Institution: University of York		
Unit of Assessment: 10 - Mathematical Sciences		
Title of case study: Marine-Ecosystem Dynamics and Balanced Harvesting: Mathematical underpinnings of a sustainable fisheries policy		
Period when the underpinning research was undertaken: 2009 - 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Gustav Delius	Senior Lecturer	Oct 1999 – present
Richard Law	Professor	Aug 1983 – Sep 2011, then Mar 2015 – Feb 2019
Richard Southwell	Research Associate	Oct 2016 – Feb 2019
Period when the claimed impact occurred: 2014 – 2020		
Is this case study continued from a case study submitted in 2014? N		

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

Fisheries policy has important implications for ecology, conservation, food security, and consumer markets. The UN Convention on Biological Diversity requires that fisheries policy should ensure conservation and sustainable use of marine resources and the preservation of ecosystems. Delius and Law's mathematical foundation for modelling Ecosystem-Based Fisheries Management (EBFM) has influenced fishing policies around the world through their work with national institutes including the National Institute of Water and Atmospheric Research (NIWA) in New Zealand and Chile's Fisheries Development Institute (IFOP). In addition, Delius' interactive web application for the R package, Mizer, enables the simulation of size-based marine ecosystem dynamics by non-specialist users.

2. Underpinning research (indicative maximum 500 words)

The research programme was initiated as a NERC-funded PhD CASE project (Datta, 2007-2010), in partnership with the Centre for Environment, Fisheries & Aquaculture Science (CEFAS), an executive agency of DEFRA, with Delius (Senior Lecturer in Mathematics) and Law (now an Emeritus Professor in Mathematical Biology) as co-supervisors. It was continued through an EU Consortium MINOUW, established after the introduction of the landing obligation in the Common Fisheries Policy of the EU in 2013.

The UN Convention on Biological Diversity requires fisheries policy to include the marine ecosystems in which exploited species live, which places major demands on the limited current knowledge of their workings. The research of Delius and Law has provided a mathematical foundation for marine ecosystem dynamics [R1 - R3]. Their modelling has shown that a proposal for fishing at the ecosystem level, termed *balanced harvesting,* is a rational solution to the problem of achieving Ecosystem-Based Fisheries Management (EBFM). This ecosystem approach is a departure from traditional fisheries policy, which has focused on the yield of single species through regulation of fishing effort, and on the selection of mature fish. The ecosystem approach is much harder to express in formal terms than single-species dynamics: it has to deal with the flow of biomass from small to large organisms through feeding, which couples together components of the marine ecosystem into a complex system.

Using a master-equation approach for the evolution of state probabilities, the team derived a deterministic integro-differential 'jump-growth equation' (JGE) as the macroscopic description of a stochastic process in which fish grow by eating smaller fish, and die when eaten [R1]. The jump-growth equation provides a firm foundation for a size-based McKendrick–von Foerster equation (MvFE), a core model for marine ecosystem dynamics. If prey size is small relative to predator size, a Taylor expansion of the JGE gives the MvFE as a first order approximation, while at second order there is an additional diffusion term. Power-law steady-state solutions are local attractors in the model [R2, R3], a property that was missing from the MvFE. The basic model readily extends to take account of special features of species and ecosystems, known

generically as 'size-spectrum dynamics', and has wide application in fisheries, as fish stocks are always embedded in ecosystems. Using this approach, a rational quantitative foundation for EBFM, dubbed *balanced harvesting* (BH), was developed, setting exploitation in proportion to production rates. BH was shown to be an effective basis for EBFM in several numerical studies by Law and colleagues, including [R4, R5], carried out prior to Law's retirement. Moreover, BH was shown to have a special significance as a Nash equilibrium for agents acting individually to maximise their biomass yields in the absence of external regulation [R6]. Traditional fisheries management has many negative effects: it leads to truncation of size-structures, gives lower biomass yields, generates imbalances between species, destabilizes fish stocks, drives fisheries-induced evolution, and generates by-catches of unwanted species and sizes. BH resolves these inherent problems of traditional fisheries management.

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

[R1] *+S. Datta, G.W. Delius, R. Law (2010) A jump-growth model for predator-prey dynamics: derivation and application to marine ecosystems. Bull. Math. Biol. 72:1361-1382. DOI:10.1007/s11538-009-9496-5
[R2] *+S. Datta, G.W. Delius, R. Law, M.J. Plank (2011) A stability analysis of the power-law steady state of marine size spectra, J. Math. Biol. 63:779-799. DOI:10.1007%2Fs00285-010-0387-z
[R3] *M. J. Plank, R. Law, R. (2012) Ecological drivers of stability and instability in marine ecosystems. Theoretical Ecology 5:465-480. DOI:10.1007/s12080-011-0137-x
[R4] *S. M. Garcia et al, including R. Law (2012) Reconsidering the consequences of selective fisheries. Science 335:1045-1047. DOI:10.1126/science.1214594
[R5] *+R. Law, M. J. Plank, J. Kolding (2012) On balanced exploitation of marine ecosystems: results from dynamic size spectra. ICES Journal of Marine Science 69:602-614. DOI:10.1093/icesjms/fss031
[R6] *M. J. Plank, J. Kolding, R. Law, H. D. Gerritsen, D. Reid, (2017) Balanced harvesting can emerge from fishing decisions by individual fishers in a small-scale fishery. Fish and Fisheries 18:212-225. DOI:10.1111/faf.12172

*= peer reviewed publication; +=returned to REF2014

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

Marine ecosystem dynamics

York is a leading international centre for the development of models of size-spectrum dynamics, and the research has a personal endorsement from Professor Simon Jennings, Chair of the Science Committee at the International Council for the Exploration of the Sea (ICES). The ICES is an intergovernmental marine science organization that provides scientific advice to governments and international commissions on the sustainable use of marine resources and protection of the marine environment. Professor Jennings states "The group at York has provided a firm theoretical basis for models of size-spectrum dynamics, and formalised this into equations that can be used to describe the flow of energy through marine ecosystems from primary producers to fished species", and adds "Their methods have influenced groups internationally that are working towards the development of tools to support ecosystem approaches to management (e.g. in Denmark, Norway, Australia, as well as the UK) … and have substantially enriched and advanced the understanding and ongoing development of tools to support ecosystem approaches to fisheries management" [E1].

York was a partner in an EU Horizon 2020 Consortium, MINOUW [E2], which ran from 2015 to 2019, bringing together scientists, fishermen, NGOs and policy makers, to foster fishing methods that reduce discarding (returning unwanted fish to the sea, often dead or dying, due to quotas or because they are undersized) for the reformed EU Common Fisheries Policy (2013). York's role was to produce modelling tools for EBFM and Delius took over development of the toolbox 'Mizer' [E3], allowing simulation of the dynamics of marine ecosystems. To make it accessible to non-specialist users in industry and conservation, he constructed an interactive web application for Mizer. This enables users to examine the consequences of fishing on the structure of and

yield from marine ecosystems. Of approximately 30,000 downloads of Mizer from CRAN (the R repository) since its inception in October 2013, about 28,000 have taken place since Delius took over in April 2014, of which about 9,000 were after the release of the latest version in April 2020.

Delius and Law's mathematical research provides a way to deal with the complexity of marine ecosystems and has been taken up by organisations around the world responsible for practical management of marine ecosystems including:

NIWA NZ: The National Institute of Water and Atmospheric Research (NIWA) is one of New Zealand's Crown Research Institutes. NIWA's National Centre for Fisheries carries out most of the fisheries research for the Ministry for Primary Industries, supporting NZ's internationally-recognised fisheries management system. Seafood was NZ's seventh largest export earner in 2019. The Chief Scientist and head of NIWA's National Centre for Fisheries, comments: "The framework for modelling dynamic size-spectra developed at York, and its implementation in Mizer, is of great help to us, as we work towards ecosystem-based management approaches" and "Balanced harvesting is a promising candidate for ecosystem-based fishing, and we are keen to develop a research programme to investigate its potential value for NZ fisheries" [E4].

IFOP Chile: Instituto de Fomento Pesquero (IFOP) supports the sustainable development of Chile's fishing and aquaculture sector. The head of Fisheries Assessment at IFOP comments: "The size-resolved multispecies models that the University of York has built are one of the few tools available to deal mechanistically with the interactions. IFOP has therefore put in place a strategic partnership with the University of York to apply size-based multispecies models to Chilean marine ecosystems" [E5].

Balanced harvesting (BH)
BH answers the call for ecosystem-based fisheries management (EBFM): it argues that fishing should be brought in line with the production rates of components of marine ecosystems. The theory developed by Law and colleagues gave a firm foundation to the argument for BH, a paradigm shift in lifting fisheries policy from the level of single-species to that of ecosystems. A *Science* paper in March 2012 [R4] has been cited more than 400 times, including by 43 non-university organisations in 20 countries around the world. This approach has influenced policy around the world in the following ways since 2014:

2014. BH was adopted by the International Union for Conservation of Nature (IUCN) which, with over 1400-member organisations, supports conservation globally. IUCN has a Fisheries Expert Group (FEG) chaired by international leaders in fisheries science. Together with the Food and Agriculture Organisation (FAO) of the United Nations, FEG organised a workshop on "Balanced Harvest in the Real World" in Sept 2014 (FAO, Rome, Italy) to discuss the implementation of BH and operational, legal and economic management implications [E6].

2017. Law was contracted to lead a report on BH for Fisheries Innovation Scotland (FIS). FIS advises and informs policy and management of Scottish fisheries, and is funded by the Scottish Fishermen's Association, Marks and Spencer, Sainsbury's, Young's Seafood, Funding Fish (NGO), Marine Scotland, Scottish Government and Scottish Natural Heritage. The report showed evidence that exploitation of the Scottish west coast shelf is seriously out of balance with the production rates of the species it contains and showed how the balance could be improved [E7].

2018. The FIS report became a source for an international programme on Indicators for practical EBFM, sponsored by the CSIRO in Australia and by the Lenfest Ocean Program which connects science to policy [E8]. The project lead comments that the method proposed in the FIS report "… has given us the tool we need for the purpose. Leveraging off that we have been able to provide clear decision criteria for judging sustainability of the management" [E9]. They add "that the size-based models will be really important for ecosystem-based management, and that there will be a continuing need for the fundamental research that York does."

2019. A report for the FAO argued that small pelagic fish in African lakes are crucial for nutrition and food security of populations in sub-Saharan Africa, although standard fisheries management discourages the capture of small fish, often making traditional fishing methods illegal. However, York's research justifies traditional exploitation of pelagic fisheries. The lead author of the report states: "The basic mathematical modelling and numerical analysis of size-spectrum models at the University of York and collaborating institutions has given a strong foundation to the call for a new approach to fisheries management in African lakes" [E10]. Having read the report, some of the world's largest donors of aid for developing countries have "expressed their interest in looking closer at developing and promoting the small-fish value chain for food and nutrition security" [E10]. A further outcome of the report is a programme *SmallFishFood* to develop sustainable utilisation of small fish resources for Africa's low-income population, inspired by the BH work from York [E10].

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

[E1] **ICES:** Letter of support from Professor Simon Jennings, Chair of the Science Committee at the International Council for the Exploration of the Sea (ICES).
[E2] **MINOUW:** http://minouw-project.eu (accessed 17/12/20).
[E3] **Mizer**: https://sizespectrum.org/mizer/ (accessed 6/11/20). 30,000 downloads.
Major organisations using Mizer include: Silvia de Juan Mohan, Instituto de Ciencias del Mar (ICM) Barcelona, Spain; Kristin Kleisner, Environmental Defense Fund (EDF) – international; Mariella Canales, Center of Applied Ecology and Sustainability (CAPES), Santiago, Chile; Maria Grigoratou, shortly to be working at the Gulf of Maine Research Institute (GMRI).
Mizer workshops: "Training and Advances in Size Spectrum Modelling" (Sept 2019); Course at Santiago (Jan 2020); Workshop at Hobart (Feb 2020).
[E4] **NIWA, New Zealand:** Letter of support from the Chief Scientist at the National Centre for Fisheries, National Institute of Water and Atmospheric Research.
[E5] **IFOP, Chile**: Letter of support from the Head of Fisheries Assessment at the Institute for Fisheries Development.
[E6] **2014 FAO/FEG meeting**: Report of 2014 meeting jointly organised by FEG and FAO: Balanced harvest in the real world. Scientific, policy and operational issues in an ecosystem approach to fisheries. IUCN Report (2015).
[E7] **FIS**: R. Law, M. Heath, K. Searle. Scoping the background information for an ecosystem approach to fisheries in Scottish waters: Review of predator-prey interactions with fisheries, and balanced harvesting. Part 2: Balanced harvesting in the context of Scottish Fisheries. A Report Commissioned by Fisheries Innovation Scotland (FIS) https://fiscot.org/wp-content/uploads/2019/06/FIS013.pdf (accessed 17/12/20)
[E8] **LENFEST:** Public meeting hosted by the Lenfest Ocean Program on: Benchmarks for Ecosystem Assessment: Indicators for Practical Ecosystem-Based Fisheries Management.
[E9] **CSIRO Australia**: Letter of support from a Principal Senior Research Scientist, at the CSIRO Oceans and Atmosphere. This includes the work both on size-spectrum dynamics, and on BH.
[E10] **FAO:** Letter of support from the author of an FAO report (http://www.fao.org/3/ca0843en/CA0843EN.pdf accessed 6/11/20) on small pelagic fish in African lakes. SmallFIshFood: https://smallfishfood.org/ (accessed 6/11/20)