Author’s Accepted Manuscript

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www.elsevier.com/locate/envdev

PII: S2211-4645(16)30328-1
DOI: http://dx.doi.org/10.1016/j.envdev.2017.02.003
Reference: ENVDEV331

To appear in: *Environmental Development*

Received date: 4 December 2016
Revised date: 6 February 2017
Accepted date: 7 February 2017

Cite this article as: Benjamin H. Sherman, Multiple marine Ecologica disturbance assessments for latin american and caribbean large marin ecosystems, *Environmental Developmen* http://dx.doi.org/10.1016/j.envdev.2017.02.003

Multiple Marine Ecological Disturbance Assessments for Latin American and Caribbean Large Marine Ecosystems

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Abstract

Comparative assessment of pollution and ecosystem health among the Large Marine Ecosystems (LMEs) of Latin America and the Caribbean requires tracking of shifting food- chain associations, loss of habitat, toxic and anoxic impacts to species, diseases, harmful algal blooms and vulnerability to climate extremes, invasive species, and overfishing. Meta-data search and extraction techniques help researchers consolidate disturbance observations into one of eight multiple marine disturbance (MMED) categories important for the creation of place specific disturbance regimes. By measuring the changing baseline condition of impact-sensitive indicator species involved in these MMED events, resource managers can better compare, mitigate, and track changes in marine ecosystem health.

Multiple Marine Ecological Disturbances

Healthy co-evolved plants, wildlife, and human interdependent systems can recover from short-term disturbance events. Conversely, when marine ecosystems are impacted by pollution, disease, habitat loss, repeated climate extremes, invasive species, harmful species and extirpation of key species, these systems lose their self-regulatory function and may no longer recycle nutrients to sustain anticipated production levels. Impacted ecosystems become brittle in the face of disturbance and susceptible to dramatic shifts (state change) in biotic community structure from dominance by relatively large, long-lived native species to dominance by smaller short-lived exotics (Hollings 1995). Throughout the 10 Latin America and the Caribbean Large Marine Ecosystems (LMEs), resource managers are finding statistical correlations between brittle marine ecosystems as described and those perceived to be most health impaired (HEED 1998, Sherman 2000). Documentary evidence within the academic literature of oil spills from the late 1960s and early 1970s, harmful algal blooms (HABs) from the mid-1970s, coral system collapses from multiple marine ecological disturbances (MMEDs) during the late 1980s, and beach closures and human marine-related illness in the 1990s describe various assemblies of sentinel species that appear representative of health status for specific locations.

Marine disturbance events, defined as anomalies, are described as such because they are unanticipated. While portions of the phenomena driving marine structural and functional change may be captured and described by epidemiologists, resource economists, climate and marine scientists, no single discipline's information network can entirely characterize widespread spatial and unprecedented temporal characteristics of these events because disciplinary health status and trends monitoring programs are full of data gaps or nonexistent within the developing world. Ample observational information does exist for which location status and trend can be re-assembled to fill information gaps, however observations are scattered among a multitude of custodians and reporting forms; effectively lost. Scientists have been performing meta-analysis to reassemble information by-products of a century′s worth of fragmented time-series studies, critical for establishing marine health baselines in specific locations (LTER 1992, NRC 1990). These baseline studies are important for reference. However, to perform a comparable task at an LME scale, >200,000 sq km, special data assembly techniques are required to re-acquire lost observations. Classification techniques that characterize MMED phenomena, an acronym coined for this purpose at a Caribbean conference (Williams and Bunkley-Williams 1990a,b and 1992), operate at scales relevant to the Latin American and the Caribbean LME projects, and have since been systematized into a discipline unifying methodology (Epstein et al. 1998, Sherman 1999) that better describes marine health status among all LMEs (Sherman 2000).

It has been left to data-scientists to pull together comparable characterizations of anomalies to answer a simple question for each recovered piece of data: "is this observation ordinary or extra-ordinary for a given place and time?" Ultimate determination requires hind-casting against other available time-series (e.g. satellite, ship-born surveys, fisheries statistics, and weather gauge networks). To begin a data archaeologist may focus on meta-data (data about data) and extract this information from bibliographic archives using keyword searches. Then, efforts can focus on the appropriate acquisition of the primary data itself. Anomaly or disturbance is a concept uniquely shared by all disciplines and is exploited to unify thematic data by describing phenomena involving multiple oceanographic, ecological and economic indicators. The spatio/temporal scale of an observational data point presents an opportunity to unify diverse anomaly data sources from any number of other disciplines provided the quality and time-structured data reside within a geographic information system's database.

Disturbance as a Device

In the Humboldt Current LME, dramatic changes in Peruvian anchoveta and sardine fisheries were not always understood to be associated with ENSO cycles (Polovina *et al.* 1995). Like other disturbance studies (Pimm 1984; Holling 1995; Rapport 1995; Karr 1991; Costanza 1992; Costanza *et al* 1992; Likens 1992; Rapport *et al.* 1985) the term "disturbance" is useful until perceptions of "normal" ecosystem processes change with respect to either widespread acceptance of re-defined recurring processes or when historical records reveal normal periodicity; rendering new observations as expected. In fact, the term *anomaly* is common to all disciplines (cultures) and exploration and is useful as long as we seek more perfect insights. In the marine environment there is ample opportunity for multi-data syntheses because morbidity and mortality observations (a disturbance byproduct) are plentiful, a normal part of field research description and typically guide taxonomic data collection strategies. Walking a beach, performing a bird survey in the field, observing diseased or out-of-place specimens; disturbance problems lead to the same sets of questions regardless of geography: why do marine mammals strand?; when will harmful algae blooms re-occur?; where will fish and invertebrate diseases move next? Pursuit of these questions is limited if only single species are tracked. Disturbance phenomena acting over wide-geographies have properties that alter multiple species activities, environments and economies. A single species indicator may not touch all of the scales necessary to understand larger disturbance patterns. Larger questions encompassing ecosystem phenomena including: cascading system collapse (Jackson *et al.* 2001), biogeochemical cycling (USGCRP 2000), disturbance conditioning (Sherman 2001), pathogen pollution (Daszak *et al.* 2001), require multi-species approaches. Moreover, "multi-indicators" (not just species) may be used to capture events impacting many parts of a food chain (e.g. fish consumption advisories plus human illness) and provide a rationale to use one indicator as a replacement (proxy) for another (e.g. mouse lethal dose toxicity studies for harmful algae concentrations and bloom duration). Ultimately, enough proxy data can be pooled so that all scales (set by the natural history of organisms, or measurement technique) may blend to visualize an emergent phenomenon/pattern.

Researchers have long argued agency mandates and priorities need to capture both ecological and economic factors aligned with disturbance, not only because society would better understand extractive/consumptive relationships, but to better highlight significant and persistent pressure upon the tipping-points for sustainability within those same ecosystems (Holling 1995, Epstein 1996, Epstein and Rapport 1996). External climate forcing on charismatic keystone species has been popularized among most LMEs as climate variability is universal and strategic selection of multiple-indicator organisms in the keystone specie's habitat can integrate across all of the necessary scales of observation (Ebbesmeyer *et al.* 1991, McGowan *et al*. 1998).

Data Discovery and Recovery Operations

Society has invested in disturbance studies, however, the tangible outlet is not raw cross-region compatible data, but rather, individual peer-reviewed publications describing segments of phenomena (a typical grantor's expectation for incremental research). A recovery strategy designed to consolidate ecosystem health disturbance knowledge comes from surveys the published results of each funded organism study in bibliographic reference collections, using spatial, temporal and anomaly keywords to unify disciplines. The benefit of this inductive investigative process is to facilitate shifts from space/time questions viewed by some academic communities as uninteresting to phenomena-based questions of keen interest to the public (Sherman and Epstein 2001). Review studies implementing such data discovery techniques (HEED 1998, Fisher *et al.* 1999, Sherman 2000) provide the research and management community with effective means to reduce data overburden and maximize information distillation (Christensen *et al*. 1996).

Methodology for MMED Indicator Selection

A disturbance indicator approach was implemented as part of the Health Ecological and Economic Dimensions of Global Change Program's Multiple Marine Ecological Disturbance project (HEED MMEDs) based at Harvard University and Harvard Medical School. The project involved more than 250 academic marine resource and science professionals in an assessment of morbidity, mortality and disease events along the eastern coast of North America, the Gulf of Mexico, and the Caribbean Sea ecosystems (a rapid global survey followed at the University of New Hampshire in 1999 and Columbia University in 2001). The objective of the HEED study was to determine if marine disturbances were increasing in frequency duration and severity (Levins *et al.* 1994, Harvell *et al*. 1999). Moreover, the consequences and possible cause and cost of the disturbance events were investigated. Teleconnected climate patterns were the anticipated object of disturbance investigation, but this notion was quickly supplanted by harmful algal blooms, the leading unanticipated disturbance factor for most marine communities (HEED 1998). Within the Gulf of Mexico, in particular, dead-zones from contaminant loads, spills and oxygen depletion and HABs were cited as the most important forcing factors.

The MMED methodology was designed to solicit, obtain, organize, and distribute data from a variety of sources while encouraging or enforcing information standards (semantic and methodological) for describing morbidity, mortality and disease occurrences. The result was a design for information flow within an idealized marine epidemiological information system (Figures 1-6). The process begins with field observations or information extracted from source material. This information is an extension of the reporting process recording: “Where, When, What” information (Figure 1 Part 1).

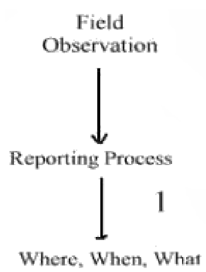

Figure 1. Absolute minimum information necessary to report a disturbance observation for a marine epidemiological information system (arrows indicate information flow).

In practice within a MMED survey, targeted keyword lists expand to catch all observational records within an LME’s literature (more articles and keywords are discovered and added by drill-down within each article’s citations) to compensate for the lack of direct field observations. In most cases metadata (not the actual data) are captured within a database and the metadata include: 1) what happened, 2) where (decimal longitude and latitude), 3) involving which species, 4) with what associated co-occurring factors in addition to citation source and source quality ranking. Each data element receives a unique identification number upon input and as such, becomes compatible with loose standards established within the general marine research community (Michener *et al.* 1986, French 1990, Davis *et al.* 1991, Michener *et al.* 1994, CENR 1997, Evans 1997, NRC 1997, NSTC 1997, Michener *et al.* 1998).

If samples are taken, they are sent to the appropriate laboratories and results and/or specimens are archived (Figure 2 part 2) and that metadata information regarding the unique laboratory custodian identification number is returned to a central relational database (Figure2 part 3); presuming an LME coordinating office can assume responsibility for that meta-data custodianship.

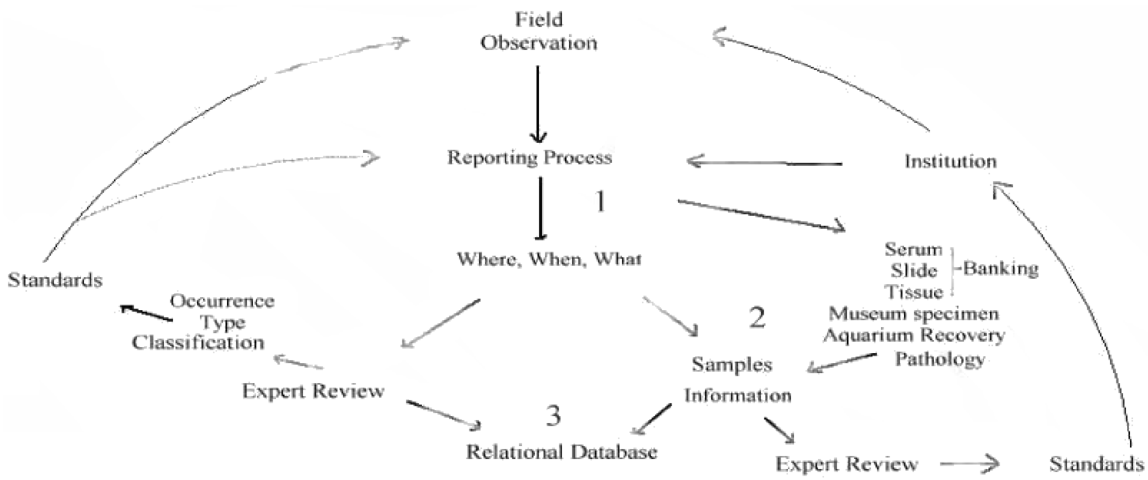

Figure 2. Coordination of information systems necessary to support consolidated reporting and future acquisition of information regarding a disturbance (arrows indicate information flow).

Queries of centralized meta-data database generate occurrence type classifications, enable comparison of co-occurring anomaly data, and help extract ancillary life history and contextual information for impacted species (including relevant mass-media accounts if no other information is available) (figure 3 part 4).

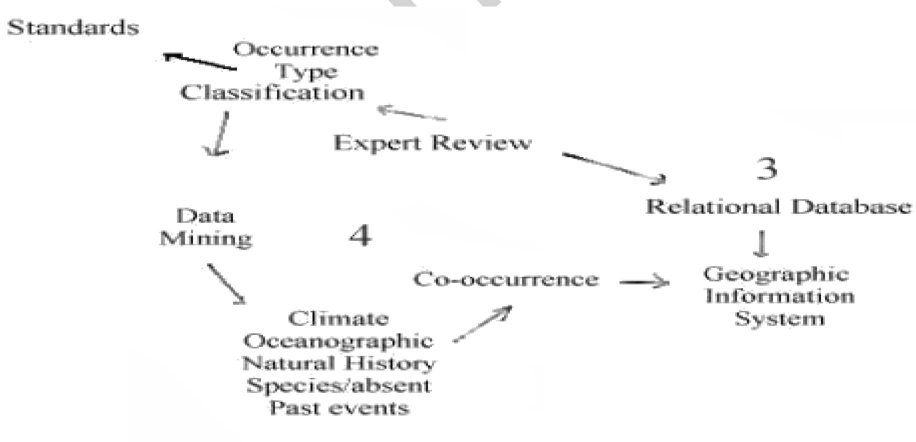

Figure 3. The database permits queries to ascertain if co-occurring anomalies are temporally linked in space and qualitatively similar in scale (arrows indicate information flow)

More specifically, to begin the query building process, searches are conducted using, species lists (taxonomic keywords) for each LME to find relevant articles involving yet to be determined place-specific disturbance keywords. The survey goal is to find articles that contain at least one taxonomic term, at least one of the disturbance terms previously yielding valid observational data, and none of the problem terms that often confound and inflate search responses. This is accomplished using inclusive/exclusive Boolean logic (e.g. and, or, not) in electronic bibliographic archives as well as within the database for cross checks.

Some keywords already within a MMED database such as kill, disease, mortality, morbidity, decline, virus, illness are only marginally useful for new searches of the literature because these terms capture too many articles involving non marine disturbances; even when smaller time slices and spatial bounds are applied to constrain a search. More specific occurrence types such as marine mammal distemper or seal influenza may or may not yield useable occurrence articles, because occurrence etiology is usually finalized long after an initial article is published. Rarely is mere naming of the mortality event considered worthy of publication if it is a 1) normal occurrence and/or 2) lacked a discernable impact. An important distinction is that the 3rd case: novel methods papers may contain useful data, but the occurrence itself could be insignificant (false positives). Iterative queries within the database and search process queries within the literature; etiological information regarding disturbances eventually gets captured. Subsequent peer-review literature searches using technical keywords become more aligned to particular occurrences. Based upon date/place similarity occurrences and different source accounts are consolidated into event reports within the database.

In practice, it becomes necessary to keep separate data structures and queries for news media search results. Less-technical words like stranding, beaching, floating and washing ashore for marine mammals are more appropriate with these archives. To reduce the number of captured articles, nuisance terms like early bird, bird-watcher, bird call, hunting, open weekend, license, obituaries, travel, dining, vacation are used as exclusionary terms because articles with these terms usually lack relevant marine occurrence descriptions. All of these decisions are tracked for future searches as the source archives continually refresh with new content (publications). The search and keyword generation process is iterative, but not completely arbitrary. A word (text) analysis tool is used to make sure decisions are thorough and complete, though the overall process starts with inherent bias introduced from expert workshops convened to establish search and ranking standards, the methods are repeatable – provided the sources do not change. Confidence in query design and classifications are resolved with cross check statistical methods outlined in Sherman (2000), Sherman (2001) and Sherman and Epstein (2001).

Queries relating event information to both longitude, latitude, and embedded code that links directly to web sites of ancillary interest (e.g. sea surface temperature anomaly data for that location, Landsat imagery captured by space/time coordinate translation) enable output in either a web-based MMED geographic information system (GIS) or stand-alone GIS. Experts are provided with paper GIS output of the occurrence point data in the form of maps for each major disturbance type for their review (Figure 4 part 5) and basic research exploration and hypothesis generation (Figure 4 part 6). In practice, expert reviewers prefer exploration of the web interfaces. Often proposed are discussion list-servers linked to the points on the interactive maps and virtual seminars held over the Internet to review each data point.

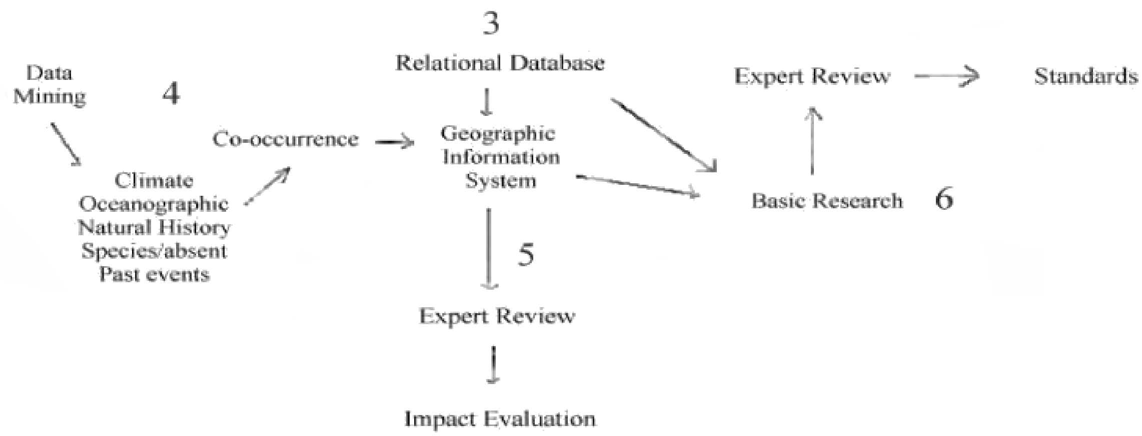

Figure 4. A Geographic Information System permits spatial queries and selection of overlaid information (arrows indicate information flow).

The expert review process adjusts the disturbance type classification appropriately (Figure 5 part 7). Because research scientists may use new insights gained from participating in quality control and observation to justify their efforts, they are provided with an incentive to participate in the peer-review process. Further analysis reveals the cost of particular events that further justifies the importance of the MMED epidemiological information system approach (Figure 5 part 8).

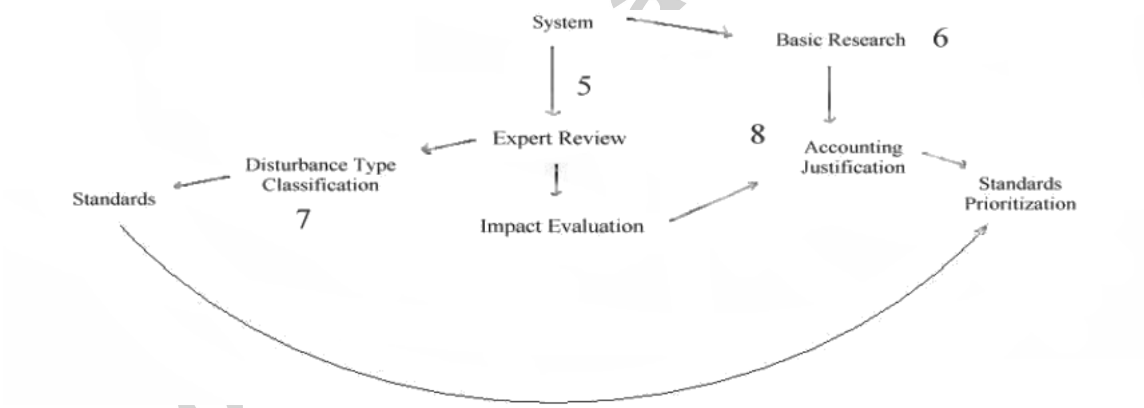

Figure 5. The expert review process adjusts the disturbance type classification appropriately (arrows indicate information flow).

All steps, feed back to the generation of nomenclature and definition standards that ultimately lead to improved reporting of observations taken in the field or new types of data collection or archiving by institutions (Figure 6).

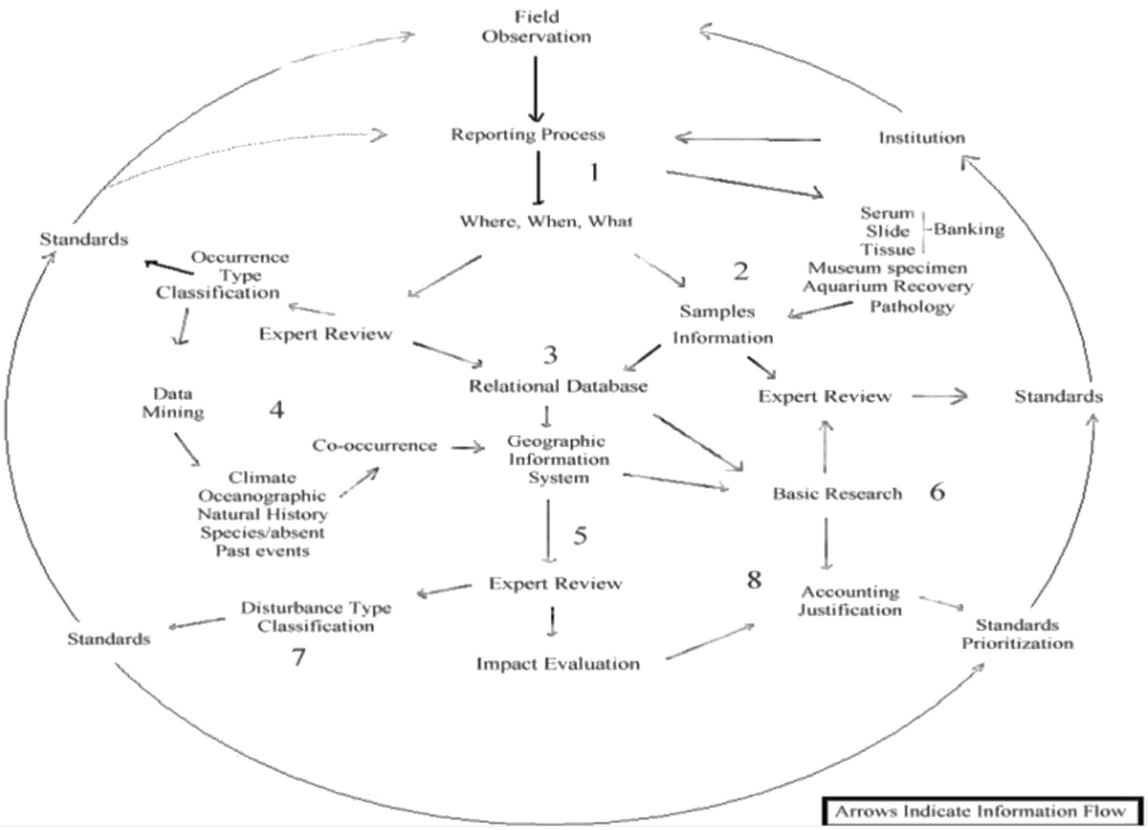

Figure 6. Standards are produced from consensus developed in the information vetting process. Feedbacks are provided to ensure continual process improvement.

For MMED relevant articles available in digital form, the data are compiled into both a database for output and the raw text of the article passed through an associative word-stem neural network algorithm that outputs recognized and repeated word associations. The procedure processes lengthy text notes fields (or text-dumps) within a database as well as entire compilations of thematic articles. Results are query sensitive and rely upon a standard input pre-selection process to repeat. There are a number of software programs capable of semantic (word-classification) artificial intelligence. As an example, “Text Analyst” is one of the software programs (www.megaputer.com) used in MMED searches to assess frequency of joint occurrences among similar words. Statistical weight is placed upon word proximity within sentences and weighted by the number of times each word combination appears within batches of articles. Text Analyst adjusts the statistical weights within the neural network, iteratively trained by the strength of the discovered word relationships, and identifies those critical words relevant to others found within a sentence, article or sequence of articles (Figure 7). The weights and discovered relationships among words are used to improve upon and benchmark the success of particular searches. The histories of prior search success and inclusion and exclusion terms are tracked carefully. Iterative searches converge to create a relatively stable set of keywords that typically yield useful articles, and hence reports of morbidity, mortality and disease. The same techniques may be used to determine confounding words: those words that should be excluded using Boolean logic from future searches.

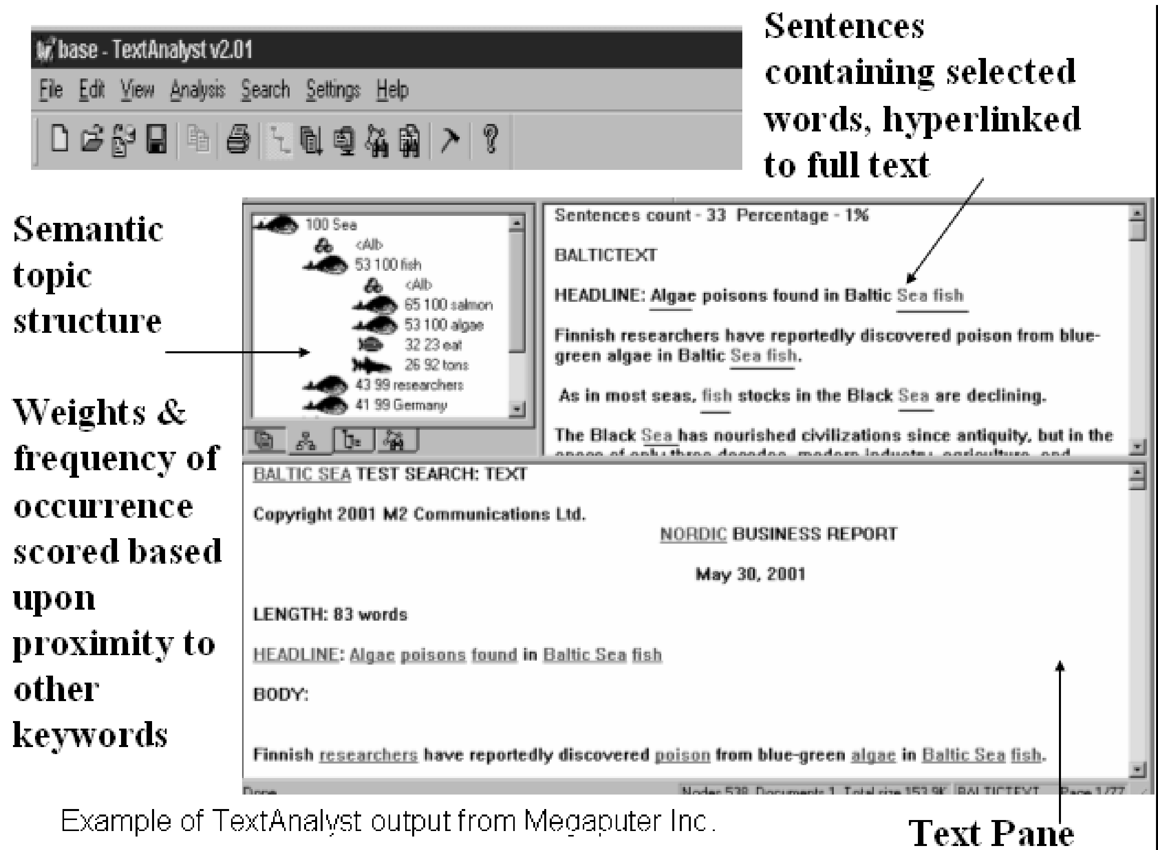

Figure 7. Example of semantic text analysts search results. The neural net algorithm correctly associated salmon with cyanobacteria blooms within the Baltic.

One finding from past semantic (word) analysis of particular interest: media reports and journal articles for the most part, concentrate on the same disturbances as found in academic literature. The media search findings reflect public perception of the importance of certain disturbances by enumerating how many and how often particular keywords appear in print. Since the mass media reports include newspapers, television and radio transcripts, and other archived and searchable international accounts, it may be assumed this information in aggregate represents societal valuation, and therefore a good starting point for a more-in-depth survey of the peer review literature. That the peer review literature tracks societal concerns is encouraging - that comparatively few studies address the disturbance mechanisms important to society is of concern.

It should be noted, when media keyword lists and newsworthy occurrences are compared against their keyword and record counterparts from the peer-review and government source searches, mass media accounts are found inaccurate, replete with factual errors and on further analysis, source accounts are often misinterpreted, manipulated or misquoted. However, without *in-situ* observing networks (the ideal) to track disturbances throughout an entire geographic region, there is no other means to conduct a rapid survey of recent occurrences. At the least, mass-media articles provide reports not otherwise found in the academic literature, contextual information not included in data base entries, and most importantly, identify the same scientists and resource managers that may in-turn provide the more accurate source information.

MMED studies should include anthropogenic impacts, such as oil/chemical spills, by-catch, dredging and errors in food preparation, and that metadata should be considered alongside health surveys. Direct and indirect human marine impact types (including persistent organic pollutants) are reviewed elsewhere (Sheppard 1998a,b,c).

Once standards are formed by expert review, feedback is ingested back into the meta-data database to further hone a classification process ensuring continual collaboration with the data providers, custodians and external peer reviewers. In practice, it is difficult to consolidate occurrences into events by date coincidence alone due to arguments related to scale and data quality. Meetings held to debate these disciplinary issues can be costly but ultimately will create precedent (Gross *et al.* 1995). The secondary and interim end product is to create disturbance regimes (Figure 8) that best describe the pattern and frequency of anomalies within a spatial area and limit debate to monthly or yearly events common among more than one local geographic area than to resolve disciplinary integration theory. The results provide a starting point for expert debates.

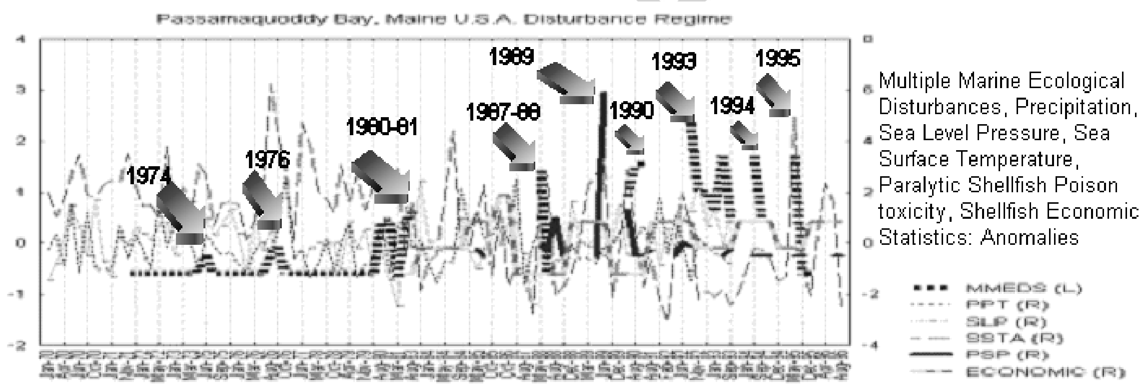

Figure 8. Example disturbance regime defined by frequency and amplitude of occurrence. Combined time series plots help fill visual data gaps from incomplete records and provide a more complete representation of disturbance regimes. Depicted here is an example of Passamaquoddy Bay, Maine, U.S.A, showing the occurrence of several types of combined disturbance patterns. MMED occurrences are displayed as points along-side paralytic shellfish toxicity (PSP) time series, an index of economic variability, sea surface temperature anomalies, standardized precipitation values and sea level pressure indices. The predominant MMED factors in this Northeast Shelf LME sub-area are blooms of the biotoxin producing A. Tamerensis dinoflagellates resulting in shellfish-bed closures due to PSP.

Forecasting with Marine Epidemiological Information Systems

Cost in dollars may also be tabulated for each occurrence using the source literature and models that account for the price of commercially valued species. Because the trophic structure is known for particular locations, any species non-valued, but consumed, could be enumerated as a derivative of those that are valued. Rather than exceed the total valuation of the system (Costanza *et al.* 1997), the MMED proxy technique can help piece together partial real cost of impacts for any given disturbance. This is typically better than the default of no valuation at all. MMEDs and their leading indicators, having once impacted a particular location can be systematically monitored to forewarn of future financial impact.

For marine ecosystems, vigor, organization and resilience (VOR) have been popularized within the peer-review literature (Mageau 1995, Costanza and Mageau 1999) because these measures determine an ecosystem's vulnerability to state-changes (Hollings 1995). MMED disturbance indicators have complex interdependencies with various VOR and ocean health indices (Halpern 2012, Pauly and Christensen 2001) that are also used to solve for evaluations of changing trajectories. More MMEDs over time in a place are viewed as undesirable and have relationships to species, fisheries and recreational regime changes important to managers. MMED indices combined with VOR indices may be visualized to show vulnerability to change. Eight disturbance types, for this purpose, were statistically derived from early MMED studies (Sherman 2000). Some disturbance types (italicized) represent events that are acute, occurring within a short time span (e.g. *biotoxin/exposure*), protracted (evolving over time) *chronic conditions involving keystone species* and *anoxia* (e.g., tumor development, eutrophication). *Trophic magnification* disturbances pass toxins through the food chain. Other categories have specific correspondence to *forcing factors* (e.g. coral bleaching events and sea surface temperatures; population declines) from *climate* variability and altered ecosystem dynamics. *Mass lethal* mortalities if not yet attributed to other factors catch geographically or temporally widespread events such as oil spills or massive salinity change. *New novel or invasive* disturbances (Mack *et al.* 2000) capture the first occurrence of a new type of event within a geographic area including the translocation of species. *Disease* disturbances are morbidity and mortality associated with a particular disease. Throughout Latin America and Caribbean these 8 disturbance event types are useful for initiation of more intensive literature surveys and serve as the foundation for surveillance information systems.

Biotoxin/Exposure Event Surveys

Biotoxin disturbances include diatom blooms, cyanobacteria, or dinoflagellate blooms that kill fish, invertebrates, and mammals and directly cause human illness (Landsberg, and Shumway 1998). Exposure disturbances include mortality of seabirds, lesions on fish, or toxicity due to bloom by-products such as domoic acid, which causes human eye irritation, memory loss, or neurological damage, and respiratory and skin irritation in humans and wildlife (HEED 1998). Toxic dinoflagellates are responsible for a majority of major marine mortalities of fish and birds from blooms. Less frequent toxic diatom blooms (e.g., Pseudo-nitzschia) concern ecologists, not only because of direct impacts upon migratory waterfowl populations but because they cause severe, debilitating illnesses in humans from casual exposure (Parsons et al, 2002). Cyanobacteria blooms have been implicated in marine mammal mortality and associated with Florida Bay sponge mortality and recruitment failure (young organisms' failure to survive) of spiny lobsters (Landsberg and Shumway 1998). Red tides, which result from algal blooms, result in widespread mortalities of near-coastal populations of fish, shellfish, and crustaceans (Butler et al. 1995). In the Pacific since the 1980s exposure mortalities of shellfish and finfish species supporting mariculture (culturing marine organisms in their natural environment) have occurred with greater frequency (HEED 1998). Humans are part of marine ecosystems too. Exposure events include gastroenteritis, hepatitis, cholera and swimmer's itch, cellulitis, conjunctivitis, otitis externa, seabather's eruption, and jellyfish stings from unanticipated swarms. Statistically short-lived, biotoxin- and exposure-related impacts cause long-term ecosystem structure and use changes if blooms and exposures persist (Epstein 1996). Beach closures and negative publicity in tourist and fishing economies cause the most worry (NRC 1990). Biotoxin and exposure impacts occur with greater constancy once an ecosystem has become porous enough to allow a large diversity of potential toxic and noxious seed species to enter and establish themselves. Ulloa et al. (2017), in this volume has reported on more recent Latin American harmful algae blooms throughout the region.

Anoxia/Hypoxia Event Surveys

Frequent blooms of nontoxic micro-algae and nuisance macro-algae are harmful because they dramatically reduce sunlight penetration in the water column. Large and long blooms can also draw a substantial amount of oxygen from the water column at night during respiration. When spent cells decompose, they remove even more oxygen from the water column, creating hypoxia. Prolonged anoxic and hypoxic conditions give sulfur-reducing bacteria a foothold, which accelerates mortality among bottom-dwelling organisms. Subsequent fish and invertebrate death provides more substrate for this decomposition disturbance regime, resulting in dead zones. The northern Gulf of Mexico's permanent dead zone has steadily grown in size since 1985, contributing to declining fisheries (Malakoff 1998). Anoxia from persistent lower nutrient picoplankton (unusually small sized phytoplankton) blooms makes it harder for filter feeders to sustain their energy requirements per square meter of effort. Chronic nutrient over enrichment from runoff and sewers further impairs elasticity following anoxic events.

Trophic Magnification Event Surveys

A trophic disturbance is one attributed to interspecies food-web relationships. Species impact increases geometrically as concentrations of toxins pass from one organism to another. Apex (top) predators become sick from the consumption of food stock harboring assimilated toxins. Heavy metals, persistent organic pollution (POP) including 1,1-Dichloro-2,2-bis(p-chlorophenyl) ethylene /dichlorodiphenyltrichloroethane (DDE/ DDT), methyl mercury, polychlorinated biphenyls (PCBs), and other biomagnifying (increased in concentration) toxins are an indirect result of near shore water pollution (Sheppard 1998a,b,c). Naturally occurring biomagnifiers include algae biotoxins primarily ingested through consumption of filter-feeding shellfish and fish having bioaccumulated microalgal toxins in their tissue (Landsberg and Shumway 1998). Short-term and permanent amnesia in humans, including fatality can result from acute toxicity (Wright et al .1998). Once scientists identify and observe the human etiology they begin looking for sentinel species that may also represent symptoms. Seabird impacts have been recorded in the California Current among the 5 Mexico bounded LMEs and within the Humboldt Current (Price et al. 1991). Paralytic shellfish poisoning (PSP) events primarily impacting seabirds, marine mammals, and shellfish themselves are also of concern to humans. PSP is caused by Gymnodinium breve in the Gulf of Mexico and periodically causes toxicity across taxonomic species. Gymnodinium catenatum is associated with PSP in the Caribbean Sea, Pacific Central American Coastal LME (Price et al. 1991). Neurotoxic shellfish poisoning (NSP) affects humans who have consumed shellfish contaminated by Gymnodinium dinoflagellates. Brevetoxins impact manatees and seabirds throughout the Gulf of Mexico. In the Caribbean Sea LME, bottom blooms of Gambierdiscus, Prorocentrum, Ostreopsis, and Coolia sp. are associated with ciguatoxic fish poisoning (CFP). CFP passes from algae to grazers and eventually to large piscivores (fish eaters) within an ecosystem. Tourists have higher body burdens of CFP because of their preferential consumption of larger barracuda and grouper (Landsberg and Shumway 1998). Zooplankton and phytoplankton serve as reservoirs for bacteria such as Vibrio cholera (Colwell and Spira 1992). Studies in the Gulf of Mexico, Caribbean Sea, and Humboldt Current LMEs suggest a viable trophodynamic transport mechanism for cholera to humans. Norwalk-type viral diseases, E. coli, and shigellosis, all of which can be passed through the food chain, readily spread from one ecosystem to another. In aquaculture areas, antibiotics and nutrient rich feces allow microbes living in biofilms to become more resistant over-time leading to persistent salmonellosis contamination.

Mass Mortality Event Surveys

Fish are the best monitored of those species apt to succumb to mass mortality. Anchoveta, herring, mullet, and other reef fish within the Caribbean have inexplicably died in large numbers at separate times (Williams 1992). Catfish within the Gulf of Mexico and along the Northeastern Brazilian Shelf ecosystem have also unexpectedly died in large numbers (Noga et al. 1988). Mass mortality disturbances include groups of reports clustered in space or time involving a single species or multiple species mortality that scientists have not yet attributed to a particular cause. In retrospect, researchers have found anoxia and HABs as causative agents (Landsberg and Shumway 1998). Anomalous massive and widespread mortalities indicate brittleness within a system, however, and die-offs of multiple species at the same time signal state changes in ecosystem health. A significant and widespread black sea urchin (Diadema antillarum) mortality occurred throughout the Caribbean during the 1983 El Niño year (Williams and Bunkley-Williams, 1990b). Coincident with the urchin die-off, many Jamaican reef species also collapsed. Sediment and nutrient runoff had already inundated the reefs (Williams and Bunkley-Williams, 1990b). Reef fish cleaners depopulated from overfishing could not clear detritus of the newly bleached reefs. Disease controlling overcrowded urchin populations (also reef cleaners) worked in concert to permanently degrade the health of this habitat. Although climate and/or disease etiologies are involved, the driver of system change is the mass mortality event itself (Lessios 1984). Marine mammal strandings along beaches in Peru, Chile, the Caribbean, the Gulf of Mexico, have steadily increased since 1970 (Sherman 2000). In Jamaica, macroalgal mats now smother the old dead reefs, and populations of all species, particularly fish, remain depressed following a few massive mortality events (Williams and Bunkley-Williams 1992).

Physical Forcing Event Surveys

The frequency of extreme events, extraordinary chemical and physical pulses, and subtle shifts in seasonality associated with regional climate change are considered physical forcing events. Populations and communities of organisms adapted to specific tolerance ranges are often ill prepared for physical extremes. Coral bleaching is the most reported physically forced event type (HEED 1998). Scientists have observed this bleaching throughout the Caribbean Sea and the Pacific Central American Coastal LME. In particular, reefs have bleached in Ecuador, Costa Rica, Colombia, Chile, Mexico, the Florida Keys, the Bahamas, and the Turks and Caicos islands (Harvell et al. 1999). Bleaching occurs when sea surface temperatures exceed 29^{o}C for extended time periods, causing the expulsion of coral polyps (Hayes and Goreau 1991). Extreme climate events in the late-twentieth and early-twenty-first centuries associated with El Niño cycles have been linked to many unprecedented disturbances. Scientists have used indicator species to better calibrate climate models (USGCRP (2000). Reproductive failure in Oceania's Kiritimati Island seabird populations long precedes dramatic changes to the Humboldt Current LME's Peruvian anchoveta and sardine/mackerel upwelling fisheries' economic impacts (Ebbesmeyer, et al. 1991). Here, the El Niño–Southern Oscillation disturbance regime is teleconnected (statistically crossing thousands of kilometers) to give Humboldt fisheries managers a chance to pre-adapt, should they heed the early warning. Less predictable have been dramatic cold-stunning events and storm (sudden pulses of fresh water) anomalies that also impact species indicators; particularly marine mammals in proximity to shore and turtles globally burdened with fibroid papilloma virus (William et al. 1991).

Disease Event Surveys

Pathogen pollution refers to the spread of disease throughout an ecosystem from adjacent or faraway sources. The frequency and extent of disease impact has increased since the 1980s (HEED 1998). Marine mammal deaths involving agents such as phocine distemper, morbillivirus, and influenza viruses are becoming less unusual as inter- and intraspecies exchanges increase due to shrinking habitat (Epstein 1996). The 1997–1998 El Niño–Southern Oscillation event altered food distribution patterns (Polovina et al. 1995). Severe weather enhanced transmission vulnerability for both crowded mammal and seabird populations. Already stressed organisms provide the perfect hosts for opportunist pathogens (Ferrer and Pumarola, 1990). Epizootic (an outbreak affecting many animals of the same kind) spread of coral disease underscores the recent increased prevalence theory (Hayes and Goreau 1991). Coral white-band, black-band, red-band, and yellow-band/blotch diseases are now found throughout the Caribbean, where they were not previously ever documented to exist (Williams et al. 1991). Sea fan aspergillus disease in Colombia, Costa Rica, Panama, Trinidad, and Tobago and ridge mortality disease observed in Mexico continue to spread (Hayes and Goreau 1991). Scientists now observe a spreading rapid wasting disease in the Netherlands Antilles (Hayes and Goreau 1991). Bivalve and shrimp diseases have also rapidly spread (HEED 1998). Taura syndrome, for instance, moved from a single shrimp farm in Ecuador to sites throughout the Americas (Garza et al. 1997). Shrimp-eating birds may be a vector (disease-spreading organism). It is not a coincidence that incidences of disease occur in highly polluted areas (Sinderman 1996). The fish disease lymphocystis, as an example, appears to become problematic when heavy rains flush toxic chemicals into fisheries areas (Sinderman 1996),

Novel and Invasive Event Surveys

New or novel occurrences are disturbances appearing for the first time in either a species or within an area. Scientists may also classify the first recorded instance of a species invasion, significant change in seasonality or novel distributions (range extensions), or extraordinary new vulnerability of susceptible populations as new or novel occurrences. One of the most effective conveyors of bio-invaders from one ecosystem to another is in the ballast water of large ships or results from deliberate fisheries, mariculture, and aquarium-trade translocations. The ecological consequences of these invasions include habitat loss and alteration, altered water flow, short-circuited food webs, the creation of novel and unnatural habitats subsequently colonized by other exotic species, abnormally effective filtration of the water column, hybridization with native species, highly destructive predation, and introductions of pathogens and disease disturbances. Evolutionary mechanisms such as cyst formation and chemosensitive triggers allow toxic species to more easily spread where disturbances are frequent and/or of sufficient magnitude to permanently establish these opportunists in new ecological niches. Mass mortalities and subsequent species substitutions eventually provide adequate substrate and biofilms to displace predators and competitors (Landsberg and Shumway 1998). Natural diffusion of genetic material has evolved as a slow local and gradual process allowing species and ecosystems time to adapt. Non-native species, are regularly transported in ballast water of ships traveling throughout the Americas and in particular Panama, highlighting a fundamental change in diffusion patterns. A novel occurrence tests the elasticity and inertia of a marine ecosystem to withstand or succumb to the new species arrival. The ease in which species invade is a measure of the porosity and vulnerability of the system. Both anthropogenic facilitation and climatic change improve the odds for survival among new, novel, and opportunistic pathogens (Epstein 1996).

Keystone, Chronic, and Dramatic Event Surveys

Algal blooms (red and brown tides), hurricanes, and oil spill events stand apart from long-term impacts recorded from dredging, coastal hydrologic modifications, loss of wetlands/dunes, coral blasting, and fisheries overexploitation. Impact to chronically disturbed keystone species, such as beach-breeding marine turtle populations or the absence of oysters and oyster reefs from the Chesapeake Bay from disease and harvest, can take a long time to manifest. The magnitude of the impact once felt within an ecosystem, rather than the duration of individual occurrences, statistically links event types in the chronic category (Sherman 2000). Dramatic oil spills define public perception of marine ecosystem health. The Santa Barbara Channel spill inspired an environmental movement. The Tampa Bay, Galveston Bay, Bay of Campeche, Tobago, West Indies spills did build a case for damage assessment, but these extraordinary spills did not evoke proportionate marine ecosystem health mitigation. Observed but insufficiently assessed spills throughout the twentieth century include spills associated with Guadalupe, the Strait of Magellan, Chile, Brazil, Colombia, and Puerto Rico. The Cox Bay, Louisiana, and proximal 2006 spills largely went unpunished and unrecorded because of the larger damage Hurricane Katrina caused. The Gulf of Mexico Deep Water Horizon and Macondo oil spill (2010 and 2011) (Fisher et al. 2014), and the Mississippi Basin Block 252 blowout event (2011) by sheer volume of released oil have restructured these marine ecosystems on the decadal scale of impact.In the twenty-first century the persistence the petrogenic hydrocarbons from oil spills such as those damaging the

Calcasieu River, Mississippi; Guanabara Bay, Brazil; Guimaras Island, Sabine Neches passage, Texas; Mississippi River (multiple spills); and Campos Basin, Brazil, built a stronger case for new forms of litigation on behalf of a marine ecosystem's environmental health. An environmental criminal complaint in Rio de Janeiro named not only corporations (as in the BP Gulf of Mexico spill) but individuals. Geographic point and nonpoint pollution including sewage and nutrient/particulate inundation, warming and cooling of ocean water, salinity gradient changes, acidification from carbon dioxide deposition, micronutrient enrichment from wind-blown Sahel sand, dissolved inorganic nitrogen, phosphate (nutrient over-enrichment), endocrine disrupters, new/novel species introductions, disease redistribution, nuisance/noxious algae bloom regimes, military sonic pollution/disruption along migration, feeding, and flyway corridors, and floating plastics/garbage patches are more gradually evolving marine health stressors. All are implicated in shifts of marine ecosystems from healthy and stable to those less stable and more brittle, especially for keystone species. Specific point-in-time events that maintain persistence include toxin spills, massive hurricanes, cyclones, tsunamis, and human/wildlife exposure to radiation from depleted uranium around Caribbean military target ranges (Hayes and Goreau 1991). These marine ecosystem health impacts include the globally felt Chernobyl and Fukushima upheavals because these event impacts will remain in the geologic record; their persistence is matched only by volcanoes, long-term climate change, pollution, and persistent resource exploitation impacts. Although impacts are not yet fully known, chronic conditions that could overshadow all other disturbance regimes may include ramifications from a global shift in the acidity of seawater due to increased carbon dioxide in the Earth's atmosphere and its subsequent sequestration (deposition) into the sea. Rapid acidification, which some models predict, could be more than most calcium carbonate–dependent marine organisms (shells and spines) can withstand. Extinctions may be forced by these chronic pressures. Marine mammals and many other charismatic species are barometers for ecosystem health. Often these keystone species, those the rest of the community depends on may serve as indicators or sentinels for change as well.

Assessing Disturbance Vulnerability

Each of the eight disturbance types has a relationship with six disturbed ecosystem characteristics: porosity, stability, amplitude, elasticity, inertia, constancy (Orians 1975). Constancy is a measure of occurrence frequency, inertia represents resistance to state changes, elasticity represents the speed of an ecosystem's recovery, amplitude is the amount of deviation from a baseline, stability is an ecosystem's resilience to perturbation, and porosity is a flow rate of material and energy through a system or the ecosystem's susceptibility to invasion. These terms are compatible with VOR syntax. The six characteristics can be used to ascertain vulnerability to future disturbance using available sentinels. By comparing an area's (spatial measure) disturbance regime (temporal measure) with 8 disturbance types and the 5 characteristics (thematic descriptors), an index can be derived and upon expert review, converted into a score reflective of differences among adjacent geographic areas. The index scores are a useful measure of variable or consistent observational effort among systems. No data or insufficient data could be considered a ninth disturbance category (but at present it is not). The subset of results provided in Table 1 provides examples of indicator (species or groups) with respect to phenomena of interest (MMED type), and VOR trajectory (a full table with all 100 examples available at http://www.heedmd.org).

Table 1. MMED Types with Respect to Disturbance Regime Criteria. Several of the candidate species indicators come from a list of 147 documented marine disturbance observation types, representing thousands of indicators (Sherman 1999). Many of these types involve harmful algae blooms as a leading indicator, but also represent marine related human disease, disease affecting marine mammals, birds, corals, fish, large invertebrates, shellfish, seagrass, sea turtles and the public and economic consequences of these major disturbances (Sherman 2001). Of the 100 examples available, just 1 fish mass mortality incident characterization is provided.

Marine Indicator Group or Proxy Indicators	Phenomena	MMED Type	Disturbance Regime Criteria	Vulnerability Health Impact Trajectory
Fish: Catfish, Mullet, Herring, French angelfish, Grey angelfish, Rock beauty, Cherubfish, Princess parrotfish, Blue chromis, Balloonfish, Whitespotted filefish, Doctorfish, Reef butterflyfish, Foureye butterflyfish	Fish mass mortalities	Mass Lethal	Amplitude, Constancy	Organization

An eight point diagram represents the aggregate state of, or disturbance type snap-shot, for a particular area (Figure 9). These are disturbance vulnerability diagrams; vulnerability is associated with the likelihood of recurrence of disturbance once a regime becomes established. Indicators contributing to each quadrant within the diagram may also serve as sentinels for future disturbances. These graphs have eight axes, beginning at a central point and radiating out in opposite directions. Visual weight corresponds to vulnerability (though order around the radius is arbitrary). An area's score (information density – availability) for each disturbance type, is marked on each axis and the points are connected to form a closed area. The size of this area is a measure of the amount of unanticipated disturbance observed across the eight components.

Anomaly scores for each Index or anomaly indicator represent a number from 1-100 (standard normal percentiles) where 100 is the anticipated baseline ecosystem condition. The range is determined by the shape of the distribution of all scores across all of the similar systems. For instance, those in the same Gulf of Mexico EPA province (Paul and DeMoss 2001), and those sharing similar Large Marine Ecosystem attributes globally (e.g. upwelling, open or closed) as also determined by trophodynamic assemblages (Sherman 2000, Pauly and Christensen 2001).

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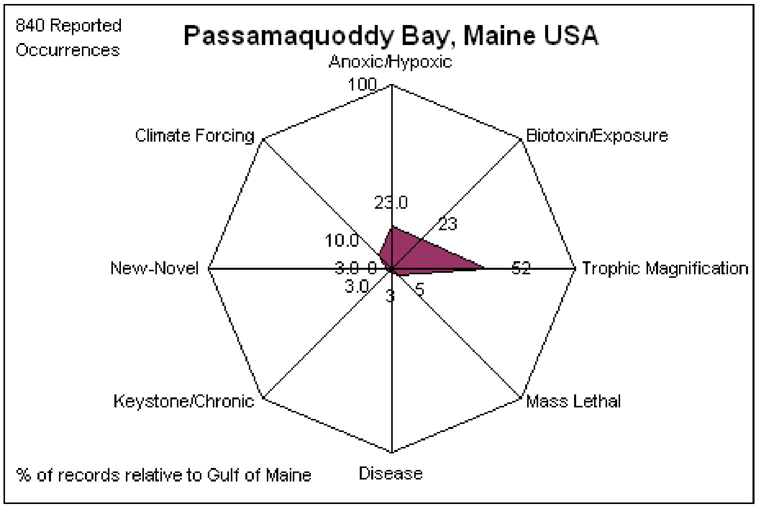

Figure 9. Example Disturbance Vulnerability Diagram. The majority of incidents reported over a 40 year time-period for one example bay within the Gulf of Maine which is within the Northeast Shelf Large Marine Ecosystem

Each disturbance regime and vulnerability diagram has an associated shaded bar graph representing score components (indicator information depth) for each harbor, lagoon, bay, estuary or reach of water. Empty bars show the average scores for the adjacent/compatible ecosystems. These scores represent the average of the standardized ("z") scores of the variables that comprise the indicators for similar systems. Higher numbers represent more anticipated conditions; lower numbers represent systems on a trajectory toward less anticipated ecosystem conditions (Figure 10). Hypothetical regime classification could lead to a regime score that is the average of the "n" indicators, presented as standard normal percentile. Each indicator if comprised of constituent indicators representing an average of the underlying variables. The eight core components receive a value equal to the average of the associated indicators, and are adjusted by the standard normal percentile. The variables may be presented in standardized form, as Z-scores. A value of "Null" within the spreadsheet indicates missing data. Greater granularity within the Null set can be associated with the qualitative ranking of source citations and reports or certainty in event consolidation (all tracked).

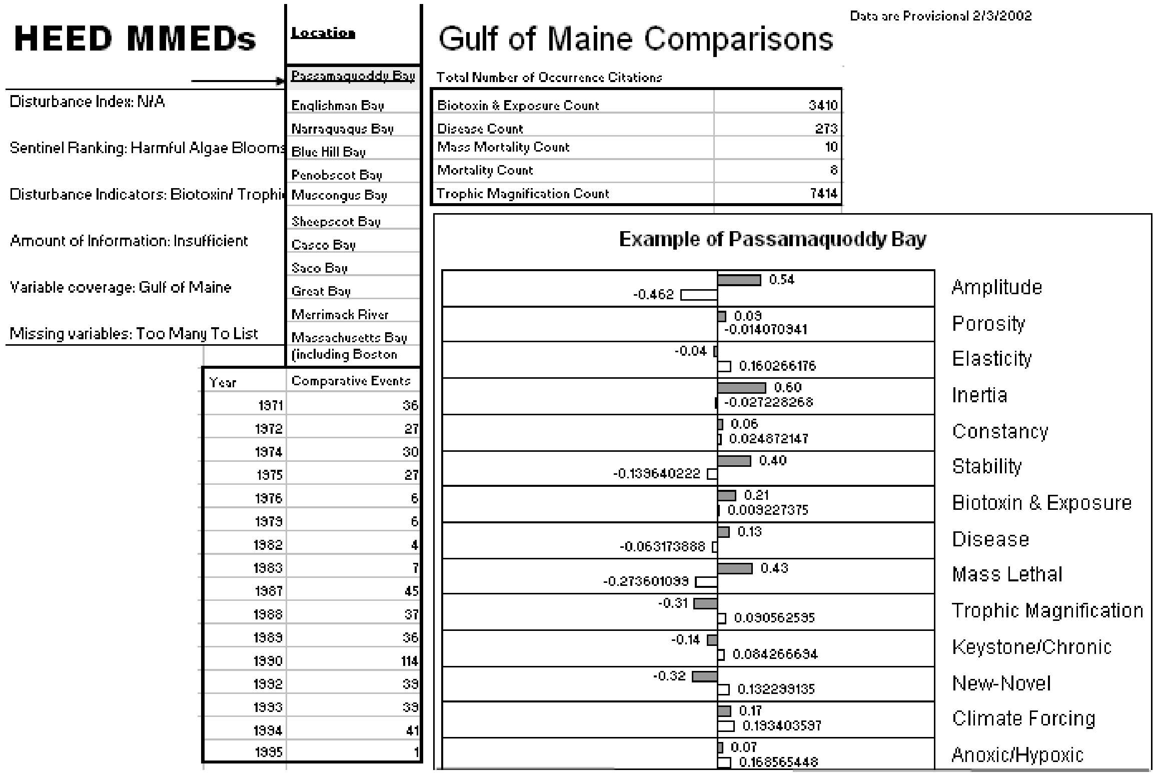

Figure 10. Example of Comparative Disturbance Scoring Bar Graph. For a MMED information system project (circa 2002) that indexed 40 years of disturbance observations within the Northeast Shelf Large Marine Ecosystem's Passamaquoddy Bay. The six indexed disturbance ecosystem characteristics are presented alongside the 8 MMED types. Index data considers prevalent LME-wide (Northeast Shelf) or LME sub-area (Gulf of Maine) MMEDs (depicted) and enumerated from the total number of citations within these areas.

Within the Gulf of Mexico and Caribbean LMEs, the MMED assessment effort resulted in several compiled databases, a report, a web based geographic information system, and a web server running services designed to facilitate information exchange and foster research (http://www.heedmd.org). These MMED systems serve as a repository of expert knowledge including, information derived from over 7000 primary peer reviewed journal articles, books, gray literature, symposium proceedings, government reports and personal communication with select field researchers. In addition, ProMed Digest reports for marine related human illnesses, and publicly referenced information including transcripts and raw text from over 18000 available newspaper articles were ingested between 1995 and 2000. These databases have content extending back in incident time to the mid-1940's (HEED 1998). Data archived within MMED epidemiological information systems can be used to assist researchers with indicator or sentinel selection. Reviewed was a process where-by some quantitative techniques are suitably applied to the vetted meta-data to assure its comparative value in LME studies. The methods described herein offer data-scientists rigorous freedom to explore data and relationships without being limited by their preconceptions of complexity or the academic requirement to ascribe mechanisms and functional relationships for all observations.

The Way Forward

MMED disturbance regime surveys and the marine epidemiological information flows described endeavor to rescue, recover and unify natural history observations extracted from published academic literature, field scientist logs, bench scientist journals, citizen observation networks and news media feeds. By expanding the definition of what can constitute an event indicator (e.g. lesions, organisms, gastro-enteritus, lost-wages or floods) time-series reconstruction using meta-data proxies can fill gaps in resource monitoring program to forewarn of pending MMED events across each LME. Coupled with other ocean health indices (Halpern et al. 2012, Tett et al. 2013, EPA 1992), MMED assessments in the developing world could better focus effort where it is most required before impacts to development are experienced.

Acknowledgements: NetScout Systems Inc. provided leave for the author to attend conferences and complete this manuscript (2016). Reviewers at the US-EPA-Gulf Breeze Laboratory (2004) and CIESIN's ESI project (2002) encouraged refinement of the multiple index approach and introduced the author to the amoeba diagram indices. Supplemental funding from the Earth Institute of Columbia University, the Wildlife Trust (2000), NASA (1998), Harvard University and Harvard Medical School (1996) allowed Sandeep Prasad (1995), Amelia Langston (1996), Erika Spanger-Siegfried (1998) and Lauren Hauser (2001) to continue the literature surveys crucial to these retrospective studies.

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