Social Drivers Forewarn Marine Regime Shifts

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Keywords: Tipping points; resilience; social-ecological systems; historical ecology

Abstract:

Some ecosystems can undergo regime shifts to alternative compositions of species. While ecological indicators can identify approaching regime shifts, we propose that rapid changes in the social drivers underlying ecosystem change may provide additional and potentially earlier indicators of impending shifts. We demonstrate this by reconstructing the underlying social drivers of four iconic marine regime shifts: Pacific kelp forests, NW Atlantic continental shelf, Jamaican coral reefs, and the Chesapeake Bay estuary. In all cases, a range of social drivers, including opening of lucrative markets, technological innovations, and policies that enhanced the driver, ultimately drove ecosystem shifts. Drawing on examples emerging from environmental management practice, we present three tangible recommendations for using social drivers as early indicators: monitor social change, identify social trigger points, and identify policy responses. In doing so we argue that accounting for the underlying social drivers of ecosystem change could improve decision-making.

In a nutshell:

- Ecosystems can undergo dramatic shifts in their composition due to increasing human pressure
- Identifying indicators of these shifts before they occur is key to early management intervention
- The underlying social factors that escalate human pressures may be useful early indicators of ecosystem shifts
- We use four well known marine ecosystem shifts to investigate this hypothesis
- We suggest social monitoring programs, actionable social trigger points, and policy responses that target incentives can help identify and manage the social factors responsible for ecosystem shifts

Regime shifts and drivers of change

Many ecosystems can undergo dramatic and relatively persistent changes in their species assemblages, termed regime shifts (WebPanel 1) (Scheffer *et al.* 2012). Following a regime shift, the services provided by the ecosystem are likely to have changed, with potential ramifications for the societies that depend on them (Graham *et al.* 2013). It may require considerable management effort to reverse regime shifts, if at all possible.

Much of the literature on regime shifts has focused on identifying direct, or proximate, drivers, such as fishing, pollution or land clearing, and relating the magnitude of those drivers to the changing ecosystem state (Geist and Lambin 2002). At low levels, a proximate driver such as fishing, may have little effect on the ecosystem. As the driver increases, however, the ecosystem's resilience, or its ability to withstand change, weakens. Pulse perturbation events, which may be natural or anthropogenic in origin, can precipitate a regime shift, particularly when interacting with chronic drivers, for example changes in grazing pressure (Holmgren & Scheffer 2001; Mumby *et al.* 2007) (Figure 1a). In theory, chronic proximate drivers can also reduce resilience to the point where the ecosystem can transition to an alternative state without a pulse perturbation (Figure 1a). In order to reverse regime shifts, some systems will need drivers to be reduced below levels that caused the original shift; a phenomenon known as hysteresis. It is therefore widely recognized that regime shifts are easier to prevent than to reverse (Hughes *et al*. 2013).

Early warning indicators of regime shifts

Natural resource management often only recognizes and responds to regime shifts at the point when a change is imminent, or once a change has already occurred (Kelly *et al.* 2015). However, anticipating when regime shifts are likely to occur is of great interest, as it offers potential for management to ameliorate impacts before a system passes a tipping point. As such, recent research has identified ecosystem behavior, such as rising variance of key system components, or slowing recovery rates post perturbation (Scheffer *et al.* 2012), which indicate a system is approaching a tipping point (Figure 1a). Other techniques, such as spatial correlation of ecosystem variables (e.g. dominant habitat cover) (Dakos *et al.* 2010), or successively incorporating new data into models as it is generated (Carpenter *et al.* 2014), may provide earlier opportunities for managers to intervene. However, in many ecosystems these signals are difficult to detect, partly due to insufficient data or long generation times of study organisms (Nyström *et* *al*. 2008). In this review, we put forward the hypothesis that underlying social factors, that escalate proximate drivers, may provide additional early warning indicators of regime shifts, and thus inform management.

Changes to the rate at which a tipping point is approached

It is possible that a range of underlying social factors, often termed distal drivers, can influence the magnitude of a proximate driver, and thus the likelihood of a regime shift (Figure 2, WebPanel 2). Distal drivers can include new technologies, opening of markets, demographic changes, or changes in governance structures or policy (Lambin *et al.* 2001; Geist and Lambin 2002; Kittinger *et al*. 2012). These distal drivers, working singly or in concert, can escalate the magnitude of a proximate driver, with consequent ecological outcomes (Brewer *et al.* 2012). For example, fishing (the proximate driver) may increase linearly through time, with the rate of increase among locations tied to a changing distal driver, such as human population growth (Mora *et al*. 2011) (slopes r1 and r2 on Figure 1b). Alternatively, the rate of change in fishing can increase, or decrease, dramatically in response to a new distal driver, such as a new technology enabling more efficient fishing (Squires and Vestergaard 2013), or connections to global markets increasing incentives to fish (Berkes *et al.* 2006, Cinner *et al.* 2013) (r3 in Figure 1b). Despite the fact that distal drivers are major determinants of the extent of human impacts on ecosystems, these social factors are rarely addressed in either the science or management of ecosystems prone to regime shifts (Brewer *et al.* 2012).

Reconstructing the distal drivers of iconic marine regime shifts

We identified the four most iconic examples (based on number of citations per year) of regime shifts in different coastal marine ecosystems (kelp forests, continental shelves, coral reefs, and estuaries) (Figure 3). We then drew from the historical literature on these case studies to assess how the magnitude of the proximate drivers of the regime shifts were influenced by underlying distal drivers.

Northern Pacific sea otter loss causing kelp forest regime shifts

One of the best known cases of predators driving ecological regime shifts, involves the northern sea otter (Estes *et al.* 1998). In the North Pacific, otter populations had been harvested by native hunters for thousands of years (Simenstad *et al*. 1978), but were driven close to extinction by commercial hunting in the 1800s, creating an explosion in urchin densities that diminished kelp forests and associated fish and invertebrates.

Commercial hunting of sea otters was driven by a lucrative market for fashionable otter fur (Figure 3a). A Russian expedition - the St. Peter - discovered the sea otter in 1741 and began selling their furs in Kamchatka, Russia. In 1778, the British entered the sea otter trade when Captain Cook sailed to Nootka Sound (Vancouver Island). Americans, inspired by reports from Cook's expeditions, entered the trade in 1792 (Fontenoy 1997). The British, and later the Americans, sold their furs in China for "nearly double the value" offered in Russia (Fontenoy 1997). This profitable market accelerated exploitation; one trip aboard the Columbia in 1792 sold 2000 otter furs for over $45 each, totaling a current value of over $1.2 million (Fontenoy 1997). As supply increased in the late 1790s, prices fell to about $20 per pelt, with the Americans supplying an average of 35,000 pelts per year to the Chinese market by the early 1800s (Fontenoy 1997).

Between 1817-1822, the US trade averaged 20,000 furs per year, falling to 2000-3000 per year in the 1830s, and by 1840 otters were depleted and trade plummeted. Trade resumed when America bought Alaska from Russia in 1867, and furs were selling for $100-165 per pelt [~$2,500-4,200 in current dollars](McClung 1978). In 1903 a single sea otter pelt sold in London for the equivalent of $28,000 in current dollars (Gibson 1992). In 1911 some 30 schooners plied Alaskan waters for sea otters, capturing just 12 individuals (McClung 1978). The North Pacific Fur Seal Treaty, banning commercial seal hunting in an effort to preserve sea otter populations, was signed in the same year.

Lucrative foreign *markets* represent the main distal driver that caused an escalation in the proximate driver - *harvesting* of sea otters - eventually resulting in the collapse of sea otter populations, an explosion in sea urchin densities, and the loss of kelp forest habitat. Although this market driven harvesting increased fairly gradually, it accelerated in pulses when new markets or countries entered the trade (Figure 4a), highlighting the importance, to environmental management, of monitoring markets.

Canadian cod collapse causing continental shelf regime shift

Canadian cod stocks have been fished for hundreds of years (Roberts 2007). However, in the mid-1980s to early 1990s fishing caused cod biomass in the northwest Atlantic to collapse, with concomitant increases in prey species such as small pelagic fish and benthic invertebrates (Frank *et al.* 2005).

Abundant cod stocks were discovered in the early 1500s (Roberts 2007), with dried and salted fish sold in Europe, the West Indies, and Brazil from the 1600s (Figure 3b, Kurlansky 1997). These markets were major drivers of exploitation rates; for example following the American War for Independence in the late 1700s, Nova Scotia gained a monopoly on the substantial British West Indies market, causing a boom in shipbuilding and an increase in cod exports from ~5000 tons in 1789 to ~25,000 tons by 1806 (Lear 1998).

The early fisheries were under sail power and principally used hook and line recording huge catches. In the mid-late 1800s, technological developments in the form of trawling by steam and diesel-powered vessels greatly intensified catch rates (Jackson *et al*. 2001). Landings declined briefly in the late 1800s due to a ~30% drop in export prices (Alexander 1974). However, exports grew steadily from 1898-1913 (Alexander 1974) and new domestic markets developed, including the sale of fresh fish, distributed by steam boats and the Intercolonial Railway (Lear 1998). By the 1920s steam trawlers with on-board fish filleting and fast-freezing technologies further enhanced exploitation rates and export to foreign markets (Roberts 2007). The 1950s and 60s saw rapid growth of distant water high capacity trawler fleets (Roberts 2007).

A series of governance changes exacerbated the decline of Canada's cod stocks. In 1977 an exclusive economic zone to 200 nautical miles was established, preventing other nations from fishing the banks. Consequently, Canada invested heavily in fishing fleets expecting substantial returns. Fisheries scientists in the 1980's, not having a long time series of unbiased scientific trawl data, based their models on catch per unit effort data from the fisheries. However, the introduction of new fish-finding technologies allowed fishers to maintain catches, despite the dwindling stock (Roberts 2007). Some scientists sounded alarm, but quotas were set far too high and the fishery collapse and associated ecosystem regime shift was already unfolding.

Market, *governance*, and *technological* changes represent the main distal drivers that acted in combination to rapidly escalate the proximate driver – *fishing* – causing cod stock collapse and an associated increase in prey species abundance (Figure 4b). The succession of technological changes in particular played a key role in rapidly escalating fishing capacity, highlighting the importance of carefully regulating this critical distal driver (Squires and Vestergaard 2013).

Coral to algal regime shifts in Jamaican coral reefs

Jamaican coral reefs underwent a dramatic regime shift in the 1980s, with coral cover declining from 52% to 3% and macroalgal cover increasing from 4% to 92% (Hughes 1994). These changes are largely attributed to long-term overfishing of herbivores and land-based pollution which together enhanced algal overgrowth, diminishing the capacity of the reefs to recover from successive perturbations - most notably hurricane Allen in 1980, and a disease in 1983 that decimated herbivorous sea urchins (Hughes 1994, Lapointe 1997).

Fishing and pollution were mediated by a number of distal drivers. Between AD 600 and 1500 Jamaica's population, dependent on agriculture and fishing for food, grew rapidly, reaching, by some estimates, 1 million (Hardt *et al.* 2009). Between 1500 and 1650, turtles and manatees were hunted extensively, and pigs and cattle introduced to the land. However, disease brought by the Spanish reduced the Jamaican population to 5,000 (Hardt *et al*. 2009).

During the British colonial period (1656-1852), changes to policy meant forested land was progressively converted to sugar, coffee, and banana plantations to serve foreign markets, with subsequent impacts to water quality (Higman 1987). Jamaica led global sugar production between 1700 and 1900, producing 100,000 tonnes at its peak in 1805. The Jamaican population grew, reaching 600,000 in 1891, due to the slaves imported to work sugar plantations (Watts 1987). Cultivated land increased throughout the 1900s with diversification of crops, and accelerated land conversion for mining and urbanization. By 1980 the population was 2.2 million (see: https://www.quandl.com/MADDISON). The 20th century saw the birth and growth of a new market for tourism; visitor numbers growing from 100,000 in 1952 to 670,000 by 1981 (Taylor 1993, Jamaica tourist board).

Prior to 1900 fish consumption consisted mainly of imported salted cod, herring, and mackerel. In the early 1900s reef fish, caught using traps and longlines, were traded for salt fish (Hardt *et al.* 2009). Technological developments in the form of new spirit sails enabled fishers to fish further from shore, and chicken wire mesh allowed fishers to develop cheaper, larger, and more durable traps (Figure 3c, Munro *et al.* 1971). This growth in fishing prompted an official statement on the degraded nature of the fishery in 1945 (Hardt *et al.* 2009). However, policy through the 1970’s and 1980’s involved subsidies (e.g. for engines, fuel, and chicken wire) encouraging fishing and increasing local fish supply.

Rapid human *population* and *market* growth, coupled with *technological* and *policy* changes represent the main distal drivers that acted to intensify the two proximate drivers - *fishing* and *pollution* - ultimately resulting in the collapse of Jamaica's coral reefs (Figure 4c). The complexity of multiple interactive drivers highlights the importance of a diverse monitoring portfolio and cross-sectoral co-operation.

Benthic to pelagic regime shift of Chesapeake Bay

The Chesapeake Bay estuary underwent a system wide regime shift in the 1950s from a clear water benthic estuarine ecosystem largely dominated by seagrasses and oyster reefs to one dominated by planktonic communities and altered food webs (Kemp *et al*. 2005). This regime shift is largely attributed to land-based pollution creating excessive nutrient input and overharvesting of filter-feeding oysters.

Europeans settled in the Bay's catchment in the 1600's, and following an initial decline, human population grew exponentially (Curtin *et al.* 2001). Policy has meant the Bay watershed has served various land-uses causing changes in land-based pollution, sediment and nutrient impacts. During the 17th century, the Bay watershed was cleared for timber and agriculture (mainly tobacco fields); however, long fallow periods meant little sediment escaped the land (Brugger 1988). Subsequent agricultural expansion for wheat, and crop rotation systems involved clearing less fertile areas with more erodible soils, (Kemp *et al.* 2005). By the 1900s, the human population in the Bay's drainage area was 16 million (Kemp *et al*. 2005) and, exacerbated by technological developments and increasingly mechanized farming practices, many tributaries to the Chesapeake were choked with sediments (Cronon 1983). In the 1900's the Great Depression spurred the expansion of infrastructure through public works projects to repair and expand the region's roads, bridges, parks, and electrical services into rural areas, encouraging further population growth. Although expanding urban areas caused agricultural land use decline, technological improvements in the form of commercial fertilizers in the 1950s continued to accelerate nutrient loading in the bay (Brugger 1988). With, over half the bay's marshes deteriorated, nutrient buffering capacity at the estuarine margins was reduced (Kearney *et al.* 2002).

Oysters, which are critical to Chesapeake Bay's ecology, have been harvested since Europeans arrived in the 1600's. A big change occurred in the late 1800s, when technological developments in the form of dredges escalated harvesting of oysters (Figure 3d) and, between 1890 and 1930, landings declined by two-thirds (Brooks 1981). Although harvests remained relatively stable between 1930 and 1950s, a pair of diseases decimated the remaining oyster populations (Kemp *et al.* 2005). While oyster populations could filter the Bay's water in three to six days prior to the 1870s, remaining populations in the 1980s would take 11 months (Newell 1988).

In Chesapeake Bay, a combination of *population* growth, *technological,* and *policy* changes were the main distal drivers that exacerbated the two proximate drivers - land-based *pollution* and oyster *harvesting* - ultimately creating a benthic to planktonic regime shift (Figure 4d).

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Interactions between distal drivers and ecosystem ecology

Each of our case studies involves a different suite of distal and proximal drivers acting on distinct ecological species or processes. Perhaps the two simplest case studies are the otter and the cod examples, with harvesting, a proximate driver, causing population collapse of key species in the ecosystem. The collapse of otter populations was much faster than cod. Commercial otter loss occurred within 100 years of commercial harvesting, while cod collapse took about 500 years. The distal drivers of harvesting differed; an explosive export market for sea otter fur stimulated rapid harvest, while markets for salt cod, changes in regulatory policy, and technological innovations drove the overexploitation of cod. However, the effects of harvesting, and the rates at which the system collapsed, are also related to differences in the ecology. Sea otters are relatively long lived and have limited reproductive capacity, so the vulnerability of their populations to heavy exploitation is high. Otters were also behaviorally susceptible, due to the accessibility of foraging grounds. Conversely, cod were somewhat more robust to exploitation due to their faster life history (growth and reproductive potential), mobility, and complex population structure. Furthermore, cod inhabit a much more inaccessible environment, with the banks of the NW Atlantic causing challenges for fishers due to the dangers of the open ocean, and the technologies required to exploit resources from the sea bottom. In situations where a keystone species is being harvested, their ecology can alert managers as to the type and rate of distal driver to monitor.

The Jamaican and Chesapeake Bay case studies are more complex, in that both involved two dominant proximate drivers; a reduction in water quality and harvesting of species that provide key ecosystem processes. The distal drivers differed somewhat, yet the impact on ecosystem processes was quite similar. While reduced water quality favored algal or plankton proliferation, the capacity of ecosystem processes (by fish in Jamaica, and oysters in Chesapeake Bay) to respond was undermined by harvesting. These two case studies highlight the importance of understanding interactions among multiple distal and proximate drivers and key ecological processes leading to system collapse.

Applied solutions to manage shifting social drivers

Our review highlights how it is incumbent on managers and scientists to look deeper into the underlying social drivers of change to aid in anticipating undesirable regime shifts. However, the science and policy options to effectively incorporate distal drivers into early warning indicators and decisive action need to be carefully developed. Importantly, the root social drivers implicated in ecological shifts are often context specific, which will require managers to gain an understanding of the history of human-environmental interactions, and of the ecology of their system.

From our review, we propose three primary ways in which distal drivers influence ecosystem condition, each with differing implications for detection and response. The first category is where a single distal driver acts continuously but at different rates in different locations (e.g. population growth). Although it may be difficult to recognize an impending shift, these slow drivers can provide managers with the time necessary to respond (Hughes *et al.* 2013). The second category is where multiple distal drivers act in combination to exacerbate change (e.g. population, economic growth, and land use change). In these instances, it is important for scientists and managers to develop an understanding of the interacting and cumulative effects these drivers have, and target interventions appropriately. The final category includes distal drivers that can have pulse effects that rapidly escalate change (e.g. a new technology, a new rapidly developing market). These drivers are likely to be the easiest to detect due to the sudden nature of their appearance, and because they have a dramatic and rapid effect on the proximate driver. Effectively responding to social drivers will require management agencies to build interdisciplinary and social science capacity through training existing staff and securing funding for new social science specific positions. We recommend the following steps to incorporate distal drivers into early warning of regime shifts:

Invest in social monitoring. In addition to monitoring ecosystem responses to proximate drivers, there is a need to routinely monitor the distal social drivers that underlie change. Although data on some distal drivers may be difficult to collect, others are relatively straightforward, through interacting with relevant agencies (e.g. government bodies for population and economic growth rates), resource user groups (e.g. fishers organizations for technological changes), market, and social surveys (e.g. consumers for changing market preferences). Indeed, recent years have seen some government agencies responsible for marine systems implementing social monitoring programs, for example the US’s National Oceanic and Atmospheric Agency (Breslow *et al.* 2013). Key to the success of this work is the involvement of social scientists from the earliest stage possible, specifying what needs to be collected and identifying the most suitable approaches, scales, and timings to do so (Meyfroidt *et al.* 2013). To ensure the drivers that accelerate ecosystem change are captured, an agency’s environmental monitoring framework should at a minimum include all five categories of distal social driver (demographic, technological, market, culture, and governance) (Figure 2). Such an approach should also allow for alternate distal drivers to be detected, if and where they exist.

Specify social trigger points. To be effective, any monitoring program needs clear guidance on what information should trigger a response. These trigger points should be informed by hypothesized scenarios of how the system will change, can be based on the distal driver reaching a certain level, or the proximate driver responding in a specific way. For example, a trigger point level that may be suitable for a single distal driver acting continuously (e.g. population growth), may have to be adjusted when multiple distal drivers act in combination. For distal drivers that have a pulse effect (e.g. new technology), trigger points should be based on variation in the rate of change of the proximate driver.

Identify policy responses. Each actionable trigger point needs to be associated with a suitable management or policy response. Typically, policy responses designed to influence social factors either attempt to control people (e.g. restricting access), or change their incentives. For example, markets are powerful drivers of overexploitation, but can also be used to shape behavior. Up to 16% of the global marine fisheries catch is controlled by just 13 corporations, presenting the opportunity to influence a significant proportion of globally harvested marine products (Osterblom *et al.* 2015). Having reached a trigger point, and enacted a response, the social ecological system needs to be monitored and assessed against the expected outcomes to ensure success and avoid any unexpected or perverse outcomes (Allen and Garmestani 2015).

Through monitoring social drivers, specifying social trigger points, and identifying policy responses, managers will be presented with a clear strategy for where action is possible; such as to regulate or close a market (e.g. for a specific species, as may have been appropriate for northern sea otters); ban or modify a technology (e.g. that spreads rapidly or impacts critical ecosystem processes, such as those in the Canadian cod or Chesapeake Bay oyster fisheries); and amend or lift a policy (e.g. that creates unexpected or perverse behaviors, such as those enhancing fishing in Jamaica). Operationalizing these ideas requires a broadening of the conventional purview of environmental management and increasing, or redirecting, resources. For example, an understanding of distal drivers is likely to benefit contemporary challenges such as fishery responses to the redistribution of fish stocks and community compositions due to ocean warming (Pinsky et al. 2013), enabling appropriate management responses. Ultimately, a greater understanding of the causal pathways through which social drivers influence ecological outcomes, may endow managers and conservation practitioners with early warning signs with long lead times to anticipate ecosystem shifts, and effectively respond to the underlying social drivers of change, thus proactively avoiding the potential onset of major impacts to ecosystems and resource users.

Acknowledgements

This work was supported through the Gordon and Betty Moore Foundation (Ocean Tipping Points project), the Center for Ocean Solutions, and the Australian Research Council. The manuscript was improved through the comments of Joshua Cinner. Jerker Lokrantz and Cindy Huchery helped with figures. Many thanks to Valery Garrett for the photo in Figure 3a, the

Archives and Manuscripts Division of the QE II Library at Memorial University, Canada for Figure 3b, Jennie Franks for Figure 3c, and the Chesapeake Bay Program for Figure 3d.

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Figure captions

Figure 1. (a) Heuristic model depicting the influence of a driver(s) on ecosystem state (usually described based on species composition and processes). In a two state system, the ecosystem, under the same magnitude of a given driver, may exist in one of two states (solid horizontal lines), separated by a threshold (dashed line). The upper solid blue dot is the forward tipping point from one state to the other, whereas the lower blue dot is the backward tipping point. The vertical arrows depict the rebound potential from acute disturbance events (e.g. hurricanes) that may displace the system. If the system is displaced across the threshold, it will transition to the other ecosystem state associated with reinforcing feedback mechanisms. Ecological early warning indicators (red arrowheads in top system state), indicate a regime shift is approaching, but typically are close to the tipping point. Based on evidence from four iconic marine ecosystem shifts, we show that underlying social factors predictably escalate the intensity of the proximate driver of change (yellow arrows in top ecosystem state), and thus may offer additional early indicators of regime shift risk. **(b)** The relationship between the intensity of proximate drivers and time, with rates of driver increase influenced by social changes. r1 and r2 could be the same proximate driver in different locations, where differences in the underlying social distal driver, such as population growth rates, create differences in the intensity of the proximate driver. The rate of change in the proximate driver can also show a dramatic change in response to distal socioeconomic change, for example a new fishing technology or new connections to global markets (r3).

Figure 2. A heuristic framework describing the linkages between distal and proximate social drivers and marine ecosystems. Social systems, like ecosystems, exhibit hierarchical patterns of organization, with distal drivers directly mediating proximate drivers, which in turn affect ecosystem structure and function. Adapted from Geist and Lambin (2002) and Kittinger *et al*. (2012).

Figure 3. Social drivers linked to iconic marine regime shifts. **(a)** Otter fur trimmed winter court gown from Qing Dynasty, China (Garrett 2008). Overharvesting of Pacific sea otters for these luxury fur markets caused regime shifts from kelp-dominated ecosystems to sea urchin barrens. **(b)** Salt cod drying in St John's, Newfoundland, in the 1800s for export to international markets (Memorial University, Canada). Overfishing of NW Atlantic cod stocks escalated through various technological innovations, causing trophic cascades and the dominance of alternative species. **(c)** Small mesh chicken wire fish trap introduced to Jamaican coral reef fisheries (Jennie Franks). Overfishing and declines in water quality driven by land use change, subsidies and new technology, caused regime shifts from coral-dominated reefs to macroalgae-dominated reefs. **(d)** Oyster dredging enhanced harvest rates and ecosystem damage in Chesapeake Bay (Chesapeake Bay Program). Increasing nutrient loads and reductions in oyster populations due to land use change and a shift to dredging, caused a shift from a clear water benthic ecosystem state to a plankton dominated ecosystem state.

Figure 4. Simplified timelines representing key changes in distal drivers contributing to regime shifts in four marine ecosystems**. (a)** North east Pacific kelp forests; **(b)** North west Atlantic continental shelf; **(c)** Jamaican coral reefs; and **(d)** Chesapeake Bay estuary. * Otter pelt price

converted to current day dollar values. ** Relative cod price index based on Spanish and US data (1505-1892) from Vickers (1996).

WebPanel 1. Glossary

Distal Driver: the underlying factors that influence the magnitude of the proximate drivers that have a direct impact on the environment.

Ecosystem Services: the range of benefits people gain from nature.

Ecosystem State: a description of the composition, traits and functional attributes of an ecosystem.

Hysteresis: the situation where the pathway of degradation differs from recovery, such that drivers of change need to be reduced beyond the original tipping point in order to reverse a regime shift.

Open Access Resource: a situation where there are no restrictions on the groups of people that can extract a resource.

Proximate Driver: the factors that have a direct impact on the environment.

Regime Shift: substantial changes in the constituent species of an ecosystem, which may be persistent through time.

Tipping Point: the point at which a system undergoes a transition from one regime to another.

Threshold: points where a system can transition to an alternative regime.

Trophic Cascades: predatory mediated changes to the abundance of prey populations through at least three levels of a food chain, often resulting in dramatic changes in ecosystem structure.

WebPanel 2. Proximate and distal drivers of change

Social systems, like ecosystems, exhibit hierarchical patterns of organization, with clear links between underlying social factors, and the proximate drivers that influence ecosystems (Geist and Lambin 2002, Kittinger *et al.* 2012). Proximate drivers are the human activities (such as fishing or pollution) that directly influence an ecosystem. Most research considers only this first interaction in the chain of causation. For example, assessments of the status or collapse of many marine fish stocks are usually based on catch rates as an indicator of fishing (Branch *et al.* 2010). Similarly, eutrophication of lakes, estuaries, or near-shore marine environments is usually linked directly to the input of nutrients and pollutants, as an indicator of agricultural land-use (Lunau *et al*. 2013). However, the magnitude of proximate drivers is determined by a range of distal factors (e.g. technologies, markets, population growth) (Geist and Lambin 2002). For example, technological developments such as fish finding equipment, opening of profitable markets, and policies such as subsidies can greatly influence catch rates in fisheries (Squires and Vestergaard 2013). Similarly, land use policy such as urbanization, or subsidies that enhance fertilizer usage on farms, can substantially alter nutrient and chemical pollution of lakes and nearshore waters (Rabalais *et al.* 2009). There is a long tradition in the social sciences examining the relationship between distal and proximate drivers and their environmental outcomes (e.g., Lambin *et al.* 2001; Geist and Lambin 2002), which can be drawn on to understand ecological regime shifts.

By assessing the relationships between distal and proximate drivers, researchers and practitioners may develop a deeper understanding of the complex pathways influencing ecosystem change and ultimately the management actions that may avoid undesirable ecosystem regime shifts. Focusing only on the proximate drivers is akin to addressing the symptoms of illness, without diagnosing and managing the root causes of a disease. Distal-proximate driver pathways of human mediated ecosystem degradation have been examined in some detail in a range of terrestrial ecosystems. For example Lambin *et al.* (2001) uncovered the complex social drivers and pathways that led to tropical deforestation. Governmental decisions to increase infrastructure (a distal driver) often increases access for both industries and migrants, leading to deforestation (Lambin *et al.* 2001). Identifying the key distal mechanisms causing escalating proximate drivers and ecosystem degradation enables policy to target the root cause of social-ecological system change.

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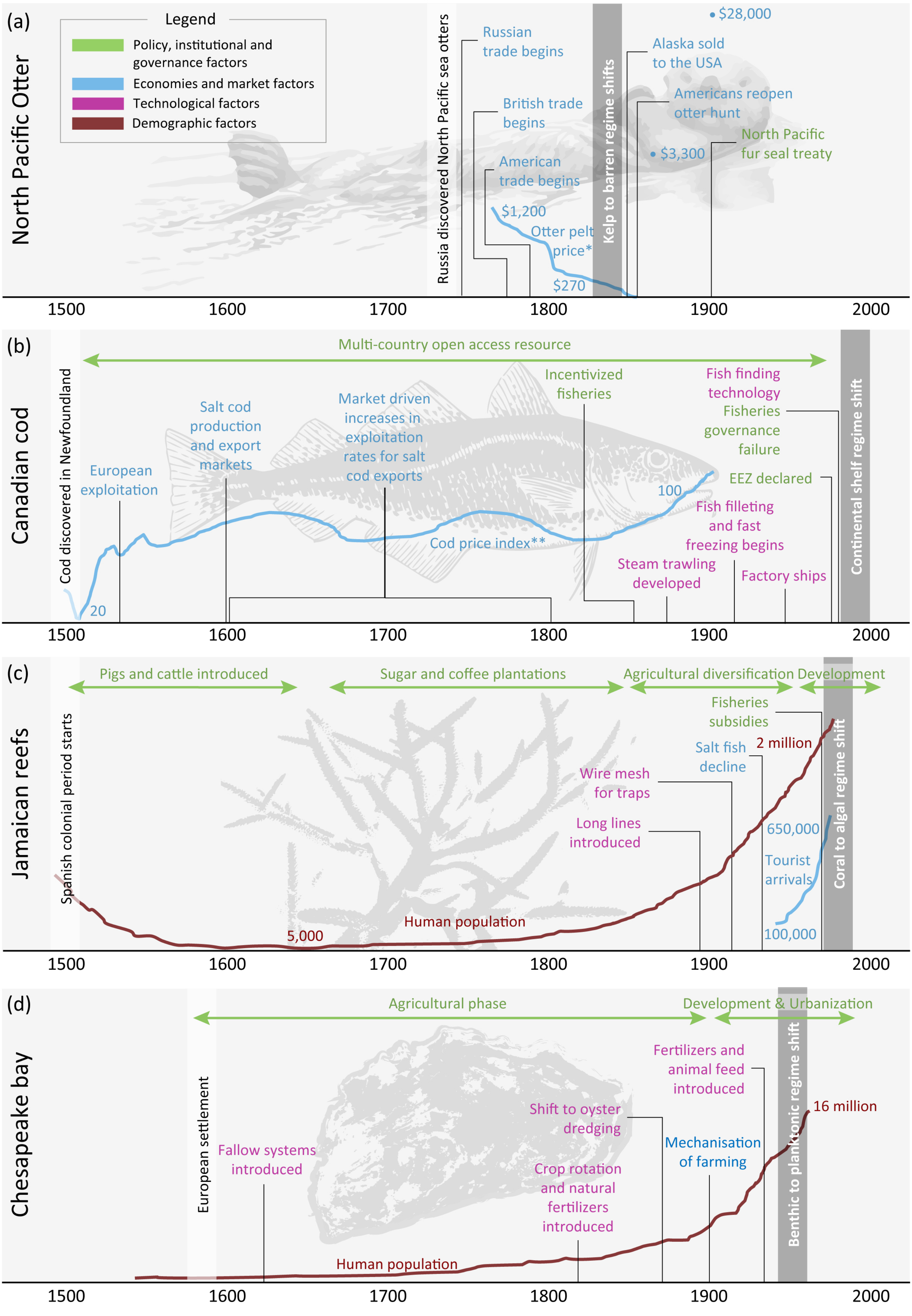
(a)
Rapid escalation in driver(s) as early warning indicators
Ecological early warning indicators
Ecosystem state
Low
Drivers
High
(b)
Socioeconomic change
Proximate driver
Time
r3
r2
r1


Distal drivers
Policy, institutional and governance factors
Economies and market factors
Technological factors
Demographic factors (population)
Cultural and sociopolitical factors (values, mores/ethics, social preferences)
Proximate drivers
Fishing, hunting, harvesting
Pollution (nutrient, sedimentation, & pathogens)
Climate change (temperature stress, acidification)
Habitat destruction
Invasive species introductions
Marine ecosystems


(a)
(b)
(c)
(d)



(a)
North Pacific Otter
Legend
Policy, institutional and governance factors
Economies and market factors
Technological factors
Demographic factors
Russia discovered North Pacific sea otters
Russian trade begins
British trade begins
American trade begins
$1,200
Otter pelt price*
$270
Kelp to barren regime shifts
$28,000
Alaska sold to the USA
Americans reopen otter hunt
$3,300
North Pacific fur seal treaty
1500
1600
1700
1800
1900
2000
(b)
Canadian cod
Multi-country open access resource
Cod discovered in Newfoundland
European exploitation
Salt cod production and export markets
Market driven increases in exploitation rates for salt cod exports
Incentivized fisheries
Fish finding technology
Fisheries governance failure
EEZ declared
Continental shelf regime shift
100
Fish filleting and fast freezing begins
Cod price index**
Steam trawling developed
Factory ships
20
1500
1600
1700
1800
1900
2000
(c)
Jamaican reefs
Pigs and cattle introduced
Sugar and coffee plantations
Agricultural diversification
Development
Spanish colonial period starts
Fisheries subsidies
2 million
Salt fish decline
Wire mesh for traps
Long lines introduced
650,000
Tourist arrivals
100,000
Coral to algal regime shift
Human population
5,000
1500
1600
1700
1800
1900
2000
(d)
Chesapeake bay
Agricultural phase
Development & Urbanization
European settlement
Fallow systems introduced
Fertilizers and animal feed introduced
Shift to oyster dredging
Mechanisation of farming
Crop rotation and natural fertilizers introduced
Benthic to planktonic regime shift
16 million
Human population
1500
1600
1700
1800
1900
2000