Institution: University of York

Unit of Assessment: 10, Mathematical Sciences

Title of case study: Balanced Harvest: Mathematical underpinnings of a sustainable fisheries policy

1. Summary of the impact

Mathematical models recently developed in York have improved our understanding of the dynamics of marine ecosystems. They underpin paradigm-changing proposals to orient fisheries policy towards a "balanced harvest" and away from the traditional selective harvesting of species and sizes. These proposals have:

- influenced, and are now being actively pursued by, international NGOs involved in shaping the future direction of fisheries policy worldwide;
- informed and stimulated debate among policy makers in the EU Parliament and elsewhere;
- been incorporated into long range planning for Norwegian fishery management.

2. Underpinning research

Traditional fisheries policy attempts to reduce ecological impact by selective harvesting of species and sizes, protecting juveniles and rare species. Evidence is accumulating that selective harvesting can destabilize ecosystem dynamics, and has led to evolutionary change in fish (see e.g. [5]). This case study concerns a mathematical model developed in York by **Datta, Delius** and **Law**, which provides a sound theoretical basis for an alternative policy called *balanced harvest*.

Gustav Delius and **Richard Law** are members of the York Centre for Complex Systems Analysis (YCCSA). **Delius** is a Lecturer in Mathematics, who began his career in Mathematical Physics and came to York in 1999 as an EPSRC Advanced Fellow. He now focusses on the stochastic modelling of ecological dynamical systems. **Law,** now an Emeritus Professor, was a member of the Biology Department from 1983 until retirement in 2011. His research interests span evolutionary ecology and the dynamics of biological communities. Working at the interface of Mathematics and Biology, he has always maintained strong links with the Department of Mathematics (e.g., via a jointly run MRes *Mathematics in the Living Environment*), such links now being facilitated by YCCSA. **Delius** and **Law** were joint PhD supervisors of **Samik Datta** on a NERC-funded CASE project, in partnership with the Centre for Environment, Fisheries & Aquaculture Science (CEFAS, an executive agency of DEFRA), 2007–10. **Datta** is now a PDRA at the University of Warwick.

Marine ecosystem models treat organisms spanning several orders of magnitude in body mass, with predation of the larger on the smaller. Understanding the resilience of an ecosystem to fishing or other interventions requires both a model for the dynamics of biomass flow and an analysis of the stability of steady state solutions, such as the power-law relationships between body mass and abundance (size spectra) widely observed in many aquatic ecosystems. The standard approach appropriates the McKendrick-von Foerster partial differential equation for age distributions and assumes that it applies also to body size. By contrast, **Datta, Delius** and **Law** [1] analysed a stochastic model of biomass dynamics in which predation events change the mass distribution through the death of the prey and growth of the predator. Using a master-equation approach, a deterministic integro-differential "jump-growth equation" was derived as the macroscopic description of the dynamics, to which the McKendrick-von Foerster equation emerges as a first order approximation; at second order there is an additional diffusion term. These results provide a firm foundation for ecosystem models of this type. In conjunction with Plank (University of Canterbury, New Zealand), a stability analysis of the power-law steady state solutions to the jump-growth equations of [1] and its first- and second-order approximations was conducted in [2]. Here, the significance of the more detailed model became apparent, because the steady state proved to be unstable in the McKendrick-von Foerster model, while the inclusion of a diffusion term yielded results that (numerically) indicate good agreement with the full jump-growth equation. The analytic results were extended to include effects of reproduction, metabolic loss and natural death in [3]. Further basic research is in progress to understand how dynamics of plankton interact with the size spectra (CEFAS-funded PhD project co-supervised in York by **Law** and Jon Pitchford, a

Mathematics/Biology jointly-appointed Senior Lecturer.)

Because the models obtained in [1] automatically take care of biomass bookkeeping, they are ideally suited to modelling marine exploitation, which **Law** and Plank have investigated with Kolding, a highly influential Norwegian fisheries biologist [4]. They give a fundamentally new perspective on fisheries management, supporting balanced rather than selective harvesting as a means of reducing the disruption of the natural (unfished) size spectrum, improving ecosystem resilience and, strikingly, substantially increasing biomass yield. This provides the mathematical foundation for intuitions Kolding had long held, but which, lacking proof, had not gained currency against standard approaches, which ignore the central truth that fish grow by eating others.

In summary, the basic modelling and mathematical analysis of [1] and [2] underpins radical new proposals for managing marine ecosystems [4], which would not have been possible otherwise. Dynamic size spectra have only been investigated by a handful of groups worldwide and [4] is the first study to demonstrate quantitatively the range of benefits of balanced harvesting.

3. References to the research

All papers were submitted prior to **Law's** retirement. (Citations: Google Scholar, 19/9/2013).

*[1] **S. Datta, G.W. Delius, R. Law.** *A jump-growth model for predator-prey dynamics: derivation and application to marine ecosystems.* Bull. Math. Biol. 72 (2010) 1361-1382. 15 citations. DOI: 10.1007/s11538-009-9496-5

*[2] **S. Datta, G.W. Delius, R. Law,** M.J. Plank. *A stability analysis of the power-law steady state of marine size spectra*, J. Math. Biol. 63 (2011) 779-799. DOI: 10.1007/s00285-010-0387-z.
J Math Biol and Bull Math Biol are among the top international journals in their field. 18 citations.

*[3] J.A. Capitan, **G.W. Delius.** *Scale-invariant Model of Marine Population Dynamics*. Phys. Rev. E81 (2010) 061901. DOI: 10.1103/PhysRevE.81.061901.
Capitan was a visiting PhD student from Madrid. Phys Rev E is a major international journal in many body/statistical Physics covering applications in Biology and complex systems. 11 citations.

[4] **R. Law,** M.J. Plank, J. Kolding. *On balanced exploitation of marine ecosystems: results from dynamic size spectra*, ICES J. Marine Science, 69 (2012) 602-614. DOI:10.1093/icesjms/fss031. 13 citations. The International Council for the Exploration of the Sea (ICES) is a major international research network, with intergovernmental support, that coordinates and promotes research and advises governments and NGOs. ICES journals aim to form part of the scientific basis for such advice.

[5] **R. Law**. *Fishing, selection and phenotypic evolution* ICES Journal of Marine Science, 57 (2000) 659-668. DOI: 10.1006/jmsc.2000.0731. [Included for wider context: relevant to the case study and based on earlier mathematical modelling work, it has lower mathematical content. 510 citations.]

Peer Reviewed Grants directly related to the work

i. *Dynamics of size spectra in marine ecosystems*, NERC CASE studentship supervised by **R. Law** and **G.W. Delius** December 2007-November 2010 c.£63,000

ii. *Aquatic ecosystem dynamics: size or species?* Marsden Fund (New Zealand) 2009-2013 NZ-$213,062 A. James, **R. Law** and M. Plank (PI), University of Canterbury, New Zealand.

iii. CEFAS PhD scholarship supporting Celina Wong, co-supervisors: J. Pitchford & **R. Law**, S. Mackinson (CEFAS) October 2010-September 2013 £55,600

4. Details of the impact

Fisheries policy has implications for ecology, conservation, food security, and major consumer markets (€55Billion p.a. in the EU). The results of [4], underpinned by [1] and [2], show that a balanced harvest policy offers the prospect of simultaneously increasing yield while conserving the structure of marine ecosystems and their resilience. They have influenced the policy of international NGOs with global reach and stimulated and informed thinking and policy debate in the EU Parliament and elsewhere, e.g., in pursuit of long-term reform of the Common Fisheries Policy and the delivery of the EU 2020 Biodiversity Strategy.

The York research has been adopted by members of the Fisheries Expert Group (FEG) of the *International Union for Conservation of Nature* (IUCN) and the *European Bureau for Conservation*

and Development (EBCD). The FEG is an influential group of international leaders in fisheries science, including **Law's** co-author Kolding, and chaired by Dr Serge Garcia, ex-Director of the Fisheries Management Division of the *United Nations Food and Agriculture Organization* (FAO). **Law** was an invited speaker at a FEG workshop in Nagoya (2010), presenting his work with **Datta, Delius** and Plank [6]. **Law's** was one of the three theoretical talks at the workshop, which aimed to "derive the practical consequences of the emerging science, to raise decision makers' and scientists' awareness [and] eventually, deliver relevant general management advice". The associated workshop report [7] is a potentially paradigm-changing contribution to global thinking on sustainable fisheries policy that puts the case for a balanced harvest approach in contrast to traditional selective fishing. The consequent *Science* Policy Forum paper [8], of which **Law** and Kolding are co-authors, makes specific proposals for fisheries management, endorsed by the IUCN in a press release: "The new approach proposed by IUCN, called 'balanced harvesting', involves targeting all edible components of the marine environment, in proportion to their productivity." [10]

The main report and the Policy Forum paper have received considerable interest (over 40 news stories/press releases worldwide [11]). Policy debate on fisheries management has been informed and stimulated at a high level among policy makers:

- Garcia addressed the ALDE (Liberal/Democrats) group of MEPs at a seminar introduced by EU Fisheries Commissioner Damanaki [12], and the Committee on Fisheries (COFI) of the UN FAO at their meeting 9-13 July 2012 [COFI is influential over the direction of FAO work].
- Kolding made invited presentations on Balanced Harvest to the European Fisheries Advisors (May 2012, Oslo), and the Nordic Council of Ministers meeting 23-24 October 2012.
- **Law** presented his joint work with Plank and Kolding at the 6th World Fisheries Congress, a major conference that "draws leading international figures influential in driving debate and shaping global policy on fishing" [9].
- **Law,** Garcia and Kolding were the main speakers at a workshop on balanced harvest [13] at the European Parliament involving the Director of Policy Development and Coordination, EU Directorate-General for Maritime Affairs and Fisheries (8 November 2012). **Law** focussed on the implications of [4] for balanced harvesting, building on [1, 2].

The success of these efforts can be gauged from a press release by Struan Stevenson MEP, the workshop Chair and Senior Vice President of the European Parliament Fisheries Committee. Entitled *Scots Euro MP showcases revolutionary new management system for fisheries*, Stevenson's press release quotes him as saying "Balanced Harvest is a hugely exciting development for fisheries sustainability… …If balanced harvesting was introduced in the North Sea, it would help end the constant battle between fishermen who use a wide variety of fishing gears and target a broad spectrum of species and sizes, and managers in Brussels, Westminster and Holyrood who try to impose size limitations and gear regulations. It may be the answer to achieving the 'Holy Grail' of fishing above Maximum Sustainable Yield (MSY), so that fish stocks are able readily to replenish themselves and catches and profits rise accordingly" [13]. Furthermore, balanced harvest ideas are incorporated into the vision document for Norwegian Fisheries in 2050 [14], which, citing [8], envisions that a much increased part of the ecosystem will be considered in determining quotas and management.

Further evidence of the influence of balanced harvesting comes from the recent ALTER-Net Conference on the EU 2020 Biodiversity Strategy, where balanced harvest appears in the preparatory statements to stimulate debate [15]. A discussion of balanced harvesting has been initiated in India by V. Vivekanandan, former Chief Executive of the South Indian Federation of Fishermen Societies [the largest NGO for small scale fishermen in India], and currently a consultant to the FAO, who wrote to a group of other Indian fisheries experts saying: "This is quite revolutionary and the "selective fishing" vs. "balanced harvesting" debate could very well turn out to be the fisheries sector equivalent of the "flat earth" vs. "round earth" debate in astronomy and Newtonian principles vs. Relativity theory in physics" [16].

Fisheries policy is intensely political; decisions are influenced not only by science but by many other powerful lobbies. However, in a relatively short time, Balanced Harvest has been established as a radical new approach on the policy scene, because it is well-supported by the models.

Kolding writes: “Balanced Harvest would never have had the impact it now has without model work. Firstly, because there are practicably no empirical observations to study ─ and even if there were, we could write volumes without getting anywhere… …[Balanced Harvest] has entered the world ‘stage’ with rocket speed AFTER the models started to look into it” [17]. In summary: not only did the pioneering work of **Datta, Delius** and **Law** find its impact through the Balanced Harvest community; the Balanced Harvest paradigm itself owes its impact to their work.

References relating to the dissemination phase, between the mathematical research and impact:

[6] *Ecological drivers of stability and instability in marine ecosystems*
R. Law, M.J. Plank, **G.W. Delius** and J.L. Blanchard, (2011) in [7].
[7] *Selective Fishing and Balanced Harvest in Relation to Fisheries and Ecosystem Sustainability* Report of a scientific workshop organized by the IUCN-CEM Fisheries Expert Group (FEG) and the European Bureau for Conservation and Development (EBCD) in Nagoya (Japan), 14–16 October 2010. S. M. Garcia (Ed.), with 18 authors including **R. Law** and J. Kolding (IUCN and EBCD, Gland, Switzerland and Brussels, Belgium, 2011).
[8] *Reconsidering the Consequences of Selective Fisherie*s, S. M. Garcia *et al.* (including J. Kolding and **R. Law**) *Science **335*** (2012) *1045-1047.*
Policy Forum papers are highly prestigious and high profile contributions to knowledge transfer in one of the foremost international scientific journals. (38 citations in Google scholar 19/9/2013).
[9] *Evaluation Of Balanced Exploitation Of Marine Ecosystems: Results From Dynamic Size Spectra,* **R. Law**, M. Plank, J. Kolding, talk PSA5.05 at the 6th World Fisheries Congress (Edinburgh, 7th - 11th May 2012) [talks PSA3.04 and PSA5.04 also relate to balanced harvests]. The description of the Congress appears in the press release *World Fisheries Congress Opens in Edinburgh* linked from www.6thwfc2012.com/press/.

5. Sources to corroborate the impact

[10] *A balanced kettle of fish – IUCN suggests a novel approach to fishing.*
IUCN news story reporting the publication of [7, 8]. www.iucn.org/?uNewsID=9313
[11] Linked list of news stories/press releases concerning balanced harvest between March 2012 and April 2013. Extended version of a list originally compiled by the University of Bergen.
[12] *Selective fishing, balanced harvesting and sustainability of fisheries and ecosystems* Presentation given by S. Garcia based on the report [7], at the seminar *The Marine Food Chain: Better Management for new Challenges* organised by the Alliance of Liberals and Democrats for Europe (ALDE) group, EU Parliament, 8/12/2010 www.alde.eu/event-seminar/events-details/article/the-marine-food-chain-better-management-for-new-challenges-35651/ Garcia's presentation is at: http://www.ebcd.org/pdf/en/338-2-2011-Balanced_harvest_and_food_chain_-Alde_seminar-_Brussels.pdf
[13] *Increased Selectivity versus Balanced Harvest: How do we best meet ecosystem objectives in fisheries?* Workshop at the EU Parliament, 8/11/2012. www.ebcd.org/pdf/en/72-Report_Balanced_Harvesting_Seminar.pdf The related press release by Struan Stevenson MEP is at: www.struanstevenson.com/media/news-release/scots_euro_mp_showcases_revolutionary_new_management_system_for_fisheries/
[14] *Verdiskaping basert på produktive hav i 2050, [Wealth creation based on productive seas in 2050.]* Report commissioned by the Royal Norwegian Society of Sciences and Letters and the Norwegian Academy of Technological Sciences, available at www.regjeringen.no/en/dep/fkd/Documents/reports-and-plans/reports/2012/verdiskaping-basert-pa-produktive-hav-i-.html?id=697596 (*in Norwegian)*
[15] ALTER-Net Conference 2013: Science underpinning the EU 2020 Biodiversity Strategy. www.alter-net.info/outputs/conf-2013/biodiversity-strategy/provocative-statements/target4 ALTER-Net comprises 26 leading environmental research institutes (primarily outside HEIs) from 18 European countries to: “assess changes in biodiversity, analyse the effect of those changes on ecosystem services and inform the public and policy makers about this at a European scale.”
[16] Email from former Chief Executive of the South Indian Federation of Fishermen Societies to a number of Indian fisheries experts (quoted with permission).
[17] Email from Professor, University of Bergen.