

Direct and indirect effects of climate and fishing on changes in coastal ecosystem services: a historical perspective from the North Sea

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Abstract Humanity depends on the marine environment for a range of vital ecosystem services, at global (e.g. climate regulation), regional (e.g. commercial fisheries) and local scales (e.g. coastal defence and recreation). At the same time, marine ecosystems have been exploited for centuries, and many systems today are under stress from multiple sources. Recent studies have shown how both climate change and fishing have caused long-term changes in the marine environment. However, there is still poor understanding of how these changes influence change in coastal ecosystem services. In this paper, an integrated modelling approach is used to assess how the final delivery of marine ecosystem services to coastal communities is influenced by the direct and indirect effects of changes in ecosystem processes brought about by climate and human impacts, using fisheries of the North Sea region as a case study. Partial least squares path analysis is used to explore the relationships between drivers of change, marine ecosystem processes and services (landings). A simple conceptual model with four variables—climate, fishing effort, ecosystem process and ecosystem services—is applied to

the English North Sea using historic ecological, climatic and fisheries time series spanning 1924–2010 to identify the multiple pathways that might exist. As expected, direct and indirect links between fishing effort, ecosystem processes and service provision were significant. However, links between climate and ecosystem processes were weak. This paper highlights how path analysis can be used for analysing long-term temporal links between ecosystem processes and services following a simplified pathway.

Keywords Marine ecosystem services · Historical ecology · Path analysis · Fisheries · Climate change

Introduction

Drivers of change in coastal ecosystems

Coastal ecosystems have been exploited for centuries (Worm et al. 2006; Roberts 2007; Lotze et al. 2010), and many today are under stress from multiple sources including overfishing, pollution and climate change (Halpern et al. 2012). Such stresses have led to marked changes in the structure of marine ecosystems, for instance in terms of the collapse of fisheries and changes in food webs (Jackson et al. 2001, Cardinale et al. 2012). Recent studies have shown the causal links between physical (climate) and social drivers (human impact), and changes in marine ecosystems (Link et al. 2009; Jennings and Brander 2010; Sumaila et al. 2011; Heath et al. 2012). The relationship between direct exploitation and changes in the abundance of target and nontarget species has been well documented (Hofstede and Rijnsdorp 2011; Luczak et al. 2012; Kerby et al. 2013). Likewise, effects of rising temperatures on species and ecosystems are increasingly well

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understood (Perry et al. 2005; Dulvy et al. 2008). However, what is still lacking is an integrated approach to assess how these processes affect the delivery of marine ecosystem services to coastal communities and how these changes are influenced by the direct and indirect links between ecosystem processes, climate and human impacts.

Classification of coastal ecosystem services

Coastal ecosystems provide vital suites of ecosystem services to local communities, visitors and wider society. For instance, they act as a source of food (fisheries), employment (fishing and tourism sectors) and recreation (tourism, water sports and wildlife watching) (Beaumont et al. 2007). Mace et al. (2012) present a system for classifying these different services by considering separately ecosystem goods and final ecosystem services (benefits) as shown for coastal ecosystems in Fig. 1. The relative contributions of these different ecosystem services to the full suite of services provided by a given coastal system will clearly change over time, as both societal priorities and states of ecosystem change. We know that ecosystem services are linked to ecosystem function and processes (Solan et al. 2012). This implies that different suites of ecosystem services will be affected by the states of different ecosystem components. However, the relationship between different services and state of the ecosystem is poorly understood (Bennett et al. 2009; Feld et al. 2009; Cardinale et al. 2012). There is thus a crucial link to be made between ecosystem processes and potential ecosystem service provision.

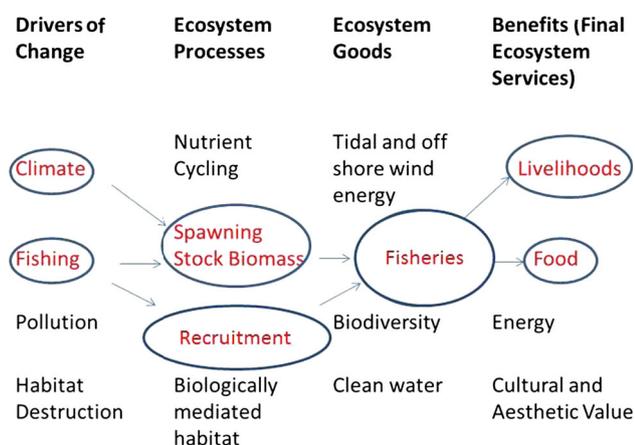


Fig. 1 Schematic diagram, based on the framework of Mace et al. (2012), showing how a selection of drivers can affect various processes in coastal ecosystems and how these in turn can affect ecosystem good and benefits (final ecosystem services). In this study, we look at the highlighted pathway linking fishing and climate (drivers) to SSB and recruitment of three demersal fish species (ecosystem processes) and the consequences for delivery of the ecosystem goods (fisheries) and ultimately on food provision and economic livelihoods (final ecosystem services)

One approach for linking anthropogenic drivers, ecosystem function and diversity, and services is to use the driver–pressure–state–impact–response (DPSIR) framework, but most implementations of this approach have been theoretical (Bowen and Riley 2003; Chan and Ruckelshaus 2010; Rounsevell et al. 2010) and empirical evidence and applications to real case studies are lacking. Overall, little applied research exists at large spatial and temporal scales on how these various factors are correlated and how they interact to bring about changes in ecosystem processes and service provision. There is thus a need to study marine processes on a large spatial and temporal scale (Cardinale et al. 2012; Raffaelli and Friedlander 2012) to connect these variables to service provision.

Using history to understand the causal links between drivers, ecosystem and services

Increasingly, researchers are turning to history to understand past ecosystem states (Jackson et al. 2001; Lotze and Worm 2009; Szabó 2010), as it offers unique insights into lost ecological communities. This approach has the potential to provide a better understanding of current processes in nature and how they have been shaped by natural climatic fluctuations and anthropogenic climate change, as well as human activities (e.g. land use change and fishing). Studies incorporating this historical dimension have shown several trends that have shifted our existing perspective on marine systems, such as the previously much higher abundances and larger individual sizes of several species and the rich diversity that existed in the past (Roberts 2003). A long-term perspective provides a means to understand these links, by analysing historic time series of physical and biological changes in a coastal ecosystem together with social changes in the provision of certain ecosystem services.

In this paper, we illustrate how this historical perspective can be applied to long-term time series, using a partial least squares path modelling approach to show how climate and fisheries can affect ecosystem processes, and through this coastal ecosystem service provision. We used the coastal region of North East England from Sunderland to Grimsby to quantify provision of an exemplar ecosystem service, the food provision and livelihoods supported by fisheries, over the course of most of the twentieth century, a period encompassing significant changes in environmental and socioeconomic drivers of change. We use the excellent records of the biological communities and climatic history of this coastal region, as well as socioeconomic data on fishing effort and fish landings, to examine how shifts in environmental drivers have affected fish populations and ultimately fisheries. In particular, we test the hypotheses that fishing effort will negatively affect both indicators of

fish populations (adult biomass and recruitment), despite being positively related to landings. In contrast, we have no clear expectation of the direction of the effects of climatic variables on either fish populations or fisheries landings.

Methods and materials

Study region

This study focuses on the North Sea, covering the spatial range between 52° N and 60° N and between 2° W and 4° E (Fig. 2). The North Sea has been heavily exploited by the industrialised and densely populated nations surrounding it. It has been fished intensively since 1900, and fishing effort has increased consistently since that time (Rijnsdorp 1996; Jennings et al. 2002). This region has been the focus of numerous long-term ecological surveys, including the Continuous Plankton Recorder survey (<http://www.sahfos.ac.uk>), UK government bottom trawl surveys of demersal fish (<http://www.ices.dk/marine-data/data->

portals/Pages/DATRAS.aspx), the Seabirds at Sea programme (jncc.defra.gov.uk/page-1547) and the North Sea Benthos Survey (NSBS; Craeymeersch and Duineveld 2011). At present, the North Sea has regained importance in Britain's fisheries as, for example, in 2009, it provided 63 % of the demersal fish landed by UK vessels into the UK and abroad (Marine Management Organization 2009). We consider the coastline from Sunderland to Grimsby, focusing on a single set of ecosystem goods and the associated final ecosystem services, fisheries landings to the Yorkshire Coast—mainly into the ports of Scarborough, Whitby, Filey, Bridlington, Grimsby and Hull (Fig. 2).

Sources of data

Time series of fish abundance spanning the period 1924–2010 are shown in Fig. 3. Historic data on the spawning stock biomass (SSB) and recruitment of three demersal species, cod *Gadus morhua*, haddock *Melanogrammus aeglefinus* and whiting *Merlangius merlangus*, were obtained from Pinnegar (2007). These species are three key commercial species in terms of landings, and they also contribute >50 % by weight of total species composition in the central North Sea demersal fish community (Harding et al. 1986; Sparholt 1990; Hislop 1996). The spatial resolution of this historical data set covered the entire North Sea, and the data are aggregated according to International Council for the Exploration of the Sea (ICES) areas IVa, b and c (Fig. 2). Further details of how these statistical rectangles are defined can be found on the ICES website (<http://www.ices.dk/marine-data/maps/Pages/ICES-statistical-rectangles.aspx>). This coarse resolution is typical of historical datasets and dictated the spatial resolution of our study.

The environmental variables we use are sea surface temperature (SST), to characterise long-term climatic trends, extracted for the study area from ICES Surface Data Source (<http://ocean.ices.dk/data/surface/surface.htm>) and averaged for each year, and the North Atlantic Oscillation (NAO) index, obtained from Hurrell (2013), to characterise short-term climatic fluctuations. Monthly NAO data were averaged across summer months (April–September) and winter months (October–March) for each year.

We extracted fish landing data to the English East Coast ports of Grimsby, Hull, Robin Hood's Bay, Scarborough, Filey, North Shields and Whitby for the three demersal fish from ICES areas IVa, b and c from 1924 to 2010 from ICES records (ICES 2013). Fishing effort data were obtained from UK Sea Fisheries Statistical Archives (http://www.marinemangement.org.uk/fisheries/statistics/annual_archive.htm). We digitised records of fishing effort in terms of number of hours in the North Sea by all sail,

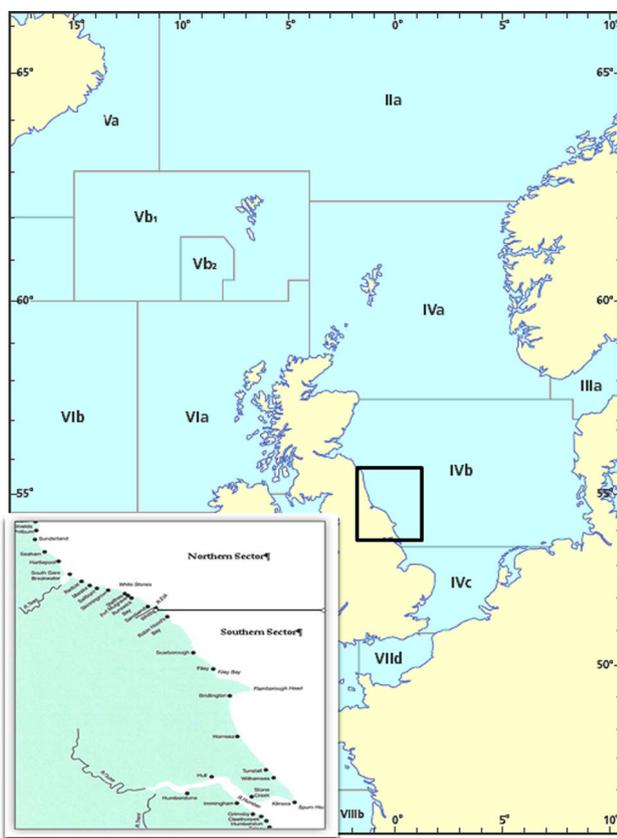


Fig. 2 Study region consists of ICES rectangles IVa, b and c in the North Sea including the fishing ports of NE England highlighted in the black box. These include all ports from Sunderland in the north to Grimsby in the south

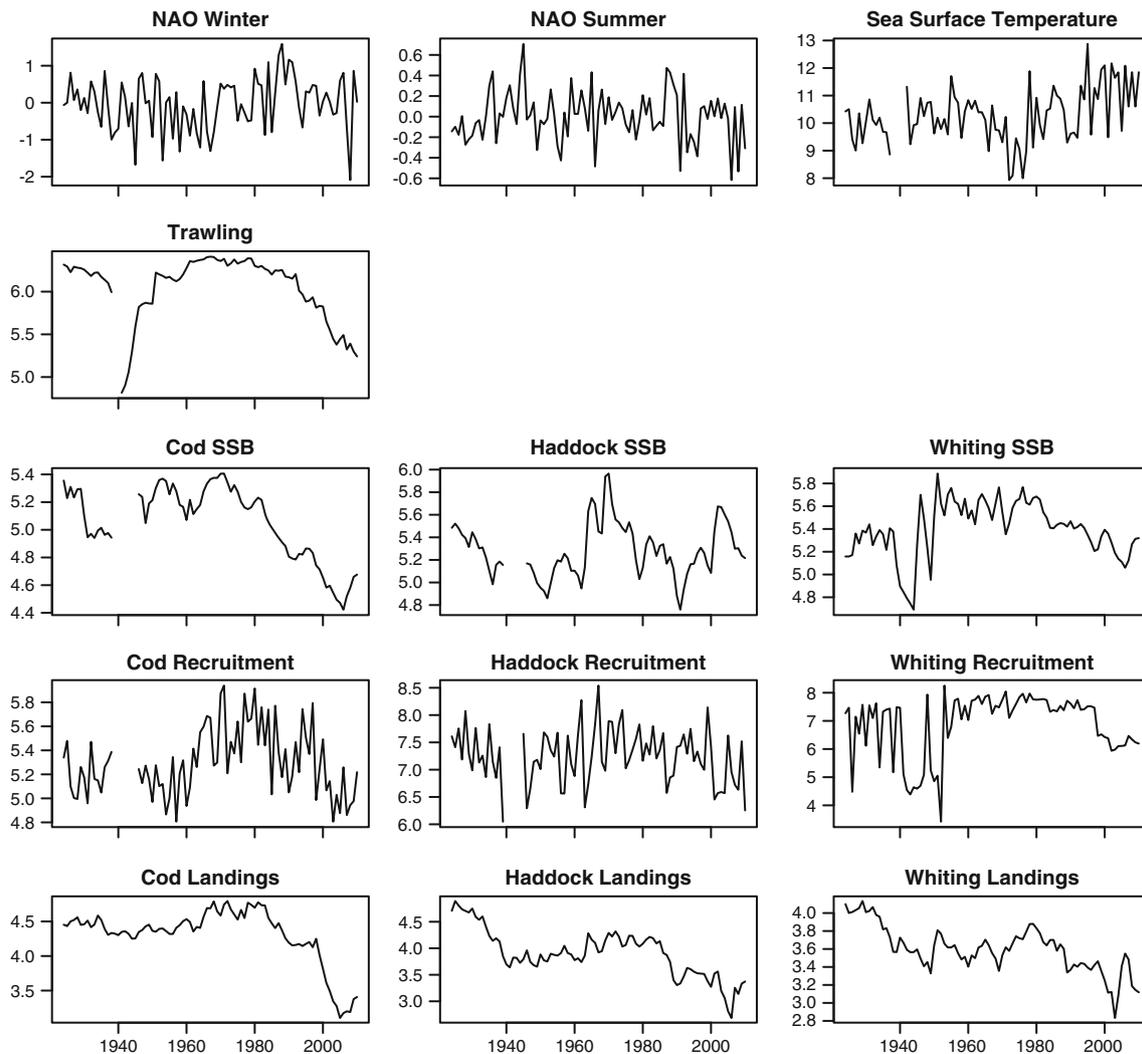


Fig. 3 Time series of the datasets used in this study. Climate is represented by the summer and winter NAO index and by sea surface temperature. Fishing effort is represented by numbers of hours fished by different types of trawlers, standardised to constant power. Ecosystem processes are represented by SSB and recruitment of

three commercial fish species—cod *Gadus morhua*, haddock *Melanogrammus aeglefinus* and whiting *Merlangius merlangus*. Goods and services are represented by landings of these three species into ports on the east coast of England by British trawlers. All variables except the climate indices (NAO and SST) are log-transformed

steam and motor trawls (beam and otter trawler >10 m) from England and Wales for the period 1924–2010 and standardised effort into smack units following Engelhard et al. (2009). Briefly, this is done by taking the fishing power of the original sail trawl as baseline and comparing all other types of trawls (steam and motor) to the fishing power of sail trawl, as recommended by Garstang (1900).

Statistical analysis

We used Partial Least Square Path Modelling using the PLSPM package (Sanchez 2013) in R version 2.15.3 (R Core Team 2013) to investigate the causal relationship between drivers of change (climate and effort), ecosystem processes (SSB and recruitment) and ecosystem services

(fish landings). PLS path modelling is a variance-based form of structural equation modelling (SEM) (Tenenhaus et al. 2005), allowing for the simultaneous modelling of relationships among multiple independent and dependent variables (Gefen et al. 2000). Path modelling is mainly used to measure both direct and indirect pathways between variables, as well latent variables (LVs) that are unobserved or hidden, and it can deal with issues of multicollinearity when modelling complex systems, making no strong assumptions on distribution, sample size and measurement scale (Tenenhaus et al. 2005). It is a component-based estimation method (Vinzi et al. 2010) that contains an inner model (structural model) which measures the causal links between LVs (i.e. variables that are not directly observed) and an outer model (measurement

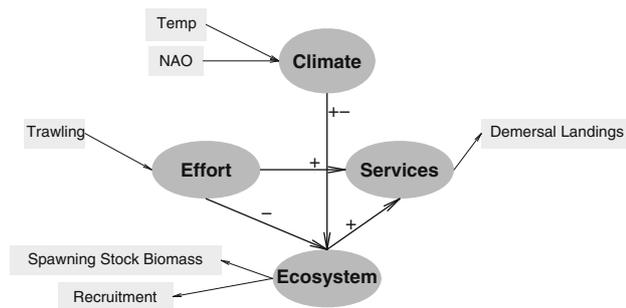


Fig. 4 Conceptual path model linking drivers of change (climate and fishing effort), ecosystem processes and services. The inner model consists of four latent variables (LVs, *dark grey ovals*). Two of these, climate and effort, are exogenous variables (not affected by any external factors). These affect the endogenous variables (ecosystem processes and services) through different pathways. Each LV is measured by its own block of manifest variables, which form the outer model (*light grey boxes*). We hypothesise that climate can affect ecosystem processes directly and services indirectly and that these effects can be positive or negative. Ecosystem processes are hypothesised to positively impact services, and fishing effort is hypothesised to impact ecosystem processes negatively and services positively

model) which shows how blocks of indicator variables measure each LV (Fig. 4). This enables indicators to be aggregated, while taking into account the impact of each indicator on its LV as well as the causal relationship between the unobserved LVs (Trinchera 2010).

Our path model is illustrated in Fig. 4, where four LVs (climate, fishing effort, ecosystem processes and ecosystem services) are each measured by their own block of indicators, and the hypothesised directional flows of the impact of drivers on the ecosystem processes and ecosystem services are indicated. We hypothesised that the exogenous (independent) variables—fishing effort and climate—have four possible pathways linking them to the endogenous (dependent) variables, ecosystem processes and services. PLSPM indicators can be constructed in reflective mode or formative mode. In our path model, climate and effort are represented by formative indicators (e.g. temperature and NAO “inform” the LV climate), whereas ecosystem and services are represented by reflective indicators (e.g. SSB and recruitment are shaped by the LV ecosystem). In reflective mode, any change in the LV will cause a same directional change in the reflective indicators. Alternatively, in formative mode, the direction of the indicator does not have to be the same within the LV. An example of this is the latent variable climate which is measured by SST and NAO, which are likely to be negatively correlated because a negative NAO is associated with mild winters. We further separated the two ecosystem processes, recruitment and SSB, into different LVs so as to better assess whether climate and fishing effort had different

impacts on each. The LV services included landings of the three demersal fish into east England ports.

Both the inner and outer models were assessed using standard measures (Chin and Dibbern 2007) of communality and redundancy, R^2 and goodness of fit (GOF). For the outer model (measurement model), we tested whether the chosen indicators represent and measure their LV effectively, taking a variable weight (for formative indicator) or loading (for reflective indicator) ≥ 0.7 to indicate a reliable construct of the indicators (Sanchez 2013). This is equivalent to a communality (squared loading) > 0.49 , indicating that 50 % of the variability in an indicator is captured by its LV. We tested for unidimensionality (i.e. that all indicators in a block act in the same direction) of LVs measured in reflective mode (ecosystem and services) using Dillon–Goldstein’s ρ (Sanchez 2013), which is considered a better indicator than Cronbach’s α (Chin and Dibbern 2007).

For the inner model, we used R^2 to measure how much of the variance in the endogenous LV is explained by its exogenous LV (Sanchez 2013), and average communality and redundancy to explain variability of the indicators in relation to the amount of variance due to measurement error (Sanchez 2013). We used path coefficients to estimate the strength and direction of the relationship between the exogenous and endogenous LVs (Sanchez 2013), and Goodness of Fit (GOF, the geometric mean of the average communality and average R^2 value) to assess the overall predictive performance of the model. Finally, we used bootstrapping as a final check of the validity of the model pathways and results, using the 95 % bootstrap confidence interval to evaluate whether the parameters are significantly different from zero.

Ecosystem processes and services may not respond instantly to the effort and climate drivers, but instead show lagged responses. We therefore checked for lags of up to 4 years in the relationships between climate and fishing drivers and ecosystem processes and services. Autocorrelation analysis revealed 2-year lags between NAO winter and both cod and whiting recruitment. We therefore included a 2-year time lag for NAO winter in our models.

Past research has shown that there might be strong temporal autocorrelation in climate time series (Sirabella et al. 2001).

When dealing with long time series, it is possible that the relationship between exogenous and endogenous variables has not been constant through time. In particular, in the North Sea, the decline in fishing effort broadly coincides with an increase in SST, suggesting a possible shift from a regime dominated by intensive fishing, to one in which climatic effects are more significant. To test for the effects of this on our model, we first checked the fishing effort time series for changes in temporal trend. Broadly

speaking (Fig. 3), with the exception of the war years, effort increased until the early 1970s and has declined thereafter. Modelling postwar (1946–2010) log-transformed trawling effort as a quadratic function of year produces an excellent fit ($R^2 = 0.96$) with an inflexion point in 1972, after which effort has declined markedly (Fig S1; see supplementary material). Trends in SST are less clear; however, if we model this time series as a two-part linear breakpoint model, the optimal year for the breakpoint (lowest AIC, highest R^2) is also 1972, with a steeper slope (more pronounced warming) from 1972 to 2010 than in earlier years (Fig S1; see supplementary material). Therefore, we re-ran our PLSPM under two different ‘regimes’—a ‘fishing’ regime from 1924 to 1971 defined by heavy fishing effort and a ‘climate’ regime from 1972 to 2010 defined by a stronger climatic influence.

Results

Full time series

The outer model results for the model using the full time series are shown in Table 1. In our model, all the LVs were measured effectively by only some the chosen indicators (Table 1). In both SSB and recruitment, loadings were above 0.7 for cod and whiting, but not for haddock. In the LV services, loadings was high for all landings (>0.7). Effort had only one indicator measuring its LV and therefore does not have a loadings score. The LV climate is formative, and so, we use weights rather than loadings for evaluation. We observed a high weight for the indicator SST (0.83), but not for NAO. Communalities were >0.5 for all the indicators with high loadings (>0.7), and as such more than 50 % of their variance is shared with its corresponding LV. Values of Dillon–Goldstein’s ρ were >0.7 for SSB, recruitment and services, so we consider the indicators to be homogenous and unidimensional in our model.

The overall GOF of our model using the full time series was 0.50, showing that the predictive performance of our model was 50 %. The inner model (showing how well the LVs are related) has R^2 values of 0.21, 0.31 and 0.55, for SSB, recruitment services, respectively (Table 2). In other words, >20 % of the variance in endogenous variables SSB and recruitment, and >50 % of the variance in services, can be explained by the exogenous variables climate and effort. All the endogenous indicators for which it could be calculated had an average communality >0.39 indicating that the indicators used to measure them are represented well in the model (Table 2).

Path coefficients show the strength and direction of the pathways, and in our full time series model (Fig. 5a),

Table 1 Outer measurement results for the three models (full time series, fishing regime and climate regime) showing how well each indicator measures its individual latent variable

Indicator variable	Full time series model	Fishing regime model	Climate regime model
Climate			
NAO ^a winter	<i>0.37</i>	<i>0.49</i>	<i>0.23</i>
NAO summer	<i>-0.29</i>	<i>-0.39</i>	<i>-0.11</i>
SST ^b	0.83	0.81	1.00
Effort			
Total hours trawled	–	–	–
SSB ^c			
Cod	0.93	0.78	0.96
Haddock	0.43	0.91	0.04
Whiting	0.77	0.26	0.95
Recruitment			
Cod	0.75	0.89	0.76
Haddock	0.47	0.59	0.35
Whiting	0.82	0.63	0.9
Landings			
Cod	0.90	0.99	0.97
Haddock	0.67	0.01	0.94
Whiting	0.73	-0.13	0.93

Formative indicator results are measured using weights (in italics), and reflective indicators are measured using loadings. Results that are significant (>0.7) are shown in bold. See text for more details

^a NAO North Atlantic oscillation

^b SST Sea surface temperature

^c SSB Spawning stock biomass

fishing effort had a significant positive effect on both ecosystem processes SSB (0.65, bootstrapped CI 0.54–0.79) and recruitment (0.63, CI 0.43–0.78) and on ecosystem services (fish landings, 0.87, CI 0.67–1.05). Climate had no significant impact on either SSB or recruitment (Fig. 5a). The impacts of SSB and recruitment on services were not significant either (Fig. 5a). PLSPM allows the total effects of LVs to be separated into direct and indirect effects. For our model, indirect effects were typically much weaker than direct effects.

‘Fishing’ versus ‘climate’ regimes

Modelling the ‘fishing’ (1924–1971) and ‘climate’ (1972–2010) regimes separately resulted in some of the path coefficients being different in the two regimes. The weights and loadings (Table 1) show that the LV climate is still measured better by the formative indicator SST in both regimes (0.81, 1.00). In the ‘fishing’ regime, the LV SSB is measured well by cod and haddock SSB (0.78, 0.91), but not by whiting SSB (0.26). In the ‘climate’ regime, LV

Table 2 Reliability convergence of the inner model showing two measures (R^2 and average communality) of the amount of variability in each latent variable (LV) explained by the exogenous LVs climate and fishing effort, for the full time series, fishing regime and climate regime models

LV	Type	R^2 full time series	Average communality	R^2 fishing regime	Average communality	R^2 climate regime	Average communality
SSB	Endogenous	0.210	0.551	0.32	0.50	0.83	0.61
Recruitment	Endogenous	0.310	0.488	0.32	0.51	0.7	0.54
Services	Endogenous	0.551	0.394	0.48	0.34	0.87	0.89

See text for more details. Results >0.5 are shown in bold

SSB is measured well by cod and whiting SSB (0.96, 0.95). The LV recruitment is measured well by cod recruitment only in the fishing regime (0.89) and by both cod and whiting in the climate regime (0.76, 0.90). LV services are measured well by only cod landing in the fishing regime and by all three indicators in the climate regime. R^2 and average communality of the two regimes are provided in Table 2 which shows that the inner model of the ‘climate’ regime had higher R^2 and average communality than the fishing regime model. GOF was also higher for the climate regime model (0.69) than the GOF for the fishing regime model (0.39).

The path coefficients and their 95 % bootstrapped CIs for the two regimes are shown in Fig. 5b and c. The pathways between climate and recruitment have the same directional trend in both regimes. The path coefficients for the pathways effort on ecosystem services were significant in the climate regime (0.47, CI 0.19–0.73), but not in the fishing regime (0.31, CI –0.31–0.79). SSB had a significant positive impact on services in the climate regime (0.50, CI 0.27–0.76), but not in the fishing regime (0.10, CI –0.68–0.69). The pathway from effort to recruitment was significant in both regimes (fishing regime: 0.55, CI 0.29–0.76; climate regime: 0.89, CI 0.70–1.04), that from effort to SSB was significant only in the climate regime (0.81, CI 0.63–0.92) and additionally the SSB to services pathway was significant in the climate regime (0.50, CI 0.27–0.76; Fig. 5b, c).

Discussion

The aim of this study was to illustrate how combining historical data with path modelling can inform our understanding of multiple drivers of marine ecosystem processes and ecosystem services. There is an inevitable trade-off between the data requirements of a model and the time period over which adequate data are available. In this initial implementation, we aimed for maximum temporal coverage which has necessarily led to a simplified and partial representation of the multiple complex pathways between the physical, biological and social drivers of

change in ecosystem service provision. Nonetheless, we have demonstrated how a partial ecosystem pathway model can be used to test several hypotheses about the long-term change in a natural system. Our hypotheses were that effort would have a negative impact on both ecosystem processes, but a positive impact on services. Climate could have either negative or positive impact on ecosystem processes. We found that effort had a positive impact on both the SSB and the recruitment of three commercially important demersal fish species, and these results were significant in all the three models. SSB also had significant positive impact on services in only the ‘climate’ regime model, although the coefficient was positive in all three models. The additional pathways of climate on ecosystem processes and recruitment on services were not significant.

The fact that fishing effort had a positive impact on both SSB and recruitment could be explained by the fact that fishing effort increased during periods of high abundance and availability, such that effort responds to ecosystem processes as well as driving them. Over the 90-year period, as effort increased, especially after 1950s, SSB and recruitment also increased. The direction of causality is unclear here, however, as it could be that fishers were responding to the ‘gadoid outburst’ of the 1960s and 1970s, when cod, haddock and whiting had some of the highest recruitment on record (Cushing 1978; Hislop 1996). Overall, the decline in fishing effort since the 1970s is mostly due to the implementation of quotas and total allowable catches beginning during the 1970s and 1980s (Hatcher 1997). As such the correlations between effort and landings are masked by other external factors such as implementation of management control and policies, which could be included in future models. Additionally, we only had fishing effort data from British vessels fishing in the North Sea. As such, we were unable to establish how total fishing effort in the North Sea (including effort from foreign vessels) impacted ecosystem processes and services.

The pathways between climate and recruitment, and climate and SSB were not significant. Past research has shown that climate affects fish communities and that certain species have shifted polewards or moved deeper due to rising temperatures (Brien et al. 2000; Perry et al. 2005;

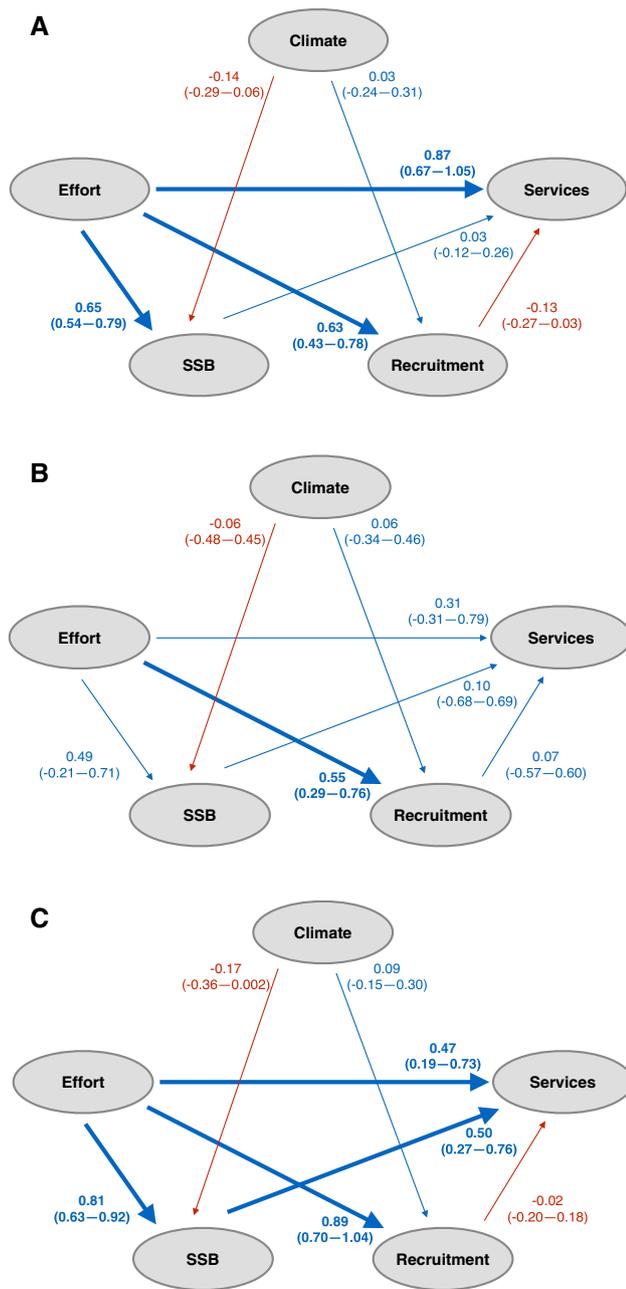


Fig. 5 Path coefficients of the inner models for all three models showing the strength and direction of all the different pathways. Positive pathways are highlighted in blue and negative pathways in red. Bootstrap validation was carried out on all the models, and the 95 % confidence intervals (CI) are given below each path coefficient. **a** Full time series model showing the significant positive effect of fishing effort on both ecosystem processes and services. The other pathways were not significant. **b** ‘Fishing’ regime model showing the only significant effect was fishing effect on recruitment. **c** ‘Climate’ regime model showing the significant positive effects that effort had on ecosystem processes and services, and SSB on services as well

Kerby et al. 2013). However, the interaction between climate and ecosystem processes is likely to be more complex than the direct links between fishing effort and landings.

Ecosystem processes might be affected by bottom-up forcing rather than top-down control (Jackson et al. 2001; Beaugrand 2004; Fauchald et al. 2011; Luczak et al. 2012); hence, we would have had to include species at lower trophic levels such as zooplankton in the model to start seeing better interaction between change in climate and ecosystem processes. It would be possible to expand our approach to include individual species from each trophic level, as demonstrated for instance by Lauria et al. (2012) who analysed effects of changes in SST across trophic levels. Additionally, although climate is well represented in our models by a simple temperature variable (SST), future models might need to include other indicators to effectively measure climate, including temperature extremes, bottom temperature or the Atlantic multidecadal oscillation (AMO).

Past studies have tried to disentangle the effects of fishing and climate on ecosystems (Rochet et al. 2010; Hofstede and Rijnsdorp 2011). Running the model separately for the proposed fishing (1924–1971) and climate (1972–2010) regimes showed that only the impact of effort on both SSB and recruitment was significantly different under the two regimes. Fishing effort had high positive correlation with both SSB and recruitment in the fishing regime, but significantly higher in the climate regime. As outlined above, this can be explained in the fishing regime by effort tracking the rise in stocks due to ‘Gadoid outburst’ (Cushing, 1978; Hislop 1996). In the climate regime, the positive relationship between effort and stocks is likely due to both declining effort due to management instigated in the 1970s, partly in response to declining stocks (ICES, 2005). SSB had a stronger positive impact on services under the climate regime than in the fishing regime. However, recruitment had a positive impact on services under fishing regime, but negative under climate regime, suggesting that these ecosystem processes might affect services in different ways, depending on how they themselves are affected by external factors. Similarly, in a study of path coefficients differ under different regimes, Cattadori et al. (2005) showed that climate impacted red grouse populations, but it was the trophic interactions with parasites that differed under different regimes which indirectly affected the population.

Here, we have shown how PLSPM can be applied to model the different drivers of change in a subset of the ecosystem (three commercially important demersal fish species) and for one particular type of provisioning service (fisheries). In future models, this could be extended to include interactions between different ecosystem components and processes (e.g. zooplankton, seabirds and benthic invertebrates) as well as to other services (e.g. recreational fisheries, livelihoods and climate regulation). In addition, PLSPM has previously been applied successfully to marketing and management strategies through identification

and measurement of LVs such as ‘satisfaction’ and ‘image’ (Hair et al. 2011). This is very pertinent to the field of valuation of ecosystem services, in particular cultural services that can be difficult to measure and that have been identified as a research priority (Chan and Ruckelshaus 2010). Path analysis could also be applied to regulating services, for instance where different factors combine to provide one particular service (e.g. disturbance prevention, flood and storm protection), because several indicators can measure a single LV.

More complex models will necessarily require more comprehensive data, which will likely come at the expense of the unusually long time series we have used in this study. We believe that this long-term historical context of ecosystem service provision can be useful for several reasons. First, by linking ecological and socioeconomic time series, we can establish functional relationships between ecosystem state and ecosystem service provision (Kremen 2005; Nelson et al. 2009; Cardinale et al. 2012). Similarly, we can track changes in ecosystem state and ecosystem service provision, which for instance, enables the ease (or cost) of transitioning between different states to be estimated. Finally, documenting the past states of ecosystems and the services they provide can expand the range of scenarios considered for future management and definitions of ‘good environmental quality’ (Pinnegar et al. 2006; MSDF, EC 2008); MacKenzie et al. 2011). This might include quantitative changes in the current suite of ecosystem services, or qualitative changes, for instance prioritizing the recovery of ‘lost’ ecosystem services (Bullock et al. 2011).

This study adds to the growing research assessing human impact on landscapes and seascapes and its effect on biodiversity and ecosystem services (Bennett et al. 2009; Nelson et al. 2009; Chan and Ruckelshaus 2010). It builds on previous studies by adding empirical analysis using complete time series of historical ecological and socioeconomic data, to identify links between anthropogenic drivers, ecosystem process and ecosystem service. To reach any solid conclusion on the overall long-term impact of climate and fishing drivers on ecosystem processes and services, it is clear that we would need to consider inclusion of additional variables. Future improvements to the model and integration of long-term time series will help to develop these links further and allow better understanding of the complex nature of how ecosystem service provision is influenced by changes in both natural and anthropogenic factors.

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