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Special edition

SeaWeb
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Oil and oil spills: the Gulf of Mexico

In order to support the response efforts to the ongoing oil spill in the Gulf of Mexico SeaWeb has assembled relevant literature from the last three decades which provide insights not only to the impact of oil on the marine and coastal environment in the Gulf of Mexico, but highlights experiences, issues and research from similar oil spills in other regions of the world. Please let us know if there are other relevant papers to add to this list. We will update this review and make it available through: www.seaweb.org/resources/msr.php.

SeaWeb will produce special editions of the Marine Science Review in response to significant ocean events or issues to ensure that any activities, efforts and media are underpinned by sound science.

In this review:

A. Impacts on human health

Aguilera, F., Méndez, J., Pásaro, E., and Laffon, B. **Review on the effects of exposure to spilled oils on human health.** *Journal of Applied Toxicology* 10.1002/jat.1521, 2010.

Notes: Harmful effects of oil spills on diverse flora and fauna species have been extensively studied. Nevertheless, only a few studies have been compiled in the literature dealing with the repercussions of oil exposure on human health; most of them have focused on acute effects and psychological symptoms. The objective of this work was to gather all these studies and to analyze the possible consequences of this kind of complex exposure in the different aspects of human health. Studies found on this topic were related to the disasters of the *Exxon Valdez*, *Braer*, *Sea Empress*, *Nakhodka*, *Erika*, *Prestige* and *Tasman Spirit* oil tankers. The majority of them were cross-sectional; many did not include control groups. Acute effects were evaluated taking into account vegetative-nervous symptoms, skin and mucous irritations, and also psychological effects. Genotoxic damage and endocrine alterations were assessed only in individuals exposed to oil from *Prestige*. The results of the reviewed articles clearly support the need for biomonitoring human populations exposed to spilled oils, especially those individuals involved in the cleanup, in order to evaluate not only the possible immediate consequences for their health but also the medium- and long-term effects, and the effectiveness of the protective devices used.

Sabucedo, J.M., Arce, C., Senra, C., Seoane, G., and Vázquez, I. **Symptomatic profile and health-related quality of life of persons affected by the *Prestige* catastrophe.** *Disasters* 10.1111/j.1467-7717.2010.01170.x, 2010.

Notes: This study analyses the impact of the *Prestige* oil spill on the mental health and the perception of physical health and functional capacity in the affected population. The sample comprised 926 residents from the section of the Spanish coast affected by the oil spill. The data was collected slightly more than one year after the accident. Scales referring to clinical symptoms (SCL-36) and health-related quality of life (SF-36) were administered. The results suggest that individuals with higher degrees of exposure or residing in areas closest to the spill show lower levels of mental health in comparison to those with lower levels of exposure or living in areas farther away from the spill. This study also finds that women and fishermen tend to suffer more from the consequences of these types of disaster.

B. Impacts on marine and coastal birds

Heubeck, M., Camphuysen, K.C.J., Bao, R., Humple, D., Rey, A.S., Cadiou, B., Brager, S., and Thomas, T. **Assessing the impact of major oil spills on seabird populations.** *Marine Pollution Bulletin* 46(7): 900-902, 2003.

Balseiro, A., Espi, A., Marquez, I., Perez, V., Ferreras, M.C., Marin, J.F.G., and Prieto, J.M. **Pathological features in marine birds affected by the Prestige's oil spill in the north of Spain.** *Journal of Wildlife Diseases* 41(2): 371-378, 2005.

Notes: A total of 2,465 seabirds, mainly common murres (*Uria aalge*), razorbills (*Alca torda*), and puffins (*Fratercula arctica*) that beached in the northwestern part of Spain after the "Prestige" oil spill on 19 November 2002 were examined by pathological methods. Birds were divided into three groups: dead birds with the body covered (group 1) or uncovered (group 2) by oil and birds recovered alive but which died after being treated at a rescue center (group 3). The main gross lesions were severe dehydration and emaciation. Microscopically, hemosiderin deposits, related to cachexia and/or hemolytic anemia, were observed in those birds harboring oil in the intestine. Severe aspergillosis and ulcers in the ventriculus were found only in group 3 birds, probably because of stress associated with attempted rehabilitation at the rescue center. The mild character of the pathological changes suggests that petroleum oil toxicosis causes multiple sublethal changes that have an effect on the ability of the birds to survive at sea, especially weak and young, inexperienced animals. Dehydration and exhaustion seem to be the most likely cause of death.

Castege, I., Lalanne, Y., Gouriou, V., Hemery, G., Girin, M., D'Amico, F., Mouches, C., D'Elbee, J., Soulier, L., Pensu, J., Lafitte, D., and Pautrizel, F. **Estimating actual seabirds mortality at sea and relationship with oil spills: lesson from the "Prestige" oil spill in Aquitaine (France).** *Ardeola* 54(2): 289-307, 2007.

Notes: Aims: Estimations were made of seabirds mortality at sea and drift in relationship with oil arrival during the "Prestige" oilspill. Location: South Bay of Biscay (Aquitaine), South-West France. Methods: meteorological data (Meteo France), the amount of hydrocarbons collected along the coast line (CEDRE), number of beached seabirds (UMSOM, DIREN) and their distribution and abundance on wintering areas at sea (MNHN-LAPHY), to assess the joint drift of oiled animals and of hydrocarbons in the south Bay of Biscay (Aquitaine) during the "Prestige" oilspill. For the first time at the time of an oil slick, we experimentally dropped into the open sea (off the French basco-landaise coast) ringed corpses of guillemots *Uria aalge* in order to estimate by capture-recaptures approach the rate of reported bodies (1 over 121) at the coast and thus to appreciate the total mortality of the populations of seabirds (UPPA-MNHN). Results: It is estimated that seabirds mortality was eleven times the amount of beached birds collected on the Aquitaine coasts. That result was in accordance with the decrease in the number of guillemots (the most beached species) observed at sea after the "Prestige" shipwreck. Conclusions: It is demonstrated that the pooling of databases of different natures and origins was necessary to assess the impact of oil spill pollutions, such as those of "Erika" and "Prestige", on the animal populations and more generally for marine biodiversity conservation.

Anderson, D.W., Gress, F., and Fry, D.M. **Survival and dispersal of oiled brown pelicans after rehabilitation and release.** *Marine Pollution Bulletin* 32(10): 711-718, 1996.

Notes: California brown pelicans (*Pelecanus occidentalis californicus*) were exposed to oil spills just prior to the 1990 breeding season and during the 1991 breeding season in the Southern California Bight (SCB); some were captured, rehabilitated (cleaned and given veterinary care) and released (total = 31 colour- and radio-marked + 81 colour-marked only; = RHB). Nineteen unoiled controls (=CON) from the SCB population, but from an unaffected area, were captured, radio-marked (11) and/or colour-marked (8) in 1990. Despite extensive surveys in the Gulf of California and western Baja California (latitude 23° to 30°N), all radio signals, recoveries and sightings were on the Pacific Coast between 30° and 47°N from 1990-1992. After release and until radio-telemetry data ceased to provide a complete sampling of RHB and CON (after about 6 months), RHB pelicans disappeared at a higher rate than CON; a continuing lower survival of RHB was also indicated from independent sightings of colour-marked pelicans by late 1992. RHB pelicans showed no breeding activity (or even presence or association with breeding colonies) in both years. In contrast, expected proportions of radio-marked CON pelicans were active at breeding colonies in 1990, and the general brown pelican population (which acted as controls in 1991) was active at breeding colonies in 1991. Postbreeding dispersal occurred as expected (mostly to the north) in 1990 and 1991 with CON. RHB pelicans remained sedentary in the SCB for at least 5-6 months in 1990 but dispersed north ahead of CON (as expected for non-breeders) in 1991, apparently in response to building ENSO (El Nino/Southern Oscillation) conditions in the SCB 1991-1992. RHB pelicans (1990) tended to remain farther away from the breeding colonies than CON (1990) in their second post-rehabilitation breeding season. At that time, their dispersal behaviour was similar to that expected for non-breeding adults and juveniles. We conclude that oil and/or rescue and treatment result in long-term injury to brown pelicans, and that current efforts do not restore them to breeding condition or normal survivability.

Briggs, K.T., Gershwin, M.E., and Anderson, D.W. **Consequences of petrochemical ingestion and stress on the immune system of seabirds.** *ICES Journal of Marine Science* 54(4): 718-725, 1997.

Notes: The immune system is a target of toxicants and there is increasing awareness of the role of environmental pollutants in altering immune function. Immune suppression may constitute a previously unappreciated source of both acute and chronic impacts on seabirds affected by spilled oil. Thus, it is important to determine (a) if immunosuppression occurs, (b) its importance compared to other mechanisms of impact, (c) its timing and chronicity relative to oil ingestion and post-spill cleaning efforts, and (d) if something can, and should be, done to mitigate its effects. The published evidence concerning immune suppression among oiled seabirds is incomplete and much of it is indirect. Among oiled birds, leukocyte numbers (especially lymphocytes) are depressed in the circulation and the major lymphoid organs (spleen and bursa of Fabricius). At the same time, bone marrow hypercellularity, with an emphasis on erythropoiesis, suggests an adaptive shift from white cell to red cell production in response to haemolytic anaemia. Secondary fungal and bacterial infections, common among seabirds in rehabilitation centres, emphasize the immunosuppressive qualities of petrochemicals. Furthermore, inflammation of the gastrointestinal tract following oil ingestion leads to malabsorption of nutrients (which is immunosuppressive), damage to mucosal immune defences, and impairment of responses to certain antigens, such as those of foods. Unfortunately, direct challenge by viral or bacterial pathogens has been incorporated into very few relevant, laboratory studies: compared with experimental controls, domestic birds fed petroleum distillates and/or oil-emulsifying agents suffer greater mortality, and have depressed ability to kill or phagocytize bacterial pathogens. Cell-mediated immune mechanisms are more sensitive to the toxic effects of petrochemical ingestion than are mechanisms related to antibody production. Petrochemical ingestion produces abnormal concentrations or accelerated metabolism of adrenal corticosteroids. The same is true for birds subjected to handling stress, such as occurs during experimentation with wild birds, and during cleaning of oil-soaked birds. Corticosteroid hormones affect the immune system in many ways, including changes in numbers, and depression of function among lymphocytes. Results of the few recent studies of birds released from cleaning facilities are consistent with the notion of chronic, toxic, or immune system problems. These birds suffer higher than expected mortality rates, disappear from expected breeding and dispersal areas, and generally fail to breed for one or more years. Better long-term success might be obtained with improved assessment of immune function during captivity, and with the use of non-specific potentiators of immune function.

Albers, P.H. **Birds and polycyclic aromatic hydrocarbons.** *Avian and Poultry Biology Reviews* 17(4): 125-140, 2006.

Notes: Polycyclic aromatic hydrocarbons (PAH) are present throughout the global environment and are produced naturally and by activities of humans. Effects of PAH on birds have been determined by studies employing egg injection, egg immersion, egg shell application, single and multiple oral doses, subcutaneous injection, and chemical analysis of field-collected eggs and tissue. The four-to six-ring aromatic compounds are the most toxic to embryos, young birds, and adult birds. For embryos, effects include death, developmental abnormalities, and a variety of cellular and biochemical responses. For adult and young birds, effects include reduced egg production and hatching, increased clutch or brood abandonment, reduced growth, increased organ weights, and a variety of biochemical responses. Trophic level accumulation is unlikely. Environmental exposure to PAH in areas of high human population or habitats affected by recent petroleum spills might be sufficient to adversely affect reproduction. Evidence of long-term effects of elevated concentrations of environmental PAH on bird populations is very limited and the mechanisms of effect are unclear.

Lance, B.K., Irons, D.B., Kendall, S.J., and McDonald, L.L. **An evaluation of marine bird population trends following the Exxon Valdez oil spill, Prince William Sound, Alaska.** *Marine Pollution Bulletin* 42(4): 298-309, 2001.

Notes: We examined post-spill trends (1989-1998) of marine bird populations in Prince William Sound (PWS) following the Exxon Valdez oil spill (EVOS) to evaluate recovery of injured taxa. Two criteria were employed. First, we examined population trends of injured taxa only in the oiled area of PWS using regression models. Second, we examined population trends of injured taxa in the oiled area relative to the unoiled area using homogeneity of the slopes tests. We considered a population recovering if there was a positive trend using either criteria; we considered a population not recovering if there was no trend using either criteria or a negative trend in the oiled area. A significant negative trend in the oiled area relative to the unoiled area was considered a continuing and increasing effect. Most taxa for which injury was previously demonstrated were not recovering and some taxa showed evidence of increasing effects nine years after the oil spill. Four taxa (loons *Gavia* spp, Harlequin Duck *Histrionicus histrionicus*, Bufflehead *Bucephala* spp, and North-western Crow *Corvus caurinus*) showed weak to very weak evidence of recovery. None of these taxa showed positive trends in both winter and summer. Nine taxa (grebes *Podiceps* spp, cormorants *Phalacrocorax* spp, Black Oystercatcher *Haematopus bachmani*, Mew Gull *Larus canus*, Glaucous-winged Gull *Larus glaucescens*, terns *Sterna* spp, murres *Uvia* spp, Pigeon Guillemot *Cepplus columba*, and murrelets *Brachyramphus* spp) showed no evidence of recovery during summer or winter. Four taxa (scoters *Melanitta* spp, mergansers *Mergus* spp, golden-eyes *Bucephala* spp, and Black-legged Kittiwake *Rissa tridactyla*) showed evidence of continuing, increasing effects. We showed evidence of slow recovery, lack of recovery, and divergent population trends in many taxa which utilize shoreline and nearshore habitats where oil is likely to persist. Potential lingering spill effects and natural variability appeal to be acting in concert in delaying recovery of many PWS bird populations.

C. Impacts on marine mammals

Geraci, J.R. and St. Aubin, J. (eds.) 1988. **Synthesis of Effects of Oil on Marine Mammals.** OCS Study, MMS 88-0049. Minerals Management Service, Atlantic OCS Region. 142pp.

Available at: http://www.mms.gov/alaska/reports/1980rpts/88_0049/mms88_0049a.pdf

Notes: This manuscript summarizes the extensive and diverse data base on subjects dealing with oil effects to marine mammals and those aspects of an animal's life history vulnerable to exposure of spilled oil. The manuscript begins with a background chapter on the composition and fate of petroleum and spill treating agents in the marine environment and is followed by separate chapters describing the ecological perspective and the physiological and toxicological effects of petroleum and spill treating agents on pinnipeds, cetaceans, sea otters, polar bears and manatees.

Matkin, C.O., Saulitis, E.L., Ellis, G.M., Olesiuk, P., and Rice, S.D. **Ongoing population-level impacts on killer whales *Orcinus orca* following the 'Exxon Valdez' oil spill in Prince William Sound, Alaska.** *Marine Ecology Progress Series* 356: 269-281, 2008.

Notes: Killer whales were photographed in oil after the 1989 'Exxon Valdez' oil spill, but preliminary damage assessments did not definitively link mortalities to the spill and could not evaluate recovery. In this study, photo-identification methods were used to monitor 2 killer whale populations 5 yr prior to and for 16 yr after the spill. One resident pod, the AB Pod, and one transient population, the AT1 Group, suffered losses of 33 and 41%, respectively, in the year following the spill. Sixteen years after 1989, AB Pod had not recovered to pre-spill numbers. Moreover, its rate of increase was significantly less than that of other resident pods that did not decline at the time of the spill. The AT1 Group, which lost 9 members following the spill, continued to decline and is now listed as depleted under the Marine Mammal Protection Act. Although there may be other contributing factors, the loss of AT1 individuals, including reproductive-age females, accelerated the population's trajectory toward extinction. The synchronous losses of unprecedented numbers of killer whales from 2 ecologically and genetically separate groups and the absence of other obvious perturbations strengthens the link between the mortalities and lack of recovery, and the 'Exxon Valdez' oil spill.

D. Impacts on sea turtles

Shigenaka, G. (ed.) 2003. **Oil and Sea Turtles: Biology, Planning, and Response.** Office of Response and Restoration, NOAA Ocean Service, Seattle, WA. 111pp.

Available at: http://response.restoration.noaa.gov/book_shelf/35_turtle_complete.pdf

Notes: This report gives a basic overview of sea turtle biology, summarizes what is known about the effects of oil on sea turtles, reviews potential response actions in the event of an oil spill, and presents case histories from previous spills that potentially could or actually have affected sea turtles.

E. Impacts on fish and invertebrates

Carls, M.G. and Meador, J.P. **A perspective on the toxicity of petrogenic PAHs to developing fish embryos related to environmental chemistry.** *Human and Ecological Risk Assessment* 15(6): 1084-1098, 2009.

Notes: Numerous studies demonstrate polynuclear aromatic hydrocarbons (PAHs) dissolved from weathered crude oil adversely affect fish embryos at 0.5 to 23 µg/l. This conclusion has been challenged by studies that claim (1) much lower toxicity of weathered aqueous PAHs; (2) direct contact with dispersed oil droplets plays a significant role or is required for toxicity; (3) that uncontrolled factors (oxygen, ammonia, and sulfides) contribute substantively to toxicity; (4) polar compounds produced by microbial metabolism are the major cause of observed toxicity; and (5) that based on equilibrium models and toxic potential, water contaminated with weathered oil cannot be more toxic per unit mass than effluent contaminated with fresh oil. In contrast, several studies demonstrate high toxicity of weathered oil; shifts in PAH composition were consistent with dissolution (not particle ablation), embryos accumulated dissolved PAHs at low concentrations and were damaged, and assumed confounding factors were inconsequential. Consistent with previous empirical observations of mortality and weathering, temporal shifts in PAH composition (oil weathering) indicate that PAHs dissolved in water should (and do) become more toxic per unit mass with weathering because high molecular weight PAHs are more persistent and toxic than the more abundant low molecular weight PAHs in whole oil.

Scarlett, A., Rowland, S.J., Galloway, T.S., Lewis, A.C., and Booth, A.M. **Chronic sublethal effects associated with branched alkylbenzenes bioaccumulated by mussels.** *Environmental Toxicology and Chemistry* 21(3): 561-567, 2008.

Notes: Crude oils are complex mixtures of many thousands of compounds, both resolved and unresolved by conventional gas chromatography (GC). Recent research using comprehensive two-dimensional gas chromatography-time-of-flight-mass-spectrometry (GC x GC-ToF-MS) identified branched alkylbenzenes (BABs) as a major component of some unresolved complex mixtures of hydrocarbons (UCMs) bioaccumulated in the tissues of North Sea mussels, *Mytilus edulis*, previously found to have poor health status. Here the effect of long-term exposure to low aqueous concentration of BABs and mussels' ability to recover, was determined. Mussels were exposed to 5 mg/L of a complex mixture of C12-14 BABs for 14 d. Feeding rates and the viability of hemocytes were measured immediately after exposure and again after 5 d depuration. Tissues were extracted, analyzed and alkylbenzenes quantified by both GC-MS and GC x GC-ToF-MS. Mussel extracts from previous acute tests were also reanalyzed and quantified using GC x GC-ToF-MS. Mussels exposed to 5 mg/L BABs for 14 d accumulated 46 to 47 mg/g dry weight alkylbenzenes; this was similar to tissue concentrations of mussels exposed to 41 mg/L for 72 h. Feeding rates were significantly reduced ($p \leq 0.05$) and were dependent upon tissue concentration. Cellular viability was not significantly affected. Following 5 d in clean seawater, the BABs were only partially depurated and feeding rates failed to fully recover. The use of GC x GC-ToF-MS in the present study has shown that mussel tissue concentrations of complex mixtures of alkylbenzenes, and their corresponding effects, are consistent with reported concentrations within UCM-contaminated wild mussel populations with poor health status.

Beiras, R. and Saco-Alvarez, L. **Toxicity of seawater and sand affected by the *Prestige* fuel-oil spill using bivalve and sea urchin embryogenesis bioassays.** *Water Air and Soil Pollution* 177(1-4): 457-466, 2006.

Notes: An evaluation of the toxicity of seawater and sand sampled from an area of the Galician coast (NW Iberian Peninsula), highly impacted by the *Prestige* fuel-oil spill, was attempted by using marine invertebrate embryogenesis bioassays with bivalves and sea urchins. Water samples were frozen and toxicity testing was delayed until the reproductive season of the sea urchins. Sand samples were elutriated and tested within 13 d from sampling, using bivalves from commercial stocks. Sand elutriates were non toxic for embryos despite visual presence of small tar balls. In contrast, seawater from the most impacted site was highly toxic during the first days after the spill, with complete inhibition of embryogenesis even after 4-fold dilution. In a lower degree toxicity persisted for two months in light-exposed coastal water. These findings stress the impact to water column organisms of the less conspicuous and frequently overlooked water-accommodated fraction, rather than the more visible oil slick.

Fuller, C., Bonner, J., Page, C., Ernest, A., McDonald, T., and McDonald, S. **Comparative toxicity of oil, dispersant, and oil plus dispersant to several marine species.** *Environmental Toxicology and Chemistry* 23(12): 2941-2949, 2004.

Notes: Dispersants are a preapproved chemical response agent for oil spills off portions of the U.S. coastline, including the Texas-Louisiana coast. However, questions persist regarding potential environmental risks of dispersant applications in nearshore regions (within three nautical miles of the shoreline) that support dense populations of marine organisms and are prone to spills resulting from human activities. To address these questions, a study was conducted to evaluate the relative toxicity of test media prepared with dispersant, weathered crude oil, and weathered crude oil plus dispersant. Two fish species, *Cyprinodon variegatus* and *Menidia beryllina*, and one shrimp species, *Americamysis bahia* (formerly *Mysidopsis bahia*), were used to evaluate the relative toxicity of the different media under declining and continuous exposure regimes. Microbial toxicity was evaluated using the luminescent bacteria *Vibrio fisheri*. The data suggested that oil media prepared with a chemical dispersant was equal to or less toxic than the oil-only test medium. Data also indicated that continuous exposures to the test media were generally more toxic than declining exposures. The toxicity of unweathered crude oil with and without dispersant was also evaluated using *Menidia beryllina* under declining exposure conditions. Unweathered oil-only media were dominated by soluble hydrocarbon fractions and found to be more toxic than weathered oil-only media in which colloidal oil fractions dominated. Total concentrations of petroleum hydrocarbons in oil-plus-dispersant media prepared with weathered and unweathered crude oil were both dominated by colloidal oil and showed no significant difference in toxicity. Analysis of the toxicity data suggests that the observed toxicity was a function of the soluble crude oil components and not the colloidal oil.

Culbertson, J.B., Valiela, I., Peacock, E.E., Reddy, C.M., Carter, A., and Van der Kruik, R. **Long-term biological effects of petroleum residues on fiddler crabs in salt marshes.** *Marine Pollution Bulletin* 54(7): 955-962, 2007.

Notes: In September 1969, the Florida barge spilled 700,000 L of No. 2 fuel oil into the salt marsh sediments of Wild Harbor (Buzzards Bay, MA). Today the aboveground environment appears unaffected, but a substantial amount of moderately degraded petroleum still remains 8-20 cm below the surface. The salt marsh fiddler crabs, *Uca pugnax*, burrow into the sediments at depths of 5-25 cm, and are chronically exposed to the spilled oil. Behavioral studies conducted with *U. pugnax* from Wild Harbor and a control site, Great Sippewissett marsh, found that crabs exposed to the oil avoided burrowing into oiled layers, suffered delayed escape responses, lowered feeding rates, and achieved lower densities. The oil residues are therefore biologically active and affect *U. pugnax* populations. Our results add new knowledge about long-term consequences of spilled oil, a dimension that should be included when assessing oil-impacted areas and developing management plans designed to restore, rehabilitate, or replace impacted areas.

Donkin, P., Smith, E.L., and Rowland, S.J. **Toxic effects of unresolved complex mixtures of aromatic hydrocarbons accumulated by mussels, *Mytilus edulis,* from contaminated field sites.** *Environmental Science and Technology* 37(21): 4825-4830, 2003.

Notes: Exposure of marine mussels (*Mytilus edulis*) to an unresolved complex mixture (UCM) of aromatic hydrocarbons isolated from a crude oil has been shown to reduce their feeding rate by 40%. The present study was undertaken to determine whether UCMs bioaccumulated by mussels in the field are also toxic. The feeding rate of mussels derived from polluted sites increased when they were placed in clean water, pointing to a loss of toxic agents from the tissues. At the end of the depuration period, water in which mussels from an oil-polluted site had been held contained a UCM. Steam-distillation extracts of the tissues of mussels taken from several polluted sites were shown to be highly toxic to the feeding activity of juvenile mussels. The tissues of mussels from these sites contained UCMs. Nontoxic steam distillates from clean mussels did not. Steam-distillation extracts of mussels from an oil-polluted site were fractionated by normal-phase high-performance liquid chromatography. A fraction, largely comprising a "monoaromatic" UCM, reduced the feeding rate of juvenile mussels by 70%. Two later-eluting fractions containing aromatic UCMs also produced smaller depressions in feeding rate. These results support our contention that some aromatic UCM hydrocarbons constitute a forgotten pollutant burden in the marine environment.

Davoodi, F. and Claireaux, G. **Effects of exposure to petroleum hydrocarbons upon the metabolism of the common sole *Solea solea.*** *Marine Pollution Bulletin* 54(7): 928-934, 2007.

Notes: On December 12th, 1999, the oil tanker Erika sank off the southern coast of Brittany (France), releasing 20 000-30 000 tons of heavy oil in the open sea. Among the affected coastal habitats were important nurseries for numerous flatfish species and particularly for the common sole, *Solea solea*. To investigate the potential impact of the spill on this economically significant resource, we employed Fry's concept of metabolic scope for activity to assess the deleterious effect of fuel exposure on the functional integrity of juvenile sole. Fish were captured from uncontaminated areas and experimentally exposed to contamination conditions mimicking those encountered during the weeks that followed the Erika spill. Using respirometry techniques we measured basal and active metabolic rates, and calculated aerobic metabolic scope, in control and fuel-exposed sole. We then compared the ability of control and fuel-exposed sole to face an episode of reduced oxygen availability. We found that whereas basal metabolic rate was not altered in fuel-exposed fish, active metabolic rate (-27%), and therefore aerobic metabolic scope, were impacted. These changes in metabolic scope were viewed as indicating changes in fishes' ability to face environmental contingencies. Finally the ability of sole to face an episode of reduced oxygen availability was found to be significantly altered following fuel exposure as indicated by a 65% increase in the critical oxygen level. It is concluded that fuel-exposed sole are functionally impaired and less able to face environmental challenges. The link between these results and the recently reported fall in the abundance of the year class that suffered the Erika oil spill is discussed.

F. Impacts on coral and coral reefs

Haapkyla, J., Ramade, F., and Salvat, B. **Oil pollution on coral reefs: a review of the state of knowledge and management needs.** *Vie et Milieu* 57(1-2): 95-111, 2007.

Notes: This paper reviews the current state of knowledge of the effects that oil pollution has on scleractinian corals. A review of results obtained in laboratory as well as in field conditions are given and suitable management tools are discussed. Studies made in the 1970s and 1980s presented conflicting results regarding the impacts of oil on coral physiology, but later results confirmed the detrimental effect of oil on corals. The world's coral reefs are severely threatened by an array of factors, one of which is oil pollution. More laboratory and field work with current oils and dispersants is urgently needed in order to update our knowledge in this field and reduce impacts in case of a major oil spill on coral reefs.

Office of Response and Restoration. 2001. **Oil Spills in Coral Reefs: Planning and Response Considerations.** NOAA Ocean Service, Seattle, WA. 78pp.

Available at: http://response.restoration.noaa.gov/book_shelf/70_coral_full_report.pdf

Notes: This report is intended to assist those who work in spill response and planning in regions where coral reef ecosystems are an important part of the coastline. The report is organised as follows: Chapter 1, *Coral Reef Ecology*, introduces pertinent aspects of this unique ecosystem. Chapter 2, *Global and Local Impacts*, addresses environmental impacts on coral from anthropogenic and natural causes. Chapter 3, *Oil Toxicity to Corals*, is a current review of the research available on oil toxicity to coral. Chapter 4, *Response Methods for Coral Reef Areas*, discusses general guidance for responding to spills in coral reefs and provides specific considerations for open-water cleanup measures. Chapter 5, *Coral Reef Restoration*, discusses the emerging science of restoration of damaged reefs, and presents data on recovery patterns and rates from a variety of impacts in coral habitats. Chapter 6, *Coral Case Studies*, reviews several case studies that illustrate a range of issues – some spills seem to have had very little impact on coral while others inflicted severe and long-lasting damage on nearshore resources. Some remote spills had long-term impacts to the entire ecosystem.

Shafir, S., Van Rijn, J., and Rinkevich, B. **Short and long term toxicity of crude oil and oil dispersants to two representative coral species.** *Environmental Science and Technology* 41(15): 5571-5574, 2007.

Notes: Oil dispersants, the tool of choice for treating oil spills in tropical marine environments, is potentially harmful to marine life, including reef corals. In a previous study, we found that dispersed oil and oil dispersants are harmful to soft and hard coral species at early life stages. In this broader study, we employed a "nubbin assay" on more than 10 000 coral fragments to evaluate the short- and long-term impacts of dispersed oil fractions (DOFs) from six commercial dispersants, the dispersants and water-soluble-fractions (WSFs) of Egyptian crude oil, on two Indo Pacific branching coral species, *Stylophora pistillata* and *Pocillopora damicornis*. Survivorship and growth of nubbins were recorded for up to 50 days following a single, short (24 h) exposure to toxicants in various concentrations. Manufacturer-recommended dispersant concentrations proved to be highly toxic and resulted in mortality for all nubbins. The dispersed oil and the dispersants were significantly more toxic than crude oil WSFs. As corals are particularly susceptible to oil detergents and dispersed oil, the results of these assays rules out the use of any oil dispersant in coral reefs and in their vicinity. The ecotoxicological impacts of the various dispersants on the corals could be rated on a scale from the least to the most harmful agent, as follows: Slickgone > Petrotech > Inipol = Biorieco > Emulgal > Dispolen.

Epstein, N., Bak, R.P.M., and Rinkevich, J. **Toxicity of third generation dispersants and dispersed Egyptian crude oil on Red Sea coral larvae.** *Marine Pollution Bulletin* 40(6): 497-503, 2000.

Notes: Harmful effects of five third-generation oil dispersants (Inipol IP-90, Petrotech PTI-25, Bioreico R-93, Biosolve and Emulgal C-100) on planula larvae of the Red Sea stony coral *Stylophora pistillata* and the soft coral *Heteroxenia fuscescense* were evaluated in short-term (2-96 h) bioassays. Larvae were exposed to Egyptian oil water soluble fractions (WSFs), dispersed oil water accommodated fractions (WAFs) and dispersants dissolved in seawater, in different concentrations. Mortality, settlement rates and the appearance of morphological and behavioural deformations were measured. While oil WSF treatments resulted in reductions in planulae settlement only, treatments by all dispersants tested revealed a further decrease in settlement rates and additional high toxicity. Dispersed oil exposures resulted in a dramatic increase in toxicity to both coral larvae species. Furthermore, dispersants and WAFs treatments caused larval morphology deformations, loss of normal swimming behaviour and rapid tissue degeneration. Out of the five tested dispersion agents, the chemical Petrotech PTI-25 displayed the least toxicity to coral larvae. We suggest avoidance of the use of chemical dispersion in cases of oil spills near or within coral reef habitats.

Guzmán, H. and Holst, I. **Effects of chronic oil-sediment pollution on the reproduction of the Caribbean reef coral *Siderastrea siderea*.** *Marine Pollution Bulletin* 26(5): 276-282, 1993.

Notes: In 1986 a major oil spill in Panama polluted and killed extensive areas of coral reefs. Five years afterwards, reef areas are chronically threatened by oil and large amounts of sediments containing toxic hydrocarbons trapped in mangroves. Sublethal effects of oil on coral reproduction were evaluated 39 months after the spill using healthy and injured colonies of the reef-building coral *Siderastrea siderea* at heavily oiled and unoiled reefs. Number of reproductive colonies and number of gonads per polyp were not sensitive to level of oiling, but gonads were significantly larger at unoiled than oiled reefs during spawning periods. Colonies with recent injuries demonstrated a consistent decrease in fecundity relative to unijured parts of the same colonies. Years after the spill, the increased number of injuries and associated reduction in colony size, and decreased size of gonads (eggs) on oiled reefs can reduce the number of reproductively viable colonies and gametes in coral populations, and ultimately reduce population survival.

Guzmán, H.M., Jackson, J.B.C., and Weil, E. **Short-term ecological consequences of a major oil spill on Panamanian subtidal reef corals.** *Coral Reefs* 10(1): 1-12, 1991.

Notes: A major oil spill (8,000,000 liters; 50,000 barrels) occurred in Bahía Las Minas on the Caribbean coast of Panama in April 1986, and oil slicks from the refinery landfill and mangroves were still common there after 21/2 years. We studied short-term effects of the spill on common shallow subtidal reef corals, at the individual, population, and community levels. Numbers of corals, total coral cover, and species diversity based on cover decreased significantly with increased amounts of oiling. Cover of the large branching coral *Acropora palmata* decreased most. Frequency and size of recent injuries on massive corals increased with level of oiling, particularly for *Siderastrea siderea*. Growth of three massive species (*Porites astreoides, Diploria strigosa*, and *Montastrea annularis*, but not *S. siderea*) was less at oiled reefs in the year of the spill than during the 9 previous years. Subtidal coral reefs, particularly those along protected coasts, may suffer extensive damage from chronic exposure after major oil spills.

Guzmán, H.M., Burns, K.A., and Jackson, J.B. **Injury, regeneration and growth of Caribbean reef corals after a major oil spill in Panama.** *Marine Ecology Progress Series* 105: 231-241, 1994.

Notes: We studied effects of a major oil spill in Panama on injury, regeneration and growth of subtidal reef corals over 5 yr. Corals exhibited much higher levels of injury, faster regeneration rates and slower growth on heavily oiled reefs. Concentrations of hydrocarbons in reef sediments were significantly positively correlated with amounts of coral injury and significantly negatively correlated with coral growth. The probable cause of persistently high levels of coral injury is chronic exposure to sediments mixed with partially degraded oil that are exported from mangroves onto adjacent reefs. lnjury apparently results in a reallocation of resources to regeneration and consequently decreased investment in fecundity and growth. There was no evidence of coral recovery 5 years after the oil spill.

G. Impacts on mangroves, salt marshes and seagrasses

Hoff, R. (ed.). 2002. **Oil Spills in Mangroves: Planning and Response Considerations.** Office of Response and Restoration, NOAA Ocean Service, Seattle, WA. 70pp.

Available at: http://response.restoration.noaa.gov/book_shelf/34_mangrove_complete.pdf

Notes: This report is intended to assist those who work in spill response and planning in regions where mangrove ecosystems are an important part of the coastline. The report is organised as follows: Chapter 1, *Mangrove Ecology*, provides an overview of mangrove forests, their associated communities, and how they respond to various natural and human stresses. Chapter 2, *Oil Toxicity*, reviews the research available on oil toxicity and impacts to mangroves. Chapter 3, *Response*, provides general guidance for responding to spills in mangroves and provides specific considerations for cleanup measures. Chapter 4, *Mangrove Recovery and Restoration*, discusses long-term recovery of mangroves from oil spill impacts and restoration techniques and approaches. Chapter 5, *Mangrove Case Studies*, provides several case studies that illustrate a range of issues from oil spills impacting various regions.

Culbertson, J.B., Valiela, I., Pickart, M., Peacock, E.E., and Reddy, C.M. **Long-term consequences of residual petroleum on salt marsh grass.** *Journal of Applied Ecology* 45(4): 1284-1292, 2008.

Notes: 1. Remnants from oil spills can persist for decades within anoxic coastal sediments affecting local flora and fauna, but few studies have examined the long-term impacts of the residual petroleum on these valuable coastal ecosystems. 2. The Wild Harbor salt marsh (Buzzards Bay, Massachusetts, USA) still harbours residual petroleum from a 1969 oil spill, which released 700 000 L of No. 2 fuel oil. Previous effects have been noted in fiddler crabs and ribbed mussels inhabiting the oiled marsh. 3. *Spartina alterniflora* biomass was sampled above- and below-ground in elevational transects through areas with different total petroleum hydrocarbon (TPH) content. Further, elevational differences were mapped in oiled and non-oiled locations. 4. Stem density and above- and below-ground biomass decreased in oiled areas. The decreased vegetation biomass led to unconsolidated sediments, increased topographical variation and, ultimately, loss of salt marsh habitat. 5. Four decades after the Florida spill, with only 100 kg of the original 595 000 kg of spilt oil persisting in salt marsh sediment, the effects on large-scale ecosystem functions are still evident. 6. Synthesis and applications. Our results demonstrate specific impacts of residual petroleum on *S. alterniflora* biomass and coastal erosion. Further, we have defined TPH content thresholds at which to expect long-term ecosystem impacts. The recalcitrant nature of these contaminants and their chronic large-scale ecosystem effects leads to the potential demand for alternative compensation, such as preservation of coastal systems at risk elsewhere.

Lewis, M.A. and Devereux, R**. Nonnutrient anthropogenic chemicals in seagrass ecosystems: Fate and effects.** *Environmental Toxicology and Chemistry* 28(3): 644-661, 2009.

Notes: Impacts of human-related chemicals, either alone or in combination with other stressors, are important to understand to prevent and reverse continuing worldwide seagrass declines. This review summarizes reported concentrations of anthropogenic chemicals in grass bed-associated surface waters, sediments, and plant tissues and phytotoxic concentrations. Fate information in seagrass-rooted sediments and overlying water is most available for trace metals. Toxicity results in aqueous exposures are available for at least 13 species and a variety of trace metals, pesticides, and petrochemicals. In contrast, results for chemical mixtures and chemicals in sediment matrices are uncommon. Contaminant bioaccumulation information is available for at least 23 species. The effects of plant age, tissue type, and time of collection have been commonly reported but not biological significance of the chemical residues. Experimental conditions have varied considerably in seagrass contaminant research and interspecific differences in chemical residues and chemical tolerances are common, which limits generalizations and extrapolations among species and chemicals. The few reported risk assessments have been usually local and limited to a few single chemicals and species representative of the south Australian and Mediterranean floras. Media-specific information describing exposure concentrations, toxic effect levels, and critical body burdens of common near-shore contaminants is needed for most species to support integrated risk assessments at multiple geographical scales and to evaluate the ability of numerical effects-based criteria to protect these marine angiosperms at risk.

Jackson, J.B.C. *et al.* **Ecological effects of a major oil spill on Panamanian coastal marine communities.** *Science* 243(4887): 37-44, 1989.

Notes: In 1986 more than 8 million liters of crude oil spilled into a complex region of mangroves, seagrasses, and coral reefs just east of the Caribbean entrance to the Panama Canal. This was the largest recorded spill into coastal habitats in the tropical Americas. Many population of plants and animals in both oiled and unoiled sites had been studied previously, thereby providing an unprecedented measure of ecological variation before the spill. Documenation of the spread of oil and its biological begun immediately. Intertidal mangroves, algae, and associated invertebrates were covered by oil and died soon after. More surprisingly, there was also extensive mortality of shallow subtidal reef corals and infauna of seagrass beds. After 1.5 years only some organisms in areas exposed to the open sea have recovered.

Gundlach, E.R., Boehm, P.D., Marchand, M., Atlas, R.M., Ward, D.M., and Wolfe, D.A. **The fate of *Amoco Cadiz* oil.** *Science* 221(4606): 122-129, 1983.

Notes: The *Amoco Cadiz* oil spill (223,000 metric tons) of March 1978 is the largest and best studied tanker spill in history. Of the total oil lost, 30,000 tons (13.5 percent) rapidly became incorporated into the water column, 18,000 tons (8 percent) were deposited in subtidal sediments, 62,000 tons (28 percent) washed into the intertidal zone, and 67,000 tons (30 percent) evaporated. While still at sea, approximately 10,000 tons of oil were degraded microbiologically. After 3 years, the most obvious effects of the spill have passed, although hydrocarbon concentrations remain elevated in those estuaries and marshes that were initially most heavily oiled.

Law, R.J. and Kelly, C. **The impact of the "Sea Empress" oil spill.** *Aquatic Living Resources* 17(3): 389-394, 2004.

Notes: The tanker "*Sea Empress*" grounded at the entrance to Milford Haven in February 1996, releasing 72 000 t of Forties blend crude oil and 480 t of heavy fuel oil into the waters of southwest Wales. An estimated 15 000 t of emulsified oil came ashore along 200 km of coastline. A fishery exclusion zone was established to protect consumers of fish and shellfish, and monitoring was instigated in order to establish the degree and spread of contamination. A wide range of further studies were conducted with the aim of assessing the overall impact of the spill. In this paper we report on the establishment and subsequent lifting of fishing restrictions and the results of the fish and shellfish monitoring programme. The application of a range of biological effects techniques which illustrated sublethal impacts is also described. In retrospect, the impact of the spill was much less than would have been expected from the quantity of oil spilled. This was due to the circumstances of the spill, which led to fresh crude oil, amenable to chemical dispersion, being released during each ebb tide and carried into deep water to the south of Milford Haven. This enabled the extensive dispersant spraying operation, which included the aerial application of 446 t of chemical oil dispersant in order to enhance the rate of natural dispersion of the oil. This reduced the impact of the spill by preventing an additional 57 000 to 110 000 t of emulsified oil from impacting the beaches.

Surís-Regueiro, J.C., Garza-Gil, M.D., and Varela-Lafuente, M.M. **The *Prestige* oil spill and its economic impact on the Galician fishing sector.** *Disasters* 31(2): 201-215, 2007.

Notes: The sinking of the *Prestige* oil tanker on 18 November 2002 off the coast of Galicia, Spain, had important economic, environmental and social ramifcations. The aim of this paper is to carry out an initial analysis of the costs related to a halt in fishing activities in Galicia between November 2002 and December 2003. This involves three different steps: an assessment of the cost of the preventative and palliative measures introduced by Spanish public administrations (compensation for affected fishermen and shellfish fisherman); an indirect evaluation of the implications of the disaster (via a study of data on production); and a direct appraisal of the economic impact of the event (reduction in income), using questionnaires completed by a representative sample of fishermen and shellfish fisherman. The results obtained from these three methods of estimating losses are compatible. By December 2003, losses to the Galician fishing sector stood at an estimated EUR 76 million.

Loureiro, M.L., Ribas, A., Lopez, E., and Ojea, E. **Estimated costs and admissible claims linked to the Prestige oil spill.** *Ecological Economics* 59(1): 48-63, 2006.

Notes: The current case study presents an evaluation of the societal costs caused by the Prestige oil spill. We conclude that the economic magnitude of the catastrophe caused by the Prestige oil spill is rather significant. Short-term losses in all affected economic sectors, cleaning and recovery costs, and all environmental losses accountable at this point, add to a lower bound estimate of €770.58 million (prices in 2001 currency), excluding all other financial and future possible losses. Such important losses justify future studies that assess potential costs and benefits derived from the application of preventive measures and other contingency plans.

Peterson, C.H., Rice, S.D., Short, J.W., Esler, D., Bodkin, J.L., Ballachey, B.E., and Irons, D.B. **Long-term ecosystem response to the Exxon Valdez oil spill.** *Science* 302(5653): 2082-2086, 2003.

Notes: The ecosystem response to the 1989 spill of oil from the Exxon Valdez into Prince William Sound, Alaska, shows that current practices for assessing ecological risks of oil in the oceans and, by extension, other toxic sources should be changed. Previously, it was assumed that impacts to populations derive almost exclusively from acute mortality. However, in the Alaskan coastal ecosystem, unexpected persistence of toxic subsurface oil and chronic exposures, even at sublethal levels, have continued to affect wildlife. Delayed population reductions and cascades of indirect effects postponed recovery. Development of ecosystem-based toxicology is required to understand and ultimately predict chronic, delayed, and indirect long-term risks and impacts.

Li, H. and Boufadel, M.C. **Long-term persistence of oil from the *Exxon Valdez* spill in two-layer beaches.** *Nature Geoscience* 3(2): 96-99, 2010.

Notes: Oil spilled from the tanker *Exxon Valdez* in 1989 persists in the subsurface of gravel beaches in Prince William Sound, Alaska. The contamination includes considerable amounts of chemicals that are harmful to the local fauna. However, remediation of the beaches was stopped in 1992, because it was assumed that the disappearance rate of oil was large enough to ensure a complete removal of oil within a few years. Here we present field data and numerical simulations of a two-layered beach with a small freshwater recharge in the contaminated area, where a high-permeability upper layer is underlain by a low-permeability lower layer. We find that the upper layer temporarily stored the oil, while it slowly and continuously filled the lower layer wherever the water table dropped below the interface of the two layers, as a result of low freshwater recharge from the land. Once the oil entered the lower layer, it became entrapped by capillary forces and persisted there in nearly anoxic conditions that are a result of the tidal hydraulics in the two-layered beaches. We suggest that similar dynamics could operate on tidal gravel beaches around the world, which are particularly common in mid- and high-latitude regions, with implications for locating spilled oil and for its biological remediation.

I. Impacts of hydrocarbon production in the Gulf of Mexico

Ko, J.-Y. and Day, J.W. **A review of ecological impacts of oil and gas development on coastal ecosystems in the Mississippi Delta.** *Ocean and Coastal Management* 47(11-12): 597-623, 2004.

Notes: We review the multiple ecological impacts of oil and gas development on coastal ecosystems in the Mississippi Delta. This area has one of the greatest developments of oil and gas production in the world. This activity has generated significant impacts on coastal ecosystems due to the toxicity of spilled oil and the secondary and indirect effects of petroleum-related activities, such as alteration of hydrology. Effects on plant communities include disruption of plant-water relationships, direct impacts to plant metabolism, toxicity to living cells, and reduced oxygen exchange between the atmosphere and the soil. Effects on consumers include growth inhibition, reduced production, altered metabolic systems, and biomagnification of hydrocarbon compounds. Petroleum-related activities have contributed significantly to wetland loss in the Delta. Subsidence

was increased by 2-3 times due to fault activation. Canals altered natural hydrology by altering water flow pathways, increasing saltwater intrusion, and reducing overland flow and sediment inputs. The combination of these factors increased plant stress and plant death.

Morton, R.A., Bernier, J.C., and Barras, J.A. **Evidence of regional subsidence and associated interior wetland loss induced by hydrocarbon production, Gulf Coast region, USA.** *Environmental Geology* 50(2): 261-274, 2006.

Notes: Analysis of remote images, elevation surveys, stratigraphic cross-sections, and hydrocarbon production data demonstrates that extensive areas of wetland loss in the northern Gulf Coast region of the United States were associated with large-volume fluid production from mature petroleum fields. Interior wetland losses at many sites in coastal Louisiana and Texas are attributed largely to accelerated land subsidence and fault reactivation induced by decreased reservoir pressures as a result of rapid or prolonged extraction of gas, oil, and associated brines. Evidence that moderately-deep hydrocarbon production has induced land-surface subsidence and reactivated faults that intersect the surface include: (1) close temporal and spatial correlation of fluid production with surficial changes including rapid subsidence of wetland sediments near producing fields, (2) measurable offsets of shallow strata across the zones of wetland loss, (3) large reductions in subsurface pressures where subsidence rates are high, (4) coincidence of orientation and direction of displacement between surface fault traces and faults that bound the reservoirs, and (5) accelerated subsidence rates near producing fields compared to subsidence rates in surrounding areas or compared to geological rates of subsidence. Based on historical trends, subsidence rates in the Gulf Coast region near producing fields most likely will decrease in the future because most petroleum fields are nearly depleted. Alternatively, continued extraction of conventional energy resources as well as potential production of alternative energy resources (geopressured-geothermal fluids) in the Gulf Coast region could increase subsidence and land losses and also contribute to inundation of areas of higher elevation.

J. Future considerations

Paine, R.T., Ruesink, J.L., Sun, A., Soulanille, E.L., Wonham, M.J., Harley, C.D.G., Brumbaugh, D.R., and Secord, D.L. **Trouble on oiled waters: Lessons from the Exxon Valdez oil spill.** *Annual Review of Ecology and Systematics* 27: 197-235, 1996.

Notes: The Exxon Valdez oil spill was the largest in US maritime history. We review post-spill research and set it in its legal context. The Exxon Corporation, obviously responsible for the spill, focused on restoration, whereas the Trustees, a coalition of state and federal entities, focused on damage and its assessment. Despite billions of dollars expended, little new understanding was gained about the recovery dynamics of a high latitude marine ecosystem subject to an anthropogenic pulse perturbation. We discuss a variety of case studies that highlight the limitations to and shortcomings of the research effort. Given that more spills are inevitable, we recommend that future studies address spatial patterns in the intertidal, and focus on the abundances of long-lived species and on organisms that preserve a chronological record of growth. Oil spills, while tragic, represent opportunities to gain insight into the dynamics of marine ecosystems and should not be wasted.

Fraser, G.S., Ellis, J., and Hussain, L. **An international comparison of governmental disclosure of hydrocarbon spills from offshore oil and gas installations.** *Marine Pollution Bulletin* 56(1): 9-13, 2008.

Notes: The cumulative effect of accidental spills from oil and gas extraction in the marine environment can have significant impacts on marine wildlife. Oil and gas operators are typically required to report spill data as part of a regulatory process. We conducted a survey of the public disclosure of hydrocarbon spill data for four countries, Australia, Canada, United Kingdom and United States. There was significant variation in the spill data statistics that were publicly reported by the regulators. No country provided full disclosure of spill data or follow-up actions taken by the regulator on their website. The lack of disclosure of spill data is of concern because the scale of environmental effects is more difficult to assess, insufficient information is available to assess the accuracy of predictions made in the environmental assessment process, and without consistency of spill reporting there is no method to compare regional differences of spill rates.

Allison, G.W., Gaines, S.D., Lubchenco, J., and Possingham, H.P. **Ensuring persistence of marine reserves: Catastrophes require adopting an insurance factor.** *Ecological Applications* 13(1): S8-S24, 2003.

Notes: When viewed across long temporal and large spatial scales, severe disturbances in marine ecosystems are not uncommon. Events such as hurricanes, oil spills, disease outbreaks, hypoxic events, harmful algal blooms, and coral bleaching can cause massive mortality and dramatic habitat effects on local or even regional scales. Although designers of marine reserves might assume low risk from such events over the short term, catastrophes are quite probable over the long term and must be considered for successful implementation of reserves. A simple way to increase performance of a reserve network is to incorporate into the reserve design a mechanism for calculating how much additional area would be required to buffer the reserve against effects of catastrophes. In this paper, we develop a method to determine this "insurance factor": a multiplier to calculate the additional reserve area necessary to ensure that functional goals of reserves will be met within a given "catastrophe regime." We document and analyze the characteristics of two relatively well-studied types of disturbances: oil spills and hurricanes. We examine historical data to characterize catastrophe regimes within which reserves must function and use these regimes to illustrate the application of the insurance factor. This tool can be applied to any reserve design for which goals are defined by a quantifiable measure, such as a fraction of shoreline, that is necessary to accomplish a particular function. In the absence of such quantitative measures, the concept of additional area as insurance against catastrophes may still be useful.
