ICES Journal of Marine Science

ICES Journal of Marine Science (2013), 70(4), 755–767. doi:10.1093/icesjms/fst067

Defining trends and thresholds in responses of ecological indicators to fishing and environmental pressures

Scott I. Large[1]*, Gavin Fay[1], Kevin D. Friedland[2], and Jason S. Link[1]

[1]*NOAA-Fisheries, Woods Hole, Massachusetts, USA*
[2]*NOAA, National Marine Fisheries Service, Narragansett, Rhode Island, USA*

**Corresponding author: tel: +1-508-495-2046; fax: +1-508-495-2258; e-mail: scott.large@noaa.gov*

Large, S. I., Fay, G., Friedland, K. D., and Link, J. S. 2013. Defining trends and thresholds in responses of ecological indicators to fishing and environmental pressures. – ICES Journal of Marine Science, 70: 755–767.

Received 30 January 2013; accepted 6 April 2013.

Both fishing and environmental forces can influence the structure of marine ecosystems. To further understand marine ecosystems and to implement ecosystem-based fisheries management (EBFM), an evaluation of ecosystem indicators is warranted. In this context, it is particularly important to identify thresholds where fishing and environmental pressures significantly influence ecological indicators. We empirically determined numerical values of environmental forces and fishing pressure that significantly altered the response of ecological indicators for the Northeast Shelf Large Marine Ecosystem. Generalized additive models predicted a non-linear relationship for each pressure–response pairing. With this smoother, 95% confidence intervals (CI) for estimated first and second derivatives for each relationship were determined via parametric bootstrap. A significant trend or threshold was noted when the CI for the first or second derivative was greater or less than zero, delineating the level at which pressure variables influence the rate and direction of ecosystem indicator responses. We identify reference levels where environmental forces and fishing pressure result in ecosystem change by collectively examining the responses of multiple ecological indicators. Individual indicators showed unique responses to pressures, however, similar values for the pressures were associated with significant changes for multiple indicators. These reference levels establish a foundation for implementation of EBFM.

Keywords: decision criteria, ecosystem-based management, generalized additive model, overfishing, reference points.

Introduction

Marine ecosystems are dynamic owning to both environmental variability (Brodziak and O'Brien, 2005; Beaugrand *et al.*, 2008) and anthropogenic extraction of living marine resources (LMR; Myers *et al.*, 1997; Pauly *et al.*, 1998; Hsieh *et al.*, 2006; Link *et al.*, 2012) that influence the structure and function of ecosystem processes (Brander, 2007). Increased demand for LMRs has resulted in global declines of targeted species and fishery status (Pauly *et al.*, 1998; Jackson *et al.*, 2001; Garcia and Leiva Moreno, 2003). However, single-species (SS) management strategies do not fully incorporate ecosystem functions such as ecological interactions and environmental factors or entirely account for cumulative impacts or systemic responses in an ecosystem of interacting LMRs (Link, 2002b; Garcia *et al.*, 2003; Pikitch *et al.*, 2004; Hall and Mainprize, 2004; Garcia and Cochrane, 2005; Link, 2010). Therefore, ecosystem-based fisheries management (EBFM) has been recommended to concurrently address human, ecological, and environmental factors that influence LMRs and evaluate these considerations collectively as a system.

To implement EBFM three steps have been proposed: (i) establish goals, (ii) assess ecosystem status, and (iii) determine decision criteria to trigger management action (Sainsbury *et al.*, 2000; Link, 2010; Murawski *et al.*, 2010). Legislative and policy goals are largely in place, although they often need to be unpacked for specific policies in particular circumstances (O'Boyle and Jamieson, 2006; Martin *et al.*, 2009). To facilitate the pathway towards EBFM, ecological indicators have been suggested as a means to evaluate ecosystem status and inform reference levels for management actions (Rice, 2000; Murawski, 2000; Trenkel and Rochet, 2003). Many ecological indicators have been proposed, and a select group has been suggested for routine monitoring of ecosystem status (Link *et al.*, 2002; Link and Brodziak, 2002; Rice and Rochet, 2005; Link, 2005; Methratta and Link, 2006; Shin *et al.*, 2010; Shackell *et al.*, 2012). These indicators represent major ecosystem processes, are typically

© United States Government 2013

sensitive to ecosystem changes attributable to anthropogenic impacts such as fishing (Jennings, 2004; Methratta and Link, 2006), and are commonly used to assess ecosystem status (e.g. EcoAP, 2009).

Establishing decision criteria that trigger management actions for EBFM requires an understanding of how pressure variables such as fishing and environmental variability influence ecological indicators, as well as the level of a particular pressure at which significant changes in ecosystem structure or function appear (Martin *et al.*, 2009; Samhouri *et al.*, 2010). Samhouri *et al.* (2010) used simulation models that examine ecosystem response to fishing pressure and near-shore habitat exploitation. In both scenarios, increased pressure resulted in a shift towards negative ecosystem status and decision criteria were suggested for management action. Similarly, empirical approaches (Link *et al.*, 2002; Coll *et al.*, 2010; Link *et al.*, 2010; Blanchard *et al.*, 2010) have also been used to examine pressure–response relationships and determine indicator levels where pressure variables result in ecosystem change. However, these studies only provide general levels where pressure variables result in ecosystem change.

The ability to clearly identify regions of change (i.e. thresholds, change points, tipping points, etc.) is valuable in a variety of fields, from ecotoxicology (Suter, 1993) to econometrics (Zeileis and Kleiber, 2005). Many techniques have been developed to identify changes in response variables (Andersen *et al.*, 2009), primarily using analyses such as cumulative sums (CUSUM; Hinkley, 1970), sequential *t*-test (Rodionov, 2004), or empirical fluctuation processes (Zeileis and Kleiber, 2005). These analyses are robust and useful; however, they generally identify discontinuities in the mean or variance of data and are conducted on sequential and equally spaced data, typically in the form of a time-series. To provide managers with values that can be translated into decision criteria, data should be analysed in a pressure–response framework—such data may not be equally spaced or sequential.

Generalized additive models (GAMs) are a non-parametric extension of generalized models in which a smoothing term is fit to the data within the context of the original model (Hastie and Tibshirani, 1990). GAMs are very flexible and robust when using unequally spaced data (Trenkel and Rochet, 2009). Patterns in non-linear pressure–response relationships can be used to identify a threshold, that is, a region where a response variable rapidly responds to a small change in a pressure variable (Sonderegger *et al.*, 2008; Dodds *et al.*, 2010). A threshold occurs when a smoother's trajectory changes significantly, such as when the second derivative changes sign (see Fewster *et al.*, 2000; Bestelmeyer *et al.*, 2011; Lindegren *et al.*, 2012; Samhouri *et al.*, 2012). Similarly, a trend occurs when the first derivative of the smoother is greater (i.e. increasing trend) or less than zero (i.e. decreasing trend). These mathematical properties can be calculated on GAM smoothing terms to clearly identify particular levels where a pressure influences the threshold or trend of a response variable.

Here we aim to identify relationships between ecosystem pressures and indicators, and to calculate explicit values where these pressures influence ecological status for a given system. Using data from the Northeast Shelf Large Marine Ecosystem (NES LME) we explored the non-linear relationship between a suite of ecological indicators and fishing and environmental pressures to determine significant trends and thresholds. In a fisheries context, these inflection points delineate decision criteria for management action. Ultimately, by obtaining the shape and magnitude of non-linear pressure–response relationships, we can identify levels of pressure where trends or thresholds are apt to occur. While a single ecological indicator is useful, a suite of ecological indicators should provide more robust performance. By identifying regions of complementary indicator change in response to fishing pressure and/or the environment, a robust set of potential reference points can be delineated.

Material and methods

Ecological indicators

Ecological indicators used in this study were compiled as part of an ongoing, multidisciplinary effort to describe the trends and conditions of the NES LME (see Link and Brodziak, 2002 for description of survey). Since 1963, the Northeast Fisheries Science Center has conducted biannual bottom trawl surveys as part of a long-term scientific monitoring program (NEFSC, 1998) that samples 350–400 stations from Cape Hatteras to Nova Scotia every spring and autumn (Azarovitz, 1981; NEFC, 1988). Data were aggregated spatially and averaged across season to create a single annual time-series for each indicator from 1964–2010 (see Link and Brodziak, 2002 for details regarding survey methodology). The indicators used in this study (Table 1) represent key ecosystem processes that have been vetted as having utility in assessing ecosystem status for this system (Link and Brodziak, 2002; Link, 2005; Methratta and Link, 2006; EcoAP, 2009; EcoAP, 2011; Shackell *et al.*, 2012).

Pressures

Both environmental and anthropogenic factors influence the ecological status of the NES LME (Table 2 and references within). We analysed a broad range of pressure variables that represent both environmental and anthropogenic factors; however, based on model selection criteria (see *GAM analysis*) only three pressure variables were significant and retained for further analysis (Table 2). Atlantic multidecadal oscillation (AMO) is a basin-scale climatic mode of variability that influences North Atlantic sea surface temperature (SST; Schlesinger and Ramankutty, 1994), creating variability in thermohaline circulation patterns (Enfield *et al.*, 2001). Localized environmental variation was measured with extended record SST (ERSST v3b; Smith *et al.*, 2008). Monthly SST was averaged across the NES LME to create a single annual SST for the entire ecosystem. Finally, fishing pressure was measured with the total live weight of commercial species landings in the NES LME, calculated by aggregating data reported to the National Marine Fisheries Service (NMFS) by dealers at weigh-out, logbooks, and vessel trip reports (NEFSC, 1998; Link and Brodziak, 2002).

GAM analysis

To identify trends and thresholds in ecological indicator responses to pressure variables we fit GAM models with the formula:

$$Y = \alpha + S(X) + \varepsilon,$$

where Y is the ecological indicator, α is held constant, X is the pressure variable, $s()$ is the smoothing function, and ε is error. If smooth functions are not properly fit in the model, complex over-fitting is likely to result. To reduce the likelihood of over-fitted models, the smoothing parameter was estimated using the generalized cross validation (GCV; Wood, 2004b) criterion as implemented in the package 'mgcv' (Wood, 2004a) in R (R Development Core Team, 2010). We used thin plate regression spline smoothing terms with

Table 1. Ecosystem indicators used as response variables in GAM analysis.

Indicator	Definition	Data source	Indicator rationale	Rationale source
Length (mean)	mean length (cm) of individual fish for all spp. from BTS	(Azarovitz, 1981; NEFC, 1988; Link and Brodziak, 2002)	size distribution	(Duplisea and Kerr, 1995; Rice and Gislason, 1996; Duplisea *et al.*, 1997; Hall, 1999; Jennings *et al.*, 1999; Bianchi *et al.*, 2000; Brodziak and Link, 2002; Nicholson and Jennings, 2004; Link, 2005; Methratta and Link, 2006)
Biomass (total)	total biomass of all surveyed spp. from the BTS ('000 t)	(Azarovitz, 1981; NEFC, 1988; Link and Brodziak, 2002)	allometric and growth dynamics, system production	(Pauly, 1979; Pauly and Christensen, 1995; Kaiser and Ramsay, 1997; Fogarty and Murawski, 1998; Jennings and Kaiser, 1998; Hall, 1999; Garrison and Link, 2000; Brodziak and Link, 2002; Link and Brodziak, 2002; Link *et al.*, 2002; Myers and Worm, 2003; Trenkel and Rochet, 2003; Garcia and Leiva Moreno, 2003; Link, 2005; Methratta and Link, 2006)
Planktivores and benthivores to piscivores and shrimp-fish feeders ratio	ratio of abundance of lower trophic level guilds to upper trophic level guilds from BTS	(Azarovitz, 1981; Garrison and Link, 2000; Myers and Worm, 2003)	trophic dynamics, energy flow, community structure	(Link, 2005; Methratta and Link, 2006)
Pelagic to demersal ratio	ratio of pelagic and demersal fishes from BTS (index)	(Azarovitz, 1981; Brodziak and Link, 2002; Myers and Worm, 2003)	energy flow, community structure	(Link, 2005; Methratta and Link, 2006)
Consumption ratio	ratio of total biomass consumed by 12 major predators to the landings of all major fisheries	(Link and Almeida, 2000; Overholtz *et al.*, 2000; Brodziak and Link, 2002; Link and Brodziak, 2002)	trophic dynamics, relative exploitation	(Pauly and Christensen, 1995; Pauly *et al.*, 1998; Jennings and Kaiser, 1998; Jennings *et al.*, 1999; Overholtz *et al.*, 2000; Fath *et al.*, 2001; Jørgensen and Müller, 2000; Link and Brodziak, 2002; Myers and Worm, 2003; Link, 2005; Methratta and Link, 2006)
Longhorn sculpin biomass (t, total)	total biomass of Longhorn sculpin from BTS (t)	(Azarovitz, 1981; NEFC, 1988; Link and Brodziak, 2002)	sensitive species, index of disturbance	(Polis and Strong, 1996; Kaiser and Ramsay, 1997; Jennings and Kaiser, 1998; Hall, 1999; Fonds and Groenewold, 2000; Brodeur *et al.*, 2002; Link and Almeida, 2002; Bilio and Niermann, 2004; Link, 2005; Methratta and Link, 2006;)
Trophic level (mt, mean)	mean trophic level of surveyed spp. weighted by abundance (biomass)	(Azarovitz, 1981; NEFC, 1988; Link and Brodziak, 2002)	size distribution, energy flow	(Pauly *et al.*, 1998)
Species richness (frequency)	number of surveyed spp. from the BTS	(Azarovitz, 1981; NEFC, 1988; Brodziak and Link, 2002; Link and Brodziak, 2002)	aggregate community status	(Jennings and Kaiser, 1998; Hall, 1999; Rice, 2000; Brodziak and Link, 2002; Rice, 2003; Nicholson and Jennings, 2004; Link, 2005; Methratta and Link, 2006)

All indicators were calculated for the NES LME from NMFS fall and spring trawl survey data.

Table 2. Environmental (EV) and anthropogenic variables (AV) used as pressure variables in GAM analysis.

Pressure variable	Definition	Data source	Rationale	Rationale source
Landings	total live weight of commercial landings for northeastern US waters ('000 t)	NAFO; http://www.nafo.int/fisheries/frames/fishery-stats.html; NEFSC (1998); Link and Brodziak (2002)	AV; relative anthropogenic exploitation	(EcoAP, 2011)
Atlantic multidecadal oscillation (AMO)	internal ocean-atmosphere variability measured via sea surface temperature (index)	NOAA, AMO smoothed; http://www.esrl.noaa.gov/psd/data/timeseries/AMO/	EV influencing dynamics of deep thermohaline circulation	(Schlesinger and Ramankutty, 1994; Enfield *et al.*, 2001)
Sea surface temperature (SST)	mean SST for NES LME and adjacent waters (°C)	NOAA ERSST v3b dataset; http://www.ncdc.noaa.gov/ersst/	EV influencing spp. distribution, growth, etc.	(EcoAP, 2011)
North Atlantic oscillation[a]	annual average of relative strength between Icelandic Low and Azores High atmospheric pressure cells (index)	http://climatedataguide.ucar.edu/category/data-set-variables/climate-indices/nao	EV influencing temperature, precipitation, and wind fields	(Hurrell, 1995; Stenseth *et al.*, 2002)
North Atlantic oscillation: winter[a]	winter (December– February) average of relative strength between Icelandic Low and Azores High atmospheric pressure cells (index)	http://climatedataguide.ucar.edu/category/data-set-variables/climate-indices/nao	EV influencing temperature, precipitation, and wind fields	(Hurrell, 1995; Stenseth *et al.*, 2002)
Wind stress[a]	force of the wind on the surface of the ocean (N m^{-2})	http://las.pfeg.noaa.gov/las6_5/servlets/dataset?catitem=1636	EV influencing vertical mixing and horizontal currents	(EcoAP, 2011)
Precipitation[a]	annual precipitation in the catchment areas associated with NES LME (cm)	http://climatedataguide.ucar.edu/category/data-set-variables/atmosphere/precipitation	EV influencing river run-off, salinity, and nutrients	(Acker *et al.*, 2005; Greene *et al.*, 2008; EcoAP, 2011)
Stratification (0–50 m)[a]	vertical stacking of layers of water having different densities due to changes in temperature and salinity (kg $m^{-3}m^{-1}$)	NEFSC hydrographic database	EV influencing the vertical distribution of nutrients	(EcoAP, 2011)

All variables were calculated for the NES LME. [a]Denotes variables that were eliminated during the model selection process.

an added ridge penalty such that the whole smoothing term could be minimized to zero (Wood, 2003). Through this eigenvalue optimization process, a smoothing term can be reduced to a linear function of the pressure variable such that it is effectively eliminated from the model if it does not improve fit.

Candidate models representing unique combinations of pressure and indicators were eliminated from further analysis based on the following criteria: (i) p-value > 0.05, (ii) the estimated degrees of freedom (EDF) were close to their lower limit (i.e. zero for thin plate regression splines with added penalty), and (iii) if the GCV score for the model decreases if the smoothing term is removed from the model (Wood and Augustin, 2002). Models that met these criteria generally appeared to be linear.

We measured uncertainty surrounding each GAM by using a naive bootstrap with random sampling and replacement. For each indicator–pressure combination, bootstrap replicates ($br = i \ldots 1000$) were selected from the raw data and each br_i was fitted with a GAM. To establish 95% confidence intervals (CI) surrounding the original smoothing function $s(X)$, we sorted br into ascending order and the value of the 2.5% and 97.5% quantiles of br estimates were considered the 95% CI for the smoothing function (see Buckland, 1984; Fewster *et al.*, 2000; Cury *et al.*, 2011).

Analysis of derivatives

The shape of the relationship between a response and pressure is captured in the smoothing function $s(X)$. Values of the pressure variable that influence the response in a particular direction can be enumerated by recognizing qualities of the shape of the smoothing function. The first derivative $\hat{s}'(X)$ of $s(X)$ indicates regions where a pressure variable causes a negative $[\hat{s}'(X) < 0]$ or positive $[\hat{s}'(X) > 0]$ response to an ecological indicator. Further, the second derivative $\hat{s}''(X)$ denotes regions where $\hat{s}'(X)$ changes sign and a threshold is crossed $[0 < \hat{s}''(X) > 0\ ]$. To measure the uncertainty surrounding both $\hat{s}'(X)$ and $\hat{s}''(X)$, we estimated the first and second derivatives using finite differences for each bootstrap replicated smoothing term $s_{br}(X)$. Both $\hat{s}_i'(X)$ and $\hat{s}_i''(X)$ were sorted into ascending order and the value of the 2.5% and 97.5% quantiles of $\hat{s}_i'(X)$ and $\hat{s}_i''(X)$ were considered the 95% CI for the first and second derivative of the smoothing function (Buckland, 1984). A significant trend $\hat{s}'(X)$ or threshold $\hat{s}''(X)$ was identified when the 95% CI crossed zero for either derivative (Fewster *et al.*, 2000; Lindegren *et al.*, 2012). To compare multiple indicators' response to the same pressure variable, we scaled and centred each indicator using z-scores. All analyses were conducted using R version 2.14.2 (R Development Core Team, 2010).

Results

Of the 24 possible GAM models among all pressure–response combinations, 17 were significant. Of these, 11 were significant ($p < 0.05$) with the smoothing function included, and six were significant ($p < 0.05$) without the smoothing function (functionally equivalent to a generalized linear model; Table 3). The deviance explained by models that include a significant smoothing function ranged from 36–58%. Models that did not include a significant smoothing function explained less than 29% of the deviance (Table 4). As non-linear responses can isolate specific regions of significant change, we focus on models that included a significant smoothing function.

The AMO was a significant driver for two of eight ecological indicators (Table 3), total biomass (Figure 1a) and species richness (Figure 1b). Total biomass increased in conjunction with AMO, and at a value of ~0.1 the CI of $\hat{s}'(X)$ is greater than zero and a significant positive trend was observed (Figure 1c). Species richness followed a similar pattern and $\hat{s}'(X)$ was >0 at an AMO value of ~0.05 (Figure 1d).

SST was a significant driver for four indicators (Table 3). Consumption over landings ratio, (Figure 2a), species richness (Figure 2e), and total biomass (Figure 2f) increased with increasing SST. Consumption over landings ratio, (Figure 2c), mean length (Figure 2d), and total biomass (Figure 2h) had a significant positive $\hat{s}'(X)$ above 12.5°C. Mean length, however, also had a significant negative $\hat{s}'(X)$ trend below a $\hat{s}''(X)$ threshold at 11.5°C (Figure 2b).

Commercial landings were a significant driver for four indicators (Table 3). As commercial landings increased, sculpin biomass (Figure 3a), total biomass (Figure 3b), pelagic to demersal ratio (Figure 3f), and species richness (Figure 3e) all decreased. These four indicators had a significant negative $\hat{s}'(X)$ trend below commercial landings of approximately 600 000 metric tons (Figure 3c, d, h and g). Above 600 000 t $\hat{s}'(X)$ was not significantly different from zero.

Although the patterns between pressure variables and responses were varied, complementary regions where several indicators responded to pressure variables were observed. For example, at an AMO value of ~0.05 we see several ecological indicators respond in a significant upward trend (Figure 4). Therefore, if AMO

Table 3. p-values for all GAM models analysed.

	Pressure variables		
Ecological indicators	**Landings**	**AMO**	**SST**
Length	0.0001 L	0.74 L	**0.001 S**
Biomass	**0.0001 S**	**0.003 S**	**0.046 S**
Planktivores and benthivores to piscivores and shrimp-fish feeders ratio	0.0001 L	0.002 L	0.82 L
Pelagic to demersal ratio	**0.0001 S**	0.0013 L	0.32 L
Consumption ratio	N/A	0.0011 L	**0.0219 S**
Longhorn sculpin biomass	**0.0001 S**	0.0001 L	0.008 L
Trophic level	0.109 S	0.86 L	0.47 L
Species richness	**0.0001 S**	**0.015 S**	**0.0001 S**

Significant models including a smoothing term (S) are shown in bold. Models with the smoothing term removed are effectively generalized linear models (L).

Table 4. Deviance explained for all GAM models analysed.

	Pressure Variables		
Ecological indicators	**Landings**	**AMO**	**SST**
Length	0.22 L	0.002 L	**0.55 S**
Biomass	**0.46 S**	**0.44 S**	**0.28 S**
Planktivores and benthivores to piscivores and shrimp-fish feeders ratio	0.21 L	0.29 L	0.001 L
Pelagic to demersal ratio	**0.53 S**	0.09 L	0.022 L
Consumption ratio	N/A	0.23 L	**0.2 S**
Longhorn sculpin biomass	**0.58 S**	0.21 L	0.14 L
Trophic level	0.11 S	0.0007 L	0.01 L
Species richness	**0.47 S**	**0.36 S**	**0.47 S**

Significant models including a smoothing term (S) are shown in bold. Models with the smoothing term removed are effectively generalized linear models (L).

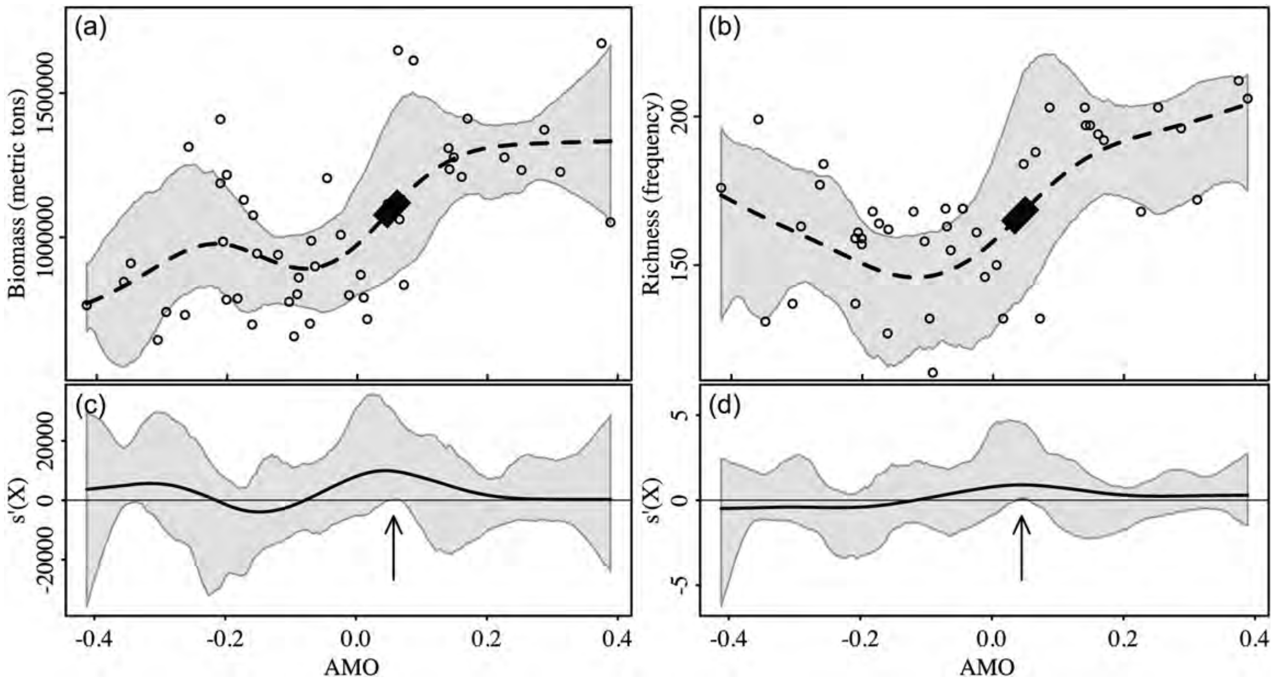

Figure 1. GAM of indicators response to pressures, where the dashed line represents the GAM smoother, the gray polygon represents 95% CI, points represent the raw data, black solid lines indicate significant positive or negative trends, and gray solid lines indicate significant thresholds. The first derivative of the GAM smoother line is below, where the solid line indicates the first derivative of smoother line, gray polygon represents 95% CI, black polygon and arrows indicate direction (positive or negative) of the trend where the 95% CI pass above or below zero, representing a significant deviation from zero. (a) Biomass ($p < 0.001$, deviance explained = 0.44) and (b) species richness ($p < 0.001$, deviance explained = 0.36) response to AMO, and the first derivative of (c) the biomass and (d) species richness GAM, respectively.

increases above ~0.05 we might expect that the ecosystem respond a certain way, whereas below ~0.05 we might expect the opposite. Similarly, commercial landings resulted in negative trends for four ecological indicators at approximately 400 000–500 000 t (Figure 6). Two indicators also had significant $\hat{s}''(X)$ thresholds at ~400 000 t and we would expect significant ecosystem change as commercial landings increase above this value. In regions of high commercial landings we see a different ecosystem state than when commercial landings are lower. SST proves more complicated as there are multiple trends; yet consistent regions of change are still present (Figure 5). Comparing multiple indicator responses to a single pressure variable, we identify regions of consistent change, which were present for AMO, SST, and commercial landings.

Discussion

Based on our results, we draw three main conclusions. First, we assert that this study uses a robust and repeatable analytical technique that clearly identifies trends, thresholds, and fundamental features in non-linear pressure–response relationships. Second, these trends and thresholds represent consistent patterns in this ecosystem's response to anthropogenic and environmental pressures. Finally, we present an approach to determine probable magnitudes where fishing and environmental pressures can notably influence the ecological status of the NES LME.

Trends, thresholds, and fundamental features from GAM models

In this study, we explored mathematical properties of GAM smoothing terms to identify trends and thresholds in pressure–response relationships. Similar techniques have successfully identified thresholds in ecological time-series data (Fewster *et al*., 2000; Andersen *et al*., 2009; Dodds *et al*., 2010; Bestelmeyer *et al*., 2011; Lindegren *et al*., 2012); however, to the best of our knowledge the present study is the first to empirically identify trends and thresholds in pressure–response relationships.

Generalized additive models are statistically robust (Wood and Augustin, 2002; Wood, 2003), yet one of the most frequent criticisms of a GAM approach is the tendency to over-fit the data. To minimize this risk, we used a penalized regression spline that enabled the smoothing term in our model to be reduced to zero (Wood and Augustin, 2002; Wood, 2004a). Further, we used GCV, an integrated model selection algorithm to ensure that the model we selected was as robust as possible (Wood and Augustin, 2002). GAMs are also sensitive to the amount of data available, but given the length of our data (46 years) and that we only used a single parameter in each model, we are confident that this is not an issue. As the goal of this research was to identify regions of values that can inform decision criteria, we did not retain GAM models that were more adequately explained using a linear model. Doing so would provide a slope for the entire model but would not offer insight into specific regions of change. Non-linear models, however, do enable us to identify regions of change, and further fundamental features within these relationships.

In addition to identifying trends and thresholds, our approach allowed us to identify fundamental features of pressure–response relationships. Both environmental pressure variables, SST (Enfield *et al*., 2001) and AMO (Kushnir, 1994), vary on inter- to multidecadal frequencies in the NES LME. Similarly, indicators

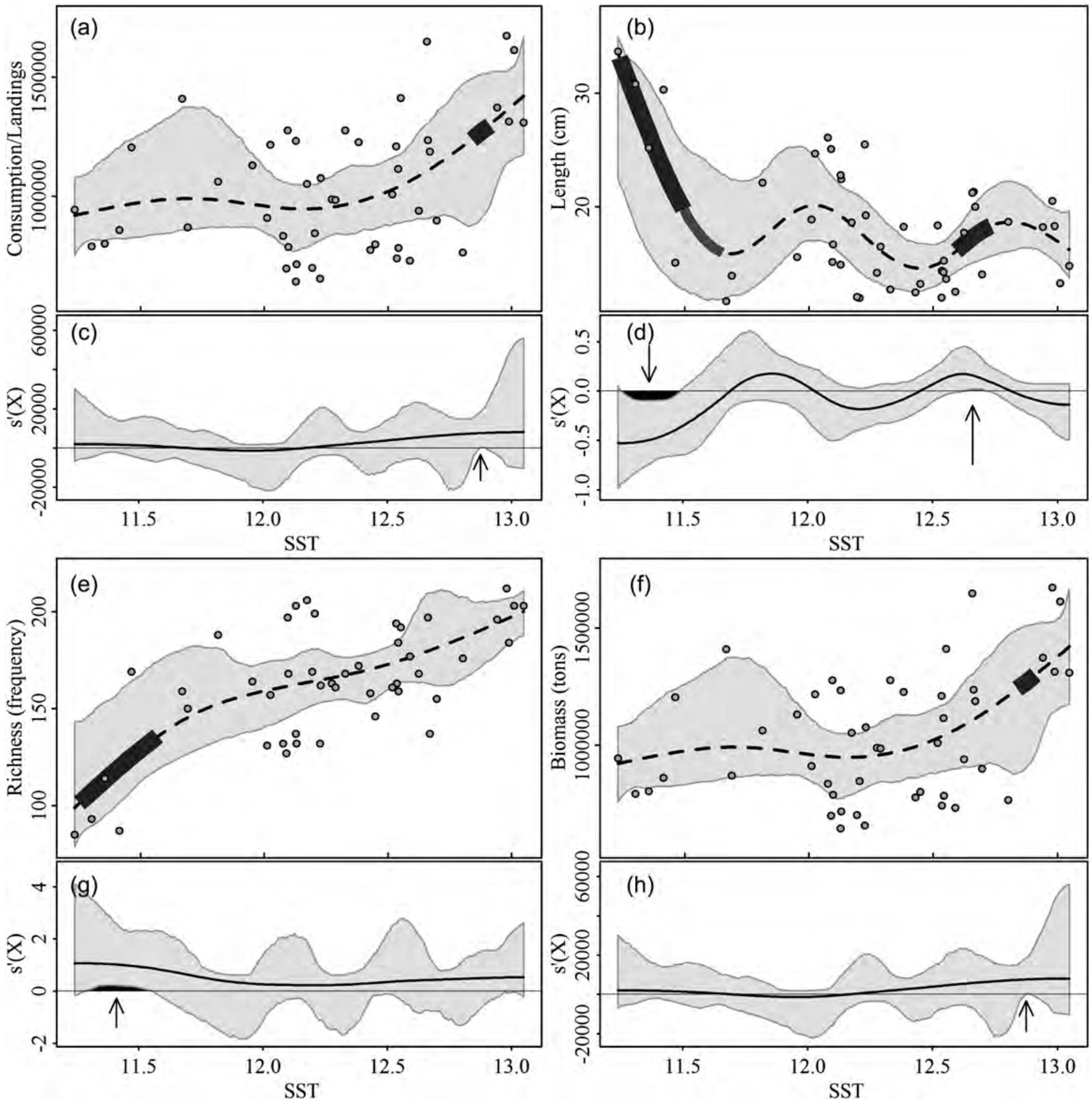

Figure 2. Please see Figure 1 label for figure designations. Where, (a) consumption/landings ($p < 0.05$, deviance explained = 0.21), (b) mean length ($p < 0.001$, deviance explained = 0.55), (e) species richness ($p < 0.001$, deviance explained = 0.48), and (f) biomass ($p < 0.01$, deviance explained = 0.29) in response to SST. First derivatives (c, d, g, and h) are labeled as described in Figure 1.

responded to both pressure variables in an oscillatory pattern with a slight increase in ecological indicators as these pressures increased. Fish production and recruitment vary according to climatic patterns (Sundby and Giske, 2000; Brander, 2007), and here we confirm and further demonstrate that these environmental effects can also influence the dynamics of ecological indicators (Link *et al*., 2010).

Ecological indicators are also influenced by fishing pressure (Rochet and Trenkel, 2003; Libralato *et al*., 2008; Link *et al*., 2010). When fishing pressure (here denoted by landings) increased, we observed that indicators tended to decrease in a non-linear and exponential fashion. Given the fundamental differences with the cyclical patterns of the environment, and the patterns of commercial exploitation, we note differing patterns in indicator response. These patterns are clearly visualized in the first derivative of the GAM smoother.

Regions of consistent change

Ecological indicators are most valuable for EBFM when examined as an ensemble rather than singly; therefore, we identified regions of consistent indicator change for each pressure variable (Link, 2005; Methratta and Link, 2006; Shin and Shannon, 2010). For example, during warm-phase AMO modes, spatial shifts in copepod populations correspond with subsequent shifts in cod spawning and recruitment (Sundby and Giske, 2000; Hare and

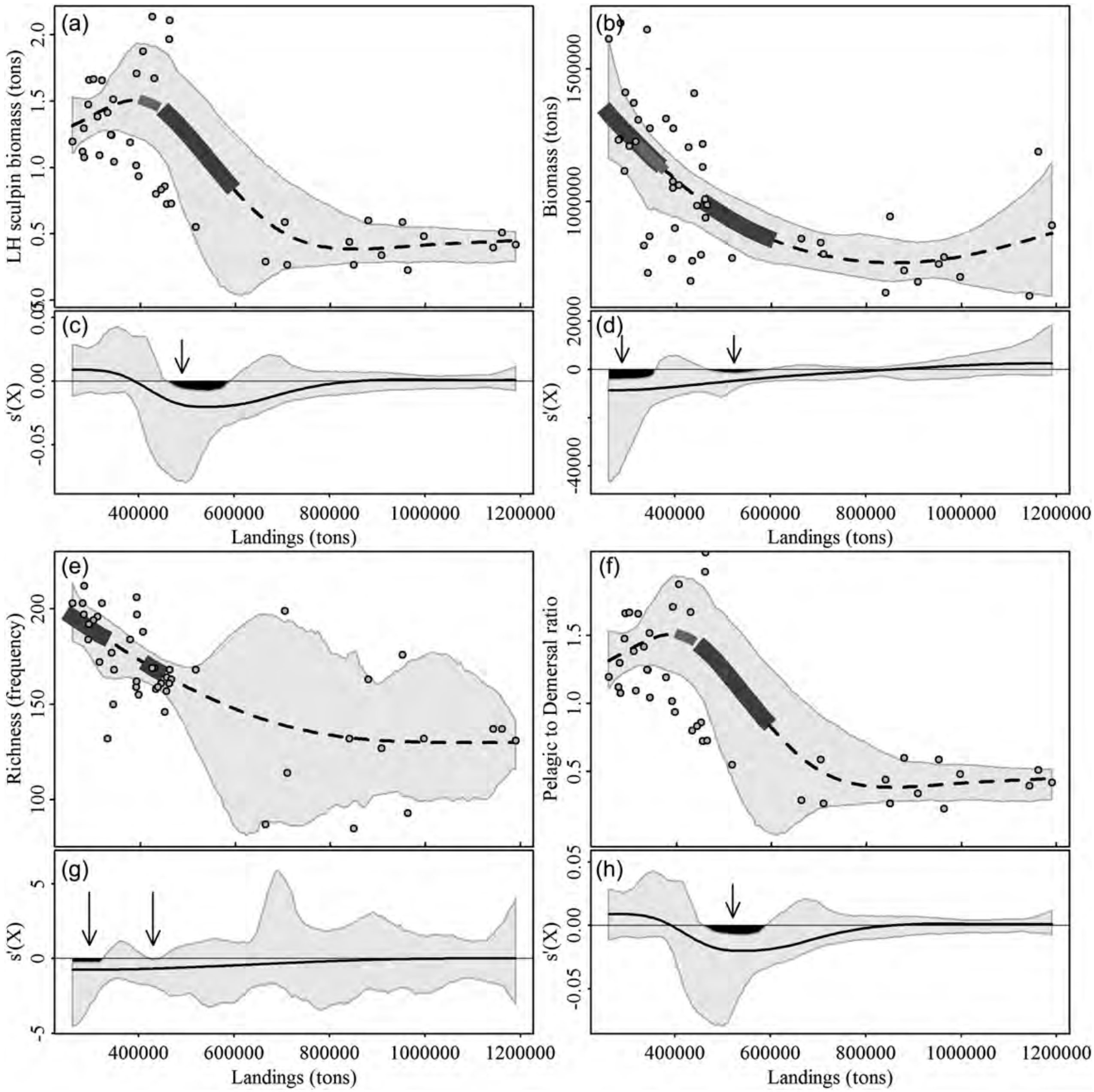

Figure 3. Please see Figure 1 label for figure designations. Where, (a) longhorn sculpin biomass ($p < 0.001$, deviance explained = 0.59), (b) biomass ($p < 0.001$, deviance explained = 0.46), (e) species ricnhess ($p < 0.001$, deviance explained=0.47), and (f) pelagic to demersal ration ($p < 0.001$, deviance explained = 0.53) in response to commercial landings. First derivatives (c, d, g, and h,) are labeled as described in Figure 1.

Able, 2007; Sundby and Nakken, 2008). Similarly, when AMO increased above ~0.05, we noted significant increasing trends of species richness and biomass, which may correspond to shifts in species assemblages (Lucey and Nye, 2010). Ocean temperature (SST) also influences primary productivity (Friedland *et al.*, 2012) and higher trophic level processes (Planque and Frédou, 1999). Although oscillatory (as noted above), we note regions where increased SST causes a significant shift in biomass, consumption/ landings ratio, mean length, and species richness. Each of these indicators could be influenced by available habitat, primary production and predation, which are all mediated by temperature (Peltonen *et al.*, 2007; Lucey and Nye, 2010; Auth *et al.*, 2011).

Excessive fishing negatively influences several ecological indicators of ecosystem status (Jennings and Kaiser, 1998; Link, 2002a, Link, 2002b, Scheffer *et al.*, 2005). When fishing pressure increases, there are often notable and negative ecosystem effects (Link and Brodziak, 2002; Link *et al.*, 2002; Rochet and Trenkel, 2003; Sala *et al.*, 2004). In our present study, when fishing pressure increased above ~400 000 t, four of the seven indicators had negative trends and/or thresholds. While this is a strong suggestion that landings >400 000 t can influence key aspects of ecosystem status for the NES LME, several curious patterns persist. When fishing pressure increases, the pelagic to demersal ratio (Rochet and Trenkel, 2003) and the biomass of scavenger populations (i.e. longhorn sculpin

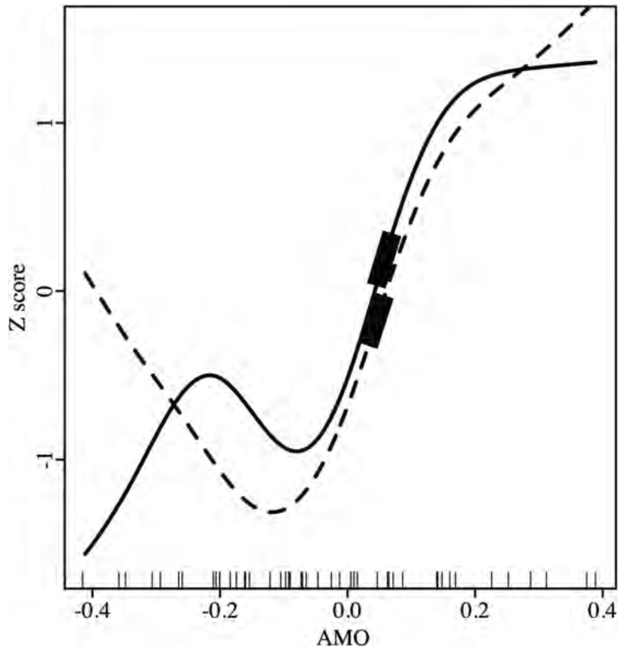

Figure 4. Centred and scaled (z-score) ecological indicators with a significant GAM (with smoothing term included) in response to AMO. Rug plot represents the spread of the data, and significant derivatives are highlighted accordingly.

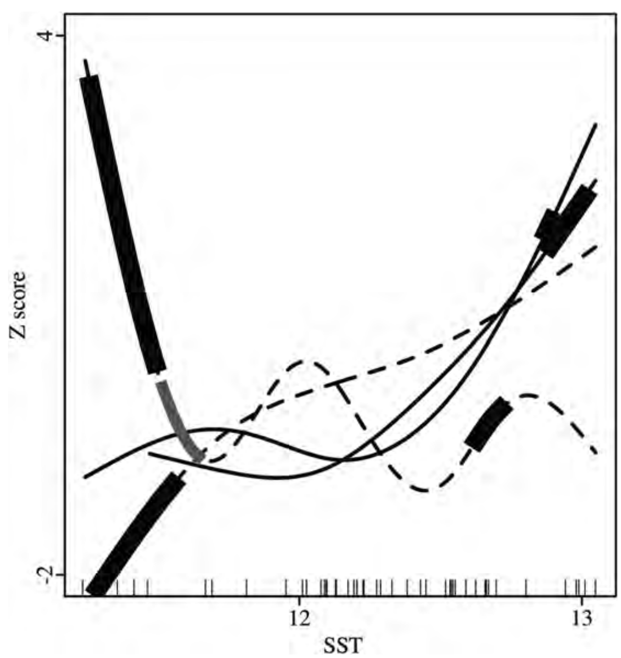

Figure 5. Centred and scaled (z-score) ecological indicators with a significant GAM (with smoothing term included) in response to SST. Rug plot represents the spread of the data, and significant derivatives are highlighted accordingly.

biomass) are expected to increase (Link, 2005). Our analysis however, showed decreases in these indicators when landings increased. We argue that both of these patterns result from selective fishing operations (Smith *et al*., 2011). For example, prior to 1977 foreign fishing fleets targeted small pelagic fish and total annual

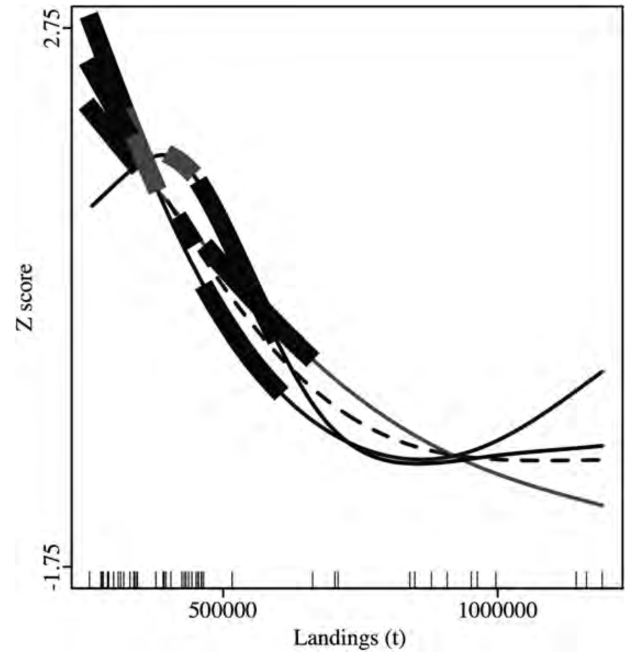

Figure 6. Centred and scaled (z-score) ecological indicators with a significant GAM (with smoothing term included) in response to landings. Rug plot represents the spread of the data, and significant derivatives are highlighted accordingly.

landings typically approached 900 000 t. After the expulsion of the foreign fleets, landings decreased below 400 000 t, and during the 70s–80s groundfish were heavily targeted. Therefore, when fishing pressure was high, small pelagic fish were targeted, and when fishing pressure was lower, groundfish were targeted. If this fishing pattern influenced the survey biomass, we may expect differing results than predicted by Rochet and Trenkel (2003). Scavenger populations are hypothesized to increase in biomass because of opportunistic feeding in response to bottom trawls (Kaiser and Ramsay, 1997; Hall, 1999; Link and Almeida, 2002; Link, 2005). Therefore, if fishing patterns are consistent over time, scavenger biomass will likely increase. However, given the historic patterns of fishing in the NES LME where the commercial fishing effort differentially targeted stocks at different times, the biomass of scavengers (e.g. sculpins) may vary accordingly. Indicator responses should not be considered universal across ecosystems, and these examples highlight the importance of understanding the history and ecological response of different fishing practices when identifying features in pressure–response relationships.

Decision criteria

In an SS context, indicators such as B_{MSY} and F are used to establish reference points or control rules to inform management decisions (Hilborn and Walters, 1992; Quinn and Deriso, 1999; Restrepo, 1999). Similarly, in an EBFM context, indicators can be used for assessing ecosystem status and creating decision criteria for management action (Sainsbury *et al*., 2000; Link, 2010; Murawski *et al*., 2010). While recommendations for decision criteria have been suggested (Link *et al*., 2002; Blanchard *et al*., 2010; Coll *et al*., 2010; Link *et al*., 2010; Samhouri *et al*., 2010), the aim of this analysis was to explore regions of environmental and anthropogenic pressures that can be translated into decision criteria. For example, when fishing pressure increases beyond 400 000 t, negative trends and thresholds are present. Indicators when landings were <400 000 t may represent a more desirable ecosystem status with high biomass and species richness. It may be that as a general feature, landings maintained below this threshold would result in ecosystem status more robust to the negative impacts of over-exploitation or environmental perturbation. However, as landings data do not reflect unconstrained pressure and include the effects of management actions, we cannot fully distinguish between the influence of over-exploitation or management action.

Environmental pressures should also be incorporated into a framework for establishing decision criteria (Gaichas *et al*., 2012; Link *et al*., 2012). In this study we found patterns in indicator response to both fishing and environmental pressures, which suggests the potential for interactions between multiple pressures upon ecological indicators. In this context, decision criteria will need to be designed to concurrently account for both fishing and environmental pressures. For example, when the AMO is in a warm-phase there may be a higher total biomass available for landings, so that landings threshold could be increased accordingly. Conversely, if SST or AMO are in a cool-phase, the landings threshold may need to be reduced. Future research is needed to fully incorporate interactions between both fishing and environmental variables for determining decision criteria.

Conclusions

Consistent and coherent features were observed with both fishing and environmental pressures causing trends and thresholds in ecological indicators, albeit with univariate responses to multiple pressures. As fishing and environmental pressures coexist, future studies should explore relationships among multivariate responses to a multivariate suite of pressures (Fu *et al*., 2012). Doing so would provide a deeper mechanistic understanding of how interactions between the environment and anthropogenic factors influence collective ecosystem status and LMR. In implementing EBFM it is necessary to identify decision criteria for management action. As single species approaches often fail to account for ecological factors, a univariate evaluation of ecological indicators may not fully account for the combined effect of environmental and anthropogenic pressure. Since EBFM aims to fully address human, ecological, and environmental factors that influence LMRs, a multivariate understanding of these factors will best advise decision criteria.

We contribute an approach that empirically identifies trends and thresholds in ecological indicator–pressure relationships. By understanding how various pressures influence ecosystem status we facilitate the development of decision criteria for management action, and further the implementation of EBFM.

Funding

This work was supported by a NOAA NMFS Fisheries and the Environment (FATE) grant. We thank all those who participated in the NEFSC bottom trawl survey and have maintained this database. We thank M. Fogarty, R. Gamble, S. Gaichas, and two anonymous reviewers for their thoughtful comments on earlier versions of this work.

References

Acker, J. G., Harding, L. W., Leptoukh, G., Zhu, T., and Shen, S. 2005. Remotely-sensed chl a at the Chesapeake Bay mouth is correlated with annual freshwater flow to Chesapeake Bay. Geophysical Research Letters, 32: L05601.

Andersen, T., Carstensen, J., Hernández-García, E., and Duarte, C. M. 2009. Ecological thresholds and regime shifts: approaches to identification. Trends in Ecology & Evolution, 24: 49–57.

Auth, T. D., Brodeur, R. D., Soulen, H. L., Ciannelli, L., and Peterson, W. T. 2011. The response of fish larvae to decadal changes in environmental forcing factors off the Oregon coast. Fisheries Oceanography, 20: 314–328.

Azarovitz, T. 1981. A brief historical review of the Woods Hole Laboratory trawl survey time series. Canadian Special Publication of Fisheries and Aquatic Sciences, 58: 62–67.

Beaugrand, G., Edwards, M., Brander, K., Luczak, C., and Ibanez, F. 2008. Causes and projections of abrupt climate-driven ecosystem shifts in the North Atlantic. Ecology letters, 11: 1157–1168.

Bestelmeyer, B. T., Ellison, A. M., Fraser, W. R., Gorman, K. B., Holbrook, S. J., Laney, C. M., Ohman, M. D., *et al.* 2011. Analysis of abrupt transitions in ecological systems. Ecosphere, 2: 129.

Bianchi, G., Gislason, H., Graham, K., Hill, L., Jin, X., Koranteng, K., Manickchand-Heileman, S., *et al.* 2000. Impact of fishing on size composition and diversity of demersal fish communities. ICES Journal of Marine Science, 57: 558–571.

Bilio, M., and Niermann, U. 2004. Is the comb jelly really to blame for it all? *Mnemiopsis leidyi* and the ecological concerns about the Caspian Sea. Marine Ecology Progress Series, 269: 173–183.

Blanchard, J. L., Coll, M., Trenkel, V. M., Vergnon, R., Yemane, D., Jouffre, D., Link, J. S., *et al.* 2010. Trend analysis of indicators: a comparison of recent changes in the status of marine ecosystems around the world. ICES Journal of Marine Science, 67: 732–744.

Brander, K. M. 2007. Global fish production and climate change. Proceedings of the National Academy of Sciences of the United States of America, 104: 19709.

Brodeur, R. D., Sugisaki, H., and Hunt, G. L., Jr. 2002. Increases in jellyfish biomass in the Bering Sea: implications for the ecosystem. Marine Ecology Progress Series, 233: 89–103.

Brodziak, J., and Link, J. 2002. Ecosystem-based fishery management: what is it and how can we do it? Bulletin of Marine Science, 70: 589–611.

Brodziak, J., and O'Brien, L. 2005. Do environmental factors affect recruits per spawner anomalies of New England groundfish? ICES Journal of Marine Science, 62: 1394–1407.

Buckland, S. T. 1984. Monte Carlo confidence intervals. Biometrics, 40: 811–817.

Coll, M., Shannon, L. J., Yemane, D., Link, J. S., Ojaveer, H., Neira, S., Jouffre, D., *et al.* 2010. Ranking the ecological relative status of exploited marine ecosystems. ICES Journal of Marine Science, 67: 769–786.

Cury, P. M., Boyd, I. L., Bonhommeau, S., Anker-Nilssen, T., Crawford, R. J. M., Furness, R. W., Mills, J. A., *et al.* 2011. Global seabird response to forage fish depletion—one-third for the birds. Science, 334: 1703–1706.

Dodds, W. K., Clements, W. H., Gido, K., Hilderbrand, R. H., and King, R. S. 2010. Thresholds, breakpoints, and nonlinearity in freshwaters as related to management. Journal of the North American Benthological Society, 29: 988–997.

Duplisea, D. E., and Kerr, S. R. 1995. Application of a biomass size spectrum model to demersal fish data from the Scotian Shelf. Journal of Theoretical Biology, 177: 263–269.

Duplisea, D. E., Kerr, S. R., and Dickie, L. M. 1997. Demersal fish biomass size spectra on the Scotian Shelf, Canada: species replacement at the shelfwide scale. Canadian Journal of Fisheries and Aquatic Sciences, 54: 1725–1735.

EcoAP (Ecosystem Assessment Program). 2009. Ecosystem Status Report For the Northeast U.S. Continental Shelf Large Marine Ecosystem. Northeast Fisheries Science Center Reference Document, 09-11: 34.

EcoAP (Ecosystem Assessment Program). 2011. Ecosystem Status Report For the Northeast Shelf Large Marine Ecosystem-2011. Northeast Fisheries Science Center Reference Document, 12-07: 38.

Enfield, D. B., Mestas-Nunez, A. M., and Trimble, P. J. 2001. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U. S. Geophysical Research Letters, 28: 2077–2080.

Fath, B. D., Patten, B. C., and Choi, J. S. 2001. Complementarity of ecological goal functions. Journal of Theoretical Biology, 208: 493–506.

Fewster, R. M., Buckland, S. T., Siriwardena, G. M., Baillie, S. R., and Wilson, J. D. 2000. Analysis of population trends for farmland birds using generalized additive models. Ecology, 81: 1970–1984.

Fogarty, M. J., and Murawski, S. A. 1998. Large-scale disturbance and the structure of marine systems: fishery impacts on Georges Bank. Ecological Applications, 8: 6–22.

Fonds, M., and Groenewold, S. 2000. Food subsidies generated by the beam-trawl fishery in the southern North Sea. *In* Effects of Fishing on Nontarget Species and Habitats. Biological, Conservation and Socio-economic Issues, pp. 130–150. Ed. by M. Kaiser, and S. De Groot. Blackwell Science, Oxford.

Friedland, K. D., Stock, C., Drinkwater, K. F., Link, J. S., Leaf, R. T., Shank, B. V., Rose, J. M., *et al.* 2012. Pathways between primary production and fisheries yields of large marine ecosystems. PLoS One, 7: e28945.

Fu, C., Gaichas, S., Link, J., and Bundy, A. 2012. Relative importance of fisheries, trophodynamic and environmental drivers in a series of marine ecosystems. Marine Ecology Progress Series, 459: 169–184.

Gaichas, S., Bundy, A., Miller, T., Moksness, E., and Stergiou, K. 2012. What drives marine fisheries production. Marine Ecology Progress Series, 459: 159–163?

Garcia, S. M., and Cochrane, K. L. 2005. Ecosystem approach to fisheries: a review of implementation guidelines. ICES Journal of Marine Science, 62: 311–318.

Garcia, S., and Leiva Moreno, I. 2003. Global overview of marine fisheries. *In* Responsible Fisheries in the Marine Ecosystem, pp. 1–24. Ed. by M. Sinclair, and G. Valdimarsson. FAO, Rome.

Garcia, S. M., Zerbi, A., Aliaume, C., Do Chi, T., and Lasserre, G. 2003. The ecosystem approach to fisheries: issues, terminology, principles, institutional foundations, implementation and outlook, FAO Fisheries Technical Paper.

Garrison, L. P., and Link, J. S. 2000. Dietary guild structure of the fish community in the Northeast United States continental shelf ecosystem. Marine Ecology Progress Series, 202: 231–240.

Greene, C. H., Pershing, A. J., Cronin, T. M., and Ceci, N. 2008. Arctic climate change and its impacts on the ecology of the North Atlantic. Ecology, 89: 24–38.

Hall, S. 1999. The Effects of Fishing on Marine Ecosystems and Communities. Blackwell Science, Oxford, UK. 296 pp.

Hall, S. J., and Mainprize, B. 2004. Towards ecosystem-based fisheries management. Fish and Fisheries, 5: 1–20.

Hare, J. A., and Able, K. W. 2007. Mechanistic links between climate and fisheries along the east coast of the United States: explaining population outbursts of Atlantic croaker (*Micropogonias undulatus*). Fisheries Oceanography, 16: 31–45.

Hastie, T. J., and Tibshirani, R. J. 1990. Generalized Additive Models. Chapman and Hall/CRC, New York.

Hilborn, R., and Walters, C. 1992. Quantitative Fisheries Stock Assessment: Choice, Dynamics, and Uncertainty. Chapman and Hall, New York.

Hinkley, D. V. 1970. Inference about the change-point in a sequence of random variables. Biometrika, 57: 1–17.

Hsieh, C., Reiss, C. S., Hunter, J. R., Beddington, J. R., May, R. M., and Sugihara, G. 2006. Fishing elevates variability in the abundance of exploited species. Nature, 443: 859–862.

Hurrell, J. W. 1995. Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. Science, 269: 676–678.

Jackson, J. B. C., Kirby, M. X., Berger, W. H., Bjorndal, K. A., Botsford, L. W., Bourque, B. J., Bradbury, R. H., *et al.* 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science, 293: 629–637.

Jennings, S. 2004. The ecosystem approach to fishery management: a significant step towards sustainable use of the marine environment? Marine Ecology Progress Series, 274: 279–282.

Jennings, S., Greenstreet, S. P. R., and Reynolds, J. D. 1999. Structural change in an exploited fish community: a consequence of differential fishing effects on species with contrasting life histories. Journal of Animal Ecology, 68: 617–627.

Jennings, S., and Kaiser, M. J. 1998. The effects of fishing on marine ecosystems. Advances in Marine Biology, 34: 201–352.

Jørgensen, S. E., and Müller, F. 2000. Handbook of Ecosystem Theories and Management. Lewis Publishers, Boca Raton, Florida.

Kaiser, M., and Ramsay, K. 1997. Opportunistic feeding by dabs within areas of trawl disturbance: possible implications for increased survival. Marine Ecology Progress Series, 152: 307–310.

Kushnir, Y. 1994. Interdecadal variations in North Atlantic sea surface temperature and associated atmospheric conditions. Journal of Climate, 7: 141–157.

Libralato, S., Coll, M., Tudela, S., Palomera, I., and Pranovi, F. 2008. Novel index for quantification of ecosystem effects of fishing as removal of secondary production. Marine Ecology Progress Series, 355: 107–129.

Lindegren, M., Dakos, V., Gröger, J. P., Gårdmark, A., Kornilovs, G., Otto, S. A., and Möllmann, C. 2012. Early detection of ecosystem regime shifts: a multiple method evaluation for management application. PLoS One, 7: e38410.

Link, J. S. 2002a. Ecological considerations in fisheries management: when does it matter? Fisheries, 27: 10–17.

Link, J. S. 2002b. What does ecosystem-based fisheries management mean? Fisheries, 27: 18–21.

Link, J. S. 2005. Translating ecosystem indicators into decision criteria. ICES Journal of Marine Science, 62: 569–576.

Link, J. S. 2010. Ecosystem-based Fisheries Management: Confronting Tradeoffs. Cambridge University Press.

Link, J. S., and Almeida, F. P. 2000. An overview and history of the food web dynamics program of the Northeast Fisheries Science Center, Woods Hole, Massachusetts. NOAA Technical Memorandum, NMFS-NE-159. 60 pp.

Link, J. S., and Almeida, F. P. 2002. Opportunistic feeding of longhorn sculpin (*Myoxocephalus octodecemspinosus*): are scallop fishery discards an important food subsidy for scavengers on Georges Bank? Fishery Bulletin, 100: 381–385.

Link, J., and Brodziak, J. 2002. Report on the status of the NE US continental shelf ecosystem. NEFSC Ecosystem Status Working Group. Northeast Fisheries Science Center Reference Document, 2: 245.

Link, J. S., Brodziak, J. K. T., Edwards, S. F., Overholtz, W. J., Mountain, D., Jossi, J. W., Smith, T. D., *et al.* 2002. Marine ecosystem assessment in a fisheries management context. Canadian Journal of Fisheries and Aquatic Sciences, 59: 1429–1440.

Link, J. S., Gaichas, S., Miller, T. J., Essington, T., Bundy, A., Boldt, J., Drinkwater, K. F., *et al.* 2012. Synthesizing lessons learned from comparing fisheries production in 13 northern hemisphere ecosystems: emergent fundamental features. Marine Ecology Progress Series, 459: 293–302.

Link, J. S., Yemane, D., Shannon, L. J., Coll, M., Shin, Y. J., Hill, L., and De Fatima Borges, M. 2010. Relating marine ecosystem indicators to fishing and environmental drivers: an elucidation of contrasting responses. ICES Journal of Marine Science, 67: 787–795.

Lucey, S. M., and Nye, J. A. 2010. Shifting species assemblages in the Northeast US continental shelf large marine ecosystem. Marine Ecology Progress Series, 415: 23–33.

Martin, J., Runge, M. C., Nichols, J. D., Lubow, B. C., and Kendall, W. L. 2009. Structured decision making as a conceptual framework to identify thresholds for conservation and management. Ecological Applications, 19: 1079–1090.

Methratta, E. T., and Link, J. S. 2006. Evaluation of quantitative indicators for marine fish communities. Ecological Indicators, 6: 575–588.

Murawski, S. A. 2000. Definitions of overfishing from an ecosystem perspective. ICES Journal of Marine Science, 57: 649–658.

Murawski, S. A., Steele, J. H., Taylor, P., Fogarty, M. J., Sissenwine, M. P., Ford, M., and Suchman, C. 2010. Why compare marine ecosystems? ICES Journal of Marine Science, 67: 1–9.

Myers, R. A., Hutchings, J. A., and Barrowman, N. J. 1997. Why do fish stocks collapse? The example of cod in Atlantic Canada. Ecological Applications, 7: 91–106.

Myers, R. A., and Worm, B. 2003. Rapid worldwide depletion of predatory fish communities. Nature, 423: 280–283.

NEFC. 1988. An evaluation of the bottom trawl survey program of the Northeast Fishery Science Center. NOAA Technical Memorandum, NMFS-F/NEC-52. 83 pp.

NEFSC (Northeast Fisheries Science Center). 1998. Status of Fishery Resources off the Northeastern United States for 1998. US Dep Commer, NOAA Technical Memorandum NMFS-NE-115. 149 pp.

Nicholson, M. D., and Jennings, S. 2004. Testing candidate indicators to support ecosystem-based management: the power of monitoring surveys to detect temporal trends in fish community metrics. ICES Journal of Marine Science, 61: 35–42.

O'Boyle, R., and Jamieson, G. 2006. Observations on the implementation of ecosystem-based management: experiences on Canada's east and west coasts. Fisheries Research, 79: 1–12.

Overholtz, W., Link, J., and Suslowicz, L. 2000. Consumption of important pelagic fish and squid by predatory fish in the northeastern USA shelf ecosystem with some fishery comparisons. ICES Journal of Marine Science, 57: 1147–1159.

Pauly, D. 1979. Theory and management of tropical multispecies stocks. ICLARM Studies and Reviews, 1: 1–35.

Pauly, D., and Christensen, V. 1995. Primary production required to sustain global fisheries. Nature, 374: 255–257.

Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., and Torres, F., Jr. 1998. Fishing down marine food webs. Science, 279: 860–863.

Peltonen, H., Luoto, M., Pääkkönen, J. P., Karjalainen, M., Tuomaala, A., Pönni, J., and Viitasalo, M. 2007. Pelagic fish abundance in relation to regional environmental variation in the Gulf of Finland, northern Baltic Sea. ICES Journal of Marine Science, 64: 487–495.

Pikitch, E., Santora, C., Babcock, E., Bakun, A., Bonfil, R., Conover, D., Dayton, P., *et al.* 2004. Ecosystem-based fishery management. Science, 305: 346–347.

Planque, B., and Frédou, T. 1999. Temperature and the recruitment of Atlantic cod (*Gadus morhua*). Canadian Journal of Fisheries and Aquatic Sciences, 56: 2069–2077.

Polis, G. A., and Strong, D. R. 1996. Food web complexity and community dynamics. American Naturalist, 147: 813–846.

Quinn, T. J., and Deriso, R. B. 1999. Quantitative Fish Dynamics. Oxford University Press, USA.

R Development Core Team. 2010. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Restrepo, V. R. (Ed.) 1999. Proceedings of the Fifth National NMFS Stock Assessment Workshop, Key Largo, Florida, USA. NOAA Technical Memorandum NMFS-F/SPO-40. 161 pp.

Rice, J. C. 2000. Evaluating fishery impacts using metrics of community structure. ICES Journal of Marine Science, 57: 682–688.

Rice, J. 2003. Environmental health indicators. Ocean & Coastal Management, 46: 235–259.

Rice, J., and Gislason, H. 1996. Patterns of change in the size spectra of numbers and diversity of the North Sea fish assemblage, as reflected in surveys and models. ICES Journal of Marine Science, 53: 1214–1225.

Rice, J. C., and Rochet, M. J. 2005. A framework for selecting a suite of indicators for fisheries management. ICES Journal of Marine Science, 62: 516–527.

Rochet, M. J., and Trenkel, V. M. 2003. Which community indicators can measure the impact of fishing? A review and proposals. Canadian Journal of Fisheries and Aquatic Sciences, 60: 86–99.

Rodionov, S. N. 2004. A sequential algorithm for testing climate regime shifts. Geophysical Research Letters, 31: L09204.

Sainsbury, K. J., Punt, A. E., and Smith, A. D. M. 2000. Design of operational management strategies for achieving fishery ecosystem objectives. ICES Journal of Marine Science, 57: 731–741.

Sala, E., Aburto-Oropeza, O., Reza, M., Paredes, G., and López-Lemus, L. G. 2004. Fishing down coastal food webs in the Gulf of California. Fisheries, 29: 19–25.

Samhouri, J. F., Lester, S. E., Selig, E. R., Halpern, B. S., Fogarty, M. J., Longo, C., and Mcleod, K. L. 2012. Sea sick? Setting targets to assess ocean health and ecosystem services. Ecosphere, 3: 41.

Samhouri, J. F., Levin, P. S., and Ainsworth, C. H. 2010. Identifying thresholds for ecosystem-based management. PLoS One, 5: e8907.

Scheffer, M., Carpenter, S., and Young, B. 2005. Cascading effects of overfishing marine systems. Trends in Ecology & Evolution, 20: 579–581.

Schlesinger, M. E., and Ramankutty, N. 1994. An oscillation in the global climate system of period 65–70 years. Nature, 367: 723–726.

Shackell, N. L., Bundy, A., Nye, J. A., and Link, J. S. 2012. Common large-scale responses to climate and fishing across Northwest Atlantic ecosystems. ICES Journal of Marine Science, 69: 151–162.

Shin, Y. J., Bundy, A., Shannon, L. J., Simier, M., Coll, M., Fulton, E. A., Link, J. S., *et al.* 2010. Can simple be useful and reliable? Using ecological indicators to represent and compare the states of marine ecosystems. ICES Journal of Marine Science, 67: 717–731.

Shin, Y. J., and Shannon, L. J. 2010. Using indicators for evaluating, comparing, and communicating the ecological status of exploited marine ecosystems. 1. The IndiSeas project. ICES Journal of Marine Science, 67: 686–691.

Smith, A. D. M., Brown, C. J., Bulman, C. M., Fulton, E. A., Johnson, P., Kaplan, I. C., Lozano-Montes, H., *et al.* 2011. Impacts of fishing low-trophic level species on marine ecosystems. Science, 333: 1147–1150.

Smith, T. M., Reynolds, R. W., Peterson, T. C., and Lawrimore, J. 2008. Improvements to NOAA's historical merged land-ocean surface temperature analysis (1880–2006). Journal of Climate, 21: 2283–2296.

Sonderegger, D. L., Wang, H., Clements, W. H., and Noon, B. R. 2008. Using SiZer to detect thresholds in ecological data. Frontiers in Ecology and the Environment, 7: 190–195.

Stenseth, N. C., Mysterud, A., Ottersen, G., Hurrell, J. W., Chan, K. S., and Lima, M. 2002. Ecological effects of climate fluctuations. Science, 297: 1292–1296.

Sundby, S., and Giske, J. 2000. Recruitment of Atlantic cod stocks in relation to temperature and advection of copepod populations. Sarsia, 85: 277–298.

Sundby, S., and Nakken, O. 2008. Spatial shifts in spawning habitats of Arcto-Norwegian cod related to multidecadal climate oscillations and climate change. ICES Journal of Marine Science, 65: 953–962.

Suter, I. 1993. GW 1993. Ecological Risk Assessment. Lewis, Boca Raton, Florida. 538 pp.

Trenkel, V. M., and Rochet, M. J. 2003. Performance of indicators derived from abundance estimates for detecting the impact of fishing on a fish community. Canadian Journal of Fisheries and Aquatic Sciences, 60: 67–85.

Trenkel, V. M., and Rochet, M. J. 2009. Intersection-union tests for characterising recent changes in smoothed indicator time series. Ecological Indicators, 9: 732–739.

Wood, S. 2004a. mgcv: GAMs with GCV Smoothness Estimation and GAMMs by REML/PQL. R package, version 1.

Wood, S. N. 2003. Thin plate regression splines. Journal of the Royal Statistical Society: Series B (Statistical Methodology), 65: 95–114.

Wood, S. N. 2004b. Stable and efficient multiple smoothing parameter estimation for generalized additive models. Journal of the American Statistical Association, 99: 673–686.

Wood, S. N., and Augustin, N. H. 2002. GAMs with integrated model selection using penalized regression splines and applications to environmental modelling. Ecological Modelling, 157: 157–177.

Zeileis, A., and Kleiber, C. 2005. Validating multiple structural change models–a case study. Journal of Applied Econometrics, 20: 685–690.

Handling editor: Marta Coll