Section A

Institution: University of St Andrews

Unit of Assessment: UoA 10: Mathematical Sciences

Title of case study: Distance sampling survey methods contribute to managing wild animal populations and quantifying biodiversity

Period when the underpinning research was undertaken: 2000 - 31 December 2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by HEI:
Stephen Buckland	Professor	01 October 1993 - present
David Borchers	Professor	01 December 1993 - present
Len Thomas	Professor	01 April 1997 - present
Cornelia Oedekoven	Senior Research Fellow	25 April 2008 – present

Period when the claimed impact occurred: 01 August 2013 - 31 December 2020

Is this case study continued from a case study submitted in 2014? N

Section B

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

Research led by Professor Buckland involved the development of distance sampling methods and the associated software package *Distance,* which is now the global industry standard. *Distance* was downloaded from 22,150 distinct email addresses from 181 countries between August 2013 and July 2020. These methods are vital for estimating the size of natural populations, and are widely used by government agencies for management and conservation (e.g. NOAA in the US and Defra in the UK), by international commissions that manage natural resources (e.g. International Whaling Commission, Inter-America Tropical Tuna Commission, International Commission for the Conservation of Atlantic Tunas), and by NGOs (e.g. Wildlife Conservation Society, BirdLife International, World Wildlife Fund for Nature). Population estimates obtained using our methods are used to inform plans to conserve threatened species (e.g. polar bears of the Barents Sea), to manage the cull or take of harvested populations (e.g. Atlantic bluefin tuna), and, increasingly, to monitor biodiversity trends (e.g. the BTO/Defra/JNCC/RSPB Wild Bird Indicators).

2. Underpinning research (indicative maximum 500 words)

To monitor biodiversity and to manage wildlife, it is necessary to estimate the size of populations. The most common method for estimating abundance of vertebrates is distance sampling. This comprises a suite of methods that involve estimating distances to detected animals from lines or points, allowing detectability to be modelled, so that animal counts can be converted to abundance estimates.

The distance sampling team was established at St Andrews in the 1990s and the key areas of development since 2000 are:

1. Model-based distance sampling methods (Buckland, Borchers, Oedekoven): to extend the applicability of distance sampling, it was necessary to develop a fully model-based approach, rather than to rely solely on a design-based approach. We published the first formulation of a fully model-based approach in 2002 (R1). Generalisations of this approach appeared in 2013, 2014 and 2016. The last of these shows that the methods developed by Royle and colleagues in the US in 2004 and 2008 are a special case of the methods we published in our 2002 book (R2).

2. Spatial distance sampling (Borchers, Buckland): this work was started by a research student, with the key publication being selected as the best JABES paper of 2004-05 (R3). With the input of Lindgren (now at Edinburgh University), INLA (an advanced spatial modelling tool) was used to provide an improved mathematical underpinning of spatial distance sampling (R4).
3. Camera-trap distance sampling (Buckland): camera-trap surveys have rapidly become a widely used method for monitoring vertebrate diversity. For animals that are individually identifiable from images (usually due to unique natural markings), spatial capture-recapture methods provide a powerful method for estimate abundance. However, methods that can be used on species for which individuals are not recognisable are less satisfactory. We therefore developed a distance-sampling approach for use in such surveys (R5).
4. Distance sampling software (Thomas, Buckland): the methodological developments described above are implemented through regular new releases of the software *Distance* (R6).

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

All articles were peer-reviewed. Articles 1 and 3 were also submitted to RAE2008.

R1. Borchers, D.L., Buckland, S.T. and Zucchini, W. 2002. *Estimating Animal Abundance*. Springer, New York. DOI: 10.1007/978-1-4471-3708-5

R2. Buckland, S.T., Oedekoven, C.S. and Borchers, D.L. 2016. Model-based distance sampling. *Journal of Agricultural, Biological and Environmental Statistics* **21**, 58-75. DOI: 10.1007/s13253-015-0220-7

R3. Hedley, S.L. and Buckland, S.T. 2004. Spatial models for line transect sampling. *Journal of Agricultural, Biological and Environmental Statistics* **9**, 181-199. (Selected as best JABES paper for 2004-05.) DOI: 10.1198/1085711043578

R4. Yuan, Y., Bachl, F.E., Lindgren, F., Borchers, D.L., Illian, J.B., Buckland, S.T., Rue, H. and Gerrodette, T. 2017. Point process models for spatio-temporal distance sampling data. *Annals of Applied Statistics* **11**, 2270-2297. DOI: 10.1214/17-AOAS1078

R5. Howe, E.J., Buckland, S.T., Després-Einspenner, M.-L. and Kühl, H.S. 2017. Distance sampling with camera traps. *Methods in Ecology and Evolution* **8**, 1558-1565. DOI: 10.1111/2041-210X.12790

R6. Thomas, L., Buckland, S.T., Rexstad, E.A., Laake, J.L., Strindberg, S., Hedley, S.L., Bishop, J.R.B., Marques, T.A. and Burnham, K.P. 2010. Distance software: design and analysis of distance sampling surveys for estimating population size. *J. App. Ecol*. **47**, 5-14. DOI: 10.1111/j.1365-2664.2009.01737.x

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

The distance sampling methods developed at the University of St Andrews are widely used as an abundance estimation tool by natural resource managers for monitoring the status of populations of conservation concern (example impact: actions triggered by trends in abundance estimates under the US Marine Mammal Protection Act), for managing the take of harvested populations (example impact: quotas for Atlantic bluefin tuna set based on aerial survey estimates of biomass), and for routine, often statutory, monitoring of biodiversity trends (example impact: Defra policy is influenced by biodiversity trends as measured by the Wild Bird Indicator, one of 15 headline UK Quality of Life Indicators).

Providing the global standard software for estimating animal abundance from sightings surveys

The Distance team at St Andrews has disseminated its work through a multi-pronged, sustained strategy: 1. Publish methodological developments in top journals. 2. Publish introductory and advanced texts. 3. Provide user-friendly software *Distance*. 4. Back this up with responsive support via email and an online forum. 5. Provide annual training workshops, and a free online course. 6. Publish papers that promote best practice in ecology and taxon-specific journals, targeting wildlife managers. 7. Provide a consultancy service to key user groups. The Royal Statistical Society recognised the success of this strategy by awarding Buckland with the Guy Medal in Gold in 2019. Part of the citation for this award read: "*Stephen has opened up advanced statistical methods to the user community by leading the development of freely-available software (notably Distance now with over 50,000 [people] users from 130 countries) and associated core textbooks*." [S1].

Our *Distance* Windows software is the global industry standard and has been downloaded from 22,150 distinct email addresses from 181 countries between 1st August 2013 and 31st July 2020. (The figures in the above quote correspond to an overlapping but mostly earlier time period.) The official reference for *Distance* is R6, and as of 26 August 2020, Google Scholar showed 2,075 citations for this paper. The software *Unmarked* is the only serious competitor; its official reference is Fiske and Chandler (J Stat Software, 2011), and had 1,409 citations in Google Scholar on the same date. As *Unmarked* is for use on a wider set of methods, many of those citations do not relate to distance sampling.

Although research papers establish the credibility and utility of methods, it is crucial to publish textbooks and tutorial-style papers to make the methods more accessible to the user community. Buckland is senior author of all four books that are dedicated to distance sampling: an initial book in 1993, an introductory book in 2001, an advanced book in 2004, which have led to the current a book on methods and applications, "Distance Sampling: Methods and Applications" published in 2015. We also offer a series of annual training workshops, which include online workshops. Software development plays a key part in making methods accessible. Underpinning research (Section 2) is implemented in the software on an ongoing basis, and since August 2013, the following features have been available or implemented: a link to the free statistical software R, providing a major expansion in analytical capabilities; a density surface modelling (DSM) analysis engine, written as a library in R; a simulation engine and a multi-analysis engine; point transect analyses for the MRDS (mark-recapture distance sampling) and DSM engines; a Shape Import Wizard. In parallel with these developments, the methods of *Distance* for Windows have progressively been made available through R packages (Miller *et a*l., J Stat Software, 2019; http://distancesampling.org/).

Supporting MCS compliance of the eastern tropical Pacific tuna fishing industry

The eastern tropical Pacific (ETP) is a massive area that extends from Central America to Hawaii, and from California to Peru. ETP tuna purse seine fleets use fishing methods that result in some dolphin mortality. There is a need to monitor trends in the affected species of dolphins, to assess whether the industry is having a negative impact on populations. In the absence of such a study, tuna exports from Mexico to the US are under threat. (Mexican exports of tuna are worth over USD150,000,000 per year, with the US accounting for well over half.) The US used to conduct surveys at a cost of around USD10,000,000 per year, but have now stopped, due to budget cuts. Our multiple-covariate distance sampling methods were used to analyse the sightings data (https://www.int-res.com/abstracts/meps/v291/p1-21/). Their final survey was in 2006. On the basis of the US stock assessments that use our methods and other evidence, the Marine Stewardship Council (MSC) for sustainable fishing awarded the Pacific Alliance for Sustainable Tuna (PAST) MSC certification in 2017. One of the conditions of the award required: "*significant financial investment in an international research program to assess dolphin populations in the Eastern Tropical Pacific Ocean*". A research programme is now underway to satisfy this condition. Oedekoven (PI) and Buckland (CI) are working closely with the Inter-American Tropical Tuna Commission and PAST to implement a new survey, and they coordinated a trial shipboard and aerial drone survey off Mexico in November 2019. The methods of analysis for the data are based on our model-based distance sampling research (R2), using both multiple-covariate and mark-recapture distance sampling. The subsequent main survey has been delayed by the Covid-19 lockdown. The Director of the Inter-American Tropical Tuna Commission, notes that our methods are "*key to determining whether the purse-*

seine fleet that catches tunas found in association with dolphins can continue to fish for tuna with the confidence that the fishery is sustainable" [S2].

Quantifying the effect of climate change on marine mammals in the Arctic for monitoring purposes

We have also worked with scientists in Denmark and Norway to design and analyse surveys of populations of beluga whales (survey conducted in 2012, estimates published in 2017), bowhead whales (survey conducted in 2006, revised estimates published in September 2013) and polar bears (survey conducted in 2015, estimates published in 2017). These surveys are important as they allow population trajectories to be estimated, and the impact of ice loss in the Arctic to be assessed. Our methods (R6) allow estimation of abundance from the data recorded on aerial and shipboard surveys. The Head of the Norwegian Polar Institute's Polar Bear Programme, which advises Norwegian authorities on matters concerning polar environmental management, comments: "*Your methods have played a key role in establishing the status of the Barents Sea polar bear population, so that we can monitor the impact on this keystone predator as summer sea ice cover reduces* …" [S3], while a Professor of the Greenland Institute of Natural Resources comments: "*Your [Buckland's] methods have played a key role in understanding the effects of sea-ice loss on beluga whale distribution and abundance, and on the population trajectories of bowhead whales and narwhals off Greenland."* [S4]. By quantifying size of populations and time trends in the size, our methods allow the impact of climate change on Arctic marine mammals to be monitored.

Changing professional practice for monitoring biodiversity of terrestrial vertebrates

In 2017, we developed camera-trap distance sampling (CTDS) to allow estimation of population sizes (R5). The method is being applied to monitor vertebrate diversity in a range of terrestrial environments, from the Himalayas to desert. Its greatest impact has been in quantifying biodiversity of rain forests, for which wildlife surveys are particularly difficult to conduct and biodiversity trends problematic to estimate, given the dense vegetation. A Senior Scientist and Project Manager of the Max Planck Institute for Evolutionary Anthropology notes that the following organisations have switched to using CTDS for monitoring in rain forests: World Wildlife Fund, Wildlife Conservation Society, Wild Chimpanzee Foundation, the government of Guinea, and the Office Ivoirien des Parcs et Réserves [S5]. The first two organisations monitor rain forests across Africa, Asia and the Americas.

Providing a scientific basis for two proposed Scottish Marine Protected Areas

To safeguard marine biodiversity around Scotland, Scottish Natural Heritage (renamed NatureScot in 2020) proposed the Southern Trench Marine Protected Area (MPA) in 2014 and the North-east Lewis MPA in 2019, whose boundaries were chosen based on SNH commissioned reports 573 and 594, published in 2014, which used our distance sampling and density surface modelling methods (R3). These reports were commissioned because at that time, no quantitative evidence was available on which to propose MPAs and their boundaries [S6, S7].

Contributing to wildlife management on a global scale with diverse applications of* Distance *software

Our *Distance* software and distance sampling methods are used for a wide range of surveys. Between 1 Aug 2013 and 26 August 2020, Google Scholar lists 2,075 publications that cite R6, and most of these are studies that have used our software to address wildlife management issues. We list a small sample of the studies published in the first 5 months of 2019 that do so to illustrate the diversity of applications and wildlife issues addressed: management of declining populations of Arabian gazelles; assessing impact of poaching on ungulate populations in Iran; estimating the distribution and abundance of guanacos (a species of conservation concern) in Patagonia; managing livestock and populations of large wild mammals in the Yaeda Valley in

Tanzania; estimating chimpanzee densities in the Ivory Coast so that population trends can be monitored; assessing viability of Madagascar lemur populations; managing rabbit populations on the Iberian Peninsula; estimating feral cat densities in an urban environment; improving ringed seal density estimates, so that harvests can be managed more effectively; modelling the spatial abundance of fin whales in the Gulf of St Lawrence; estimating blue whale density off California so that their recovery may be assessed; effect of windfarms on upland bird densities; evaluating methods for assessing abundance of a forest songbird in the US; monitoring forest bird populations in New Zealand; estimating the sizes of raptor populations in Uganda's conservation areas; response of reptiles to fire in NW Africa [S8].

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

S1. Royal Statistical Society announcement of honours recipients for 2019. https://rss.org.uk/news-publication/news-publications/2019/general-news-(1)/announcing-our-honours-recipients-for-2019/

S2. Inter-American Tropical Tuna Commission. Letter from the Director of IATTC.

S3. Norwegian Polar Institute. Letter from the Head of the NPI's Polar Bear Programme.

S4. Greenland Institute of Natural Resources. Letter from a Professor of the GINR.

S5. Max Planck Institute for Evolutionary Anthropology. Letter from a Senior Scientist and Project Manager of the MPIEA.

S6. Scottish Natural Heritage report: https://www.nature.scot/sites/default/files/2017-11/Marine%20Protected%20Area%20-%20Data%20confidence%20assessment%20-%20Southern%20Trench%20MPA%20proposal_0.pdf See references on pp. 3, 6 and 8 to Paxton et al., 2014, which used the methods of R3.

S7. Scottish Natural Heritage report: https://www.nature.scot/sites/default/files/2019-06/North-east%20Lewis%20possible%20MPA%20-%20Data%20Confidence%20Assessment.pdf See references on pp. 2, 3, 6 and 8 to Paxton et al., 2014 a,b, which used the methods of R3.

S8. Studies amalgamated into a single pdf.