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A scrutiny of the evidence for pressure-induced state shifts in estuarine and nearshore ecosystems

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Abstract The concept of nonlinear, sudden responses of ecosystems or species to environmental change has engendered significant interest in the past two decades. Many reviews and theoretical papers have addressed alternative states or stable states, regime shifts, tipping points and phase shifts, but the empirical evidence for these phenomena, which we refer to as *stark changes*, has not been evaluated in estuaries and nearshore marine ecosystems. We developed standard definitions for these phenomena and examined the functional forms of ecological responses to environmental pressures (i.e. proximate influences on ecosystem state). We searched for publications related to estuaries and nearshore marine ecosystems that included common descriptors of stark change in their keywords. Our search yielded 376 papers, of which we retained 98 that met four criteria: (1) claimed a stepped biological change; (2) inferred change from empirical data; (3) addressed changes that occurred in one or more semi-enclosed, tidally influenced ecosystems; and (4) described a connection to long-term patterns of ecological change. Although there were many instances of changes in ecological states, most were not stark changes. Evidence generally was not derived from time-series data, and many studies inferred temporal change from spatial differences. We describe the eight studies that provided some evidence of stark changes in ecosystem state. We suggest that compelling evidence of stark changes that can be related to pressures requires concurrent time-series data on the ecological response and pressures that were claimed to induce the stark changes.

Key words: alternative stable state, phase shifts, regime shift, stark change, sudden change, time series.

INTRODUCTION

The notion of abrupt changes in diverse systems, from physical to financial to ecological, seems to be alluring (Dyson 2005; Lenton *et al.* 2008; Carpenter *et al.* 2011). Understanding and, if possible, predicting abrupt, nonlinear changes in system characteristics (*stark changes*) (Biggs *et al.* 2009; Scheffer *et al.* 2012; Boettiger & Hastings 2013) may increase the chances of avoiding or ameliorating the effects of entering into, and possibly the chances of remaining in, states that are regarded generally as undesirable. Knowledge of linkages between apparent stark changes and pressures arising from human actions (e.g. resource extraction, alteration of water flows or land use) is critical to developing effective management responses, but identifying these linkages is a challenge given the lack of data and differences in the scales at which ecosystem characteristics and pressures are measured.

There appear to be four major impediments to the detection of stark changes in ecosystems. First, terms are imprecise and used inconsistently. Second, many claims of stark change are based on observations at just two points in time, so it is uncertain whether these changes are substantial relative to historical variation. Third, it is unclear whether stark changes are frequent compared with stasis or monotonic change. Fourth, it is not apparent whether demonstrated stark changes in ecosystem state have been convincingly linked to variation in human or natural factors that have been invoked to explain the changes.

The ecological literature is replete with terms related to stark change, including ecological threshold; catastrophic, abrupt, step or sudden change or shift; phase or regime shift; tipping point; and alternative (alternate [*sic*]) stable state. Our interpretations of stark changes do not rely on stability per se but only of substantial differences between conditions before and after the ecological response (Hansen *et al.* 2013). Moreover, we address stark changes within a window of time pertinent to human observations, and we do not consider long-term shifts (e.g. decades or longer) that cannot be distinguished from monotonic changes.

To facilitate the evaluation of empirical evidence for these phenomena, we first developed standard definitions of the associated terms. Then, given that there have been many conceptual descriptions of the

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functional relations between ecological responses and pressures, which we define as proximate influence on ecosystem state (Gordon *et al.* 2008), we illustrate the concepts.

The concept of stark ecological change is applicable to all types of ecosystems, as illustrated by previous reviews (Knowlton 2004; Steele 2004; Schröder *et al.* 2005; Dudgeon *et al.* 2010) (see *Discussion*). We focus here on estuarine and nearshore aquatic ecosystems. These ecosystems often are highly productive, and generally are of high social and economic value. About 75% of humans live in coastal watersheds that drain into estuaries; both the proportion and number of people living in these watersheds (also called catchments) continues to increase (Kennish 2002). Estuaries accumulate the products of natural and anthropogenic processes occurring in their watersheds, including nutrients, sediments and toxicants. Projected effects of climate change on estuaries include water-level rise and increases in the frequency and intensity of storms (Wrona *et al.* 2006; Capon *et al.* 2013).

There were three steps in our assessment of evidence for stark changes in ecosystem state. First, we searched for published papers that included terms related to stark changes in ecosystem state in estuaries or nearshore ecosystems. Second, we evaluated those papers against a set of criteria related to: location; ecosystem type; temporal and spatial extents and resolutions of responses, pressures and drivers; statistical evidence of change points; and, if the paper claimed alternative states, convincing evidence for response-pressure relations and feedback mechanisms. Third, we examined the prevalence of evidence for stark changes, and described studies that might support the concept of major qualitative changes in ecosystems as a function of human-driven or natural changes in pressures.

Definitions

We define *ecosystem state* as a numerical description of multiple attributes of an ecological system, typically including values of species abundances or biomasses and of ecosystem processes, such as primary production and respiration. We define individual components of the ecosystem state (e.g. abundance of a given species or primary production) as *ecological responses*. *Pressures*, defined above, often are called stressors in the literature. We define *driver* as a widespread, distal process (e.g. land-use change) that may induce multiple pressures. *Ecological threshold* has been used to describe both a stark change in ecosystem state or ecological responses (Strayer *et al.* 2008) and the critical value of a pressure at which the stark change in ecosystem state occurs (Stow *et al.* 2005). We use *ecological threshold* in the latter sense. Threshold also has been used to refer to a value of a variable beyond which there is a deterministic change in ecological state, regardless of whether the change is gradual or abrupt (e.g. an extinction threshold when the density-dependent population growth rate becomes less than zero; Hefley *et al.* 2013). We define a *tipping point* as an ecological threshold beyond which a former ecosystem state cannot be regained even when the pressure is released and restoration actions (e.g. provision of propagules) are taken. We synonymize tipping point with irreversible change (Gordon *et al.* 2008). We regard the ecosystem states that occur before and after the tipping point is reached as *alternative stable states*, and we assess whether there is evidence that these are maintained by internal feedback mechanisms, as is often suggested in the literature (Scheffer *et al.* 1993). We do not regard permanent stability as highly relevant to the concept of stark change. Instead, we focus on whether the states differ statistically before and after the effect of the nominal pressure because we are interested in whether these changes are detectable, in which case the concept of alternative stable states might be useful in the context of ecosystem management. We equate the term *regime shifts* with alternative stable states but we do not use this term except when referring to others' work. More-detailed definitions are in Appendix S1.

Representing dynamics

We represent the temporal relationships that may occur between an ecological response (or collectively, the ecosystem state) and the nominal pressure (Fig. 1). Although there are many conceptually similar figures in the literature (Schröder *et al.* 2005; Gordon *et al.* 2008), none of them concisely represented the dynamics of ecosystem state in relation to the value of the pressure and the potential effects of restoration actions. The linear response (Fig. 1a) implies that the magnitude of change in the ecosystem state is proportional to the magnitude of change in the pressure but of opposite sign; there are no stark changes and no lags in responses. Some empirical data and theoretical results suggest that lags may be common (D'Odorico *et al.* 2013). A case in which ecosystem state changes starkly over a small range of pressure values (the ecological threshold) might allow rapid recovery of ecosystem state if the pressure were released over that same small range of values, but not over other small ranges of values (Fig. 1b).

If there is hysteresis, then the trajectory of the ecosystem state does not simply retrace the trajectory of decline in ecosystem state *if the pressure is reduced* after having reached the value of the pressure at which the ecological threshold transition occurred (P_t) (Fig. 1c).

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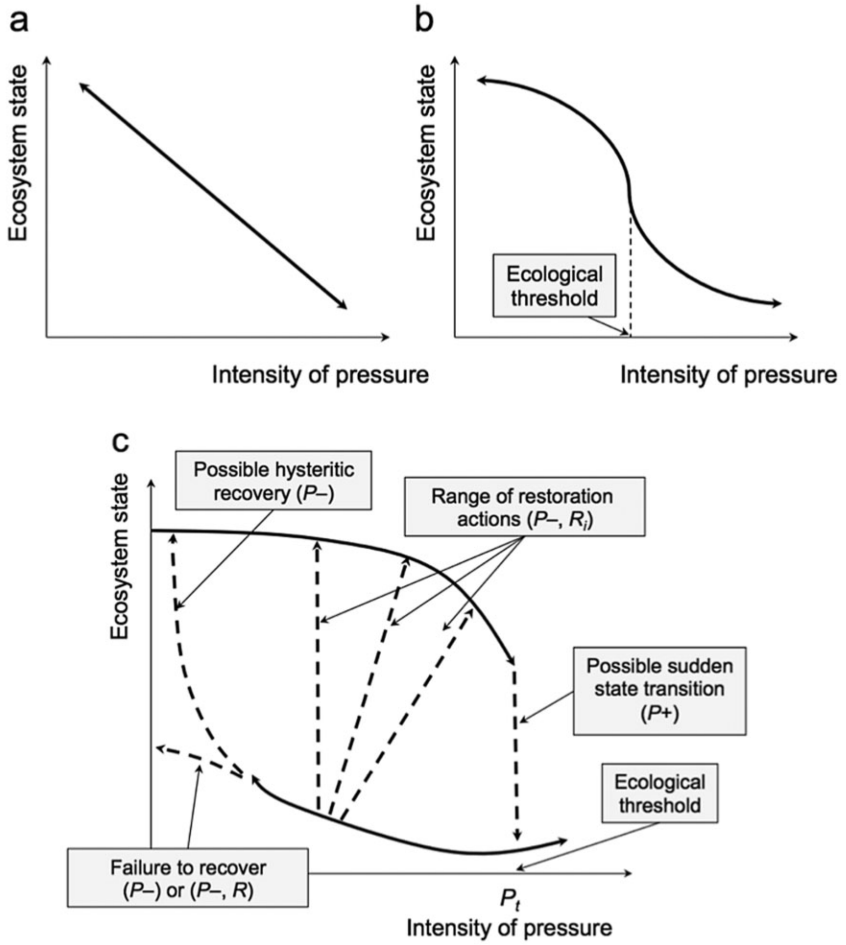

Fig. 1. (a) Simple linear response of ecosystem state as a function of a pressure. (b) Nonlinear, non-hysteretic response of ecosystem state as a function of a pressure. (c) Conceptual model of ecosystem state as a function of a pressure; the model assumes hysteresis. Ecosystem state declines monotonically as the pressure increases, potentially reaching a bifurcation at which there is a stark change at a pressure value of P_t (bottom right). As the pressure is released (lower curve), the ecosystem may return to the initial state. Restoration actions (R_i) might accelerate the return to the upper curve. Failure to recover is effectively irreversible (i.e. a tipping point). $P+$, pressure is maintained at or is greater than P_t; $P–$, pressure is reduced after having reached P_t.

If the pressure is reduced to less than P_t, then the ecosystem state may recover in response to the implementation of actions to restore physical or biotic attributes ($R+$; Fig. 1c). When the intensity of the pressure has been reduced substantially after reaching P_t, the ecosystem state might return to the initial state without restoration actions. Alternatively, the ecosystem might be maintained in a much-different state, possibly by feedback mechanisms, regardless of whether restoration actions are taken (Gordon *et al.* 2008).

We believe that strong, albeit correlative, evidence for stark change and a tipping point requires parallel time series measures of ecological response and pressures at similar spatial and temporal extents (e.g. both response and pressures measured throughout the entire estuary) and resolutions (e.g. both response and pressures measured each spring over multiple years). If the changes in ecosystem state and pressure are proportional, then the trajectories are inverse (Fig. 2a). If there is an ecological threshold, then ecosystem state changes rapidly as values of the pressure cross the threshold from either direction (Fig. 2b). If the pressure is relieved, which is sometimes called a pulse rather than a press pressure (Bender *et al.* 1984; Villnäs *et al.* 2013) but no restoration actions are implemented, then the altered ecosystem state is evidence of a stark, pressure-induced change, but not of alternative stable states *per se* (Fig. 2c). If the altered ecosystem state is maintained when the pressure is relieved and restoration actions are implemented, then there is evidence for an alternative stable state (Fig. 2d).

Some form of change-point statistical analysis is needed to provide convincing statistical evidence

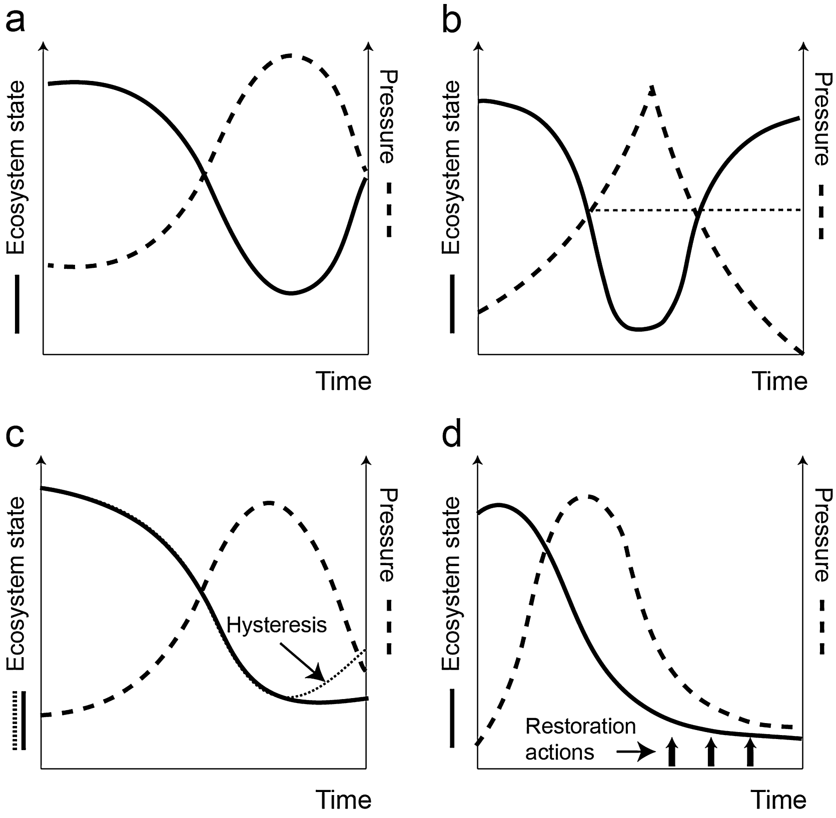

Fig. 2. Temporal responses of ecosystem state as a function of pressures. (a) Change in ecosystem state is proportional to the change in pressure. (b) Ecosystem state changes little until the pressure reaches the ecological threshold (dotted horizontal line) and then alters to a substantially different state. The ecosystem state does not recover until the pressure is reduced to the level of the ecological threshold. (c) Ecosystem state is maintained until the ecological threshold of the pressure is reached. There may be a long delay in recovery of ecosystem state after the threshold is passed (hysteresis), or ecosystem state may remain altered. (d) Alternative stable states: ecosystem state does not recover even when the pressure is reduced and restoration actions are implemented.

for a stark change in ecosystem state. If a putative pressure, represented as a covariate in the analysis, explains variation in a stark response, then there is correlative evidence that the pressure caused the stark change. Change-point models that are based on modern methods, such as hierarchical Bayesian models, are available and estimable. For example, for a single pressure, a general form of such a change-point model is

$$\Lambda(R_t) = \alpha_0 + \sum_{j=1}^{N_\alpha} \psi_j I(t \geq d_j) + \sum_{k=1}^{N_\beta} \xi_k I(P_t \geq \zeta_k)(P_t - \zeta_k),$$

where Λ is a link function that depends on the nature of the response variable (e.g. log for a Poisson variate); R_t is the value of the response at time t; P_t is the value of the pressure at time t; α_0 is the initial value of the intercept; N_α is the number of step changes in the intercept, with increments of ψ_j for the jth step change occurring at and later than time d_j; N_β is the number of step changes in the functional relation between the response and the pressure, with increments of ξ_k for the kth step change occurring at and above the pressure value of ζ_k; and $I()$ is an indicator function that is 0 unless $t \geq d_j$ or $P_t \geq \zeta_k$ (Thomson *et al.* 2010). The model allows for nonlinear trajectories in the response conditional on the effect of the pressure. If $N_\beta = 0$, then the pressure has no effect; if $N_\beta = 1$, then the pressure has a linear effect; and if $N_\beta > 1$, then the pressure has a nonlinear effect. It is possible to include temporal lags in both R (autoregression) and in the dependence of R on P (i.e. replace P_t with P_{t-L} for lag L) (Mac Nally *et al.* 2010).

If the pressure were responsible for the change, then its release should be followed by a return of the response to its previous state, possibly after a lag if the system is hysteretic. There would be evidence for a tipping point if the ecosystem state did not reverse after release of the pressure and if restoration actions were taken. The demonstration of alternative stable states requires the identification of internal feedback mechanisms that maintain the alternative states (Gordon *et al.* 2008).

METHODS

We searched the Thomson-ISI Web of Science for papers published up until 31 December 2012. We searched on a combination of ecosystem-related and non-monotonic change-related terms. Our search criteria ('*' denotes a match-all wildcard) for ecosystems were estuar* OR nearshore OR 'near shore' OR 'restricted embayment' OR lagoon OR intertidal OR 'saline wetland' OR mangrove OR mudflat OR saltmarsh OR 'saltwater marsh' OR 'salt marsh' OR 'transitional waters' OR 'tidal stream' OR 'tidal flat' OR (delta AND river). Our search criteria for change were threshol* OR 'catastrophic change' OR 'abrupt change' OR 'sudden change' OR 'catastrophic changes' OR 'abrupt changes' OR 'sudden changes' OR bistab* OR 'phase shift' OR 'phase shifts' OR hystere* OR 'regime shift' OR 'regime change' OR 'regime shifts' OR 'regime changes' OR 'stepped change' OR 'step change' OR 'step changes' OR 'tipping point' OR 'tipping points' OR 'stable states' OR 'state changes' OR 'state change' OR 'abrupt shift' OR 'catastrophic shift' OR 'sudden shift'.

We retained papers that met four criteria:

1. Claimed a stepped biological change. We did not retain papers that claimed stepped change or regime shifts in abiotic attributes such as temperature, sediments, or water chemistry without associated biological responses.
2. Assessed stepped ecological change on the basis of empirical data. We omitted reviews and theoretical modelling papers but we retained papers that developed theoretical models and fitted them to empirical data (i.e. process models or structural equation models).
3. Data were from a semi-enclosed, tidally influenced ecosystem, but not from rocky or coral reefs.
4. If a threshold response was claimed, it was connected clearly to a long-term pattern of ecological change (e.g. we omitted laboratory experiments that tested whether toxicity thresholds existed).

We assessed papers in relation to location, survey methods, statistical analyses, and research and management objectives. These classifications provided information on the consistency and representativeness (e.g. geographical) of the literature. Although one ideally might wish to undertake a formal meta-analysis (Arnqvist & Wooster 1995) to provide a mean and credible interval for the claimed stark changes as functions of nominal pressures, our preliminary classification established that very few papers included data with a structure that could be employed for such a meta-analysis.

We classified each retained paper on the basis of the following: (1) continent, (2) country, (3) climate zone, (4) ecosystem type, (5) management aims, (6) data collection method (e.g. survey, experiment), (7) spatial extent, (8) spatial resolution (grain), (9) temporal extent (duration), (10) temporal resolution (sampling frequency), (11) measured response variables, (12) how the stark change was described, (13) drivers, (14) temporal trajectories of drivers (pulse [transient], press [persistent], ramp [monotonic change in magnitude over time], oscillatory), (15) pressures, (16) temporal trajectories of pressures, (17) explicit statistical methods (e.g. analysis of variance [ANOVA], ordination), and (18) evidence for state-maintaining feedback mechanisms.

RESULTS

Our literature search yielded 376 papers (Appendix S2). We omitted the 54 theoretical papers and 14 reviews. Ninety-eight papers met our criteria and the results refer to these papers (Appendix S2). In some cases, totals do not equal 98 because information on a given class was not provided or because a paper could be included in more than one class (e.g. data from both surveys and for field experiments).

Summaries of the 18 classifications of retained papers are in Appendix S3. Thirty-six papers focused on ecosystems in Europe and 35 on ecosystems in North America. At the country level, the greatest number of papers (32) reported on ecosystems in the United States. Ninety-one papers were based on studies conducted in temperate zones, of which 25 were conducted in Mediterranean climates; two were conducted in the tropics. Thirty-six papers described studies in estuaries and 18 in coastal lagoons. The management objectives or applications of studies reported in 55 papers were not stated. Twenty papers asserted that the derived knowledge would inform management, and 20 papers stated credible management aims or applications. Eighty-five papers included data from field observations or surveys, whereas 18 included data from experiments. Fifty-three of the papers were focused on a single sampling location, whether a major or minor estuary, bay, or lagoon (multiple papers concentrated on either Chesapeake Bay or San Francisco Bay) or portions of major systems. Twenty papers compared multiple units. The spatial resolution of surveys or experiments (when specified) generally was small, with 54 papers focusing on locations ≤100 m^2. Seven papers collected information at resolutions of hectares or larger. Studies in 68 papers were conducted for at least two years, and data collection was discontinuous in five of those studies. Ten papers reported studies conducted for ≤3 months. The greatest number of papers (32) reported temporal resolutions or sampling frequencies of fortnight to month. Temporal resolution was seasonal or finer in 50 papers. Seventeen papers included data that were collected fewer than three times, and data in 13 papers were collected once; these mostly were papers related to chronosequences (space-for-time substitutions) or spatial gradients.

The 44 response variables were dominated by measures of plants (59) and animals (49). Benthic macroinvertebrates were the response variables in 30 papers, but chlorophyll *a* (18), algae (13), phytoplankton (13) and seagrasses (12) also were common response variables. Sixty-three papers reported on monitoring of multiple response variables, indicating that the conventional single-response representations (e.g. Fig. 1) do not reflect well how studies are conducted. The patterns of change in response variables in 19 papers were over

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spatial gradients rather than over time (chronosequences), which does not address the temporal character of response-pressure dynamics. Descriptors ranged from the hyperbolic (*catastrophic change*) to the more conservative *threshold* (34). Alternative states, stable or otherwise, were inferred in 26 papers, whereas hysteresis and positive feedbacks were inferred in four and nine papers, respectively.

Eight major drivers (sources of change that may induce multiple pressures) were prevalent, with 22 papers on nutrient loading (14 as sole driver, eight in conjunction with other drivers). Forty-six papers concentrated on a single driver, and five papers considered three drivers concurrently. Hydrological modifications, either of inflows from catchments or watersheds or within the study system, were coupled with climate in four papers and with invasive species in another four papers. Forty-nine papers addressed single drivers that were press (30; maintained at a higher level than in the past) or pulsed (19; rose sharply and then declined). Forty other studies reported press (20) or pulse (20) trajectories in conjunction with other forms of trajectories. Twenty-two papers reported multiple trajectories for multiple drivers, and 14 papers reported on ramp and oscillatory trajectories.

There were tens of specific pressures, which we grouped into broad classes. Sixty papers identified two or more pressures, and 18 papers focused on a single pressure. Pressures associated with water quality, including physical and organic components, were included in 53 papers. Pressures related to water availability and weather or climate were a focus in 19 and 32 papers respectively. Eight papers concentrated on human activities (e.g. harvesting) and ten on biotic interactions. Press and pulse pressures were reported in 44 and nine papers, respectively. Few reviews and theoretical papers featured an oscillating pressure within a press driver. Press drivers occur primarily as a function of seasonal variation and, in 51 of the papers, reflected the potential effects of invasive species. Four papers addressed ramp (increasing or decreasing) pressures and eight described multiple trajectories.

There were more than 50 methods of analysing changes in response variables. Seventeen papers relied on visual interpretation without concomitant statistical analysis. Eighteen papers reported parametric and nonparametric correlation analyses. Categorical comparisons of the responses and sometimes the pressures (e.g. ANOVA, *t*-tests) were included in 35 papers, explicit change-point analyses of times series in 14 papers, and generalized linear models in 26 papers. Six papers used time-series data to estimate process models. Reflecting that ecological data on responses and predictors often are multivariate, 34 papers applied multivariate analytical methods. Fifty-four papers relied on a single method (including visual interpretation), 29 used two, and 14 used three or more.

Seventy-four papers did not mention feedback mechanisms, whereas 16 papers discussed feedback mechanisms without providing numerical or statistical evidence. Eight papers provided some evidence of feedback mechanisms.

Studies offering limited evidence of pressure-associated stark changes

Evidence for change was not uncommon, but given that many papers reported ecosystem states measured at only two points in time, it is impossible to gauge whether the changes were substantial relative to historical variability. We found little evidence of stark changes that plausibly could be linked to specific pressures. In most cases, trajectories of ecological responses were not linked, even correlatively, with the nominal pressures. Many assertions were not based on formal statistical models linking the response with the nominal pressure, and the analyses of response variables and pressures rarely were connected. For example, shifts in food webs or in species composition may have been inferred with a two-stage analysis of similarity or an ordination, whereas the trajectory of nominal pressure was presented graphically, often without an analysis (Petersen *et al.* 2008; Pillay *et al.* 2008; Hewitt & Thrush 2010). No study provided convincing evidence for a tipping point and, because the pressure was not released, no study could provide evidence for a recovery following the release of a pressure (Cloern *et al.* 2007; Petersen *et al.* 2008; Strayer *et al.* 2008; Trowbridge *et al.* 2011).

In eight papers, a stark ecological change was plausibly linked with a pressure change. We discuss these in decreasing order of credibility. There was a substantial shift in trophic structure of San Francisco Bay (California, USA) following a strong El Niño in 1997–1998 and La Niña in 1999 (Cloern *et al.* 2007, 2010). The resulting pronounced upwelling and decrease in ocean surface temperatures, which persisted for at least five years, appeared to result in substantial decreases in abundances of bivalves and increases in primary production, zooplankton biomass, and abundance of cold-water pelagic fishes. These were characterized as a regime shift (Cloern *et al.* 2007, 2010).

A small, relatively sudden increase in salinity in Ringkøbing Fjord (Denmark) resulted from the manipulation of salt-water inflow to dilute nutrient concentrations. The change in salinity was associated with a change from a turbid to clear system, which is consistent with a stark change (Petersen *et al.* 2008). Recruitment and growth of a suspension-feeding clam (*Mya arenaria*) apparently led to a reduction in biomass and cover of benthic vegetation, which in turn was associated with decreases in abundance of waterbirds (Petersen *et al.* 2008).

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The seagrass *Zostera noltii* spatially dominated Vaccare's lagoon in the Rhône delta in southern France during years in which salinity was high (c. 14 p.p.t.). Salinity in the lagoon was low (about 6 p.p.t.) for three years following a winter with two substantial floods. For the first two of those three years, the cover of *Z. noltii* was similar to that during periods of higher salinity, but the species was nearly extirpated in the third year (Charpentier *et al.* 2005). Values of salinity became higher during years four and five after the floods, and the extent of seagrass returned to the previous levels three to four years after the salinity increased. The biotic response (seagrass cover) appeared to be closely correlated with the pressure (low salinity), but with a lag of about two years. This paper did not demonstrate the development of an alternative stable state because the release of the pressure led to the recovery of the response variable.

A change in climate in the eastern Pacific Ocean from 1975–1993, referred to as a climate regime shift, was associated with a decrease in proportional volume of plankton biomass in the northern San Francisco Estuary (Lehman 2000). There was potential to connect the plankton response variables with physical and chemical covariates, but temporal patterns were obscured because data were not analysed as time series (Lehman 2000).

Numerous biotic and abiotic variables were monitored for ≥ 18 years in the Hudson River Estuary (New York, USA) (Strayer *et al.* 2008). The introduction of zebra mussels (*Dreissena polymorpha*) in 1992 was associated with substantial changes in many of these variables, which the authors called a regime shift in the littoral food web. Mean phytoplankton biomass fell from about 20 μg chl *a* L^{-1} before 1993 to about 6 μg chl *a* L^{-1} in 1993. The analyses treated herbivory by mussels as a binary pressure although there appeared to be quantitative data. Given that the mussel pressure was not relieved, one cannot determine whether an alternative stable state was induced by the mussel.

Composition and abundances of intertidal soft-sediment macrofauna in Manukau Harbour in New Zealand changed considerably shortly after a change in municipal sewage disposal reduced nutrients and abundance of a tubeworm that appeared to function as an ecosystem engineer. The change in values of nutrients was regarded as a tipping point (Hewitt & Thrush 2010). However, the analytical methods were not presented clearly and there was a chronosequence, so we were uncertain whether the claims were justified.

Both decadal change in macroalgal assemblages in a lough in southwestern Ireland following decreases in density of a native urchin (*Paracentrotus lividus*) and concurrent increases in density of a non-native invasive alga were termed regime shifts (Trowbridge *et al.* 2011). Inferring whether the data suggested a stark change was complicated because abundance of the urchin increased approximately six-fold between 1990 and 1995, and then declined from 2000 to 2010 to abundances similar to those in 1990.

DISCUSSION

The body of empirical data on substantial ecological changes in estuaries and near-shore marine ecosystems does not support the concept that changes in these systems often are stark relative to historical variability. The assertion that spatial variation in pressures is analogous to temporal trends is relatively common. However, neither the latter assertion nor the many associated experiments provided evidence for stark changes arising from pressures because coincident time-series data on the responses and pressures were not collected. There is little credible evidence that stark changes result from anthropogenic pressures, whether direct (e.g. toxicants, harvest) or indirect (e.g. climate change). Evidence of tipping points in these ecosystems is not convincing, almost always because the nominal pressures have not been released (i.e. pressures were of a press trajectory) and so the stability of the putative alternative state could not be evaluated (Cloern *et al.* 2007; Petersen *et al.* 2008; Strayer *et al.* 2008; Trowbridge *et al.* 2011). We do not mean to imply that human actions have not engendered profound ecological changes. However, strong evidence of causal or correlative relations is weak in papers that themselves invoke stark change.

Ecological responses and nominal pressures rarely have been measured at the same spatial and temporal extents and resolutions over the long term. An exception is the data collected since the late 1960s in the San Francisco Estuary. Yet even with such detailed data, pressure-induced stark change is difficult to demonstrate statistically (Thomson *et al.* 2010). More recent analyses suggests that the invasion of multiple plankton species has induced a change in food-web structure in the San Francisco Estuary (Kratina *et al.* 2014); however, the pressure has not been released so one cannot asses whether the apparent state change is permanent. There are at least two reasons why pressure-induced changes in ecosystem state are difficult to establish credibly. First, stark ecological changes often are observed unexpectedly, so there usually are few data for the responses prior to the change. When responses and pressures are measured only twice, it is difficult to establish whether the change is stark relative to natural, long-term variability. Even if the change is stark relative to an historical trajectory, concomitant measurements of potential pressures are rare. Second, ecosystems rarely experience a single dominant pressure, and influential pressures may increase, decrease, and interact in complex ways (Ormerod *et al.* 2010). Multivariate methods might be applied to distinguish responses to

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individual and interactive nominal pressures (Breiman 2001; Ellis *et al.* 2011), including nonlinear responses (Lunn *et al.* 2005), but these require extensive time-series data on spatially and temporally matched responses and pressures (Thomson *et al.* 2010).

We assessed whether our conclusions were affected by our focus on a specific sets of ecosystems. A working group including RM evaluated published evidence for stark change in freshwater ecosystems on the basis of the same search terms used here (S. Capon *et al.*, unpubl. data, 2011–2012). The resulting papers were dominated by reports on lakes, and limitations of the response variables and potential pressures were similar to those we outlined here. The group's consensus was that there is reasonable evidence for stark change and alternative stable states in small, shallow, permanent lakes, but not in other freshwater ecosystems. Within these small lakes, positive feedback loops may maintain alternative stable states after one of the states is established (Scheffer *et al.* 1993). Multiple papers reported decadal and longer-term changes in food webs in open-ocean and coastal marine systems that were coincident with changes in climate and oceanic conditions. These changes commonly have been characterized as regime shifts (Steele 2004; Lees *et al.* 2006). Although the observations appear compelling and have precipitated much work on regime shifts, many of the analytical techniques used to attribute changes in ecological responses to changes in climate have been unsuitable for identifying regime shifts (Steele 2004) because they do not effectively distinguish ecologically meaningful pattern from background variation (Rudnick & Davis 2003). There is much published work on rocky intertidal and coral reef ecosystems associated with the concept of alternative stable states despite a paucity of conclusive empirical evidence of their existence (Knowlton 2004; Dudgeon *et al.* 2010). Inconsistencies in definitions of regime shifts (Mantua 2004; Lees *et al.* 2006), phase shifts, and alternative stable states (Dudgeon *et al.* 2010) hinder efforts to evaluate the evidence for their existence in these ecosystem types. Our and others' analyses (Knowlton 2004; Schröder *et al.* 2005) have identified few compelling examples of pressure-induced stark change in ecosystem state in aquatic ecosystems.

Undesirable changes in ecosystems are more likely to be ongoing and nearer monotonic than stark (Caughley 1994). Stark change seemingly is more provocative and compelling than monotonic change, perhaps because the potential management responses to stark versus monotonic change in many spheres, from environment to finance, are so different (Jackson *et al.* 2001). Maintaining support and funding for addressing an undesirable ecological change may be easier if a small reduction in a pressure potentially might result in a large intended change in the ecological response. For example, if an ecological response decreased proportionately to the intensity of a pressure increased, then restoring ecosystem status to 90% of its initial value would require releasing 90% of the pressure. This degree of release would require a profound change in the magnitude of human actions that induced the pressure. If ecosystem state or an ecological response decreased sigmoidally as the intensity of a pressure increased, then it might be possible to reduce the pressure without substantially diminishing human actions that have induced the pressure.

There is little convincing evidence of changes in ecosystem state of estuaries and nearshore ecosystems that are both stark relative to historical variation and plausibly can be linked to specific pressures. We evaluated papers that included terms commonly associated with stark change, so if there was a bias, it should have been toward the detection of stark changes. If stark changes exist, documenting strong evidence requires significant improvements in data collection and statistical evaluation.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Appendix S1. Definitions of terms in our analysis of stark change in ecosystem states.
Appendix S2. A list of the 376 papers that we identified in a search of the Thomson-ISI Web of Science and the 98 that met our four criteria for retention.
Appendix S3. Classifications of retained papers on the basis of 18 criteria.

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