Institution: University of Strathclyde

Unit of Assessment: 10

Title of case study: Recovery of cod stocks in the North Sea achieved by a change in EU fisheries policy driven by evidence from mathematical models

1. Summary of the impact (indicative maximum 100 words)

In 2012, cod stocks in the North Sea were assessed as having recovered almost to a level at which their viability is considered to be safe. This recovery followed 3 decades of progressive depletion to only 50% of the safety threshold of abundance. Achieving this recovery required the EU to abandon an earlier 'closed area' policy banning fishing in selected areas of the North Sea, and instead enforce drastic cuts in overall activity on national fishing fleets. The policy change was prompted in part by predictions from mathematical modelling of cod populations by researchers at Strathclyde, showing that the 'closed area' policy was unlikely to be an effective strategy for recovery. The recovery has so far restored £17 million in annual value to the fishery.

2. Underpinning research (indicative maximum 500 words)

Context: Simulating spatial patterns in the demography of mobile species is particularly challenging and a general problem in mathematical ecology. However, validated models of this type are extremely powerful tools since they provide a means of conducting virtual experiments to diagnose the key factors affecting populations. This includes predicting the consequences of climate change and, for commercially exploitable taxa, changes in spatial patterns of harvesting. The research described here provided a significant advance in capability in this area and was used to support a policy change in fisheries management.

Key Research Findings: [*Numbers in parentheses refer to research articles listed in Section 3*]

A numerical technique for modelling spatial populations was developed during two NERC research grants between 2000 and 2006 [1]. The technique was used to simulate the spatial distribution and population dynamics of a marine plankton species (*Calanus finmarchicus*) which is particularly abundant in the North Atlantic Ocean and is an indicator species for impacts of climate change [2]. The life cycle involves spawning, development and dispersal by ocean currents in the surface waters during spring and summer, alternating with a dormant phase at depths of >600 m in the winter. The modelling technique was able to represent these developmental and dispersal processes at a spatial resolution of a few tens of kilometres over the whole North Atlantic, combining data on water currents and temperatures from an ocean circulation model, and on the food of *Calanus* from satellite remote sensing archives [3].

The modelling technique was then used to simulate the spatial population dynamics of cod in the North Sea during a Defra funded research project (2001-2005) [4], building on a body of work on the mathematics of growth in fish [5]. It was fitted to cod distributions derived by statistical analyses of survey data [6] as part of an EU funded project, and explained changes in cod distribution in terms of temperature, migration behaviour, and spatial patterns of fishing. On the basis of this capability, Defra commissioned researchers at Strathclyde to simulate the effects of imposing fishing moratoria in various configurations of spatial regions (marine protected areas) in the North Sea as part of the evidence base for a policy consultation by the EU Commission.

The development of this modelling technique [1], combining mathematical representations of key biological processes with spatial resolution, was a major technical achievement and a significant advance in the field. A key finding of the research on *Calanus* [2] was that sub-regions of high population abundance around the North Atlantic are interconnected by passive transport of *Calanus* life stages. Key findings from the research on cod were that transport of eggs and larvae by water currents, and active migrations of adults to spawning sites were major factors in maintaining the spatial structure of the stock [4]. Displacement of fishing effort from small scale closed areas into the remaining open spaces negated any beneficial effect of the closure as a conservation measure. The models predicted that the most effective action for stock conservation was to reduce the overall regional fishing effort.

The research was published in leading marine science journals, specifically those with top ten

impact factors in the "Fisheries" category such as the *Canadian Journal of Fisheries and Aquatic Science* and *Fisheries Oceanography* or the second top journal in the "Zoology" category, the *Journal of Animal Ecology*. The novel technical aspects of these models have also been published in leading mathematical and statistical journals (*Bulletin of Mathematical Biology*, *Journal of the Royal Statistical Society: Series C*.).

Key researchers at the University of Strathclyde:
The research was originally conceived and led by W.S.C Gurney (Professor in Department of Mathematics in 2000; retired 2011, then part-time contract until 2014) and continues under the leadership of Professor M. Heath, who was involved in the project during previous employment at Marine Scotland Science, joining the University of Strathclyde in 2010.
Dr D. Speirs (postdoctoral researcher) worked on the spatial modelling of Calanus in the North Atlantic during 2000-2006. Dr J. Bridson nee Andrews (postdoctoral researcher 2001-2006) worked on developing the model to represent cod in the North Sea. E. McKenzie (Professor of Mathematics 2001; retired 2011) and Dr R. Hedger (postdoctoral researcher 1999-2002) contributed the statistical analysis of cod data.

Key collaborators at other institutions:
Calanus modelling – University of St Andrews (S. Woods and E. Clarke)
Cod modelling – Centre for Environment, Fisheries and Aquaculture Science, Lowestoft (C. Darby and C. O'Brien); Marine Scotland Science, Aberdeen (M. Heath, now University of Strathclyde member of staff, and P. Wright)

3. References to the research (indicative maximum of six references)

References 1, 2 and 3 best exemplify the quality of the underpinning research

1. *Gurney, W.S.C., Speirs, D.C., Wood, S.N., Clarke, E.D. and* Heath, M.R. (2001). Simulating spatially and physiologically structured populations. *Journal of Animal Ecology 70, 881-894.*
2. *Speirs, D., Gurney, W.S.C., Heath, M.R., Horbelt, W., Wood,* S. and de Cuevas, A. (2006). Ocean-scale modelling of the distribution, abundance, *and seasonal dynamics of the copepod C*alanus finmarchicus. *Marine Ecology Progress Series* 131, 183-192.
3. Clarke, E.D., Speirs, D.C., Heath, M.R., Wood, S.N., Gurney, W.S.G., Holmes, S.J. (2006). Calibrating remote sensed chlorophyll *a* data using penalized regression splines. *Journal of the Royal Statistical Society: Series C (Applied Statistics)* 55(3) 331-353.
4. Andrews, J.M., Gurney, W.S.C., Heath, M.R.,Gallego, A., O'Brien, C.M., Darby C. and *Tyldesley, G. (2006). Modellin*g the spatial demography of cod on the European continental shelf. *Canadian Journal of Fisheries and Aquatic Sciences*, 63, 1027-1048.
5. Gurney W.S.C., Veitch R. (2007). The dynamics of size at age variability. *Bulletin of Mathematical Biology* 69, 861-885. .
6. Hedger, R., McKenzie, E., Heath, M., Wright, P., Scott, B., Gallego,A. and Bridson, J. 2004. Analysis of the spatial distributions of mature cod (Gadus morhua) and haddock (Melanogrammus aeglefinus) abundance in the North Sea (1980-1999) using Generalised Additive Models. *Fisheries Research* 70, 17-25.

Other evidence for quality of research (grants, patents etc.)
The research group at Strathclyde developed and supported its research programme, and continues to do so, on the basis of competitive funding from NERC and Defra. Development of the initial model methodology was supported by two consortium grants (2000-2004, £593k), led by Strathclyde, from the NERC Marine Productivity Thematic Programme. Further development of the models to investigate cod populations was carried out in a Strathclyde led consortium project funded by Defra (2000-2003, £500k). On the basis of this, Defra commissioned the targeted research on closed areas which ultimately yielded the impact on cod stock recovery.
Additional relevant funding has been a stake in an EU project on North Atlantic cod (1998-2001, EU-FAIR-CT98-4122, consortium total award 1.13M Euro), and the research has continued under a NERC consortium grant from the Sustainable Marine Bioresources programme (2009-2012, £114,363 to Strathclyde).

4. Details of the impact (indicative maximum 750 words)

Process from research to impact

In the early 1990's, the International Council for the Exploration of the Sea (ICES) viewed cod stocks in the North Sea to be in a declining state and consistently advised cuts in fishing, to the point of recommending zero Total Allowable Catch (TAC). Nevertheless, the EU Council of Ministers consistently agreed on TAC's in excess of the scientific advice. The problem was that cod were caught in a mixed-species fishery so vessels fishing for other species could not avoid catching cod regardless of whether they were legally allowed to land them. Zero TAC for cod would have effectively closed the North Sea for all demersal fisheries with severe economic consequences. However, in 2000 the Commission was asked to seek additional conservation measures that might protect cod whilst enabling a continuing fishery for other species. The first of these, in 2001, was the emergency establishment of 'closed areas' containing high densities of cod, where fishing for all species was prohibited [Source A]. The Commission then sought scientific advice from member states as to whether the 2001 closed areas were likely to be effective in promoting stock recovery. In the UK, Defra then commissioned the research at Strathclyde into spatial simulation modelling methods for cod in the North Sea, as a means of analysing the effectiveness of the closed area strategy. The resulting advice from Strathclyde was that simply closing selected areas to fishing was unlikely to be effective due to displacement of effort into neighbouring regions. The most effective measure was permanent removal of fishing capacity from the system [Source C]. These results formed part of the UK evidence supplied to the Commission [Source D] and, on the basis of this evidence, the Commission abandoned the closed area policy in 2004 and instead implemented the 'Cod Recovery Plan' [Source B].

Impact on the state of cod stocks, 2008-2012:

Although the Recovery Plan was implemented in 2004 significant impact on cod numbers was not expected to be seen for a number of years, and the aim was to reverse the decline of stocks by 2009. Annual stock assessments showed that the decline was successfully halted by 2007 and by 2012 the stock in the North Sea had recovered to just below the level at which its viability is considered to be at risk [Source E].

Impact on fisheries policy, 2004-2012:

The Recovery Plan required EU member states to enforce drastic reductions in catch quotas for cod and overall fishing capacity [Source F]. In the case of the UK this was achieved by a scheme for decommissioning vessels and restricting the permitted number of days a vessel was allowed to spend at sea [Source G].

Economic impact:

The peak value of the North Sea cod fishery was more than £450 million per annum in the late 1970's (first sale value, standardised by the Consumer Price Index to year 2000). However, this was not sustainable and resulted in the overfishing which caused the decline in stocks. Current estimates of the long-term sustainable value are around £150 million per year. Between 1978 and 2007 the first sale value of cod landings declined by an average £14 million per year to a minimum of less than £35 million. Since 2008 the quay-side value has increased, and by 2011 the Recovery Plan and its successors had restored the annual value of the North Sea cod landings to £52 million. Hence, the Strathclyde research contributed to a £17 million per annum increase in the value of the cod fishery by 2011 compared to the low-point in 2007. The UK share of this international fishery is around 45%.[Source H]

Public awareness of recovery of cod stocks:

The crisis in the fishing industry precipitated by the Closed Area Policy and the Recovery Plan attracted media attention and raised public awareness of the state of the stocks. High profile conservation campaigns encouraged consumers to avoid buying cod. However there is evidence that public opinion now recognises that cod stocks are recovering. Recent media interest, for example via the BBC [Source I], reports that Barrie Deas, the Chief Executive of the National Federation of Fishermen's Organisations, which represents fisherman in England, Wales and Northern Ireland, told Radio 4's Today programme that the recovery of stocks was a "*dramatic turnaround …I think a major part of it is there are fewer vessels out there. There have been big*

decommissioning schemes. There's also been a change in the mindset in the industry. We work very closely with the scientists now." Another recent example of media interest was an item in the Daily Telegraph (10th June 2013) quoting Richard Benyon, the Fisheries Minister, as saying: "*We should not be complacent, there is still a long way to go, but this is really good news. People can eat cod without feeling guilty because there are large quantities being caught further north, and our cod stocks in the North Sea are recovering. Much of the credit for this must rest with the fishermen who have introduced a vast number of [sustainable fishing] measures*" [Source J]. This reflects both the impact of the Recovery Plan, and the extent of public awareness of the issue.

Reach and significance: The impact extended through the UK government fisheries agencies (Defra and Marine Scotland), to the EU Commission [B,C,D]. Cod is the most important fish species targeted by trawl fisheries in the North Sea [E], and the crisis in the fishing industry associated with its decline and recovery raised public awareness of the research that underpins fisheries policy [I,J]. The short-term hardship (due to curtailed fishing opportunities [G]) and the accruing economic benefits due to recovering cod stocks [H] are being felt by fishing communities and industries throughout Europe and Norway which have an economic interest in the North Sea demersal fisheries. The general public are now more aware that cod stocks are recovering.

5. Sources to corroborate the impact (indicative maximum of 10 references)

A. Commission Regulation (EC) No 259/2001 of 7 February 2001 establishing measures for the recovery of the stock of cod in the North Sea (ICES subarea IV) and associated conditions for the control of activities of fishing vessels. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2001:039:0007:0010:EN:PDF

B. EU Council Regulation (EC) No 423/2004 of 26 February 2004 establishing measures for the recovery of cod stocks http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2004:070:0008:0011:EN:PDF

C. Darby C., Hutton T., Andrews J., Gurney W.S.C., Beveridge D., Hiddinck J.G. (2006) Investigations into closed area management of the North Sea cod. Cefas Contract report, p62-75. (Peer reviewed final report from a research project commissioned by Defra to investigate the effectiveness of closed area policies for conserving cod using the Strathclyde model - Defra Reference: SFCD15, January-May 2005).

D. http://www.cefas.co.uk/publications/files/EU_Norway_expert_gp_codrecovery-may-2003.pdf STECF meeting on cod assessment and technical measures, Brussels, 28 April–7 May 2003 127 pp.

E. ICES (2012). Advice Book 2012. Section 6.4.2 Cod in Subarea IV (North Sea), Division VIId (Eastern Channel), and IIIa West (Skagerrak) http://www.ices.dk/sites/pub/Publication Reports/ICES Advice/2012/ICES ADVICE 2012 BOOK 6.pdf

F. Council Regulation (EC) No 1342/2008 of 18 December 2008 establishing a long-term plan for cod stocks and the fisheries exploiting those stocks and repealing Regulation (EC) No 423/2004 http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32008R1342:EN:NOT

G. Almond, S & Thomas, B. 2011. The UK fishing industry in 2010. Structure and activity. UK Marine Management Organisation, 62pp. http://marinemanagement.org.uk/fisheries/statistics/documents/ukseafish/2010/structure_activity.pdf

H. Evidence derived from: Almond, S & Thomas, B. 2011. The UK Sea Fisheries Statistics 2010. UK Marine Management Organisation, 158pp. http://www.marinemanagement.org.uk/fisheries/statistics/documents/ukseafish/2010/final.pdf

I. http://www.bbc.co.uk/news/science-environment-22820162 BBC coverage of cod recovery

J. Article in The Telegraph, 10 June 2013: Britons "*Should not feel guilty about eating cod".* (http://www.telegraph.co.uk/earth/wildlife/10108952/Britons-should-not-feel-guilty-about-eating-cod.html