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ENSURING PERSISTENCE OF MARINE RESERVES: CATASTROPHES REQUIRE ADOPTING AN INSURANCE FACTOR

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Abstract. 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.

Key words: disturbance; hurricane; marine reserves; oil spill; rare events.

Introduction

Marine reserves have gained extensive attention in recent years as a powerful additional tool in marine conservation and resource management (Bohnsack 1992, Roberts 1995, Hockey and Branch 1997, Castilla and Fernández 1998, Hastings and Botsford 1999, Murray et al. 1999). The science of marine reserves continues to develop as practical experience and additional research provide new information (Carr and Reed 1993, Allison et al. 1998, Airamé et al. 2003, Carr et al. 2003, Grantham et al. 2003, Leslie et al. 2003, Palumbi 2003).

Reserves are usually established to achieve goals such as (1) replenishment of populations and/or biomass, (2) increased reproductive potential of economically important species, (3) conservation of sufficient critical habitat, (4) maintenance or restoration of biodiversity, (5) increased educational, scientific and tourist value, or (6) some combination of these. The ability of single reserves or reserve networks to meet such goals is dependent on reserves maintaining the ecological structure and functioning that made the site worth saving or restoring. This maintenance of structure and functioning is dependent upon processes and events occurring both within the site and external to it. Control of some external events and processes is possible (e.g., regulations specifying quality or quantity of inputs from upstream watersheds). However, in most cases, many factors are typically beyond the control of reserve management. The success of reserves may be seriously compromised unless allowance is made for the reality of these externalities (Allison et al. 1998). The focus of this paper is on one class of external events, catastrophes, and how reserves might be designed to withstand their impact.

Large-scale catastrophes, while rare, can essentially prevent a single reserve or network from fulfilling its goals. Consider a situation in which, because of habitat degradation throughout a region, it is decided that a reserve network will be established to protect a certain fraction of critical habitat. Twenty percent is set aside because reserve designers determine that that amount is required to maintain enough critical habitat for key species. Because habitats outside the reserve are de-

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graded, they supply few or no recruits to the reserve. Any events, such as oil spills or severe storms, that remove protected habitat from the network will effectively prevent the goal from being met until that habitat recovers. Thus, beyond the familiar concerns in the design of marine reserves (e.g., the area needed to fulfill the functional goals of the reserves, the degree of protection required, and the placement of reserves in a network), there is an additional critical issue not usually considered: mitigating the influence of rare but catastrophic events. If marine reserves are to fulfill their potential as an integrated part of the management of marine ecosystems, a long-term perspective that provides insurance against catastrophes is required.

One simple way to increase the probability that reserve goals are met even in the face of catastrophes is to build into the planning process the expectation of some loss of component reserves and to set aside a compensatory amount of area within the reserve (Murray et al. 1999). In this paper, we propose a methodology for quantifying how much extra area is needed. While this analysis does not indicate where reserves should be placed or how far apart they should be spaced within a region, it does provides a pathway for determining the amount of extra area needed for a given catastrophe regime and set of reserve goals. The method offers a new perspective on the problem of reserve design and provides a way of incorporating critical factors not typically considered. In the absence of perfect knowledge of catastrophe regimes, planning for reserves must rely on approximations. The approximations used in this paper for calculations of what we term ‘‘the insurance factor’’ will give reserve designers a tool to better assess these and other important ‘‘external’’ factors.

Catastrophes

Disturbance events in marine ecosystems vary considerably in frequency, scale, and effect (Sousa 1984, Connell and Keough 1985, White and Pickett 1985). Our focus here is catastrophes, which we use to mean relatively large-scale perturbations that involve significant mortality, habitat loss, or disruption of ecosystem functioning. Medium- to large-scale events that are known to dramatically affect marine populations include harmful algal blooms (Hallegraeff 1993, Burkholder et al. 1999), disease epidemics (Lessios et al. 1984, Littler and Littler 1995, Harvell et al. 1999), coral bleaching events (Smith and Buddemeier 1992, Glynn 1993, Brown 1997), hypoxia events (Stachowitsch 1984, Rabalais et al. 1998, Burkholder et al. 1999), oil spills and hurricanes (summarized in the following two subsections), and others.

By their very nature, catastrophes in marine systems are hard to study because they are relatively rare and their extent is often difficult to quantify without a spatially extensive monitoring system. Typical records of marine catastrophes are those for disturbances that are local in scale and close to observation stations; as a consequence, estimates of damage and recovery are inconsistent. However, we acquired extensive data sets maintained by United States federal agencies for two important catastrophe types, oil spills and hurricanes. These data allow us to infer the frequency and extent of some of the major events affecting marine communities along shorelines. We can, thus, estimate a catastrophe regime within a particular region and consider its effect on reserve design. Although oil spills and hurricanes are only two of many types of large-scale events affecting marine systems, they are capable of substantial impact. We suggest they are good models of how catastrophes in general may impinge on reserve effectiveness.

Oil spills

Oil spills in coastal areas can have significant impacts on marine populations. Spills devastate directly by poisoning and smothering (Keller and Jackson 1993, Wolfe et al. 1996), and indirectly through physiological trauma (Loughlin et al. 1996, Spies et al. 1996), reducing food availability, and decreasing developmental success of larval or juvenile forms (Carls et al. 1999, Heintz et al. 1999).

Very large spills are a catastrophic form of marine pollution and, on a global scale, are not uncommon. Between 1974 and 1992, there were 28 tanker spills of greater volume than the *Exxon Valdez* oil spill (Anderson and Leer 1994), or on average, an extreme tanker spill every 8 mo during that period (Fig. 1). Extreme spills are not limited to tanker accidents; for example, 3.5 million barrels were released during the *Ixtoc I* oil well blowout of 1979 and ~8 million barrels were spilled directly into the marine environment during the 1991 Persian Gulf War (National Oceanic and Atmospheric Administration/Hazardous Materials Response and Assessment Division [NOAA/HMRAD] 1992). Such extreme spills can coat hundreds of kilometers of shoreline. These spills can leave oil deposits in sediments and biotic structures such as mussel beds and mangrove forests over extensive areas (Keller and Jackson 1993, Babcock et al. 1996). These deposits are often resuspended later, creating new oiling events. Spill events can create pools of heavier fractions 1 m or more deep in subtidal zones (NOAA/HMRAD 1992; *Sensinena* explosion), and can even form asphalt pavement over wide stretches of shore (Hann 1976).

Although these extreme spills garner extensive media attention, it is not well appreciated that smaller spills are actually quite common. For example, during the years of 1985–1997, there were at least 620 oil spills >200 L in Californian coastal areas (Fig. 2). While smaller spills may not produce the dramatic damage of an *Amoco Cadiz*- or *Exxon Valdez*-class spill, they can still affect lengths of shoreline that are

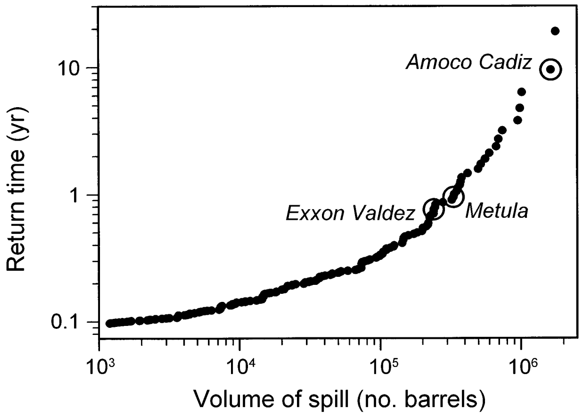

FIG. 1. Occurrence of monthly extreme oil spills by tanker ships, worldwide, 1974–1992. The source of data is Anderson and Leer (1994). Global monthly maximum spills were ranked by size. The expected return time for different spill sizes during that 19-yr period can be inferred from the curve traced by these ranked values. For example, a spill the size of the *Exxon Valdez* spill or larger is expected, on average, every 8 mo during this period. Because there is a decreasing trend in large spills during this period (USCG 1999), these rates should not be extrapolated to future rates (Gaines and Denny 1993).

significant to the goals of marine reserves. It is important to note that not all spills are reported, especially those in remote areas. Thus the available record is undoubtedly an underestimate of the occurrence of catastrophes.

Hurricanes

Hurricanes are extremely powerful natural events. Sustained wind speeds at sea level can exceed 240 km/h. Damage to coastal marine habitats and populations occurs because of large wave forces (Kjerfve et al. 1986, Rogers et al. 1991, Bell and Hall 1994), sediment suspension and subsequent smothering (Hubbard 1992, Kobluk and Lysenko 1992), influx of large volumes of freshwater and terrestrial sediment due to heavy rains (Nowlis-Sladek et al. 1997) and winds and storm surge in intertidal and onshore habitats (McCoy et al. 1996, Swiadek 1997).

Hurricanes are natural events and part of the general environment that many marine ecosystems experience. However, if species or habitats persist only or primarily in reserves and a reserve is severely damaged, it may lose the special features that made it desirable in the first place. Many tropical and subtropical marine habitats such as coral reefs, mangrove forests, and seagrass beds are strained from development, pollution, and fishing pressure (Fortes 1988, Smith and Buddemeier 1992, Done et al. 1995, Twilley et al. 1995). As these pressures grow, marine populations will be increasingly affected and habitats will continue to be degraded such that populations may be constrained primarily to reserves, as is the case for many terrestrial species. Reserve designers that strive to set aside areas of sufficient size to maintain populations and ecosystem functioning are likely to underdesign a reserve network if they ignore large-scale disturbance events that will further reduce the effective contribution of a reserve.

In this paper, we first develop a simple tool, an ''insurance factor,'' to estimate the amount of extra reserve necessary given a particular catastrophe regime. Next, we review and summarize patterns of oil spills and hurricanes. We use the extensive data that have been compiled on the occurrence and spatial distribution of these events to characterize disturbance regimes in different coastal regions. We then summarize these data as the average fraction of shoreline impinged per year by these events. Finally we apply the insurance factor to case studies for different catastrophe regimes to illustrate how such data can be used.

AN INSURANCE FACTOR: A PROTECTIVE MULTIPLIER

For marine reserves to be effective, designers should do everything possible to ensure that the entire area protected is not simultaneously disturbed by catastrophes. In other words, they should plan a reserve system that would likely be buffered against the effects of catastrophes by being sufficiently large that, on aver-

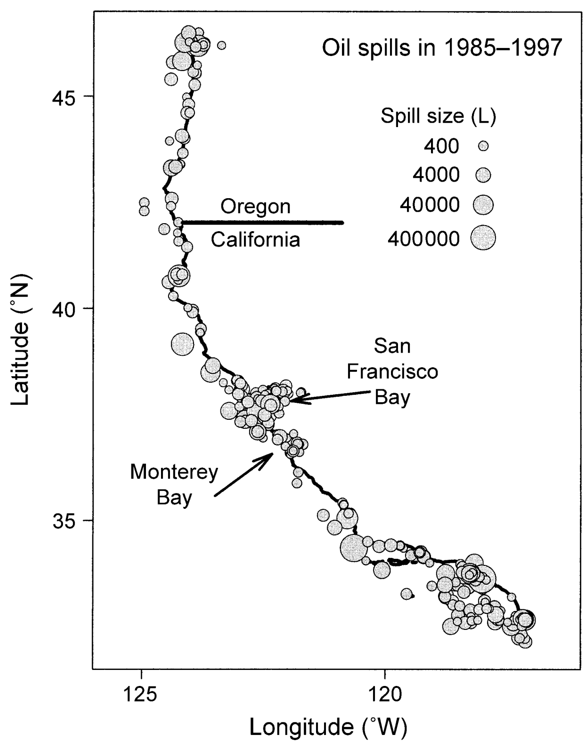

FIG. 2. Geographic distribution of oil spills on or near the shores of California and Oregon, USA. The source of data is the U.S. Coast Guard (USCG 1998). The sizes of the symbols represent the relative volume spilled; the actual shoreline area affected should not be inferred from this figure.

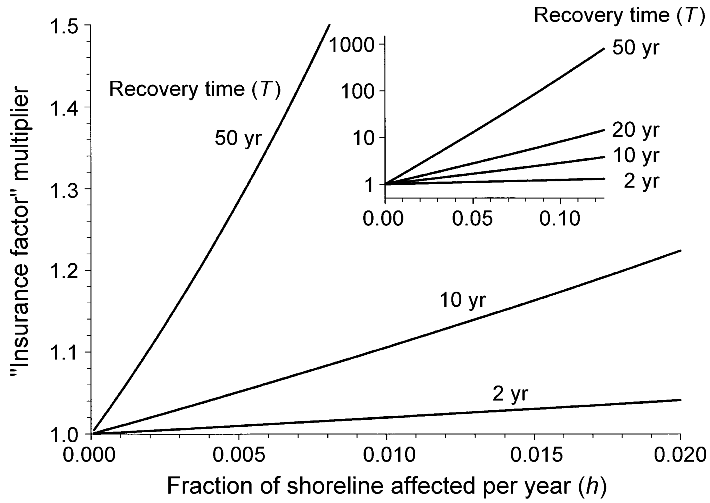

FIG. 3. Illustration of values of the insurance factor given different recovery times and fractions of shoreline affected per year.

age, the total area set aside in reserves has not recently been subjected to a catastrophe.

In this section, we develop an insurance factor, M that is used in the following way. If we wish to conserve at least x kilometers of coast in a condition that has not been rendered ineffective by catastrophes then we must set aside $M \times x$ kilometers.

For the simplest form of this insurance factor, we make a number of assumptions (we present other forms with fewer assumptions in the Appendix):

1) Assume that we are concerned with a long length of coastline.

2) Assume that a fraction, h, of that coastline is affected by catastrophes each year. We will call h the annual affected fraction and assume it is constant each year.

3) Assume that catastrophes strike the coast randomly so that the probability of any point being affected is constant and independent of the point's prior history of catastrophes.

4) Assume that it takes T years for a site to recover from a catastrophe, at which point it becomes valuable for management or conservation again.

Given these assumptions, the fraction of coastline unaffected by catastrophes, U, is

$$U = (1 - h)^T. \tag{1}$$

In other words, the chance of any single point being unaffected is the chance that there has been no catastrophe in the last T years. Because all points are independent, the fraction of coastline unaffected is the probability any particular point is unaffected.

The insurance multiplier is simply $M = 1/U$. If at any time about half the coastline is in a disturbed state then $M = 2$; that is, designers would need to set aside twice the area they would otherwise need had there been no disturbances. Thus, if the desired goal is to have, on average, at least R% of the coastline in a ''recovered'' state then we multiply R by $1/U$. We plot this insurance factor as a function of the annual fraction affected, h, for different values of recovery time, T, in Fig. 3.

In the Appendix, we relax some of the above assumptions (constant hazard rate, spatial independence, and single hazard type) and explore the robustness of the simple form of the insurance factor (Eq. 1). Because our intent is to illustrate the concept, we will use the simple form of the insurance factor throughout most of the paper. For application of the insurance factor to real-world uses, the appendix forms may be more useful.

CATASTROPHE REGIMES

Effective use of the insurance factor is enhanced by an understanding of the specifics of the catastrophe regimes in which a reserve network will be embedded. Below, we examine the characteristics of two different types of catastrophes—one anthropogenic (oil spills) and one natural (hurricanes). We chose these two types because both are relatively well documented. While other catastrophe types may be more important to any particular reserve, these two serve to illustrate the need for consideration of catastrophes in the design and planning for networks of reserves.

Analysis of the spatial characteristics of oil spill and hurricane events is relevant to our task, and in particular, how they interact with shorelines. Marine reserves are often shore-based and the marine impacts of hurricanes and oil spills are most often studied and probably most severe in shallow and intertidal areas. To analyze the spatial characteristics of these catastrophes, we used a shoreline database consisting of point-based maps. Adjacent points on these maps average 0.9 km apart and all nonshoreline boundaries were removed. Territorial islands are included in these maps. The highly detailed contours of this map produce total shoreline

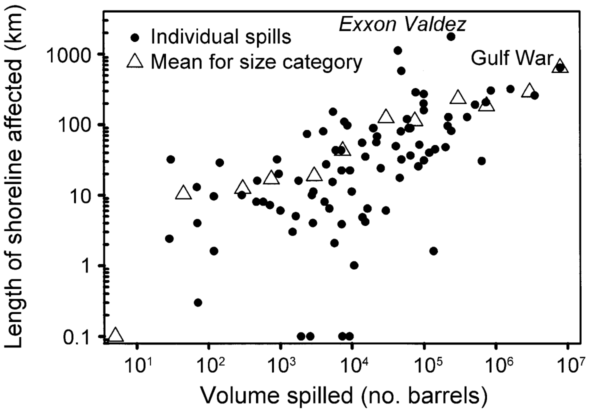

FIG. 4. Relationship of spill volume for coastal spills and the length of shoreline affected. For spills that occurred close to shore but never directly soiled the shore because weather conditions moved the slick out to sea, we display the value of 0.1 km here to accommodate the logarithmic scale. Triangles represent the arithmetic mean of all spills within a volume class; these means are used to assign a shoreline length to all spills in the USCG data set.

lengths greater than would be estimated from, for example, tracing the shoreline on a coarse-scale map. The California shoreline database is ~2700 points and Florida is 7300 points.

Distribution of oil spill events

The distribution of lengths of shoreline affected by spills over a given time period should provide a reasonable estimate of the overall area affected by oil spills in a particular region. We use two sources of data to develop this distribution. First, the United States Coast Guard has compiled data on all point-source oil spills over ~200 L for many areas in U.S. waters since the early 1970s (U.S. Coast Guard [USCG] 1998). These data include volume, type, and location of the materials spilled. Although this data set includes spills into rivers, lakes, and marine areas out to ~320 km from shore, we extracted only those marine spills within 40 km of the shore and only those of a petroleum nature.

Second, because data on actual shoreline lengths affected by an oil spill are unavailable for most spills, we explore the relationship of volume of oil spilled to the length of shoreline affected by using a subset of well-studied spills. These data were collected from reviews of many spills (van Gelder-Ottway and Knight 1976, Ford 1985, NOAA/HMRAD 1992) and from reports on specific spills (e.g., Spooner 1970). This collection of well-studied spills is shown in Fig. 4. This figure summarizes 86 spills and includes those spills occurring close to but not contacting the shore.

The variable nature of oil spills along coastlines makes predictions of oil spill impacts rather coarse (National Research Council [NRC] 2002; note the log-log scale of Fig. 4). Predictions of the impact of any one spill using the relationship among these data would be of low precision (Ford 1985) because the range of potential variability within a size class is large. Further, a linear regression of log-transformed data would not be appropriate here because that would drastically underestimate the arithmetic mean of any given volume. (For a treatment of the linear regression for a smaller set of spills, see Ford 1985.) However, because we are interested in the mean area affected by oil within a region for a large number of spills, this relationship is still useful for that given population of events. To translate a known volume into an estimate of shoreline length affected, we divided the spills in Fig. 4 into size categories and calculated a shoreline mean for each category. For subsequent analysis, we used these means as an estimate for the length of the impacted shoreline where only volume is known. We assume that spills in the smallest category (<1600 L) did not affect the shore.

We determine the length of shoreline affected for all spills in the U.S. Coast Guard database using the relationship shown in Fig. 4. We use the nearest shoreline point as the center of the affected area. While this assumption is likely to be only coarsely correct because of the uncertain nature of oil slick movement (Smith

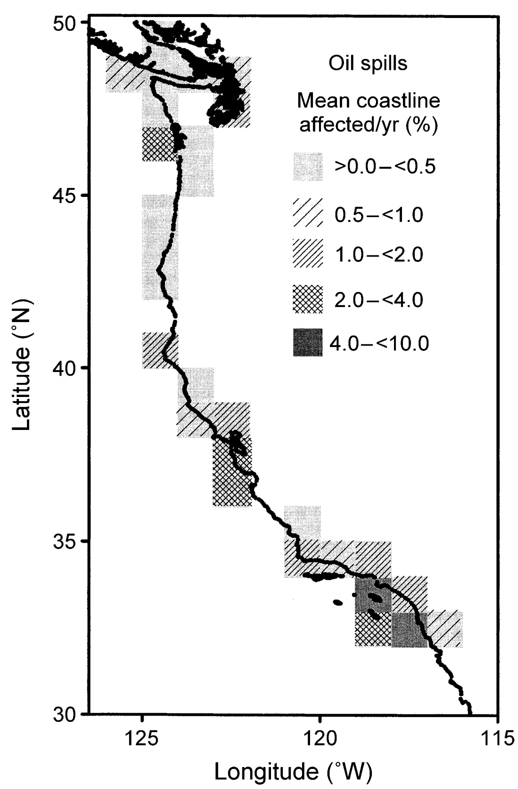

FIG. 5. Mean percentage of U.S. West Coast shoreline affected by oil spills per year. Results are based on an analysis of 1 × 1 degree latitude/longitude cells. Data are based on the U.S. Coast Guard data set (USCG 1998) for those spills occurring between 1985 and 1997 and the relationship of spill volume to shoreline affected developed in Fig. 4.

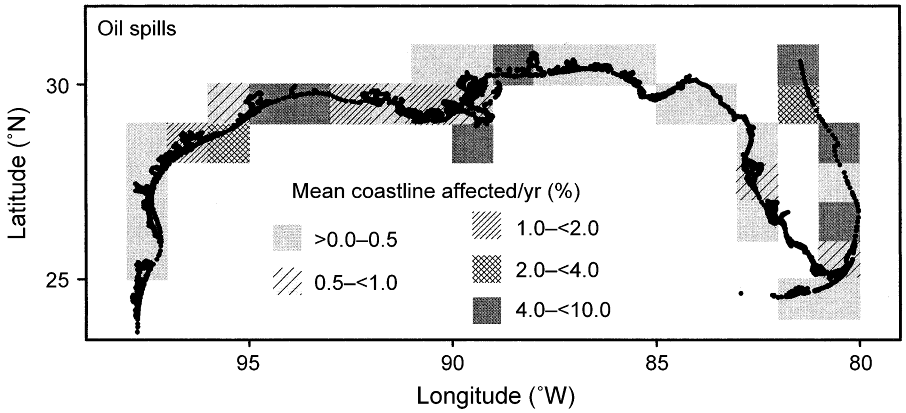

FIG. 6. Mean percentage of U.S. Southeast Coast shoreline affected by oil spills per year. See caption of Fig. 5 for more details.

et al. 1982, Ford 1985), it will not have a meaningful influence on our estimate of region-wide disturbance rates. Next we assign all the shoreline points within the affected length as disturbed for a given spill. Once we assign these affected shoreline points for all spills in a region, we determine the average amount of shoreline affected per year. We present results based on analyses of 1×1 degree latitude/longitude cells. As we describe in the *Discussion*, the scale at which the analysis is performed should be dependent on the scale of the reserve network under consideration. For our purposes here, the 1×1 degree analysis illustrates the degree of variability across very large areas.

Figs. 5 and 6 document the mean fraction of shoreline affected per year during the years 1985–1997 for the U.S. West and Southeast coasts. These figures clearly highlight ''hot spots'' of oil spills—areas of oil production (southern California, eastern Texas, and Louisiana) and areas of heavy transport such as port locales. However, even outside such hot spots, the mean fraction of coastline affected can still be substantial. It is important to note what makes a hot spot ''hot.'' Because our disturbance rates are the mean fraction of shoreline disturbed per year, high rates may be due to many smaller spills spread over time, or just one very large spill that affected a very large area. While, on average, these two scenarios produce similar insurance factors, reserve designers should consider the difference for their particular area: regular, small spills imply more chronic conditions and perhaps a higher long-term risk of future big events. Rare, large spills may force careful consideration of reserve spacing to prevent an entire network from being affected by a single event.

Distribution of hurricanes

The tracking of hurricanes and their progenitors has received considerable attention because of their potential for serious destruction on land and sea. Moreover, characteristics of past storms can now be reconstructed from multiple sources of information (e.g., Kjerfve et al. 1986). Consequently, there is a relatively complete record of storms for many areas. The U.S. National Oceanographic and Atmospheric Administration (NOAA) maintains a database of the geographic tracks of hurricanes and tropical storms in the western Atlantic that includes data back to the 1880s (from 1886 to 1997 there were 959 storms). These data include position of the storm and wind speed for every 6 h during its life. Details of this database are described in Jarvinen et al. (1984; the database is currently available online).[6]

Scale of storm effects.—We combine the hurricane data set with archived data on wave height from several meteorological buoys near Florida, Texas, and Louisiana in order to investigate the scale of the physical effects of hurricanes on marine communities. These data are available from the National Data Buoy Center.[7] We standardize wave height to monthly means across all dates available with a unity standard deviation. Then, for each 6-h period for all storms during which a buoy was active, we calculate the distance between the storm center and the buoy and plot the relationship between distance from the storm and significant wave height (Fig. 7). This plot suggests that wave force can be quite severe even at distances of 500 km from the center of a storm (more than eight times the standard deviation from the monthly mean). Because wave forces are a primary source of damage in intertidal and shallow subtidal communities, these data indicate that the ''footprint'' of hurricanes may be quite large for such communities.

Index of storm intensity.—For this paper, our primary interest in this hurricane database is the distribution of catastrophic events, both for the overall distribution of

[6] URL: ⟨http://www.nhc.noaa.gov/⟩
[7] URL: ⟨http://www.ndbc.noaa.gov/⟩

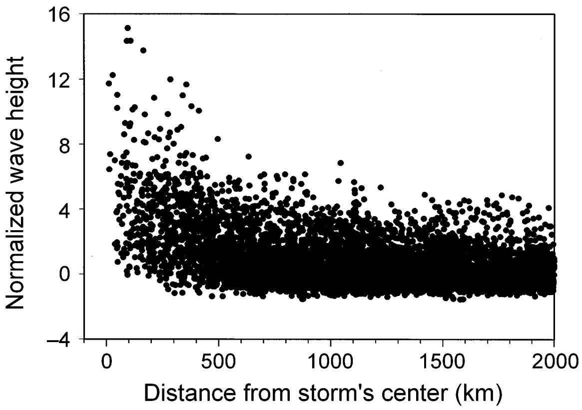

FIG. 7. Scale of storm effects for all storms in the NOAA data set that occurred during the life of a selection of weather buoys. Illustrated are the recorded extreme significant wave heights during a 6-h period at buoys near Texas, Louisiana, and Florida. Buoy identification numbers: 41009, 42002, 42003, 42007, 42036, 42039, and 42040. Note that, although data were standardized (mean = 0, standard deviation = 1) to all buoy records, data displayed here represent the maximum measurement during each 6-h of a storm's life; thus, data displayed do not have a mean of 0.

intense events and the fraction of shoreline impinged on by the event. Because we are interested in the intensity of a given storm at a given point on the shore, we generate an index, S, that is the cumulative ''intensity'' of a storm from the perspective of a point in space

$$S = \sum w^2/\ln(d) \tag{2}$$

over all time intervals of the storm where w, wind speed, is ≥120 km/h and d, distance, is ≤500 km for all shoreline points in the North Western Atlantic and Gulf of Mexico (latitude 0°N to 60°N). The cumulative nature of this index reflects our expectation that storms dwelling over one area will have a more severe effect than on an area over which the storm passes quickly. This index is calculated for all shoreline points and all storms. For this paper, S is scaled to range between 0 and 1, where 1 is the maximum value for all coastline points throughout the 112-yr data set. The distribution of this index is shown in Fig. 8.

We calculate S for the locations of a collection of studies that documented change in coastal populations before and after storms within the primary area of storm activity to verify that high values of S corresponded to conditions under which coastal ecosystems were under high risk of damage. The calculated values are marked on Fig 8. The areas with the most severe damage lie mostly in the upper 10% of S, indicating that the index is a reasonable predictor of areas that are at high risk. It is important to note that although damage caused by hurricanes can be quite patchy (Yoshioka and Yoshioka 1987, Edmunds and Witman 1991, Rodriguez et al. 1994, Connell 1997), reports about the lack of damage following extreme events are rare. Thus, high values of S indicate only those areas impinged upon by severe events, but not necessarily severely damaged.

We perform a geographically specific analysis to determine the mean fraction of shoreline impinged by severe storms throughout the western North Atlantic and the Gulf of Mexico (Fig. 9). We use $S \geq 0.2$, that is, we report the fraction of shorelines impinged by storm intensities that are in the highest ~5%.

Summary of catastrophe distributions

It is clear for both oil spill and hurricane regimes that the probability of catastrophes can vary dramatically among regions. Within regions, there are likely to be hot spots such as areas of oil production or oil transit centers, but areas outside these hot spots are not immune to severe events. Further, although we do not consider it in detail here, some local habitats will be more susceptible than others: for oil spills, because most fractions of petroleum products float, intertidal areas may be most prone to the effects (but see National Research Council [NRC] 1999). For hurricanes, factors such as shore orientation and degree of wave exposure determine the susceptibility of a given habitat (Connell 1997). However, reserve designers often include several habitat types within a single reserve and thus it is more appropriate to focus on reserve-scale or network-scale probabilities instead of partitioning reserves into small pieces. Finally, it may be important to consider the history of disturbance in a region. For hurricanes,

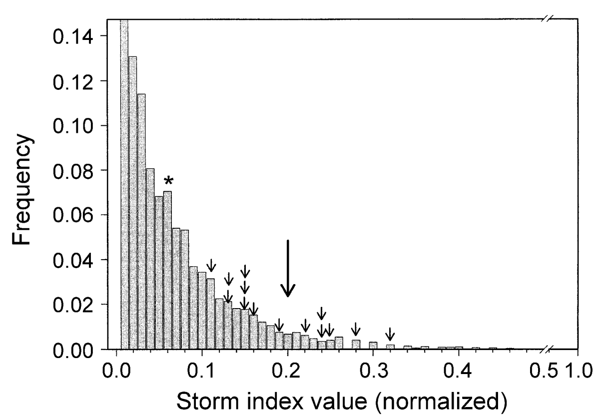

FIG. 8. Distribution of nonzero values of S for all storms in the hurricane database (n = 959) and for all shoreline map points in the western north Atlantic and Gulf of Mexico. The small arrows indicate values of S for studies that reported moderate to extensive hurricane damage in marine habitats from a specific storm, and the asterisk indicates that only light damage was recorded in a study. Studies reviewed: Woodley et al. (1981), Kaufman (1983), Yoshioka and Yoshioka (1987), Edmunds and Witman (1991), Fenner (1991), Hubbard (1992), Kobluk and Lysenko (1992), Bythell et al. (1993), Bell and Hall (1994), Blair et al. (1994), Bouchon et al. (1994), Rodriguez et al. (1994), and Aronson et al. (1998). The large arrow indicates the value of S that was used for the spatially explicit analysis presented in Fig. 9.

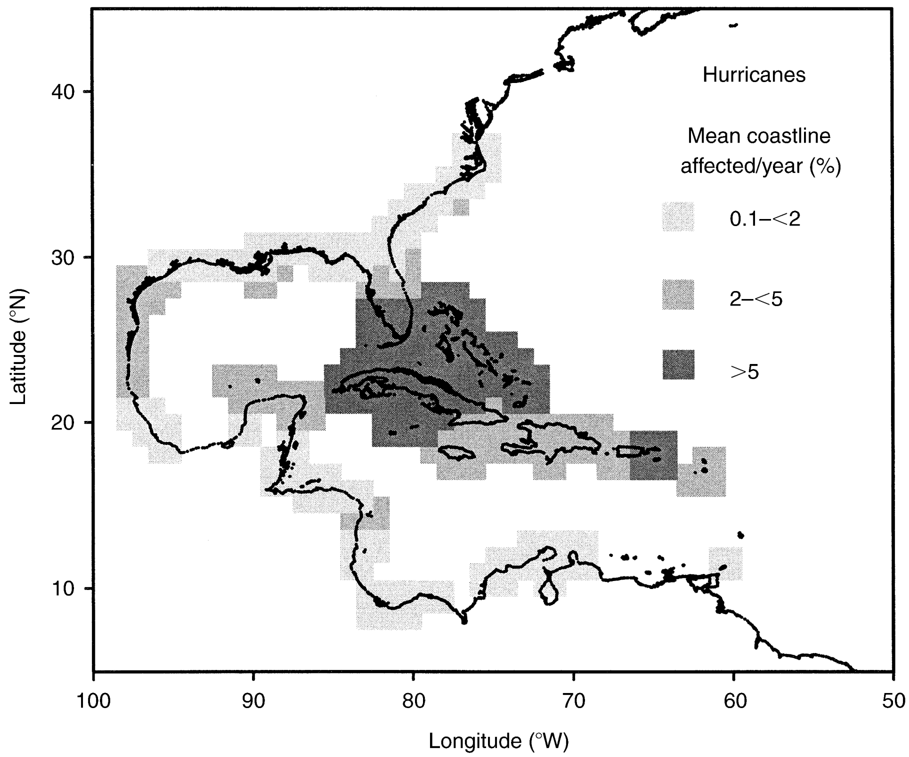

FIG. 9. Mean percentage of the western North Atlantic and Gulf of Mexico shoreline affected by severe storms per year. This figure illustrates the mean area impinged by a storm index (S) of 0.2 or greater. These data are based on the NOAA database (all years; 1886–1997) and the storm index illustrated in Fig. 8.

this may determine the level of complexity or fragility that an area can develop between extreme events. For stress due to oil, frequent release of small spills in an area or chronic, nonpoint-source pollution may increase the susceptibility of organisms to a larger events and would likely retard community recovery. Alternatively, frequent natural disturbances may select against species or individuals with low disturbance tolerance and slow growth.

Recovery Rates and Reserve Goals

The insurance multiplier requires two estimates: the disturbance rate, which we have already discussed, and the recovery rate. While a review of recovery rates from severe events is beyond the scope of this paper, several important points should be noted. First, the recovery rate one uses is dependent on the response variable of interest. For example, one could use the biomass of a community: once the biomass had returned to some fraction of precatastrophe values, one would consider the area recovered. Alternatively, if one used the population demographics of a species of interest, recovery would be the length of time it takes for the population to return to approximately precatastrophe demographics. When you consider that biomass may recover rapidly due to ephemeral species (Suchanek 1993), whereas the recovery of long-lived species may take decades or longer (e.g., mangroves in Keller and Jackson 1993), the choice of the response variable is clearly critical.

Second, the most appropriate recovery response should be based upon reserve goals. If the goals of the reserves specify precisely what aspects of a marine system the reserve is meant to protect, the choice is uncomplicated: T is the time it takes for that protected aspect to return to predisturbance values. Goals may specify targets such as commercial species (as in a ‘‘fishing-refugia’’ design) and in such a case the recovery time is the period for just that species to recover (which may intrinsically depend on the recovery of other species such as prey and habitat-forming species). Reserve goals may instead specify a particular level of ecosystem process; for example, a certain amount of kelp production may be required because it is habitat for many other species (Carr 1994). Even for some relatively nonquantifiable goals, recovery responses can be identified. For example, if the goal was to maintain a certain fraction of the coastline in as natural a state as possible, one could operationalize ‘‘recovered to natural’’ as the recovery of the longest-lived species in the community or the return of a community structure to a state indistinguishable from the nondisturbed state. Thus, multipliers for some goals (such as the ‘‘fraction-natural’’ goal) will be larger than multipliers

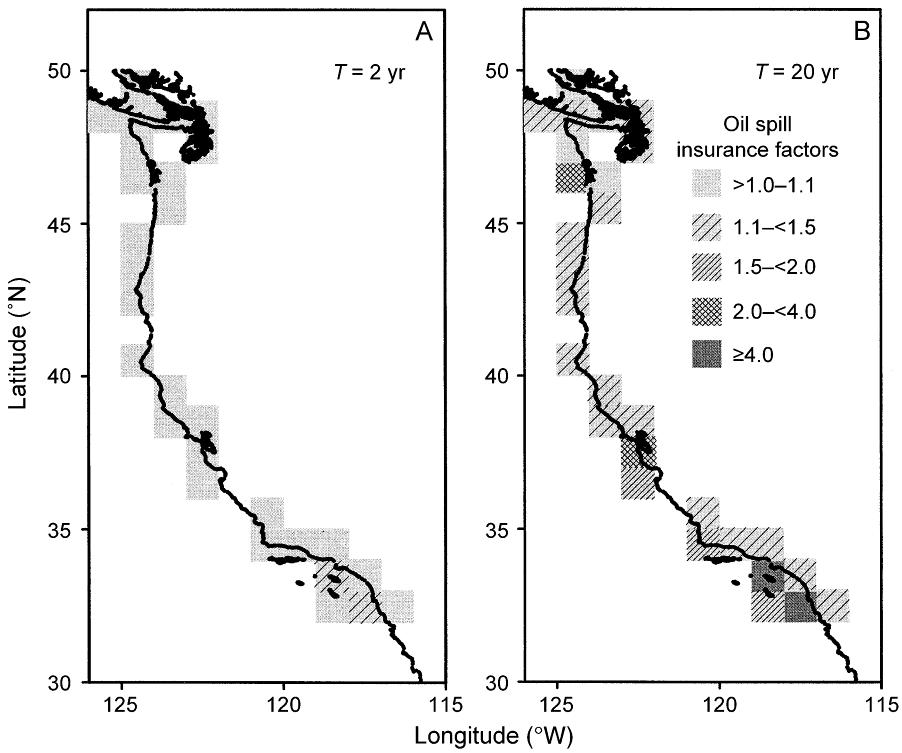

FIG. 10. Insurance factor values for oil spills on the U.S. West Coast for two different values of T (recovery time). Disturbance rates used for these estimates are illustrated in Fig. 5. The insurance factor was calculated using Eq. 1.

for simple functional goals (such as level of kelp biomass). These target recovery rates can be estimated from published reports of other severe events (e.g., Keller and Jackson 1993, Rice et al. 1996, Connell et al. 1997).

Finally, another important consideration about both recovery rates and disturbance rates is the synergism among perturbations to marine communities. A community that is already stressed due to chronic pollution, invasive species pressures, or climate extremes such as El Niño/La Niña events will likely be more susceptible to disturbance and recover much more slowly than unstressed communities. Connell (1997) found recovery in coral communities was significantly retarded in areas with chronic, long-term stresses. An especially poignant example is Discovery Bay in Jamaica and its poor recovery after Hurricane Allen due apparently to the synthetic effects of several stresses (Woodley et al. 1981, Hughes 1994). On St. Lucia in the Bahamas, coral areas near development in cities were more susceptible to storm damage caused by sediment transported down rivers and subsequent smothering (Nowlis-Sladek et al. 1997); slower recovery was also expected.

While these recovery considerations are critical, the insurance factor developed above is quite flexible because it is adaptable to many types of reserve goals and disturbance types. Goals are matched with recovery rates specific to the functional nature of the goals. Below we illustrate the use of the insurance factor with different recovery rates for the oil spill and hurricane regimes.

ILLUSTRATION OF THE INSURANCE FACTOR

We develop four examples to illustrate use of the insurance factor as a multiplier. The first two cases apply the insurance factor equation to the oil spill and hurricane data sets described in *Catastrophe regimes: Distribution of oil spill events* and *Catastrophe regimes: Distribution of hurricanes.* The third example considers how to deal with two catastrophe types such as oil spills and hurricanes together. The fourth example examines the trade-offs in using average years vs. worst-case years for analyses.

Example 1: oil spills.—Insurance factors depend upon the frequency of the catastrophe and the time it takes for recovery. The interactions of these factors are depicted in Figs. 10 and 11 for the two oil spill regimes documented in Figs. 5 and 6. Panel A in Figs. 10 and 11 depicts the insurance factor for recovery times (T) of 2 yr. For most of the areas along these particular coastlines, multiplier values are small, <1.1, indicating that reserve goals associated with this relatively quick recovery time could be met by adding 10% or less of the target to the actual amount set aside in a reserve network. In other words, if 20% of the habitat is

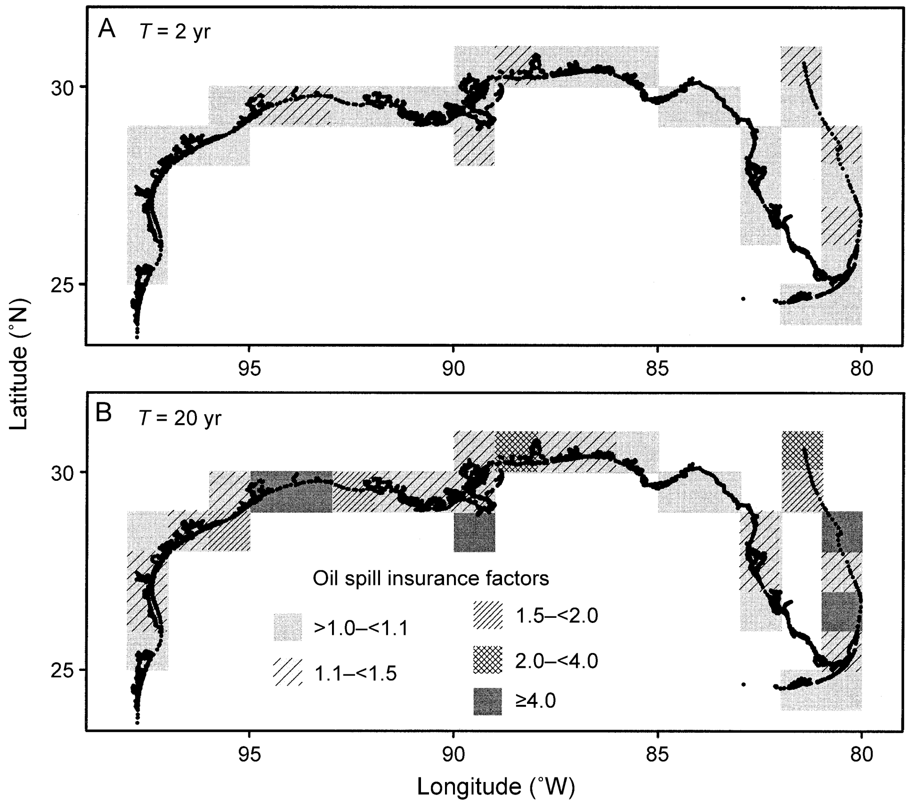

FIG. 11. Insurance factor values for oil spills on the U.S. Southeast Coast for two different values of T (recovery time). Disturbance rates used for these estimates are illustrated in Fig. 6. The insurance factor was calculated using Eq. 1.

deemed the desirable target amount of area to protect, one would multiply 20% by 1.1 to arrive at the total amount of area (in this case 22%) to be set aside in order to increase the probability that on average, 20% would always be contributing to the identified reserve goals. Areas with greater risk would require more area to be protected. For example, areas in southern California, Louisiana, Texas, and east Florida have insurance-factor multiplier values as high as 1.26. An insurance factor of 1.26 applied to the target of 20% would result in 25% of the area requiring protection.

When the expected recovery time is much longer (for example, Figs. 10B and 11B; $T = 20$ yr), substantially more area would need to be added to account for the larger fraction of area expected to be recovering at any particular time. In the high risk areas illustrated, multipliers range from 4.8 to 10.7, greatly increasing the amount of total area required to satisfy reserve goals.

Example 2: hurricanes.—The results for hurricanes show similar patterns. When recovery times are relatively short ($T = 2$ yr), multipliers for hurricanes are between 1.0 and 1.23 (Fig. 12). When recovery times are longer, insurance factors would be larger.

The determination of recovery time is obviously critical to these calculations. Recovery time may be affected by a number of factors, for example, regional difference based on the historic frequency of extreme events. Areas where hurricanes occur frequently are likely to have communities composed of species with different life histories than those where hurricanes are infrequent. Recovery times may differ accordingly. For example, the effect of tropical storm Bret on the reefs of Curaçao was substantial (Van Veghel and Hoetjes 1995) even though the value of S (the cumulative intensity of the storm) was quite small. Curaçao is outside the ‘‘hurricane belt’’ and because it is not likely to receive storms of large magnitude, more fragile coral communities develop there than in areas frequently battered by large events. These more fragile communities are more susceptible to even moderate tropical storms. In our analyses, due to computational constraints of producing storm indices tuned to local historic events for each cell we examine, we use the same storm index across the entire storm basin. However, analysis for specific reserve networks should be tailored to local conditions whenever possible.

Example 3: additive effects.—Sites may be susceptible to more than one catastrophe. If catastrophes are independent of one another, they may be considered additive. (See Appendix, Eq. A4, for the derivation of the insurance factor when more than one catastrophe

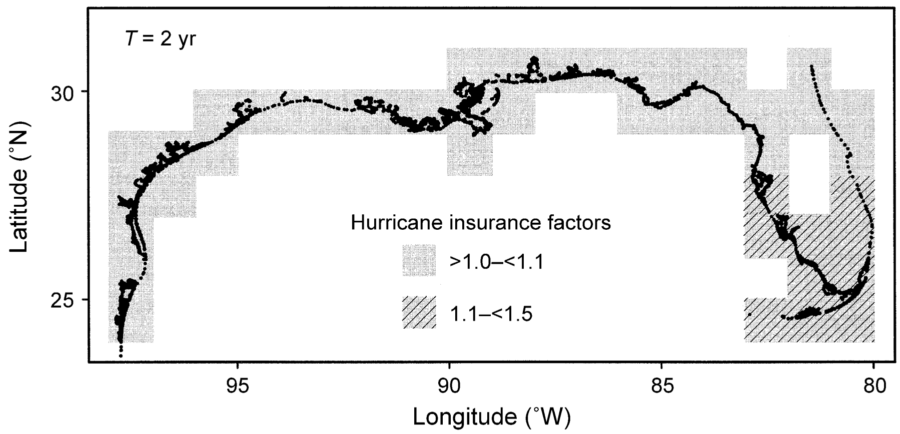

FIG. 12. Insurance factor values for severe storms on the U.S. Southeast Coast for a single value of T (recovery time). Disturbance rates used for these estimates are illustrated in Fig. 9. The insurance factor was calculated using Eq. 1.

exists). When the additive effects of oil spills and hurricanes are considered, insurance factors increase (Fig. 13A, B). However, because these two catastrophe types are spatially independent and their hot spots generally do not overlap, insurance factors do not increase much beyond that for the greater of the two catastrophes individually. Note that the independence assumption of this form of the insurance factor implies there is independence in both incidence and recovery from disturbance events. If one suspects otherwise, catastrophes should not be considered simply additive. An example would be if recovery time from hurricanes is strongly influenced by the frequency of oil spills. Treating catastrophe types as independent when they are not may severely underestimate the extra area needed for adequate insurance.

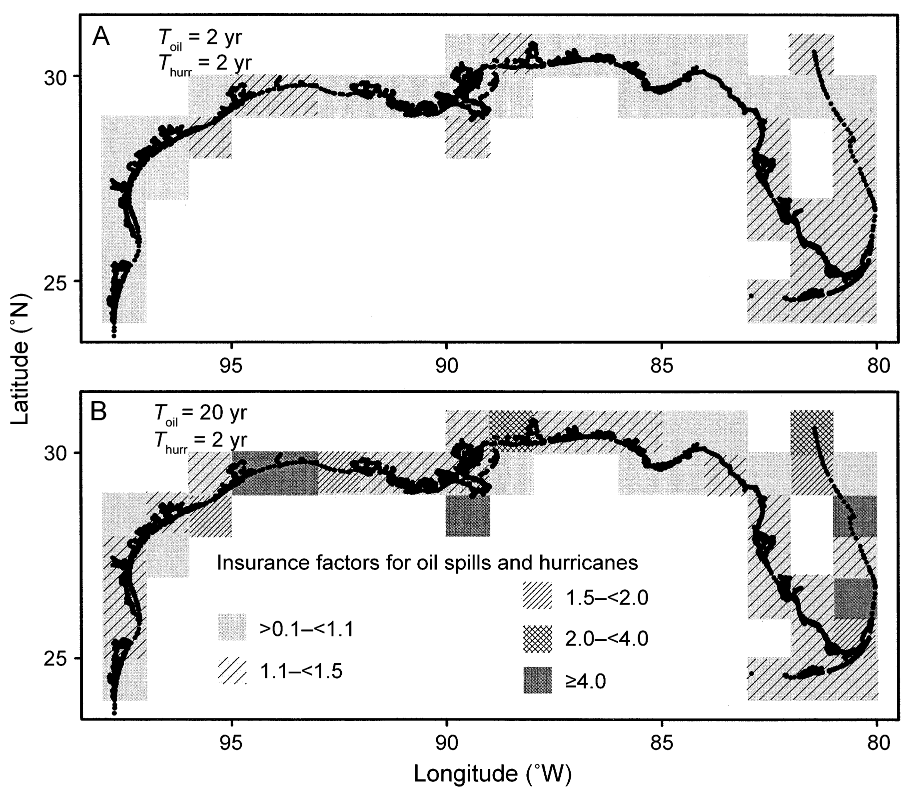

FIG. 13. Insurance factor values for both oil spills and severe storms on the U.S. Southeast Coast for two different sets of T (T_{oil}, recovery times from oil spills; T_{hurr}, recovery times from hurricanes). Disturbance rates used for these estimates are illustrated in Figs. 6 and 9. The insurance factor was calculated using Eq. A4 (in the Appendix).

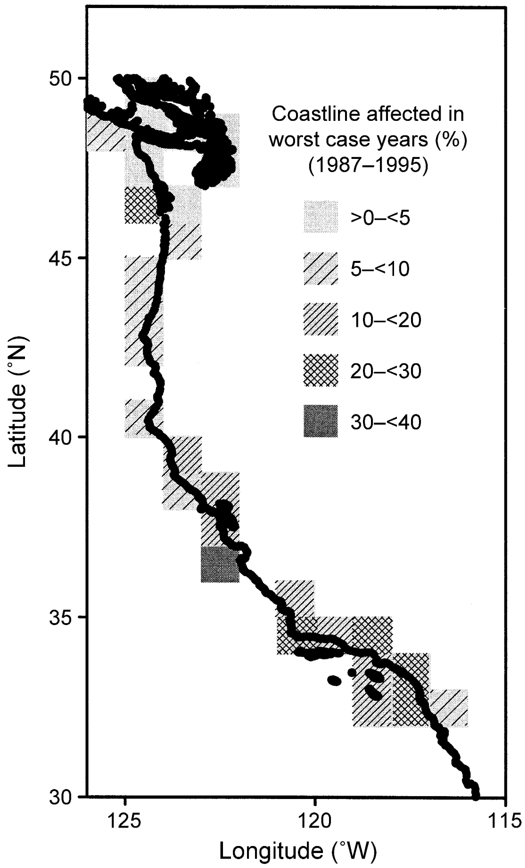

FIG. 14. Percentage of U.S. West Coast shoreline affected by oil spills in the year that was locally the worst between 1987 and 1995. These percentages do not include additional area within each cell that may still be recovering from previous disturbances. See Fig. 5 for other details.

Example 4: using average vs. worst-case years.—The above analyses are based on average rates of disturbance. They specify the extra amount of area required on average to ensure that the target amount of habitat along the shoreline is in the desired state. However, there will be years in which that percentage may fall well below average. If reserve goals are defined such that there is a minimum requirement for habitat in a fully functioning state rather than an average requirement, then a more conservative approach would be to design a reserve network based on the maximum area expected in the nonrecovered state during an extended period. One such analysis is shown in Fig. 14: the fraction of area affected by oil spills in the worst year within each local cell between 1985 and 1997. Such data could be used directly to estimate the extra area needed within a reserve network. One justification for this approach is that, for many types of events, occurrence data are less than complete (harmful algal blooms, disease epidemics, etc.). Planning to accommodate those occurrences may be more effectively done by considering the largest known event to occur in an area. In such cases, it may be further instructive to use the statistics of extremes (Gaines and Denny 1993) to estimate the maximum likely disturbance in any time horizon.

DISCUSSION

Catastrophes can have a major influence on effectiveness of marine reserves. From a long-term, large-scale perspective, they are ubiquitous. Inclusion of these realities into the design of reserve networks will substantially improve the probability that reserves will accomplish their goals. The development of the insurance factor above and its application to existing data sets for two types of catastrophes illustrates a new framework for accommodating the reality of catastrophes into reserve planning.

The treatment earlier in this paper of oil spills and hurricanes is necessarily simplistic. In the next few paragraphs, we examine some of the complexities that may be relevant to consider in particular cases. First, the data sets we use in this paper allow us to estimate the frequency and extent of catastrophes. Other characteristics of disturbances (patchiness, greater impact on certain types of organisms or habitats, and persistence of effects), if known, could yield more specific predictions. For example, the impact of an oil spill is not uniform over the area it affects (e.g., Keller and Jackson 1993, DeVogelaere and Foster 1994, van Tamelen and Stekoll 1996). A marine reserve that is patchily disturbed or that is one of the nondisturbed patches in a larger mosaic of oiled areas is clearly better off than a reserve that is completely disturbed by oil. Further, recovery times are likely to be dependent on the size and patchiness of disturbance events because recolonization into a disturbed area will be a function of the distance from viable propagule sources. Unfortunately, detailed information about the patchiness of large-scale disturbances in marine systems is rare. Our use of simple frequency and extent of catastrophes is a reasonable proxy for the scale of effects that designers of marine reserves should consider.

Implicit in our analysis is the assumption that reserves will be spaced across a region such that the entire reserve area is not affected by a single disturbance event. We do not address spacing issues here. The optimal spacing for reserves that takes catastrophe regimes into account will be dependent on the mean size of disturbance events and typical dispersal distances. Additionally, data from past catastrophe regimes can be used to determine a range of acceptable spacings for a particular region (G. Allison, *unpublished data*). Such spacing criteria can be used during the development phase of reserve networks (Airamé et al. 2003, Leslie et al. 2003, Roberts et al. 2003).

Further, the catastrophe regimes we characterize are based on historical data. One assumption is that past regimes are a good predictor of future catastrophes.

Expected changes in the frequency, intensity, or area of catastrophes in future years should modify the conclusions. For anthropogenic catastrophes, one hopes that disturbance rates will be reduced in the future. Indeed, encouraging improvements in rapid response to oil spills in recent decades have reduced the overall impact of many spill events (U.S. Coast Guard [USCG] 1999). But other factors imply an increase in frequency of some important disturbance events. Expected oil spill rates are a function of the volume transported (Anderson and Leer 1994); as global use of oil increases, we should expect spill rates to increase as well. It is unclear how the ongoing warming of the planet will translate into changes in the frequency and intensity of extreme storm events such as hurricanes in specific coastal regions. However, increasing habitat degradation will likely increase the overall negative influence of hurricanes through synergistic effects. While these changes are not certain, even current rates of disturbance are sufficient to warrant careful consideration during planning of marine reserves.

Finally, we focus on only oil and hurricanes because data for those events is most readily accessible. A plethora of other catastrophes may have profound impact on given reserves. For instance, harmful algal blooms, disease outbreaks, hypoxic events, and coral bleaching can all have significant effects on the scale of individual reserves. The frequency and extent of most of these disturbance events are likely to remain steady if not increase: harmful algal blooms (Hallegraeff 1992, 1993, Paerl 1997), coral bleaching (Glynn 1993, Berkelmans and Oliver 1999), and disease outbreaks (Harvell et al. 1999). Unfortunately, even less is known about the spatial and temporal distribution of these disturbance types than about oil and hurricanes.

Even in the face of limited data and uncertainty, several aspects of the insurance factor make it useful. When specific values for disturbance and recovery rates are not available for a given region, extrapolation from well-studied areas and/or similar types of disturbances can provide useful guidelines to increasing the effectiveness of reserves. In addition, the simple exercise of attempting to calculate a value for the insurance factor explicitly forces designers to consider long-term probabilities of severe events and the dynamic nature of the complex biogeochemical systems addressed by the goals of the reserve. The insurance factor is flexible and can be tailored to different recovery responses and different types of reserve goals. Further, throughout this paper, we have focused on U and h as fractions of the total shoreline in a region. However, other uses are also appropriate such as fractions of a particular habitat type or fractions of the spatial extent of a focal species. In this way, the insurance factor can, for example, be used to identify the actual amount of habitat necessary to set aside to reach a particular habitat conservation target.

Note that the insurance analyses does not take into account areas outside the reserve system in the sense that it focuses primarily on helping to ensure that what happens within the reserve system meets its target goals. If reserve designers determine that 5% of viable habitat needs to be protected in a reserve system, then the insurance factor provides a way to ensure that 5% is protected, despite catastrophes. We presume that reserve designers' goals will be driven, in part, by the amount and status of all resource in a region. This is particularly important because the potential for a reserve to recover from disturbance may be contingent upon the propagules arriving from outside the reserve.

We have illustrated the use of the insurance factor with a very specific spatial scale: 1×1 degree of latitude/longitude. The most appropriate spatial scale to use for a particular reserve system is an essential consideration for reserve designers. Because one goal of reserve networks is to spread risk over a large area and the insurance factor analysis implicitly assumes that reserves are spread throughout the analyzed area, analysis for risk for any given area should include the entire network range, but no more. For example, plans for a network in the San Francisco Bay region of California should consider only the risks for that area; because that area is an oil hot spot, using an estimate from all of the West Coast would underestimate the insurance factor. On the other hand, one way to lower an insurance multiplier is to expand a network to areas with lower disturbance rates; including lower risk areas reduces the network-wide risk.

Furthermore, such analyses will highlight where use of reserves may not accomplish desired goals. Where anthropogenic threats are pervasive, the resulting insurance factor may be so large as to render any reserve system unlikely. In such situations, the only solution to meeting goals is to reduce the risk. That is, there are at least two ways to mitigate the threats of catastrophes for a particular goal: (1) to reduce the risk or (2) to expect losses but to compensate for them. In some cases, the most expedient method is the first option because designers and managers may have some control over the risk. For example, managers may have some control on degree of tanker and freighter traffic in a reserve area. However, there will clearly be cases when the risks are far beyond the reach of management: global climate change or an increase in global use of petrochemical products. In such cases, a designer's only choice is the second option. Thus, these analyses can indicate where reserves are be particularly useful and, conversely, where they may be pointless for a particularly ambitious goal: for example, in a heavy oil-producing region that has an insurance factor >5, it is simply impossible to reach a goal of 20% ''pristine'' shoreline. It is important to note that there are likely to be regions that, although highly disturbed, are still good targets for reserves because of their unique habitats, because of the presence of threatened species, or because of their broad public support. Insurance-factor analysis can inform discussions about what can be expected from reserves in such marginal areas.

Marine reserves will always be embedded in regimes of small and large-scale events that will negatively influence their overall effectiveness. Considering how little is typically set aside for marine reserves and how their perceived success will be dependent on having adequate size, it is not likely that we are currently giving them a fair test. Using the perspective afforded by the insurance factor presented here, marine reserves can provide a more robust conservation and management tool.

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APPENDIX

Extensions of the Insurance Factor

Eq. 1 presented in the main text provides the simplest from of the insurance factor. That form requires a number of assumptions about the randomness and variability of disturbance. Our approach in the paper is to illustrate the insurance factor by using this simple form and to presume that deviations from the assumptions are minor. For our treatment, the spatially explicit analysis based on 1×1-degree cells reduces the concerns of spatial assumption violations. For example, although the assumption that events are independent is violated by the presence of hot spots along a long stretch of coast, our smaller scale analysis separates hot spots from less disturbed areas such that, within cells, the independence assumption is more likely to be valid.

An example illustrates the conservative nature of the simple form of the insurance factor (Eq. 1). Consider an extreme ''hot spot'' situation: a coastline where $h = 1$ over 3% of the coast (always disturbed/never recovered) but for the rest of the coast, $h = 0$ (never disturbed). In this case, $U = 97\%$ and $M = 1.031$. Applying this to an initial goal of, say, 20% in reserve yields 20.6% as the amount to actually set aside. If, on one hand, when reserves are actually placed in this system, the entire hot spot is avoided, the insurance factor has only overestimated the amount of reserve needed by 0.6%. If, on the other hand, the entire hot spot is included in the reserve network, the actual amount in the reserve network is only 17.6% (since 3% is always in recovery) or an underestimate of 2.4%. If the reserves are chosen randomly across the coast, with no regard to the catastrophe regime, variation in h appears to decrease the insurance factor.

When there are instances where deviations from the assumptions are great, Eq. 1 may be less appropriate than other forms. Below, we present some expanded versions of the insurance factor for which some of the assumptions can be relaxed. We also present a form that incorporates multiple catastrophe types.

What if the annual affected fraction, h, *varies from year to year (relaxing assumption 2)?*

If h varies from year to year, taking values $h_1, h_2 \ldots$, then the chance of a particular point on the coast not being affected over T years is $(1 - h_1)(1 - h_2) \ldots (1 - h_T)$. This means that the mean chance of not being hit when H is a random variable that is the probability of a catastrophe each year is the geometric mean of $(1 - H)$ raised to the power of T. If the mean of H is reasonably small, say <0.1, this is not much different from Eq. 1. For example, consider the following cases where the mean of H is 0.1 and the consequent effect on the multiplier M. Let the recovery time be $T = 10$ in every case.

1) Assume H is fixed at 0.1 every year, then $U = (0.9)^{10} = 0.349$ so $M = 2.87$

2) Assume H is 0.05 five times in ten years and 0.15 five times in ten years, then $M = 2.91$

3) Assume H is 0 five times in ten years and 0.2 five times in ten years then $M = 3.05$

As we would expect, variation in the catastrophe probability from year to year does increase the insurance factor, but only slightly for realistic parameters.

What if the annual affected fraction, h, *varies from place to place (relaxing assumption 3)?*

Let h be a function of the position on the coastline, say $h(x)$, where x is the position on the coastline scaled to length 1, i.e., x [0,1]. Now the mean annual affected fraction in space is

$$\bar{h} = \int_0^1 h(x)\, dx. \tag{A1}$$

For the entire coastline the mean unaffected fraction is now

$$\bar{U} = \int_0^1 (1 - h(x))^T\, dx. \tag{A2}$$

For example, if $h(x) = 0.01$, i.e., it is constant for the whole coastline, and $T = 50$, then $U = (0.99)^{50} = 60.5\%$. If $h(x) = 0.02x$ so the mean unaffected fraction is the same but there is a linear increase in hazard rate from north to south, say, and $T = 50$, then $U = 64.1\%$, which is slightly higher. In general, variation in h will increase the size of the unaffected area for a fixed mean h, but not much for small values of h and large values of T. Note that the expression for U when $h(x)$ declines linearly from 1 to 0 is

$$U = \frac{1 - (1 - 2\bar{h})^{T-1}}{2\bar{h}(T - 1)}. \tag{A3}$$

This generates the 64.1% for this set of numbers.

The largest difference will occur if we can preferentially select reserve sites away from areas of high hazard. This can reduce the required insurance factor a great deal. However, as we address in the main text, it may be unattractive to avoid areas of high hazard due to specific resources that require protection or high levels of public support in more populated regions where hazards are typically higher.

What if there are two or more types of catastrophes?

If there are two or more types of catastrophe and each has its own mean annual affected fraction h_i, and time to recovery T_i, then the unaffected proportion has a product form

$$U = (1 - h_1)^{T_1}\,(1 - h_2)^{T_2} \ldots (1 - h_i)^{T_i}. \tag{A4}$$

This form assumes that the catastrophes are independent within catastrophe type, as above, but also between catastrophe types, as one would usually expect with hurricanes and oil spills together.