Institution: University of St Andrews

Unit of Assessment: B10 Mathematical Sciences

a. Context

With a diverse research portfolio, often at the interface between mathematical sciences and other areas, impact features prominently within the present state and future plans of the School of Mathematics and Statistics. We describe our main impact activities.

Our work on statistical ecology has impact on environmental management, decision-making and public policy. A diverse set of user groups use our methods and software to aid wildlife management in most countries of the world. Recently, the rapid expansion of renewable energy developments has sparked greater use of our methods. For example, the UK now has by far the largest offshore wind power capacity in the world; without the underlying ability to quantify possible consequences, the strategic development on such a massive scale would not be possible.

Methods for analysing extremely large data sets have an increasing importance in the modern information-based society. There is a rapidly-expanding range of users and several areas of our research impact on this, taking advantage of our high-performance parallel computing facility, one of the largest in the UK. NASA's Solar Dynamics Observatory is building the understanding necessary to address the effects of "space weather" on our life and society, e.g. transpolar air traffic, telecommunications, GPS systems. Researchers at St Andrews are heavily involved in developing the mathematical tools for automated analysis of the vast quantities of data generated.

There are many users of research on fluid dynamics of the atmosphere and oceans. The UK Meteorological Office and the European Centre for Medium-Range Weather Forecasts are collaborating with our vortex dynamics group to develop improved models of flow for large systems, with direct relevance for modelling ocean currents and the effects of climate change.

There is a wide public audience who seek to understand mathematics through its history and development. Students, school pupils, their teachers, interested lay persons, and popular writers all make heavy use of our History of Mathematics Web Archive, which grew out of the pioneering teaching software *MacTutor*, created in St Andrews in the 1990s. The Archive now includes biographies of over 2700 mathematicians and over 2000 other files. With around 2 million hits each week, it is the most widely used mathematics teaching and information resource worldwide.

Computer technology has changed the face of mathematical sciences in the second half of the 20th century. Algorithmic mathematical tools are required in industry and education. Students with a need for computational methods in algebra and discrete mathematics make heavy use of *GAP*, a vast open source computer package. *GAP* incorporates implementations of many state-of-the-art mathematical algorithms for computing with key mathematical structures such as groups, graphs and codes. It enables the users to investigate material at the frontiers of current knowledge and import aspects of experimentation into traditionally theoretical mathematical work. St Andrews contributes much of the software and underlying theory to *GAP*, is one of four coordinating centres worldwide and the only one in the UK. We host most of *GAP* infrastructure, including its website.

b. Approach to impact

As the School's research portfolio spans the spectrum of pure and applied research, it interfaces many areas of potential impact. Our research has had different kinds of impact in many such areas and for a wide variety of users. For pure research these include: teachers, students, school pupils and mathematically-inclined members of the public; and for applied research: government agencies, international commissions, NGOs, energy companies and consultants.

Economic impacts. Much of our research has great potential for economic impact. Our approach is to build links with potential partners, as exemplified by a 3 year Knowledge Transfer Partnership project, which placed a postdoc from the School in Scottish and Southern Energy, to model extreme weather events. This resulted in predictive models to identify the likely type and location of power failure given weather forecast data, which aids the deployment of resource crews and materials and minimises customer power interruptions. Many further activities have indirect economic impact, for example fisheries modelling, publication and software licensing, see below. Two dedicated University units help us to exploit our links: Research Business Development and Contracts, which provides skilled negotiation for research contracts and consultancy; and the Knowledge Transfer Centre, which supports knowledge transfer to other organisations.

Impact on public policy. It is essential for prosperity and efficiency that public policy be informed by appropriate scientific expertise, in particular in matters underpinned by science and also in educating future scientists. Our staff have developed access to various channels to public policy making. Buckland was a member of an RSE group that reviewed the state of Scottish fisheries, and made recommendations on future policies. He is also on the Expert Panel that advises the Scientific Advisory Committee of Scottish Natural Heritage. The statistical ecologists have worked with the staff of several European fisheries institutes to improve methods of stock assessment, which influence policies on fishing. Links are also strong with government organisations from several countries involved in wildlife management. Members of the School are also able to influence public policy by membership of committees of RSE, LMS, EMS, ISSI and RSS. Campbell is on the Joint Mathematical Council which exists "to promote the advancement of mathematics and the improvement of the teaching of mathematics".

Impact on practitioners. Certain areas of our research have been specifically developed to make available widely sought expertise. Since the mid-1990s, the statistical ecologists have developed a strategy to establish and strengthen relationships with key practitioners through training workshops, user-friendly software, conferences and books. During 2008-13, CREEM offered 19 workshops on distance sampling, 2 on Bayesian methods in ecology, 1 on spatial modelling using INLA, 2 on methods for assessing impact of wind farms, plus several others less directly linked to our active research areas. Over 90% of attendees at these training workshops are from outside higher education, and the resulting contacts often lead to new non-academic collaborations and contracts. Workshop income enables us to fund further research and software development.

Impact through disseminating research. Much of our research generates interest and impact far beyond its immediate area. To ensure that it reaches the full range of potential users, we publish scientific books and software aimed at practitioners and educators. In addition to software such as *GAP* and *Distance*, relevant texts include: Buckland et al, *Introduction to Distance Sampling*; Buckland et al, *Advanced Distance Sampling*; Borchers et al, *Estimating Animal Abundance*; King et al, *Bayesian Analysis for Population Ecology*; Falconer, *Fractal Geometry*; Roney-Dougal et al, *The Maximal Subgroups of the Low-dimensional Finite Classical Groups*. Furthermore, we provide training workshops to the relevant user groups, especially in environmental statistics and computational algebra, through which we disseminate our research to practitioners and interact with user communities. This in turn enables us to identify and prioritise areas of research that will have impact, to establish links with key groups, and to identify new sources of research funding.

Impact on the environment. Our Statistics Division, with its expertise in wildlife population assessment and modelling, is uniquely placed to have significant impact on several environmental issues. The strategy for ensuring relevance of our research is partly guided by consultancy and contract requests, and partly by emerging priorities. For example, recent Convention on Biological Diversity targets highlighted a need for better methods to quantify regional biodiversity trends. We responded by establishing a group, headed by Buckland, to develop such methods through two projects: a Scottish Government-funded project with the British Trust for Ornithology and Scottish Natural Heritage as partners is modelling the effects of climate change on biodiversity; the other assesses the effects of overfishing and climate change on North Sea fish biodiversity. After a need was identified for developing methods to mitigate the effects of sonar systems on marine fauna, funding was secured from the US and UK navies to establish a group led by Thomas. Further projects relate to assessing the environmental impact of renewable energy developments.

Impact on society. Given the importance of science and mathematics for the modern society, it is important that the public are offered appropriate insights into these areas, and thus develop a certain acceptance of and empathy with its principles. Our research interests (e.g. those relating to wildlife, the sun or fractals) are well-suited to stimulating public interest, and our staff engage with the public on many levels to make the most of this. Staff have given broadcasts (e.g. episodes of *In Our Time*, Roney-Dougal), popular lectures (LMS/EMS Popular Lectures, Edinburgh Science Festival, British Science Festival, International Heliospheric Year, masterclasses for selected school pupils, lectures in local schools, etc), and expert advice to media (Hood, Priest, Robertson, Roney-Dougal). Several staff (De Moortel, Mackay and Parnell) are guides and contributors for the *sun|trek* educational website (http://www.suntrek.org/). Falconer is author of the book "Very Short Introduction to Fractals" (OUP, 2013), which targets the popular market.

c. Strategy and plans

Impact of our research, in all its diverse forms, academic or non-academic, will continue to be a major aspect of our future research strategy. The School will aim to maintain, and indeed increase when opportunities arise, both its engagement and its income from impact-related research. Particularly important are consultancy or contract income and research grants from impact-based priority areas. Potential for impact is taken into consideration when making new appointments.

The School intends to maximise the impact of its diverse portfolio of research expertise by adopting a flexible approach to supporting initiatives with potential impact. Public engagement and education will remain key components of our impact. Additionally for applied research, training provision for the user community, coupled with software development, will ensure that our methodologies enjoy widespread use in different areas of commercial and public life.

Priority areas for funding applications linked to anticipated future impact include: a) addressing the effects of water vapour on climate (NERC Climate System Theme), b) developing software for spatially explicit capture-recapture methods (EPSRC Statistics Priority Area), and c) computational discrete mathematics (EPSRC New Connections Between Mathematical Sciences and Information Communication Technologies Priority Area).

Facilitating impact is a major component of several of our research areas and the staff time required is taken into account when balancing teaching and administrative loads. Research-active staff often incorporate activities to enhance impact as part of a sabbatical work programme. The University's Knowledge Transfer Centre (http://www.st-andrews.ac.uk/ktc/) provides advice and support to enable expertise to be utilised to enhance impact.

The School actively supports areas which we anticipate will have substantial impact in the future. Thus we are expanding activities under the following topics: mark-recapture methods for quantifying numbers of drug users, HIV positive individuals, and other human populations that are difficult to monitor; prediction of power failures from weather forecasts; quantifying temporal trends in biodiversity and how these vary spatially; climate change models; developing software for global models of the atmosphere and oceans; developing understanding of the effects of "space weather" on our life and society, e.g. transpolar air traffic, telecommunications and GPS systems.

Through continuing development of computational methods and software for both serial and parallel computers, the School will remain at the cutting edge of technology, such as the use of Graphical Processing Units, to make the most of opportunities for impact as they arise. We expect *Distance* and *GAP* to remain industry standards for their respective domains, and we will work to improve and expand their capabilities. In parallel, we will continue to provide training workshops to make our methods available to user communities, and to enable knowledge exchange.

The School will expand its substantial contract work activities, ensuring that our research remains relevant to solving problems in the real world. Some of the funds generated are used to further increase impact, through software development and new workshop initiatives.

We remain committed to continual enhancement of research-teaching linkages, through authoring of books and development of user-friendly software for both courses and practitioners. Finally we will take every opportunity for public engagement on all levels. For example, we will maintain and develop the History Archive and liaise with the University to ensure its long-term future.

d. Relationship to case studies

Case Study 1 on Distance Sampling exemplifies the approach of the statistical ecologists to ensure impact, by offering training workshops, user-friendly software, and books targeting practitioners.

Case Study 2 on Environmental Impact Assessment illustrates the importance of developing software, of training workshops to make methods accessible to the user community, and of engaging with government agencies that oversee the development of renewables.

Case Study 3, the History of Mathematics Archive, demonstrates the School's commitment to stimulate public interest and engagement in mathematics and science.

Case Study 4, *GAP*, shows our commitment to research-teaching linkages by developing software for both research and pedagogical purposes.