was 31.6% lower in disturbed sites than in reference states.

Following the single pass of a trawl, abundance of corals, including alcyonarians, gorgonians and sea whips, declined by 1-57% (median = 5.0%, excluding data from Troffe et al. (2005) which suffered from low statistical power and uncertainty in transect locations) while sponge abundances were reduced by 20-91% (median = 40.0%) (Fig 1). Other invertebrate taxa including bivalves, anemones, and crabs exhibited responses that ranged from an 88% decline to an increase of 245% following disturbance events (median = 34% decline).

In sites that were repeatedly fished, the relative abundances of corals and sponges were also lower relative to reference states (Fig. 2), and the median effect of disturbance was greater on corals and sponges than on other invertebrate taxa. Coral and sponge abundances were 19-100% (median = 88.8%) and 22-100% (median = 98.3%) lower in areas that were repeatedly disturbed compared to reference states. By contrast, the relative abundance of invertebrates and fishes ranged from 100 lower to 12 times greater than the reference abundance.

Community-level responses following single disturbance events included a reduction in species richness across all studies (median = 49% reduction, Fig. 3a). By contrast, the median difference in species diversity was a 6% reduction, and diversity only declined in approximately half of the studies that measured diversity.

Recovery of corals and sponges

While most (>94%) studies included in this analysis monitored temperate marine ecosystems over spatial scales relevant to marine ecosystems (100 km^2 – 100000 km^2, Fig. 4), few (<11%) monitored ecosystems for longer than one year following fishing impacts. As a consequence, there were relatively few data to characterize the magnitude and timing of recovery at species, community, and ecosystem levels following disturbance. Qualitative and quantitative data on the recovery of corals and sponges were sparse.

Some taxa, including sponges, showed evidence of recovery within one year following single disturbance events. After a single disturbance event, the median relative abundance of invertebrate taxa (excluding corals and sponges) immediately following a single disturbance event was 34% lower than the reference state, whereas 6-12 months following the disturbance, median relative abundance was only 10.8% lower than the reference state, suggesting recovery over relatively short time scales. Sponges exhibited signs of recovery on this same time scale in one study (Wassenberg et al. 2002), which reported that sponge abundance was 6% greater than the reference state within one year following the impact. No quantitative data were available to evaluate recovery rates for corals.

Recovery was also evident after disturbances had ceased in repeatedly fished areas, with an increasing trend in relative abundance across all taxa during the first 10 years following cessation of disturbance (Fig. 5). Median increase in abundance within 1-2 years was 54%, and 204% within 6-10 years. However, in most studies, there were no data from reference states with which to gauge the absolute magnitude of recovery in repeatedly disturbed ecosystems. No data on ecosystem changes were available over the time periods required for identification of SAIs (i.e. >12 years following cessation of disturbance).

Although data limitations preclude evaluation of temporal trends in species diversity following cessation of disturbance, species richness data were available from studies that monitored ecosystems following single disturbance events. In general, species richness appeared to increase in the first few years following disturbance, but generally decreased after 3-5 years

DISCUSSION

The results of our analysis were presented at the National Science Advisory Process Concerning Corals, Sponges, and Hydrothermal Vents in Canadian Waters, 9-12 March 2010, Ottawa (DFO 2010) as an oral presentation (Appendix 5). The ecological impacts of fishing depend not only on the frequency, intensity and type of fishing, but also on the susceptibility of species to fishing and their potential for recovering following disturbance. Trawling and other forms of fishing disturbance, whether they were single or repeated events, generally caused declines in the abundance of surveyed taxa. Declines in relative abundance were on average greater for corals and sponges than for other invertebrate taxa or fishes. Very little information was available on the recovery of individuals or colonies of corals and sponges over time, and no empirical studies on the susceptibility or recovery potential of hydrothermal vents were identified using our keyword searches.

Indicators of ecosystem impacts and recovery

The selection of ecosystem indicators should be based on study objectives and the degree to which variables are measurable, sensitive, specific, and cost-effective (Rice and Rochet 2005). Ecosystem variables can differ widely in their potential ability to indicate changes in ecosystem state, and most are suitable for characterizing one or a few ecosystem attributes. Ideally, multiple indicators should be used to measure and monitor changes in ecosystem state over time and space, because ecosystem components respond to and recover from disturbances in different ways and over different time scales. Table 1 summarizes strengths and limitations of some of the more commonly reported indicators of population abundance, community structure, ecosystem function, and impacts.

The most common measurements of ecosystem recovery reported in the literature we reviewed were indices of the relative abundance of individual taxa. Common units included density, % cover, and biomass. Indices of the relative abundance of individual taxa can be easily measured and compared among sites and changes in the abundance of individual taxa may be detectable sooner following disturbance than changes in community composition. A focus on changes in the abundance of functional groups (as opposed to individual taxa) could better inform assessments of the impact of disturbance on ecosystem processes as well as community structure (Auster and Link 2009).

Species richness (number of species) was also widely reported in the literature we reviewed, as were various indices of diversity such as Shannon-Weiner diversity index and Simpson index. Species richness is among the easiest community-level variables to measure but provides an insufficient description of community structure and can fail to indicate community or functional changes (Cryer et al. 2002). Moreover, species richness is highly sensitive to sampling effort and the ability of observers to distinguish taxa. Indices of species diversity provide more information about community structure than species richness, but as our results show, the two types of indicators can respond differently to disturbances and reflect changes that are non-intuitive. For instance, disturbances can be followed by a temporary increase in species richness (Newell et al. 1998, as cited in Cooper et al. 2007), and a moderate amount of disturbance can enhance the diversity of benthic species (Asch and Collie 2008). Multivariate analyses of community structure could be more informative than richness or diversity indices for describing differences or changes in community structure, but these were infrequently applied in the literature we reviewed (but see, for example, Asch and Collie et al. 2008).

Susceptibility of corals

Relatively few studies in our review provided quantitative data on the response of corals to single impacts or repeated disturbances, but all studies that did provide such data indicated a susceptibility of corals to removal, destruction, or damage by mobile or static fishing gears. Of the five studies in our review that monitored the responses of corals to single disturbance events, all were studies of trawling impacts (Freese 1999; Wassenberg et al. 2002; Gordon et al. 2005; Troffe et al. 2005; Henry et al. 2006), and one study also monitored the effects of traps (Troffe et al. 2005). Gordon et al. (2005) note that soft corals (*Gersemia* spp.) were among the most affected taxa following experimental otter trawling. Where there was a reported reduction in relative abundance, coral abundance declined by 1-57% following the single pass of a trawl (median = 5% reduction). In one survey of repeatedly trawled and untrawled areas, Clark & Rowden (2009) reported that the % occurrence and % cover of habitat-forming corals were 95% and 99% lower on fished seamounts than on unfished seamounts, respectively. Declines in coral abundance observed in reviewed studies are consistent with qualitative and anecdotal observations of fewer live corals and greater coral damage and destruction in fished areas (e.g. Krieger 2001; Fossa et al. 2002; Waller et al. 2007; Clark & Rowden 2009).

Coral damage attributable to trawling was extensive, but static gears were also associated with damage to corals (Krieger 2001; Fossa et al. 2002; Troffe et al. 2005). Following bottom trawling, studies reported severely damaged or dead corals, and coral debris and rubble (Harter et al. 2009) from several taxa, including bamboo corals (Koslow et al. 2001), *Lophelia pertusa*, and *Paragorgia* spp. (Fossa et al. 2002; Waller et al. 2007). Estimates of the proportion of damaged or dead corals ranged from 23-100% for *Primnoa* spp. (Krieger 2001), 50% for sea whip colonies (Freese et al. 1999), and 92-100% for corals in general (Wheeler et al. 2005). During experimental trawling, 4.8% of Alcyonaria were entrained by the net while 3.2% were broken as the net passed over (Wassenberg et al. 2002). During an ROV survey of a trawl path, 27% of corals were detached from the substrate, and these were missing 50-90% of their polyps (Krieger 2001). Krieger (2001) estimated in a trawled site that 17-27% of the volume of coral colonies were removed (Krieger 2001), 95-99% of branches were missing from five large trawled *Primnoa* spp. colonies, and 80% of polyps were missing from two smaller trawled colonies. All damaged coral colonies observed by Krieger (2001) were located on tipped or dragged boulders. In areas subject to frequent trawling, damaged corals were encountered on 29% of video survey transects and overall, 4% of coral colonies were damaged; specifically, 7.9% and 3.4% of *Paragorgia* and *Primnoa* spp. were broken or tilted, respectively (Mortenson et al. 2005). Troffe et al. (2005) observed sea whips that were entangled, damaged, and removed by prawn traps. The number of live corals on one trawled seamount was negligible, but dead fragments and debris of *L. pertusa* and broken branches of *Paragorgia* sp. indicated long-term damage to benthic communities (Waller et al. 2007).

Susceptibility of sponges

Eleven studies included in our analysis reported reductions in the abundance of sponges following single or repeated disturbances. During one experimental trawling study where the fate of sponges was observed, 8.3% of sponges were caught in the net, while as much as 81.3% were displaced by the net but left *in situ* (Sainsbury et al. 1997). The susceptibility of sponges to removal varied among size classes and growth forms and ranged from 20-91% (Wassenberg et al. 2002). Other estimates of sponge removal rates range from 3.4-95% (Sainsbury et al. 1993; Poiner et al. 1998, as cited in Collie et al. 2000; Moran and Stephenson 2000). Moreover, 14-67% of sponges exhibited signs of damage and 10% showed signs of necrosis in recently trawled areas (Freese et al. 1999, 2001; Krieger 2001).

Quantitative estimates of removal and damage to sponges in fished areas are consistent with qualitative and anecdotal observations of relatively few sponges in trawled (Collie et al. 2000) and dredged areas (Asch & Collie 2008). Asch & Collie (2008) noted that sponges are the colonial species most affected by bottom trawling in shallow sites on Georges Bank.

Damage to species other than corals and sponges was infrequently reported. However, Freese et al. (1999) estimated that 23% of sea stars and brittle stars also exhibited signs of damage.

Variability in response of corals and sponges to disturbance

The highly variable response in abundance of corals, sponges, and other invertebrate taxa following disturbances (Figs. 1 & 2) has been related to differences in life history, growth habit, structural flexibility, and height (e.g. Wassenberg 2002; Boutillier et al. 2010), as well as to differences in gear-specific impacts (e.g. Blyth et al. 2004; Troffe et al. 2005). Smaller and more flexible corals and sponges were less susceptible to capture in or damage by demersal trawl nets (Wassenberg et al. 2002). Notably, two studies reported that flexible sea whips did not exhibit reduced abundance or greater damage in trawled areas (e.g. Troffe et al. 2005; Stone et al. 2005, but Freese et al. 1999 observed damage to sea whips in trawled areas), while taller and more rigid corals, including gorgonians and alcyonarians, were removed, tipped over, or broken by trawl nets (Wassenberg et al. 2002). Poiner et al. (1998, as cited in Wassenberg et al. 2002) also note that sea whips and gorgonians were more resilient to shrimp trawling, and plate corals were more vulnerable. However, sea whips were tangled in, damaged and removed by traps (Troffe et al. 2005), underscoring the need to consider the interactions between life history, growth form and type of disturbance. In one study of the effects of fishing on sponges, trawling had the greatest impact on large (>300mm tall), inflexible sponges (Wassenberg et al. 2002).

Other life history attributes that influence susceptibility of sponges to disturbance include motility, dispersal mechanisms, growth rates, age at maturity, and longevity (Mortenson et al. 2005; Asch and Collie 2008). The aperiodic recruitment and perennial life history of sponges also make them vulnerable to fishing (Hughes 1989, as cited in Asch & Collie 2008). Many invertebrate taxa in our review were motile species with relatively fast growth rates, early age at maturity, and short generation times (e.g. decapods, echinoderms, polychaetes), in other words species capable of relatively rapid recovery from disturbances. The responses of these other invertebrates ranged from an 87% decline to an increase of 245% in relative abundance following disturbance (median = 34.3% decline). The generally less severe reductions in abundance (Figs. 1 & 2) of these taxa compared to corals are consistent with previous findings (Bradshaw et al. 2002, as cited in Asch & Collie 2008).

Although rarely considered in the studies we reviewed, it is noteworthy that demersal fishing can exert indirect effects on nearby unfished areas through transport and settling of sediments following disturbance (see Bluhm 2001), which could smother sedentary species.

Recovery of corals and sponges

Relatively few studies monitored benthic ecosystems for more than a year following disturbance, which makes it difficult to quantitatively assess ecosystem recovery potential, especially for those dominated by corals. However, other invertebrate taxa and fishes showed signs of increased abundance when repeated disturbances ceased (Figure 5).

Based on expert opinion and extrapolations in the reviewed papers, recovery of corals likely requires decades to centuries (e.g. Krieger 2001; Waller et al. 2007), due in part to a life history characterized by slow growth rates (Andrews et al. 2002; Risk et al. 2002) and long life spans (e.g. colonies of *Primnoa resedaeformis* may live >300 years (Risk et al. 2002). New coral recruits were not observed 7 years post-impact in one study (Krieger 2001). Koenig et al. (2005) found little evidence of coral recolonization in a protected area, where one might have expected to find ivory tree coral (*Oculina varicosa*). Similarly Waller et al. (2007) found limited evidence of coral recovery on seamounts. Once established, Mortensen et al. (2005) estimated it would take 46 years for *Primnoa* spp. to achieve 80 cm in height. Another study reported that damaged corals were sometimes parasitized by zooanthids (Mortensen et al. 2005), which may slow regrowth and recovery.

Data gathered from our review suggested that some sponges (glass sponges, *Geodia*) may recover in terms of numerical abundance within a year following disturbance, but only one study in our review reported relative differences in sponge abundance following the initial impact of trawling disturbance (Freese 2001). In individual studies, new sponge recruits were not detected after 1-10 years following disturbance (Freese et al. 1999; Wassenberg et al. 2002), but Freese (2001) reported 1.4% of damaged sponges exhibited signs of repair and growth one year following trawling disturbance.

More than half (4/7) of the unique glass sponge reefs in the Georgia Basin (British Columbia, Canada) surveyed with remotely operated vehicles (ROVs) showed evidence of damage (i.e. scattered fragments of sponge skeletons) and tracks consistent with mobile fishing gears (Cook et al. 2008); potential signs of recovery were observed on two damaged glass sponge reefs.

Recovery may be influenced by the degree of mobility and substrate type (Bluhm 2001). The expected time for recovery for invertebrate taxa other than corals and sponges ranged from 5 years to several decades depending on the type of disturbance and life history (Sainsbury et al. 1997; Hutchings 2000; Harvey et al. 2006). Recovery time may also be related to the spatial extent of disturbances: while other invertebrate taxa were expected to take at least 6-10 years over large spatial scales (Henry et al. 2006; Kenchington et al. 2006; Asch and Collie 2008), signs of recovery were evident at smaller experimental scales over shorter time periods (Henry et al. 2006). Cooper et al. (2008) noted that recovery times depended in part on the intensity of disturbance and the characteristics of the benthic community. For instance, Jennings et al. (2002, see also 2001) found that frequent trawling did not have a significant impact on the production of small infauna or polychaetes, but large infauna exhibited large decreases in production over trawling frequencies of 0.35 – 6.14 times per year. Hiddink et al. (2006) caution that monitoring changes in the biomass of mobile species after small-scale experimental disturbances, as many studies tend to do, effectively measures immigrants rather than self-recruitment *per se*, which may lead to biased estimates of the magnitude and timing of recovery that are not applicable to larger-scale disturbances.

Caveats, limitations, and future sampling considerations

Reviews of scientific literature are subject to a number of caveats and limitations, including potential publication biases and data gaps. Moreover, the types of articles identified in a review are sensitive to search terms. Given that our search terms did not specifically refer to corals or sponges, we may have missed important literature that could be used to quantify the susceptibility of corals and sponges to fishing disturbances, and their potential for recovery over time. However, a number of studies in our review also reported finding limited information related to response and recovery of corals and sponges following disturbance.

Publication bias, whereby authors and editors favour publication of results or studies that demonstrate a significant effect of disturbance on taxa, may lead to over-estimates of ecosystem impacts. Apart from being aware of the potential for bias, there is little we can do to address it in our review except to identify the trends in response and recovery as being within the range of possible outcomes following disturbance.

Most studies of marine ecosystems and their responses to disturbance focus on shallow, coastal areas over small spatial scales (Cryer et al. 2002). However, anthropogenic disturbances in deeper marine ecosystems, including those in the high seas, are hypothesized to exert stronger impacts than in shallow ecosystems because species in the former systems are often adapted to a less frequent and intense natural disturbance regime (Asch & Collie 2008). In our review, we focussed our analysis on studies in deeper ecosystems, but studies ranged widely in depth (>10m to >500m).

Our review indicated that there are few true undisturbed control sites in marine ecosystems (Engel and Kvitek 1998) that can be used to measure impacts and provide science advice on the susceptibility and recovery potential of coral and sponge communities. This generality underscores the value of establishing baseline values for indicators at population, community and ecosystem levels prior to changes in disturbance regimes.

Studies that monitor ecosystem change following disturbance over long time scales that are relevant to fisheries management decisions (e.g. 5-20 years, FAO 2008) would help with identification of VMEs and SAIs, and inform decisions on the development of encounter protocols (DFO 2011). However, the majority of studies in our review assessed the immediate ecosystem response to a disturbance, or compared the states of ecosystems that were continually (and currently) being disturbed to undisturbed sites. Such studies provide useful information about the relative impact of different disturbances on different ecosystems, but no information about how much time is required for the ecosystem to recover (if it recovers at all). Of the studies that monitored sites over time, the majority measured ecosystem response within 5 or fewer years following disturbance; in most of these studies, recovery to the pre-disturbance state was not observed at the time of completion of the study. Longer time series datasets are needed to be able to characterize ecosystem recovery, or to predict whether or not an ecosystem will recover within the 5-20 year timeframe proposed for SAI identification by FAO. In addition, longer time series would allow us to quantify any lags in ecological responses, which can occur when interactions operate on different temporal and spatial scales.

Blyth et al. (2004) note the importance of spatial scale of disturbance in experiments, and its effects on inferences about ecosystem responses and recovery potential. Smaller disturbances tend to recover more quickly than larger disturbances that are more relevant to fisheries management. Blyth et al. (2004) also argue that experiments assessing the recovery rates following a single disturbance event tend to show faster recovery than those following a repeated or ongoing disturbance.

Conclusions

The timing and relative direction of ecosystem responses sometimes varied within studies depending on the indicator measured. This finding underscores the importance of measuring multiple indicators to quantify ecosystem impacts and recovery potential.

Corals and sponges are highly susceptible to damage, mortality and removal by fishing. While impacts measured as changes in relative abundance varied widely across studies, taxa and type of fishing gear, corals and sponges were generally more susceptible to fishing activities than other benthic invertebrates and fishes.

The timing and magnitude of recovery of communities dominated by corals and sponges following disturbance was difficult to assess quantitatively due to a dearth of long-term monitoring studies. While some sponge taxa showed evidence of recovery over relatively short time periods (e.g. <1 year), the recovery of coldwater coral communities is expected to take several decades or centuries. More long term studies that allow comparison of disturbed and undisturbed sites over large spatial scales are needed to provide quantitative estimates of the timing and magnitude of ecosystem recovery. In the meantime, the life history of slow growing species, such as coldwater corals suggests that coral-dominated ecosystems are unlikely to recover from fishing impacts within a reasonable time frame (e.g. 5-20 years) that is relevant to the identification of VMEs and SAIs (FAO 2008). Thus fishing disturbance, and trawling in particular, likely represents an SAI for coral-dominated communities.

Given the challenges associated with estimating recovery potential of deepwater benthic ecosystems with empirical data, there is a need to develop an alternative framework for identifying vulnerable marine ecosystems and serious adverse impacts, based on the life history, growth form, and distribution patterns of dominant taxa, as well as the type of disturbance (Boutillier et al. 2010).

Here, we focus on the impacts to and recovery potential of coral and sponge communities, but it is important to note that VMEs may be dominated by species in other taxonomic groups.

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TABLES

Table 1 Strengths and limitations of some of the more commonly reported indicators of population abundance, community structure, ecosystem function, and impacts

	Indicator	**Strengths**	**Limitations**
Indicators of abundance	Number of individuals	Suited to conspicuous and distinguishable taxa	Poorly suited to colonial, gregarious, or indistinguishable taxa
	Number of colonies	Efficient for colonial or gregarious species	Does not account for size structure
	Density	Repeatable, comparable	Challenges with spatial-references (ROV, trawl)
	Biomass (e.g. in catches)	Comparable within and among gear types	Losses during net tow & retrieval unknown; poor spatial referencing; relevant to fishing
	% Cover	Suited to abundant, colonial, gregarious, or large species with indeterminate growth	Challenges with spatial-referencing, complex bottom structure, & species overlap
	Frequency of occurrence	Easy, provided taxon can be distinguished	May require more sampling, ensure standard sampling
	Habitat suitability model	Predicts presence and/or abundance in unsurveyed areas	May be highly uncertain, requires validation
Indicators of community Structure	Species richness	Measures one dimension of biodiversity; does not require estimates of abundance	Sensitive to sampling effort, requires ability to distinguish among taxa
	Species diversity	Measures the number and evenness among species	Requires occurrence and relative abundance data; may not be sensitive to disturbance
	Number and types of functional groups	Index of community structure	Sensitive to sampling effort; requires knowledge of functions
	Indices of community similarity	Can relate differences to multivariate factors	Difficult to compare among studies or ecosystems
	Size structure (e.g. biomass size spectrum)	Does not require high taxonomic resolution	Requires detailed measurements from diverse organisms; sensitive to sampling design
	Trophic structure	Index of community structure	Requires knowledge of trophic levels; may be insensitive to physical disturbance
Indicators of ecosystem function	Interaction strengths between trophic levels	Index of resilience	Requires knowledge of functional responses among taxa
	Production	A measure of productivity or ecosystem service	Repeated sampling
	Recruitment success	A measure of productivity and of ecosystem service for some target species	Recruitment may be independent of local disturbance regime(s); can be difficult to observe/measure
	Density of burrows/tubes and sediment structure	A measure of biogenic structure in sediments	Requires high quality ROV/diver survey data
Indicators of impacts	Volume of colonies, or of missing colonies	May indicate availability or loss of structural habitat	May be poor linkage between structural complexity and species of interest
	Incidence of damaged, dying, or dead organisms	Comparable among studies, species, ecosystems	May be unrelated to disturbance regime(s)
	Removal rate	Estimates of direct mortality and short-term declines in abundance	Difficult to estimate (in situ, or from catch data); does not account for damage rate
	Type of disturbance (e.g. gear type)	Can partition variance in response accordingly	Gear modifications or behaviour may alter impact
	Tow area	Spatial extent of single disturbance	Does not account for cumulative impacts
	Trawling (or fishing) Footprint	Spatial extent of cumulative disturbances	Does not account for spatial differences in frequency/effort

FIGURES

Figure 1a

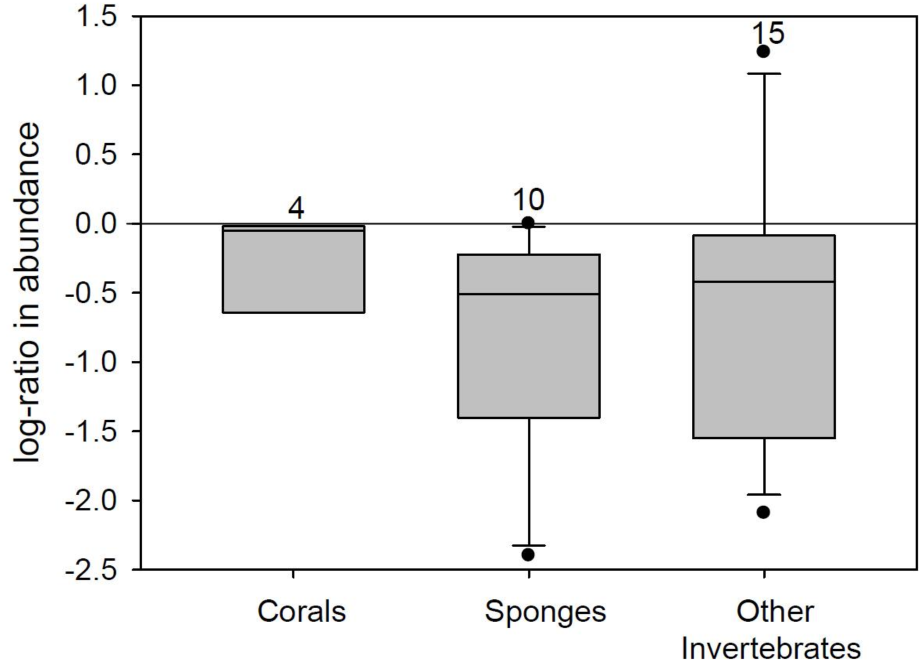

Figure 1b

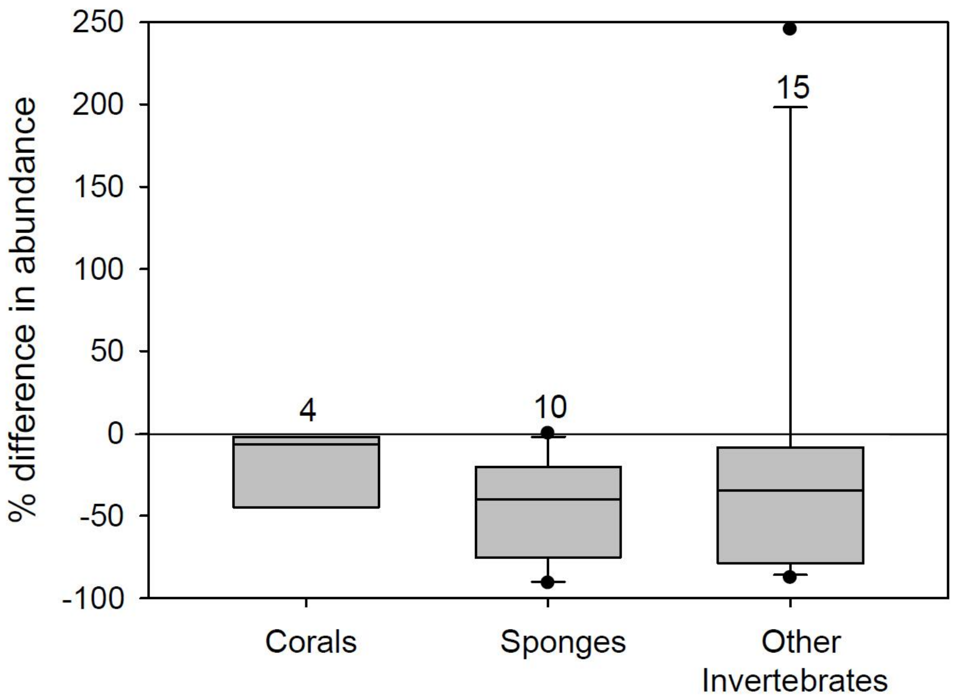

Figure 1 Log-ratios (a) and % differences (b) in relative abundance of corals, sponges, and other invertebrates in sites subjected to a single pass of a trawl compared to the reference state. Horizontal lines represent median values, boxes indicate 25th and 75th percentiles, and error bars denote the 10th and 90th percentiles. The number of records available for each category is indicated above bars.

Figure 2a

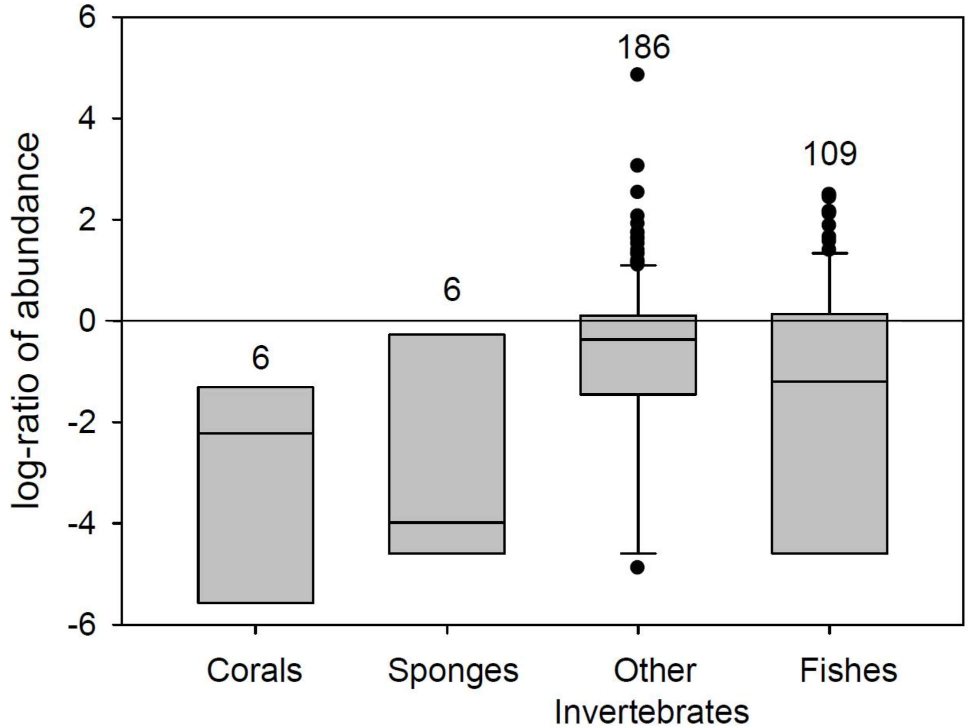

Figure 2b

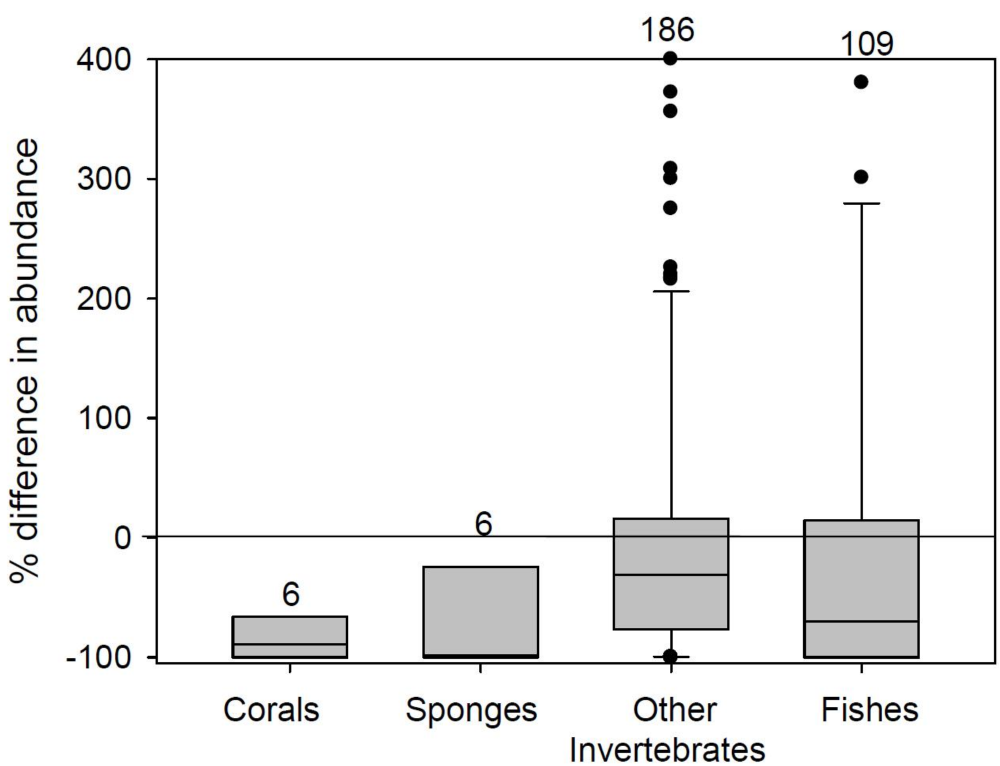

Figure 2 Log-ratios (a) and % differences (b) in relative abundance of corals, sponges, and other invertebrates in sites subjected to repeated fishing disturbances compared to the reference state. Horizontal lines represent median values and error bars denote the 10th and 90th percentiles. The number of records available for each category is indicated above bars.

Figure 3a

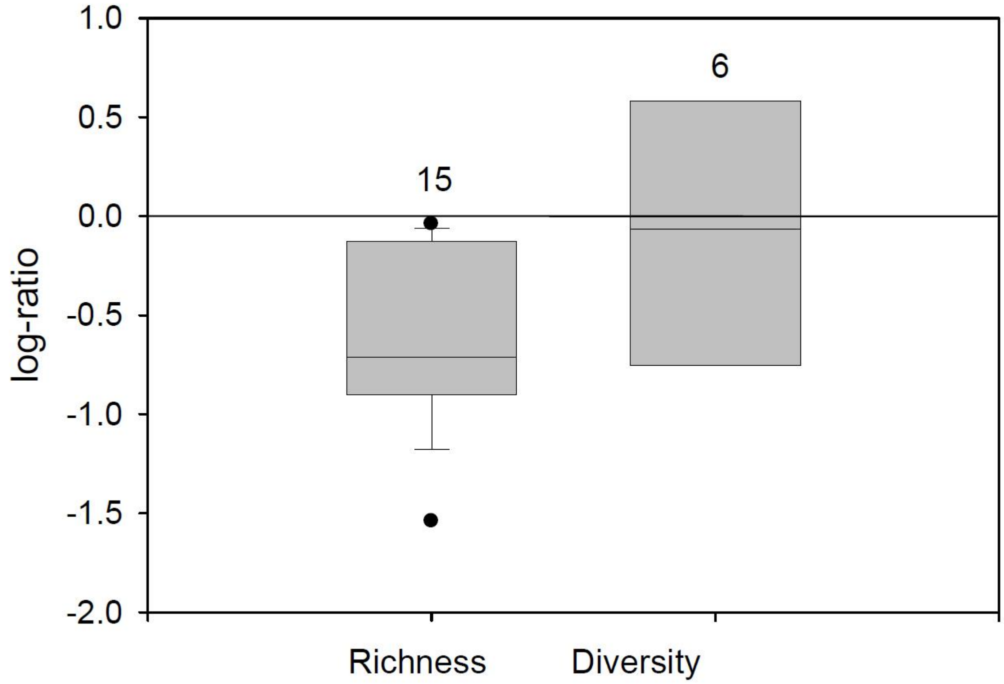

Figure 3b

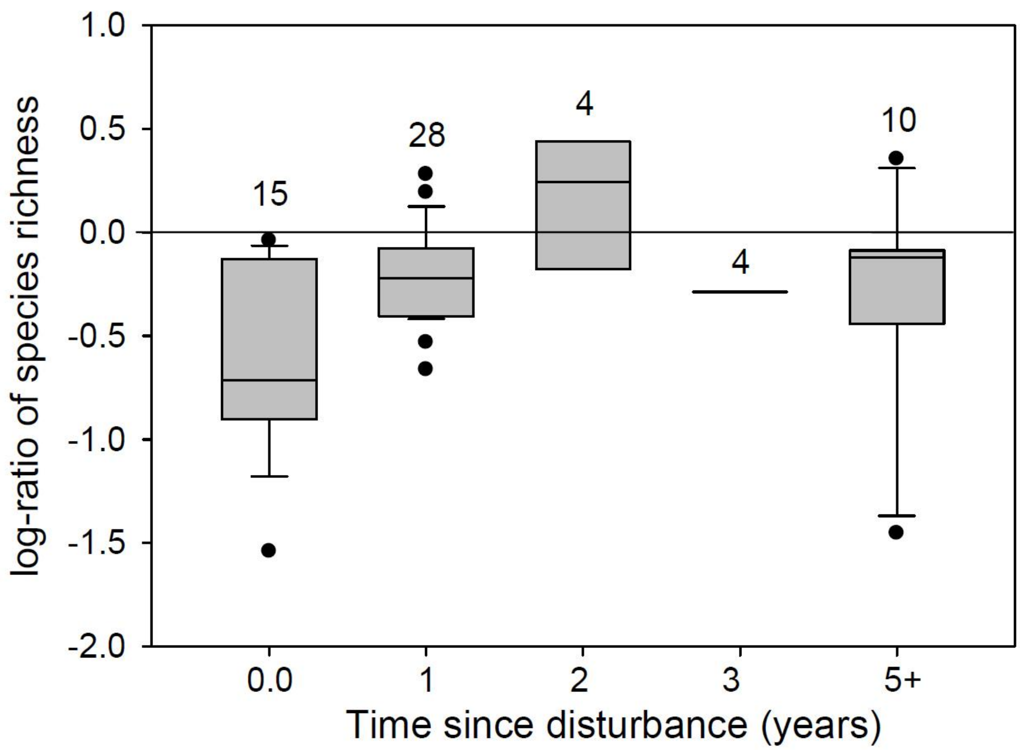

Figure 3 (a) Relative differences in species richness and species diversity in sites subjected to one or more disturbances compared to reference states, expressed as log-ratios. (b) Changes in species richness over time and in relation to reference states following a disturbance. Horizontal lines represent median values and error bars denote the 10th and 90th percentiles. The number of records available for each category is indicated above bars.

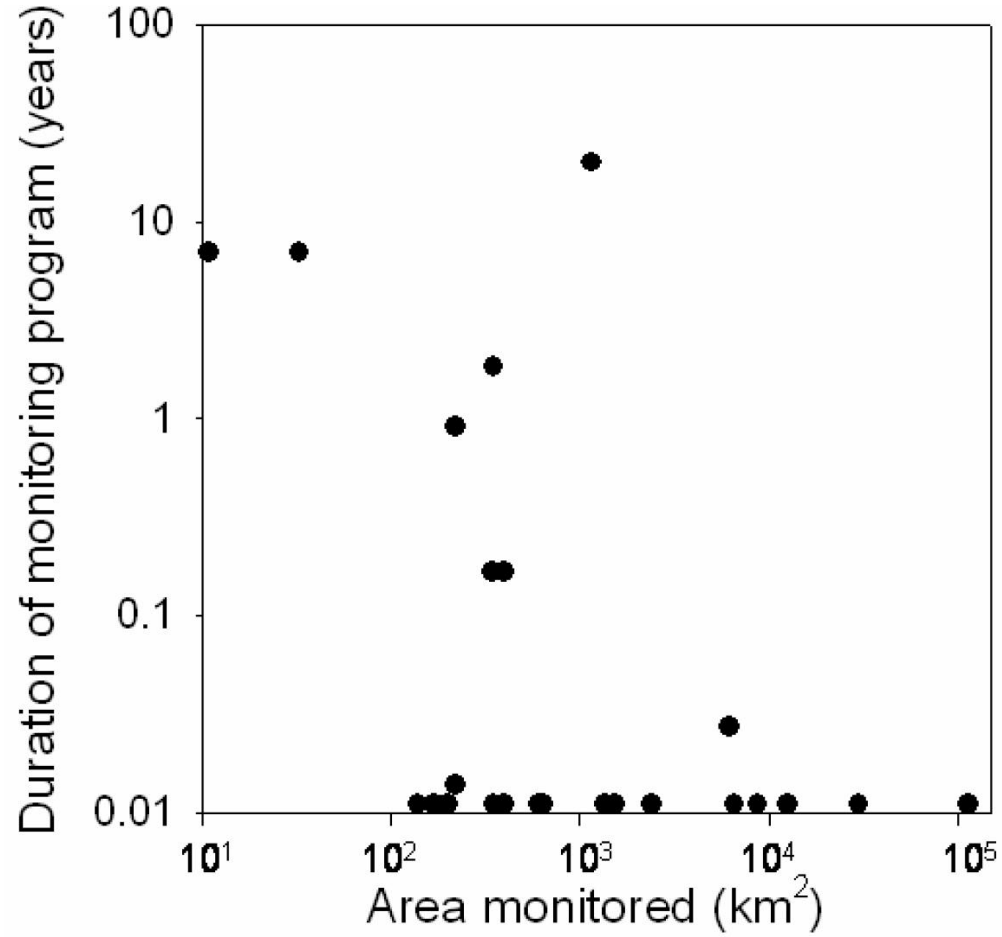

Figure 4 Time elapsed following impacts plotted as a function of the total area monitored (n = 41 studies).

Figure 5a

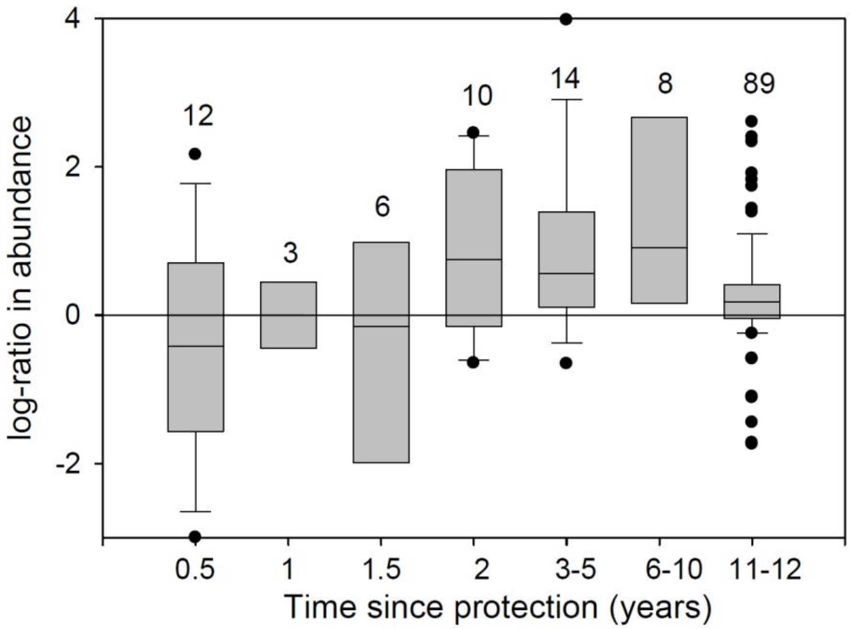

Figure 5b

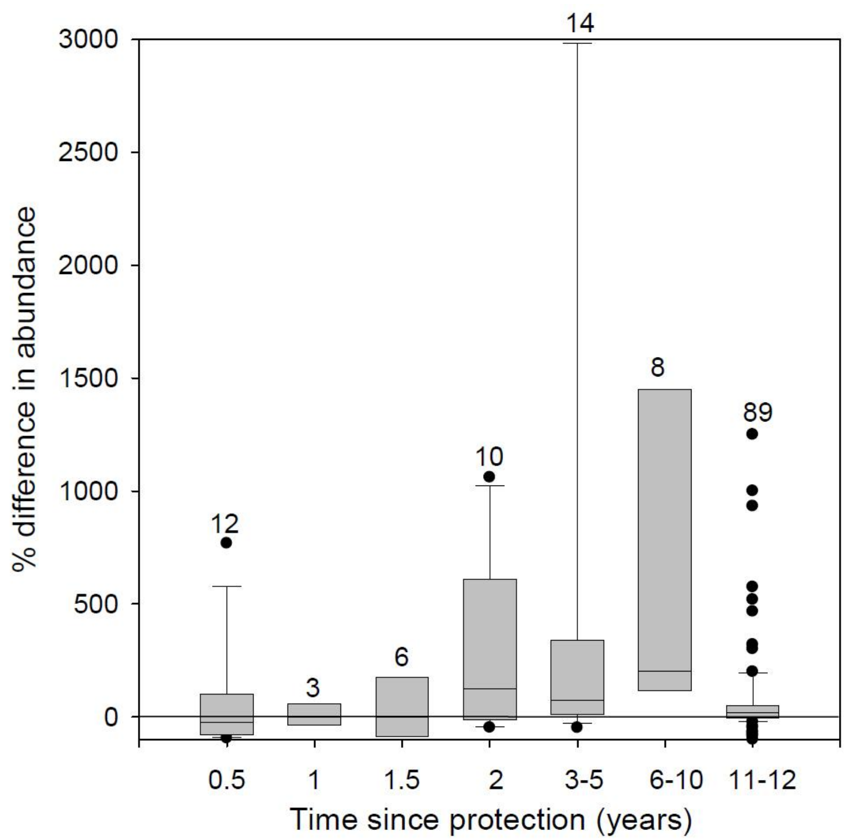

Figure 5 Temporal trends in log-ratios (a) and % differences (b) in relative abundance of all taxa following cessation of disturbance regimes (e.g. implementation of a marine protected area). Horizontal lines represent median values and error bars denote the 10th and 90th percentiles. The number of records available for each category is indicated above bars.

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APPENDIX 2 INDICATORS USED TO CHARACTERIZE THE INITIAL IMPACT AND RESPONSE OF TEMPERATE MARINE ECOSYSTEMS TO FISHING DISTURBANCE.

Indicators related to abundance	**References**
Number of individuals	Collie et al. (2000b); Freese (2004); Stone et al. (2005); Clark & Rowden (2009)
Number of colonies	Krieger (2001)
Density (abundance per unit area)	Freese et al. (1999); Bluhm (2001); Gilkinson et al. (2003); Kenchington et al. (2006); Cooper et al. (2007); deJuan et al. (2007); Hixon & Tissot (2007); Asch & Collie (2008)
Biomass (e.g. kg per sample or unit area)	Sainsbury et al. (1997); McConnaughey et al. (2000); Koslow et al. (2001); Gordon et al. (2005); Henry et al. (2006); Kenchington et al. (2006); Cooper et al. (2007)
Abundance of specific taxa (benthos, epifauna, fish, rockfish, sponges, functional groups, etc)	Sainsbury et al. (1997); Hutchings (2000); Freese et al. (2001); Cryer et al. (2002); Harvey et al. (2006); Kenchington et al. (2006); Cooper et al. (2007); deJuan et al. (2007); Asch & Collie (2008); Auster & Link (2009); Casini et al. (2009)
Biomass of specific taxa (e.g. all taxa surveyed, benthic community, epifauna, functional groups, zooplankton, etc)	McConnaughey et al. (2000); Jennings et al. (2001b); Koslow et al. (2001); Blyth et al. (2004); Gordon et al. (2005); Henry et al. (2006); Kenchington et al. (2006); Queiros et al. (2006); Tillin et al. (2006); Cooper et al. (2007); Casini et al. (2009)
% cover	Sainsbury et al. (1997); Asch & Collie (2008)
% cover live coral	Koslow et al. (2001); Mortensen et al. (2005); Wheeler et al. (2005); Asch & Collie (2008); Clark & Rowden (2009); Harter et al. (2009)
Frequency or proportion of occurrence	McConnaughey et al. (2000); Gilkinson et al. (2003); Gordon et al. (2005); Mortensen et al. (2005); Queiros et al. (2006); Asch & Collie (2008)
% change in abundance	Sainsbury et al. (1997); Engel & Kvitek (1998); Freese et al. (1999); Collie et al. (2000b); Hutchings (2000); McConnaughey et al. (2000); Bluhm et al. (2001); Jennings et al. (2001); Koslow et al. (2001); Wassenberg et al. (2002); Gilkinson et al. (2003); Blyth et al. (2004); Freese (2004); Gordon et al. (2005); Stone et al. (2005); Henry et al. (2006); Kenchington et al. (2006); Cooper et al. (2007); deJuan et al. (2007); Hixon & Tissot (2007); Waller et al. (2007); Asch & Collie (2008); Auster & Link (2009); Clark & Rowden (2009); Harter et al. (2009)

Indicators related to community structure	References
species richness (number of species, genera, families, class, phyla, or distinguishable taxa)	Freese et al. (1999); Collie et al. (2000b); McConnaughey et al. (2000); Bluhm (2001); Koslow et al. (2001); Cryer et al. (2002); Blyth et al. (2004); Freese (2004); Stone et al. (2005); Henry et al. (2006); Kenchington et al. (2006); Cooper et al. (2007); Asch & Collie (2008)
Margalef's Index for species richness	Stone et al. (2005)
Number of functional groups	Collie et al. (2000b); McConnaughey et al. (2000); Freese (2004); Stone et al. (2005);deJuan et al. (2007); Hixon & Tissot (2007)
Simpson's Index for species dominance	Stone et al. (2005); Asch & Collie (2008)
Pielou's Index of evenness	Kenchington et al. (2006); Hixon & Tissot (2007)
Shannon-Weiner Index of diversity	Collie et al. (2000b); Cryer et al. (2002); Kenchington et al. (2006); Hixon & Tissot (2007); Asch & Collie (2008)
Evenness index	Collie et al. (2000b)
Diversity of fishes	Harter et al. (2009)
Bray-Curtis Index of similarity	Koslow et al. (2001)
ANOSIM community assemblage analysis of similarities	Kenchington et al. (2006); Cooper et al. (2007); deJuan et al. (2007); Asch & Collie (2008); Cooper et al. (2008); Clark & Rowden (2009); Harter et al. (2009)
Index of community similarity	Cooper et al. (2007); Asch & Collie (2008); Cooper et al. (2008); Auster & Link (2009)
Community structure (fish, invertebrates, all surveyed taxa)	Engel & Kvitek (1998); Bluhm (2001); Koslow et al. (2001); Gordon et al. (2005); Henry et al. (2006); Kenchington et al. (2006); Cooper et al. (2007); Hixon & Tissot (2007); Asch & Collie (2008); Auster and Link (2009); Harter et al. (2009)
Rao's Q	Cooper et al. (2008)
Infaunal trophic index	Cooper et al. (2008)
Taxonomic distinctiveness	Cooper et al. (2008); Harter et al. (2009)
Trophic structure	Jennings et al. (2001b); Badalamenti et al. (2002)
Biomass size spectrum (epifauna, infauna)	Jennings (2001); Jennings (2002)
Size and/or age structure	Badalamenti et al. (2002); Jennings et al. (2002); Stone et al. (2005); Harvey et al. (2006); Quieros et al. (2006)
Biological traits analysis	Cooper et al. (2008)
Niche breadth	McConnaughey et al. (2000)

Indicators related to ecosystem function	References
Interaction strengths between trophic levels	Casini et al. (2009)
Production (epifauna, infauna, macrofauna)	Jennings et al. (2001); Jennings et al. (2002); Quieros et al. (2006); Cooper et al. (2008)
Recruitment success	Casini et al. (2009)
Rao's Q	Cooper et al. (2008)
Density of burrows/tubes	Gilkinson et al. (2003)
Sediment structure	Schwinghamer et al. (1998); Gilkinson et al. (2003); Gordon et al. (2005); Cooper et al. (2007)
Volume of missing coral colonies	Krieger (2001)
Biological traits analysis	Cooper et al. (2008)

Indicators related to damage	References
Incidence of damage (%) or necrosis associated with damage (%)	Freese et al. (1999); Krieger (2001); Freese (2004); Wheeler et al. (2005)
Coral damage	Krieger (2001); Fossa et al. (2002); Mortensen et al. (2005); Wheeler et al. (2005)
Volume of missing colonies (coral)	Krieger (2001)
% of structural species damaged (e.g. broken coral)	Sainsbury et al. (1997); Fossa et al. (2002); Wassenberg et al. (2002); Mortensen et al. (2005); Stone et al. (2005); Wheeler et al. (2005)
% structural species removed	Sainsbury et al. (1997); Wassenberg et al. (2002); Stone et al. (2005); Wheeler et al. (2005)
% dead coral	Wheeler et al. (2005)
Loss of functional groups	Koslow et al. (2001); Tillin et al. (2006); deJuan et al. (2007)
Qualitative observations of damage to structural species	Collie et al. (2000b); Koslow et al. (2001); Krieger (2001); Fossa et al. (2002); Wassenberg et al. (2002); Freese (2004); Mortensen et al. (2005); Waller et al. (2007); Asch & Collie (2008); Clark & Rowden (2009); Harter et al. (2009)

APPENDIX 3 INDICATORS OF FISHING DISTURBANCE.

Variables related to disturbance and/or sampling design	References
Month and year of disturbance	Koslow et al. (2001); Krieger et al. (2001); Blyth et al. (2004); Stone et al. (2005); Clark & Rowden (2009), etc
Type of disturbance	Engel & Kvitek (1998); Freese et al. (1999); Koslow et al. (2001); Krieger (2001); Blyth et al. (2004); Stone et al. (2005): Hixon & Tissot (2007); Clark & Rowden (2009), etc
Area of individual disturbance (e.g. tow area)	Schwinghamer et al. (1998); Freese et al. (1999); Koslow et al. (2001); Fossa et al. (2002); Jennings et al. (2002); Wassenberg et al. (2002); Gilkinson et al. (2003); Blyth et al. (2004); Freese (2004); Gordon et al. (2005); Henry et al. (2006); Kenchington et al. (2006); Queiros et al. (2006); Clark & Rowden (2009)
Dimensions of disturbance	Schwinghamer et al. (1998); Freese et al. (1999); Jennings et al. (2001b); Koslow et al. (2001); Krieger (2001); Cryer et al. (2002); Fossa et al. (2002); Jennings et al. (2002); Wassenberg et al. (2002); Gilkinson et al. (2003); Blyth et al. (2004); Freese (2004); Gordon et al. (2005); Wheeler et al. (2005); Henry et al. (2006); Kenchington et al. (2006); Tillin et al. (2006); Queiros et al. (2006); Cooper et al. (2007); Cooper et al. (2008); Clark & Rowden (2009)
Distance between disturbed sites	Schwinghamer et al. (1998); Freese et al. (1999); Koslow et al. (2001); Krieger (2001); Wassenberg et al. (2002); Gilkinson et al. (2003); Blyth et al. (2004); Freese (2004); Gordon et al. (2005); Wheeler et al. (2005); Henry et al. (2006); Kenchington et al. (2006); Cooper et al. (2007); Cooper et al. (2008); Asch & Collie (2008); Clark & Rowden (2009)
Distance between undisturbed sites	Engel & Kvitek (1998); Schwinghamer et al. (1998); Freese et al. (1999), Jennings et al. (2001); Jennings et al. (2001b); Koslow et al. (2001); Krieger (2001); Cryer et al. (2002); Fossa et al. (2002); Jennings et al. (2002); Wassenberg et al. (2002); Gilkinson et al. (2003); Freese (2004); Gordon et al. (2005); Henry et al. (2006); Kenchington et al. (2006); Queiros et al. (2006); Tillin et al. (2006); Cooper et al. (2007); Cooper et al. (2008)
Total area disturbed	Sainsbury et al. (1997); Engel & Kvitek (1998); Schwinghamer et al. (1998); Bluhm (2001); Cryer et al. (2002); Fossa et al. (2002); Wassenberg et al. (2002); Gilkinson et al. (2003); Blyth et al. (2004); Freese (2004); Gordon et al. (2005); Wheeler et al. (2005); Harvey et al. (2006); Henry et al. (2006); Kenchington et al. (2006); Queiros et al. (2006); Tillin et al. (2006); Cooper et al. (2007); deJuan et al. (2007); Cooper et al. (2008); Auster & Link (2009); Harter et al. (2009)
Intensity or effort, exploitation, bycatch etc.	Engel & Kvitek (1998); Schwinghamer et al. (1998); Hutchings (2000); Bluhm (2001); Jennings et al. (2001); Jennings et al. (2001b); Koslow et al. (2001); Cryer et al. (2002); Jennings et al. (2002); Wassenberg et al. (2002); Gilkinson et al. (2003); Blyth et al. (2004); Freese (2004); Gordon et al. (2005); Wheeler et al. (2005); Harvey et al. (2006); Henry et al. (2006); Kenchington et al. (2006); Tillin et al. (2006); Cooper et al. (2007); deJuan et al. (2007); Hixon & Tissot (2007); Asch & Collie (2008); Cooper et al. (2008); Clark & Rowden (2009)

Variables related to disturbance and/or sampling design	References
Catches of target, bycatch, or both (e.g. tonnes)	Engel & Kvitek (1998); Freese et al. (1999); Krieger (2001); Wassenberg et al. (2002); Harvey et al. (2006); Clark & Rowden (2009)
Abundance of trawl gouges in substrate	Schwinghamer et al. (1998); Bluhm (2001); Koslow et al. (2001); Cryer et al. (2002); Gilkinson et al. (2003); Gordon et al. (2005); Wheeler et al. (2005); Waller et al. (2007); Clark & Rowden (2009)
Frequency of impact	Engel & Kvitek (1998); Freese et al. (1999); Bluhm (2001); Jennings et al. (2001); Jennings et al. (2001b); Koslow et al. (2001); Krieger (2001); Cryer et al. (2002); Jennings et al. (2002); Gilkinson et al. (2003); Blyth et al. (2004); Freese (2004); Gordon et al. (2005); Stone et al. (2005); Henry et al. (2006); Kenchington et al. (2006); Tillin et al. (2006); Clark & Rowden (2009)
Duration of impact	Freese et al. (1999); Koslow et al. (2001); Krieger (2001); Wassenberg et al. (2002); Gordon et al. (2005); Henry et al. (2006); Kenchington et al. (2006); Queiros et al. (2006); Clark & Rowden (2009)
Time elapsed since last disturbance	Sainsbury et al. (1997); Engel & Kvitek (1998); Schwinghamer et al. (1998); Freese et al. (1999); Collie et al. (2000b); Hutchings (2000); McConnaughey et al. (2000); Bluhm et al. (2001); Jennings et al. (2001); Jennings et al. (2001b); Koslow et al. (2001); Krieger (2001); Cryer et al. (2002); Fossa et al. (2002); Jennings et al. (2002); Wassenberg et al. (2002); Gilkinson et al. (2003); Blyth et al. (2004); Freese (2004); Gordon et al. (2005); Mortensen et al. (2005); Stone et al. (2005); Wheeler et al. (2005); Henry et al. (2006); Kenchington et al. (2006); Tillin et al. (2006); Cooper et al. (2007); deJuan et al. (2007); Waller et al. (2007); Asch & Collie (2008); Cooper et al. (2008); Clark & Rowden (2009); Harter et al. (2009)
Proportion of available habitat impacted	Collie et al. (2000b); Koslow et al. (2001); Cryer et al. (2002); Fossa et al. (2002); Wassenberg et al. (2002); Gilkinson et al. (2003); Wheeler et al. (2005); Queiros et al. (2006); deJuan et al. (2007)
% removed	Freese et al. (1999); Wassenberg et al. (2002)
Catch rate of target species	Sainsbury et al. (1997)

APPENDIX 4 COMMONLY REPORTED PHYSICAL DESCRIPTORS OF ECOSYSTEMS.

Variables related to study area	**References**
Latitude and longitude	Engel & Kvitek (1998); Koslow et al. (2001); Blyth et al. (2004); Freese (2004); Stone et al. (2005); Hixon & Tissot (2007); Clark & Rowden (2009), etc
Depth	Sainsbury et al. (1997); Schwinghamer et al. (1998); Freese et al. (1999); Collie et al. (2000b); McConnaughey et al. (2000); Bluhm (2001); Jennings et al. (2001); Jennings et al. (2001b); Koslow et al. (2001); Krieger et al. (2001); Cryer et al. (2002)
Sediment type (e.g. mud, sand, pebble, cobble, etc)	Schwinghamer et al. (1998); Freese et al. (1999); Collie et al. (2000b); McConnaughey et al. (2000); Bluhm (2001); Jennings et al. (2001b); Koslow et al. (2001); Krieger et al. (2001); Fossa et al. (2002); Jennings et al. (2002); Wassenberg et al. (2002); Gilkinson et al. (2003); Freese (2004); Gordon et al. (2005); Mortensen et al. (2005); Stone et al. (2005); Henry et al. (2006); Kenchington et al. (2006); Queiros et al. (2006); Tillin et al. (2006); Hixon & Tissot (2007); Asch & Collie (2008); Cooper et al. (2008); Clark & Rowden (2009); Harter et al. (2009)
Sediment grain size	Schwinghamer et al. (1998); Freese et al. (1999); Collie et al. (2000b); Jennings et al. (2001b); Krieger et al. (2001); Gilkinson et al. (2003); Freese (2004); Gordon et al. (2005); Stone et al. (2005); Henry et al. (2006); Kenchington et al. (2006); Hixon & Tissot (2007)
Water temperature	Jennings et al. (2002); Mortensen et al. (2005); Wheeler et al. (2005)
Salinity	Mortensen et al. (2005)
Wave exposure	Mortensen et al. (2005)
Current speed	Collie et al. (2000b); McConnaughey et al. (2000); Mortensen et al. (2005); Stone et al. (2005); Wheeler et al. (2005); Cooper et al. (2007); Cooper et al. (2008)
Productivity (e.g. somatic production, kJ / m^2 per year)	Cooper et al. (2008)
Natural disturbance regime	McConnaughey et al. (2000)
Index of habitat heterogeneity	Clark & Rowden (2009)
Bottom shear stress	Tillin et al. (2006)
Lateral visibility	Krieger (2001); Freese (2005)

APPENDIX 5 PPT SLIDES PRESENTED AT THE NATIONAL SCIENCE ADVISORY PROCESS CONCERNING CORALS, SPONGES, AND HYDROTHERMAL VENTS IN CANADIAN WATERS, 9-12 MARCH 2010, OTTAWA

Indicators of impact and recovery in marine ecosystems

Janelle Curtis, Chris Wood
Pacific Biological Station

Katrina Poppe
University of Victoria

Andrés Araújo
Simon Fraser University

Fisheries and Oceans Canada

Vulnerable marine ecosystems and serious adverse impacts

FAO (2008) Report of the Technical Consultation on International Guidelines for the Management of Deep-sea Fisheries in the High Seas:

Vulnerable marine ecosystems (VME):

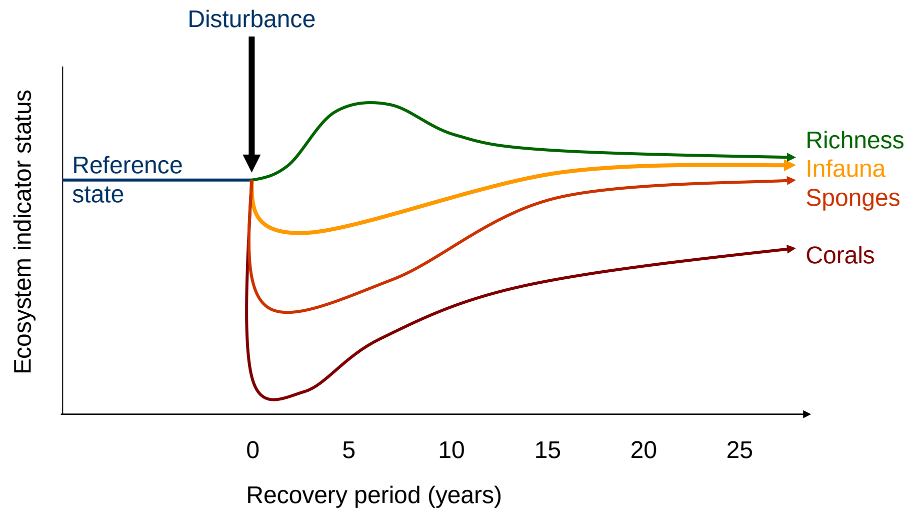
- ecosystems likely to show a substantial negative response to disturbance

Serious adverse impacts (SAI):

- a disturbance that precludes ecosystem recovery within an acceptable timeframe (e.g. 5-20 years)

Fisheries and Oceans Canada

Objectives: review impacts & recovery potential in high seas



Fisheries and Oceans Canada

Systematic review of literature

Roberts et al. (2006) Biological Conservation

Science Citation Indices:

Web of Science http://isiwebofknowledge.com/
Scopus www.scopus.com

Topic = (marine OR deep* OR cold-water OR pelagic OR benth*) AND (ecosystem*) AND (trawl* OR fishing OR fisher* OR oil OR gas OR dredg*) AND (recover* OR vulnerab*)

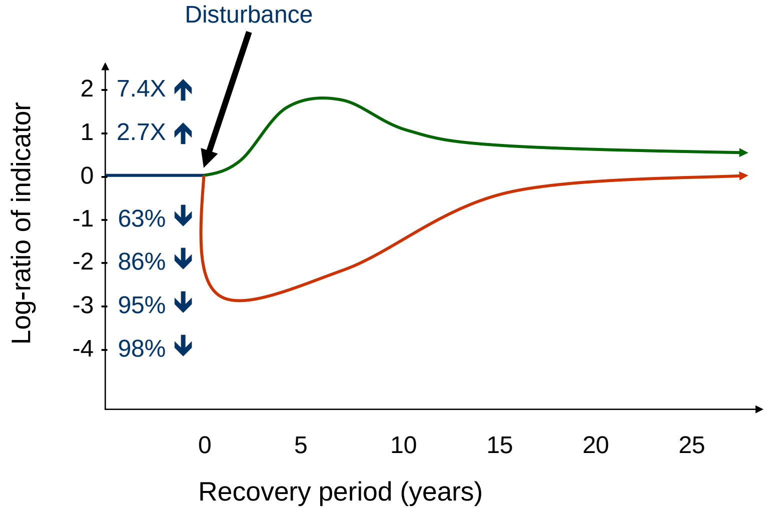
2000-2009:

- 545 primary papers, 46 fit criteria
- temperate deepwater ecosystems
- measuring ecosystem response to anthropogenic disturbance
- spatial or temporal reference site(s)
- 79% trawling studies
- 49% in Northeast Pacific and Northwest Atlantic Oceans

Fisheries and Oceans Canada

Log-ratios of indicators

$$\ln\left(\frac{I_{disturbed}}{I_{reference}}\right)$$



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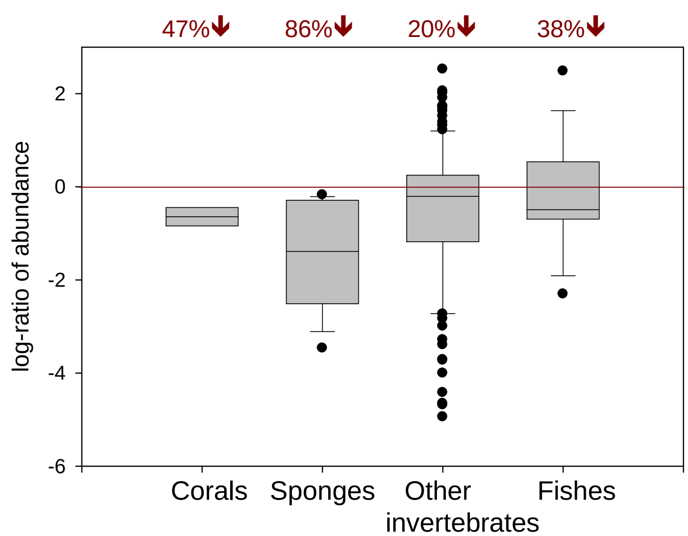
Initial impact – relative abundance

(number of individuals, number of colonies, % cover, density, biomass, frequency, etc)



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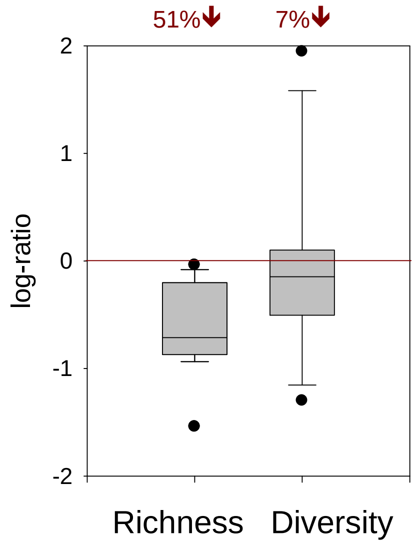
Initial impact – species richness and diversity

(number and evenness of species, taxa, or functional groups)



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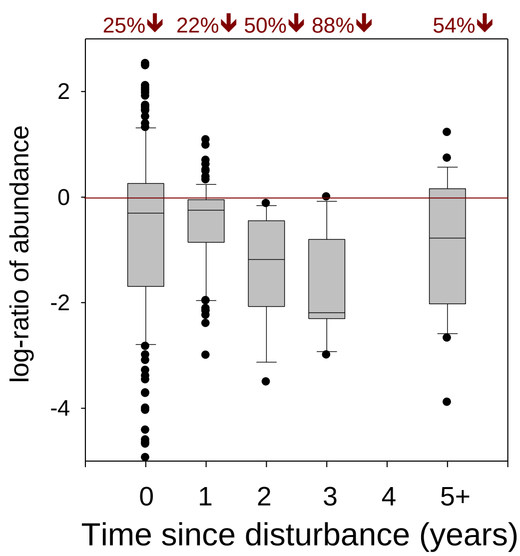
Recovery – abundance, all taxa pooled



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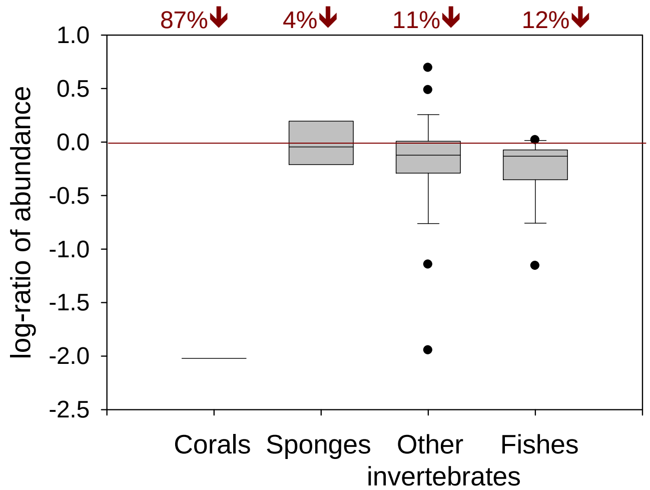
Recovery – abundance at 3+ years post-impact



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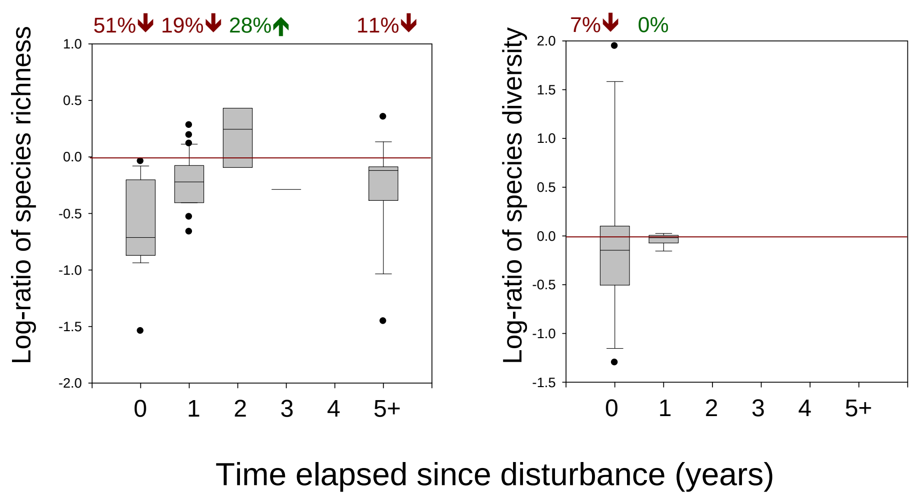
Recovery – species richness and diversity



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Indicators of abundance

Indicator	Strengths	Weaknesses
Number of individuals	Suited to conspicuous and distinguishable taxa	Poorly suited to colonial, gregarious, or indistinguishable taxa
Number of colonies	Efficient for colonial or gregarious species	Does not account for size structure
Density	Repeatable, comparable	Challenges with spatial-references (ROV, trawl)
Biomass (e.g. in catches)	Comparable within and among gear types	Losses during net tow & retrieval unknown; poor spatial referencing; relevant to fishing
% Cover	Suited to abundant, colonial, gregarious, or large species with indeterminate growth	Challenges with spatial-referencing, complex bottom structure, & species overlap
Frequency of occurrence	Easy, provided taxon can be distinguished	May require more sampling, ensure standard sampling
Habitat suitability model (e.g. SDMs)*	Predicts presence and/or abundance in unsurveyed areas	May be highly uncertain, requires validation

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Indicators of community structure

Indicator	Strengths	Weaknesses
Species richness	Measures one dimension of biodiversity; does not require estimates of abundance	Sensitive to sampling effort, requires ability to distinguish among taxa
Species diversity	Measures the number and evenness among species	Requires occurrence and relative abundance data; may not be sensitive to disturbance
Number and types of functional groups	Index of community structure	Sensitive to sampling effort; requires knowledge of functions
Indices of community similarity	Can relate differences to multivariate factors	Difficult to compare among studies, ecosystems?
Size structure (e.g. biomass size spectrum)	Does not require high taxonomic resolution	Requires detailed measurements from diverse organisms; sensitive to sampling design
Trophic structure	Index of community structure	Requires knowledge of trophic levels; may be insensitive to physical disturbance

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Indicators of ecosystem function

Indicator	Strengths	Weaknesses
Interaction strengths between trophic levels	Index of resilience	Requires knowledge of functional responses among taxa
Production	A measure of productivity or ecosystem service	Repeated sampling
Recruitment success	A measure of productivity and of ecosystem service for some target species	Recruitment may be independent of local disturbance regime(s); can be difficult to observe/measure
Density of burrows/tubes and sediment structure	A measure of biogenic structure in sediments	Requires high quality ROV/diver survey data
Volume of colonies, or of missing colonies	May indicate availability or loss of structural habitat	May be poor linkage between structural complexity and species of interest

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Indicators of impacts

Indicator	Strengths	Weaknesses
Incidence of damaged, dying, or dead organisms	Comparable among studies, species, ecosystems	May be unrelated to disturbance regime(s)
Removal rate	Estimates of direct mortality and short-term declines in abundance	Difficult to estimate (in situ, or from catch data); does not account for damage rate
Type of disturbance (e.g. gear type)	Can partition variance in response accordingly	Gear modifications or behaviour may alter impact
Tow area	Spatial extent of single disturbance	Does not account for cumulative impacts
Trawling (or fishing) Footprint	Spatial extent of cumulative disturbances	Does not account for spatial differences in frequency/effort
Frequency of disturbance	Accounts for cumulative impacts	Does not account for spatial extent of disturbance
Catches (target and bycatch species)	Provides information on presence of species, possibly relative abundance	Biased sample of ecosystem structure due to differences in catchability and retention; does not account for damage

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Interpretation

Abundance of most taxa declines following fishing disturbance

- more pronounced declines for corals and sponges

Abundance of most taxa continues to decline during first few years

- studies within first few months of impact may underestimate effects

Corals show no evidence of recovery

Species diversity less sensitive to disturbance than species richness

Species richness increases during first few years

Caveats:

- short time series, limited data
- preliminary analysis
- publication bias

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On-going work – comments and suggestions welcomed

Expand database to include 1990-2010

Multivariate analysis of impact and recovery

- ecosystem type (depth, sediment, currents,…)
- life history
- growth form
- nature, frequency, and intensity of disturbance

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Thank you