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Evidencing a regime shift in the North Sea using early-warning signals as indicators of critical transitions

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ABSTRACT

One of the longest marine monitoring programs in the North Sea has been the spatiotemporal surveying of subsurface plankton since 1931. During this period a regime shift was detected in the late 1980s culminating in marked changes in phytoplankton, zooplankton and in the fisheries of horse mackerel. Here we used the phytoplankton colour index, a visual biomass estimate, from 1948 to 2010 and total diatom abundance from 1958 to 2010 to test whether the well-documented regime shift could have been anticipated by the recently developed Early-Warning Signals for critical transitions (EWS). We estimated EWS, namely autocorrelation and standard deviation, within moving windows along the time series prior to the regime shift. We found that both statistics increased revealing that the North Sea ecosystem was becoming progressively unstable prior to the regime shift. Moreover, this high-resolution time series permitted us to test for robustness, error and significance of the EWS. We did that by dividing the time series into independent blocks and estimating EWS after bootstrapping and randomising the blocks. This alternative approach confirmed the robustness of the EWS with limited associated errors. In particular, we found that the warning was significantly evident years before the onset of the regime shift. We conclude that EWS may provide robust and timely warning for upcoming regime shifts depending on the quality and quantity of recorded data in marine ecosystems.

1. Introduction

Ecosystems at times don't respond gradually to changing external pressures but undergo abrupt changes or regime shifts (Andersen et al., 2009; Mollmann et al., 2011). Regime shifts are driven by gradual external environmental changes like over-exploitation of fish stocks or eutrophication, and they are triggered by stochastic perturbations such as climatic fluctuations or strong hydrological disturbances (Scheffer et al., 2001; Andersen et al., 2009). In the North Sea, such a regime shift was detected in the late 1980s characterised by extensive changes on three trophic levels (Reid et al., 2001; Weijerman et al., 2005). At that time, phytoplankton stock monitored by the 'phytoplankton colour index' (PCI), which correlates well with fluorometric and satellite derived chlorophyll-a concentrations, increased significantly (Batten et al., 2003a,b; Leterme et al., 2005). Simultaneously zooplankton species abundances changed and the catches of the horse mackerel experienced a 4-fold increase over a period of 5 years (from 100×10^3 to 400×10^3 tonnes) (Reid et al., 1998a, b; Reid and Edwards, 2001).

Due to the fact that regime shifts might have socio-economic implications as they alter ecosystem's goods and services, the development of tools to anticipate, and thus, potentially mitigate them is crucial for the management of biotic resources (Boettiger et al., 2013; Dakos and Hastings, 2013; Elliott et al., 2007). One recently suggested method for the detection of regime shifts uses Early-Warning Signals (EWS) for critical transitions (Scheffer et al., 2009; Drake and Griffen, 2010; Lenton, 2011; Scheffer et al., 2012; Wang et al., 2012). EWS are statistical indicators that measure the dynamical phenomenon of 'critical slowing down' (CSD). CSD is defined as decreased recovery rate when ecosystem's resilience is low (Scheffer, 2010). As CSD occurs close to a transition, ecosystem variables tend to become more temporally correlated and to show

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higher variability. This results that time series of stable ecosystems (far from a transition) have distinct correlation and variance patterns when compared to less stable ecosystems (close to a transition) (Fig. 1a,b) (Dakos et al., 2012a). In that sense, autocorrelation and standard deviation are both theoretically expected to increase in case of loss of resilience as ecosystems approach a transition and can be used as EWS (Scheffer et al., 2009, Fig. 1c). EWS have been demonstrated to occur prior to paleo–climate transitions (Dakos et al., 2008), lake eutrophication (Wang et al., 2012), trophic cascades (Carpenter et al., 2012), experimental zooplankton extinctions (Drake and Griffen, 2010), or the collapse of photo-inhibited green algae (Veraart et al., 2012).

Despite EWS's promising applications, care is needed in the interpretation of the results, as not all regime shifts are associated with CSD (Lenton et al., 2012a,b; Dakos et al., 2012b; Boettiger et al., 2013). Moreover, from a practical perspective, testing these tools in the field is limited due to the high quality time series required (Boettiger et al., 2013). Robust detection of EWS depends on the frequency of the observations (e.g. yearly versus monthly), and the turn-over of the variables upon which they are applied: measures of primary production or nutrient recycling might be more appropriate than species abundance with long life cycles (Wouters et al., 2013). Indeed, comparing multiple EWS leads at times to discrepancies that are not always in line with theoretical expectations (Lindegren et al., 2012; Dakos et al., 2012b). One main constraint in the use of temporal indicators relates to the length of the time series: shorter time series may limit robustly detecting EWS as a lengthy timespan prior to the regime shift is necessary (Dakos et al., 2012a,b).

Despite the well-developed theoretical background for EWS, the above limitations have restricted real world testing especially in marine ecosystems. Few studies have addressed their potential of detecting marine regime shifts so far. Lindegren et al. (2012) estimated EWS in a large-scale reorganization of the Baltic Sea ecosystem using two indicator copepod species but found no clear patterns. Litzow et al. (2008) used a measure of community composition of trawl survey data and observed increased spatial variability accompanying the reorganization of two continental shelf ecosystems in the North Pacific (Gulf of Alaska) and the North Atlantic (Scotian Shelf), while Litzow et al. (2013) compared collapsing and non-collapsing fisheries models of Crustacean fisheries. Despite this work, we still lack understanding on the applicability of EWS as tools for anticipating regime shifts in marine ecosystems.

In this study, we tested the validity of EWS in anticipating a marine ecosystem regime shift in retrospect. We chose the well-established North Sea regime shift to assess whether and how early it could have been anticipated using EWS. Our overall aim was to evaluate whether the particular marine regime shift could be considered a critical transition characterised by CSD. In addition, our results indicate whether EWS may have the potential to forecast upcoming regime shifts in marine ecosystems. To this end, we develop a new method for applying and interpreting EWS in a marine context that can be of use in cases of available long-term and high-resolution data sets.

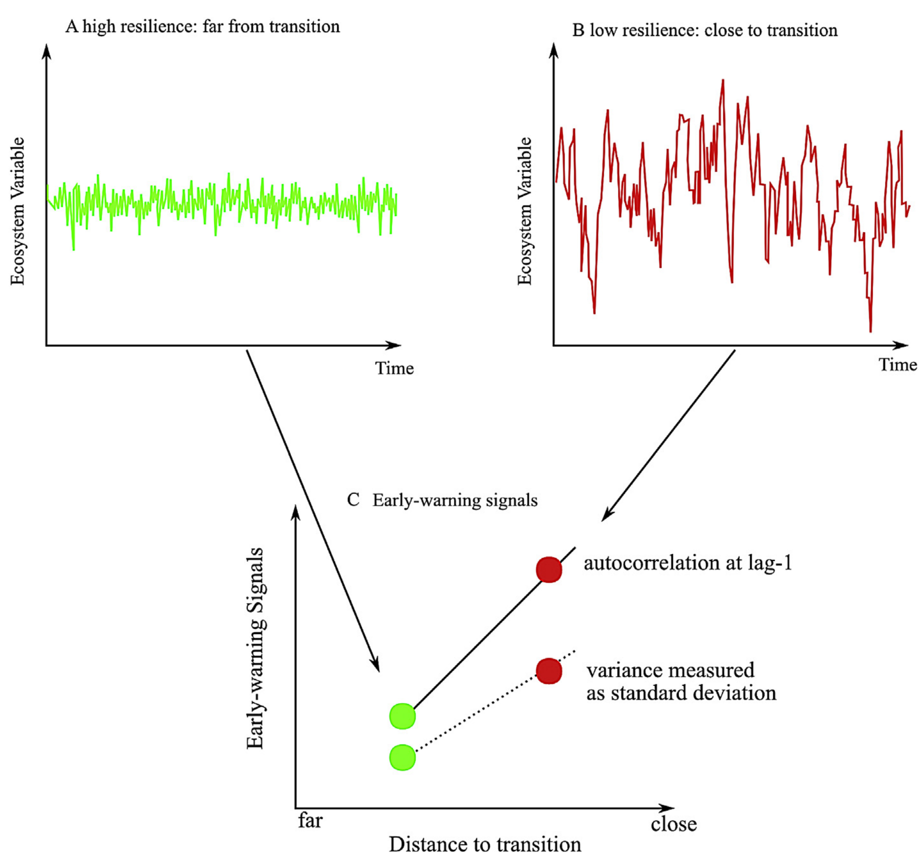

Fig. 1. Conceptual diagram of ecosystem dynamics far and close to a critical transition. a. hypothetical time series of an ecosystem that is far from a transition (high resilience) b. hypothetical time series of the same ecosystem but close to a transition (low resilience). c. autocorrelation at lag-1 and variance (measured as standard deviation) both increase when the ecosystem is close to the transition (b) due to critical slowing down and can therefore be used as Early-Warning Signals (EWS) indicating the loss of resilience and the proximity to a transition.