Institution: University of Sheffield

Unit of Assessment: 10 - Mathematical Sciences

Title of case study: Improving Radiocarbon Calibration

1. Summary of the impact

Statistical research undertaken at Sheffield has resulted in the provision of internationally-agreed calibration curves for radiocarbon dating that offer greater accuracy and higher resolution, and which (for the first time) span the full range of timelines over which radiocarbon dating is feasible. Since the amount of radioactive carbon in the Earth's atmosphere has not remained constant over time, anyone seeking to interpret a radiocarbon determination now calibrates it using one of these curves, which results in up to 50% reduction in calibrated date intervals over those previously obtainable. Non-academic users of these curves include staff in commercial radiocarbon laboratories, those working in commercial archaeology units, freelance archaeological consultants, palaeoenvironmental scientists working in governmental and intergovernmental bodies, private and public sector staff charged with the care of ancient buildings and environments, and freelance consultants who undertake radiocarbon dating in order to advise private customers, public sector companies and government agencies.

2. Underpinning research

Radiocarbon dating is crucial to the establishment of archaeological chronologies and of timelines for many Holocene and late Pleistocene palaeoclimate studies, and palaeoenvironmental reconstructions. In order to provide useful dating evidence, all radiocarbon determinations must be calibrated because the proportion of radioactive carbon (^{14}C) in the earth's atmosphere has varied over time. Our knowledge about the scale and timing of variations in ^{14}C levels comes from radiocarbon determinations for known-age samples. The data are used to derive calibration curves that map radiocarbon to calendar ages. Until the late 1990s, these curves were based on measurements on tree rings, for which the calendar ages are well established, and were estimated using rather *ad hoc* statistical methods.

By 2000, however, it had become clear that significant other potential sources of calibration data existed and that, if they could be utilised, it should be possible to both extend the length of the calibration and improve its resolution. Such data derive from long environmental archives (such as marine sediments, stalactites and stalagmites) and are considerably more difficult to utilise than those from tree rings because of the complex nature and scale of the uncertainties in the calendar age estimates associated with them. These age estimates derive from methods such as uranium–thorium dating, counting of annual laminations and age-depth modelling, each of which leads to a different error structure, some of which produce calendar age estimates that are highly correlated with those of other samples in the database [**R1-R6**].

The key research that gave rise to the impact was undertaken in the School of Mathematics and Statistics at Sheffield, between 2001 and 2009, by Professor Caitlin Buck, Professor Paul Blackwell and Dr Tim Heaton. It involves the development of a fully probabilistic, Wiener process-based modelling framework for the estimation of radiocarbon calibration curves [**R1-R3**] and Bayesian implementation of those methods in such a way that they can be extended as new data structures become available [**R5**]. Users typically appreciate that the internationally-agreed calibration curves are at the heart of the calibration software that they use and most cite both the software and the paper that launched the curve they utilised in their work. Given that academic, commercial and public sector users all publish work in the academic literature, it is not practical to distinguish the citations from authors working in different sectors but, as of October 2013, there have been more than 4,000 citations of [**R4**] and [**R6**].

The IntCal Working Group (IWG), coordinated by Paula Reimer at Queen's University Belfast (QUB), is responsible for providing the internationally-agreed estimates of the radiocarbon calibration curve. Buck was invited to join the group in 2001, and other Sheffield staff (Blackwell, Heaton) joined between 2002 and 2008. Since 2001, the work has been funded by the Leverhulme Trust and NERC. The calibration database is managed at QUB, but all statistical work was undertaken at Sheffield [**R1-R3**, **R5**], and all internationally-agreed curves have been constructed at Sheffield since 2004 (notably [**R4**] and [**R6**]).

3. References to the research [* = References that best indicate the quality of the research]

R1* Buck, C.E., Blackwell, P.G. (2004). Formal statistical models for estimating radiocarbon calibration curves. *Radiocarbon*, 46, 1093–02.

R2 Buck, C.E., Gómez Portugal Aguilar, D., Litton, C.D., O'Hagan, A (2006). Bayesian nonparametric estimation of the radiocarbon calibration curve. *Bayesian Analysis*, 1, 265–88. doi: 10.1214/06-BA109

R3 Blackwell, P.G., Buck, C.E. (2008). Estimating radiocarbon calibration curves (with discussion). *Bayesian Analysis*, 3, 225–68. doi: 10.1214/08-BA309

R4* Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B.G.M., Manning, S., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W.;, van der Plicht, J., Weyhenmeyer, C.E. (2004). IntCal04—terrestrial radiocarbon age calibration, 0–26 cal kyr BP. *Radiocarbon*, 46, 1029–58. [**2,437** citations (ISI)]

R5 Heaton, T.J., Blackwell, P.G., Buck, C.E. (2009). A Bayesian approach to the estimation of radiocarbon calibration curves: the IntCal09 methodology. *Radiocarbon*, 51, 1151–64.

R6* Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J., Weyhenmeyer, C.E. (2009). IntCal09 and Marine09 Radiocarbon Age Calibration Curves, 0–50,000 Years cal BP. *Radiocarbon*, 51, 1111–50. [**1,690** citations (ISI)]

4. Details of the impact

An informal survey of radiocarbon dating laboratories worldwide suggests that over 50,000 radiocarbon determinations are undertaken annually, at a cost of around £350 each, i.e. more than £17.5m pa. Most users interpret radiocarbon determinations with freely-available radiocarbon calibration software such as CALIB (http://calib.qub.ac.uk/calib/), OxCal (http://c14.arch.ox.ac.uk/oxcal.html) or BCal (http://bcal.sheffield.ac.uk). Due to improvements in accuracy, and for reasons of consistency, the providers of such software automatically migrate their packages to the new curves as they are published. Consequently, curves estimated at Sheffield have been at the core of all of these software packages since 2004 until the present time. One of the three packages, BCal, is an on-line service based at Sheffield, which is offered free-of-charge to the international community by Buck and a team of volunteers.

Users in the public and private sectors since 2008 include:

- commercial radiocarbon dating laboratories (e.g. Beta Analytic)
- commercial archaeology units (e.g. University of Leicester Archaeological Services and Trent & Peak Archaeology)
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- palaeoenvironmental scientists in governmental and intergovernmental agencies (e.g. the British Antarctic Survey and the Intergovernmental Panel on Climate Change)
- private and public sector staff charged with the care of ancient buildings and environments (e.g. English Heritage)
- freelance experts who undertake radiocarbon dating to advise private customers, public sector companies and government agencies.

Economic impact

The need to reduce the costs of archaeological work has made the improved accuracy offered by the Sheffield curves increasingly important. The Head of Research at Trent & Peak Archaeology, UK says: "*As a commercial archaeological unit ... we are of course reliant upon accurate calibration methodologies, and hence support strongly the IntCal team's work on refining calibration curves. Refinements in calibration have increased confidence in the accuracy of this dating technique and in our area of activity have spurred its wider use ... This demonstrable increase in accuracy is especially crucial in view of the ever greater pressure to reduce the costs of archaeological work in advance of development, and hence the need to defend more fiercely investments in appropriate programmes of radiocarbon dating*" [**S1**].

Impact on national and international policy and services

Consistency is particularly important to those working on international policy since it allows them to compare and combine results from different projects. Eric Wolff FRS, Science Leader (Chemistry and Past Climate), British Antarctic Survey says that "*Correct and consistent dating of past events in the palaeorecord is crucial to our ability to understand processes in the Earth system, and therefore to verify and improve models of its future behaviour. In this sense the work of IntCal is one of the cornerstones that allows us to use the past to provide insights that can inform policy*" [**S2**]. One of the lead authors, Jonathan Overpeck, of the Palaeoclimate chapter in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report [**S3**] – the most authoritative document influencing international climate change policy during 2007–13 – says that the work undertaken by the IntCal group was "*a critical underpinning of much of the chapter that relied on radiocarbon chronologies. More specifically, a number of papers assessed in the chapter produced timescales based on calibration of radiocarbon ages using IntCal04*" [**S4**].

Impact on practitioners

Practitioners confirm that the Sheffield curves have offered substantial improvements, not only providing a common standard and improved method, but extending the range of calibration. The President of Beta Analytic (the world's largest commercial radiocarbon dating laboratory) says that he supports IntCal as "*the primary (and preferably only) database used in radiocarbon dating calibrations*" [**S5**]. The President of archaeology consultancy, T. S. Dye & Colleagues, Archaeologists, Inc., Honolulu, states that incremental improvements to the calibration curve "*have become increasingly important as Hawaiian archaeologists solve the substantial problems of chronologically ordering and dating events important to the short prehistoric sequence in the islands*" [**S6**].

The Scientific Dating Coordinator, English Heritage defines the IntCal programme as '*industry standard*' in both economic and professional practice terms. He says that the new curves are adopted "*not only because they form a common standard, but also because of the enhancements which the new data and compilations provide. ... Key benefits ... include improved methods for the modelling of the tree-ring data (Buck & Blackwell 2004* [**R1**]*), which enable more robust wiggle-matching procedures to be adopted. This is critical for the development of this technique to allow the dating of historic buildings (e.g. Tyers et al. 2009* [**S7**]*) to an equivalent level of precision and accuracy as routinely provided by dendrochronology. Both this curve and the subsequent 2009*

release have extended the range of radiocarbon calibration to the limit of the technique" [**S8**].

Impact on public engagement in science

The dating aspects of high-profile projects also provide archaeologists with effective ways to engage the general public in the complexities of modern science-based archaeology. The lead archaeologist on the "Searching for Richard III" project, says of IntCal09 that "*Without such a calibration curve it would not have been possible to place any of the remains on a real timescale and thus to determine their validity as belonging to the era of Richard III. The IntCal calibration curve has thus played an important role in helping the project to capture the public imagination*". He also says that there have been "*many thousands of hits*" on the web page http://www.le.ac.uk/richardiii/science/carbondating.html on which his team documented the radiocarbon dating parts of their work, that "*5 million people watched the Channel 4 programme on which we discussed the interpretation of the radiocarbon dating evidence*" and that "*the exhibition at the Guildhall in Leicester in which details of the dating are presented has had over 60,000 visitors*" [**S9**].

5. Sources to corroborate the impact

S1 Letter from the Head of Research at Trent & Peak Archaeology corroborates economic impact of research.

S2 Science Leader (Chemistry and Past Climate) at the British Antarctic Survey, Cambridge, UK corroborates impact on national/international policy and services.

S3 Jansen, E. J. et al. (2007). Palaeoclimate. In S. Solomon, et al. (eds). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, pp. 433–97.

S4 Co-director, Institute of the Environment, and Professor of Geosciences and Atmospheric Sciences, University of Arizona, USA, lead author on Palaeoclimate chapter in Jansen et al. (S3) corroborates underpinning of IPCC report by Sheffield research.

S5 President of Beta Analytic, USA, corroborates impact on practitioners.

S6 President of T.S. Dye & Colleagues, Archaeologists, Inc., Honolulu, corroborates impact on practitioners.

S7 Tyers, C., Sidell, J., van der Plicht, J., Marshall, P., Cook, G., Bronk Ramsey, C., Bayliss, A. (2009) Wiggle-matching using known-age pine from Jermyn Street, London, UK. *Radiocarbon*, 51, 385–96.

S8 Scientific Dating Coordinator, English Heritage, UK, corroborates impact on practitioners

S9 Director of University of Leicester Archaeological Services, UK, corroborates impact on public engagement in science (http://www.le.ac.uk/ulas/about/index.html).