Proposal to NOAA Fisheries and the Environment (FATE) program

Title: An Early-Warning Index For Abrupt Change in Northeast Pacific Ecosystems

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Background

Information overload is a recurring problem with efforts to monitor the status of marine ecosystems. Many time series are collected, all of them are typically quite variable, and it can be impossible to make sense of the noisy information that results. The goal of this proposal is to summarize information from a large set of biological time series from the California Current Ecosystem (CCE), the Gulf of Alaska (GOA) and the Eastern Bering Sea (EBS), using the most advanced and informative analysis techniques currently available. Our specific goal *is to develop indices that: 1) provide early detection of changes in community state; and 2) provide early warning of an impending regime shift.*

Ecological regime shifts are an important source of uncertainty, affecting our ability to successfully manage fisheries in the northeast Pacific (NEP). The best-known examples are the sudden ecological changes that followed shifts in the Pacific Decadal Oscillation (PDO) in 1946/47 and 1976/77 (Mantua & Hare, 2002). Though rare, the degree to which these past events disrupted commercial fisheries in the NEP can hardly be overstated; abrupt stock collapses were widespread in the three ecosystems considered in our proposal, as were simultaneous booms in previously depressed stocks (Mantua et al., 1997; Anderson & Piatt, 1999; Litzow & Urban, 2009). This history of abrupt change has led to incorporating early warning of future shifts in ecosystem state as a leading goal of ecosystem-based management in the NEP (NWFSC Science Plan 2013).

While past NEP regime shifts have been associated with sudden change in the PDO, an important prediction of ecological theory is that sudden regime shifts are also expected in ecosystems undergoing persistent or incremental external perturbation (Scheffer et al., 2001). In the NEP, these perturbations include bottom water hypoxia, eutrophication, habitat loss and fishing pressure (Halpern et al., 2015). In addition to these "background" perturbations, the NEP is currently undergoing a remarkable climate perturbation. Previously unobserved patterns in atmosphere-ocean interactions were linked to a highly anomalous "warm blob" of surface temperature anomalies in winter 2013-14 (Bond et al., 2015). The warm water anomalies that now extend along the entire U.S. west coast are expected to interact with the current positive PDO phase and a strong developing El Niño, with several possible, but currently unknown outcomes. It is too early to know if the warm temperature anomaly will be ephemeral or persistent. Similarly, though anecdotal evidence has accrued concerning biological responses to current warm conditions, it is too early to know if biological response to the warm anomaly will result in a regime shift to a persistent new state. *This project will build capacity across three NOAA Fisheries Science Centers to provide more rapid detection of future ecological regime shifts, in response to the current warm anomaly or to future perturbations to the systems.*

We propose using the long-term monitoring efforts in the CCE, GOA and EBS to quantify the state of these systems with two empirical metrics, a <u>State Index</u> and an <u>Early Warning Index</u>. We will also <u>develop reference points</u> based on how these have performed in the past. The goal of the State Index is to reduce the time required to detect abrupt community-level changes in each system. The goal of the Early Warning Index is to apply generic regime shift indicators to track changes in the relative likelihood of a sudden ecological shift. Further, *the goal of the reference points is to enable scientists and managers to distinguish normal variability from changes signaling a major shift.* This information could be used to adjust management strategies (FATE research priority 2).

Our Early Warning Index is based on rapidly developing research proposing that characteristic statistical signals (e.g., rising variance and autocorrelation) should provide leading indicators of declining resilience and an increased chance of an ecological regime shift (Scheffer et al., 2009, 2012). While these indicators began as strictly theoretical predictions, there has been some research demonstrating that they may have utility in predicting sudden change in real ecosystems (Wouters et al., 2014; Dakos et al., 2015). For instance, commercial catches of crabs and shrimp in the GOA and EBS showed increasing spatial variability prior to historical stock collapses, as predicted by theory (Litzow et al., 2013). There is some disagreement over whether these indicators will be useful for forecasting abrupt shifts that are not preceded by critical slowing down (CSD), such as ecological shifts triggered by stochastic climate variability (Dakos et al., 2015). However, there is theoretical support for the idea that EWI signals should precede non-CSD shifts (Kéfi et al., 2013), and retrospective analysis found regime shift indicators in the Gulf of Alaska ecosystem prior to the 1976/77 PDO shift (Litzow et al., 2008). Specifically, increasing variability in trawl survey predator:prey ratios gave a one-year warning of a persistent shift from a prey-rich to a predator-rich state. Given the strong theoretical basis for these indicators, and research demonstrating that they may have utility in real ecosystems, both in Alaska and elsewhere, these tools *are a logical next step for improving the utility of leading indicators in ecosystem-based fisheries management* (FATE research priority 1).

Approach

Data. The State Index and Early Warning Index will be based on the same set of biological time series. The key characteristic of biological parameters included in our indices is that they are expected to show a response to climate fluctuations with a lag of only 0-1 years. Examples of suitable parameters include primary production phenology; zooplankton abundance; abundance of short-lived animals like shrimp, jellyfish, forage fish and age-1 gadids; and catches of salmon species that spend only 1 year in the ocean, and thus have short lags to the year of ocean entry. We will also use time series that are sampled at least annually, can be updated without a long lag for processing data, and are preferably at least 15 years long. Our proposed index also includes taxonomic variety to allow for inferences about community-scale variability. With the exception of the publicly available salmon catch data, collaborators maintaining each of the individual time series have committed to providing data for the proposed research (Table 1). We will continue to search for additional suitable time series during the first phases of our project. *However, the data secured to date are sufficient for the success of study goals.*

Only a minority of time series have any observations from before the last wholesale ecological shift in the North Pacific, in 1976/77 (Table 1). However, time series need not cover historical regime shifts to be useful for our purposes. The goal of both indices is simply to detect a shift away from the current ecosystem state. To be useful in this context, time series only need to be long enough (we judge about 15 years or more) to provide a baseline of conditions in the current quasi-stable ecosystem state. Given the current warming in the NEP, any shift in the near future is extremely unlikely to take the form of a return to the pre-76/77 cold-regime community, so ecological conditions prior to 1976/77 are in a sense not relevant to our goal of early detection of the next shift. What is relevant, though, is reference points for how our indices behave under normal ecological variability, and how they might behave during a major ecosystem shift. We will use subset of the longest-running time series to evaluate the utility of our indices for these purposes (see below).

State Index. This index will evaluate changes in mean community state, as measured with ordination of the collected time series. Ordination will be conducted with either Dynamic Factor Analysis (DFA) (Zuur et al., 2003), or Multivariate Autoregressive State-Space Models (MARSS) (Holmes et al., 2012), along with hierarchical Bayesian analogs of these approaches. Selection of the appropriate ordination method, and identification of time varying parameters will be part of the research. The value of leading axes of variability across all time series (e.g., the leading common trend from DFA) will allow managers to evaluate community state. Appropriate statistical approaches for detecting changes in axes of variability at the ends of time series will also be examined as a part of the research (e.g., STARS analysis of DFA trends; Rodionov, 2006). Large changes in ordination axes will indicate large changes in the underlying community; reference points (see below) will give managers formal rules for evaluating observed variability.

The advantage of our State Index over existing efforts to monitor community data lies in the application of ordination techniques and in the characteristics of the underlying time series. Ordination of monitoring time series remains rare in the NEP (Zador and Aydin, FATE Project 13-13). Mapping a large number of taxonomically diverse data sources to a small number of underlying processes is justified by the well-documented history of coherent community variability in the NEP (Hare & Mantua, 2000; Litzow & Mueter, 2014), and is a logical step to combat the problem of information overload from an overabundance of individual noisy time series. Further, our underlying data sets are expected to react to climate perturbations with short lags (0-1 years) and are all updated quickly, without long lags for gathering or processing data. These qualities contrast with existing efforts to monitor community status, which either rely on parameters such as community biomass, that are expected to show multi-year lagged responses to perturbation (e.g., community biomass in the EBS Report Card; Zador, 2014), or include information that can only be updated with multi-year lags (e.g., groundfish recruitment in Hare & Mantua, 2000; Litzow & Mueter, 2014). We expect that our State Index will provide indication of a change in community state 2-3 years earlier than existing community monitoring efforts. This prediction will be tested by comparing the performance of the different approaches across historical regime shifts.

Prior to ordination we will group time series to achieve fairly consistent representation of different data types. Individual time series will be transformed to achieve approximate normality and scaled as standardized anomalies prior to analysis. We will also consider whether to lag individual time series before ordination, as, for instance, salmon catches were lagged to year of ocean entry by Hare and Mantua (2000).

Early Warning Index. The Early Warning Index will use emerging research on leading indicators of regime shifts to attempt to provide early warning of an increased chance of an impending ecological regime shift. Existing research on regime shift indicators in marine ecosystems highlights the need to combine information from many different time series to provide enough statistical power to overcome the noisy nature of ecological data (Lindegren et al., 2012; Litzow et al., 2013; Wouters et al., 2014). This is our motivation for combining data from across the community in our index. The index will track metrics including variability and autocorrelation in time series, as these indicators have a strong theoretical basis as leading indicators of regime shifts, and have also been supported in a number of empirical studies (Litzow et al., 2013; Wouters et al., 2014; Dakos et al., 2015). Multivariate variability across

time series will be calculated with MARSS models (Holmes et al., 2012); tracking annual changes in multivariate variability will allow us to test for the rising variance that is predicted prior to a regime shift. Lag-1 autocorrelation (AR1) will be calculated on a running window both for leading common trends from DFA models (Zuur et al., 2003). The utility and past performance of our Early Warning Index will be evaluated as a part of our research on index reference points (see below).

Reference points. For both indices, we will construct reference points for: 1) performance under normal ecological variability; and 2) performance before and during a major ecosystem shift. We will begin with analysis of both indices constructed from a subset of time series that extend at least five years prior to the 1976/77 PDO shift (Table 1). Analysis of these data will allow us to document the range of normal variability (both in ecosystem state and regime shift indicators) during periods of normal variability, and prior to/during the 1976/77 NEP-wide regime shift and lesser shifts in particular ecosystems (e.g., 1988/89 in the EBS; Hare & Mantua, 2000). Additionally, analysis of the behavior of both indices from the full set of time series will allow us to demonstrate the range of normal variability in the full indices over the past 15-20 years, a period of generally stable community state in the NEP. By standardizing index scores (e.g., in units of standard deviation), we will be able to compare the historical behavior of the full data set, which provides the most comprehensive picture of contemporary community behavior, with the restricted data set, which provides information about index performance over dramatic regime shifts at decadal time scales.

The analysis of time series pre-dating the 1976/77 regime shift will also allow us to test the ability of our Early Warning Index to give early warning of an impending regime shift. Specifically, we will test whether historical changes in the Early Warning Index (e.g., as detected by STARS; Rodionov, 2006) predated changes in the State Index, as expected under theory. Empirical examples of regime shift indicators remain rare in marine ecosystems; though existing studies are promising, research is needed to determine exactly how useful these indicators are for management (Wouters et al., 2014). Accordingly, this part of the project will make a useful contribution to developing the science of regime shift indicators for management use. Finally, reference point evaluation is expected to be an ongoing, annual process, as PIs will update information on the behavior of the indices in their own systems and across the NEP. Results from evaluation of the Early Warning Index will also be used to make improvements to the statistical approach for calculating index values. In this way the project will contribute to an ongoing increased capacity within NOAA Fisheries for early detection of regime shifts.

Spatial scale. Climate variability is coherent across the spatial scale of the North Pacific; thus the North Pacific is characterized by strong basin-scale biological variability (Hare & Mantua, 2000; Schwing et al., 2010). However, variability at the scale of Large Marine Ecosystems is at times independent of basin-scale variability (Hare & Mantua, 2000); understanding variability at both scales is important for ecosystem management. All analyses in this project - the evaluation of past index performance and the updating of indices for ecosystem monitoring - will be run at both spatial scales.

Benefits This project will provide increased capacity, on an ongoing basis, for early detection and early warning for major ecosystem regime shifts. The project will thereby *increase the value of individual ongoing monitoring events and indicators that are currently used in ecosystem*

assessments (FATE Research Priority 1), including the AFSC's Ecosystem Status Report to North Pacific Fishery Management Council and the CalCOFI Ecosystem Status Reports. The application of these new indices in management will be also be facilitated through the CCIEA interactions with the Pacific Fishery Management Council and its committees (e.g., IEA can coordinate and pay for technical review by the SSC). The proposed work will advance ecosystem assessments beyond data-based summaries of ecosystem status (e.g. stoplight charts) to model-based indices, reducing "information overload" by using ordination of community-wide monitoring parameters. Further, if testing of our Early Warning Index is successful, it will give managers advanced warning of an impending ecosystem shift and *could serve as a trigger for management actions that mitigate impacts on managed fish stocks and other ecosystem components* (FATE Research Priority 2). The set of reference points constructed based on empirical histories of index behavior relative to system variability *could be considered alongside stock assessment output* to inform fishery managers about whether ecosystem behavior is outside of the normal range of variability and indicate whether a more precautionary management strategy is warranted (FATE Research Priority 4). In addition, the framework and R scripts created to produce the two indices for the NEP will be made available to scientists at other Fisheries Science Centers to produce similar indices.

Deliverables

1. Produce a State Index and an Early Warning Index for the EBS, GOA and CCE that can run on an "autopilot" basis. PIs will provide annual data updates for five years after project ends.
2. Create R scripts to produce both indices, at both spatial scales, along with interpretive plots, from annual updates and make publicly available.
3. Provide time series of the indices for the CCIEA report, the State of the California Current manuscript, and the Alaska ecosystem reports.
4. Publish a peer-reviewed paper describing indices, their "background" levels of variability and behavior across historical ecosystem shifts, and the reference points derived from this analysis.
5. Present the indices to the relevant stock assessment Scientific Statistical Committees for consideration as an addition to the management process for assessed species.

Table 1: Datasets that our collaborators (to date) have committed the project.

Ecosystem	Source	Data	Years
CCE	NOAA Newport Line	Copepod density/biomass and ichthyoplankton density	1996-present
CCE	BPA survey	Ichthyoplankton density	1999-present
CCE	CalCOFI	Ichthyoplankton density	1951-present
CCE	NOAA SWFSC RREAS	Juvenile / forage fish abundance	1983-present
CCE	WA Dept Fish & Wildlife	Pink salmon abundance or catch	1950s-present
CCE	OR Dept Fish & Wildlife	Coho salmon abundance or catch	1950s-present
CCE	Farallon Institute	Seabird counts and reproductive success	1970-present
CCE	NOAA NMML	Sea lion pup production and survival	1975-present
EBS	NOAA AFSC RACE survey	Abundance of jellyfish, shrimp, juvenile gadids	1982-present
EBS	Sea Duck Joint Venture	Spectacled and common eiders phenology, egg production	1985-present
EBS	NOAA AFSC/ABL BASIS	Zooplankton abundance	1997-present
EBS/GOA	U.S. Fish & Wildlife	Seabird phenology, reproductive success	1997-present
EBS/GOA	AK Dept Fish & Game (ADFG)	Pink and coho salmon commercial catch	~1920-present
GOA	NOAA SEAK coastal monitoring	Zooplankton phenology, abundance, community composition	2000-present
GOA	NOAA Seward Line	Nutrients, chl-a, zooplankton abundance, community composition	1998-present
GOA	ADFG small mesh survey	Shrimp, forage fish, juvenile gadids, jellyfish abundance	1972-present
GOA	NOAA AFSC FOCI	Zooplankton, ichthyoplankton, age-0 groundfish	1972-present
GOA	SeaWifs / MODIS-Aqua	Chl-a phenology, abundance, spatial pattern	1998-present
GOA	Continuous plankton recorder	Zooplankton phenology, abundance, community composition	2000-present

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