| | | |
|---|---|---|
| **Institution:** University of Sheffield | | |
| **Unit of Assessment:** C-14 Geography and Environmental Studies | | |
| **Title of case study:** Transforming time: understanding climate change and human history using IntCal radiocarbon calibration | | |
| **Period when the underpinning research was undertaken:** 2004–2014 | | |
| **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:** |
| C E Buck | Professor | 2000–present |
| **Period when the claimed impact occurred:** August 2013–December 2020 | | |
| **Is this case study continued from a case study submitted in 2014?** N | | |

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

Radiocarbon ($^{14}C$) is the most frequently used approach to dating organic artefacts from the last 55,000 years. However, all radiocarbon dating requires calibration to transform $^{14}C$ measurements into calendar ages. The IntCal Working Group (IWG) is an international team of 27 scientists formed in 2001 to establish criteria for calibration data and methods for curve construction. Sheffield researchers conducted the key research that gave rise to the curve being developed. The IntCal calibration curve has international reach as the global standard for radiocarbon calibration, being used by all major commercial $^{14}C$ laboratories. It has underpinned global climate change policy, and impacted archaeological practice and planning and development decisions in the heritage sector.

## 2. Underpinning research (indicative maximum 500 words)

Radiocarbon dating relies on the simple idea that, while alive, organisms take in carbon from their surroundings and so have a ratio of isotope $^{12}C$ to $^{14}C$ that is in equilibrium with their atmosphere. Once an organism dies, it stops taking in new carbon, the stable $^{12}C$ remains but the $^{14}C$ decays at a known rate. Measuring the ratio of $^{14}C$ to $^{12}C$ left in a sample therefore provides a dating technique.

If the concentration of atmospheric $^{14}C$ had been constant throughout history, this would be straightforward. However, it has fluctuated significantly. In order to date organisms precisely scientists need calibration curves, which provide a reliable historical record of this $^{14}C$ variation to accurately transform their radiocarbon measurements into calendar ages. Uncalibrated radiocarbon measurements differ substantially from the best estimates of actual calendar dates and so are of little interpretive value. Sheffield researchers, together with their international collaborators, provide the globally ratified standard for this calibration via the series of IntCal calibration curves.

The IntCal Working Group (IWG) is an international team of 27 scientists formed in 2001 to establish criteria for calibration data and methods for curve construction. Sheffield researchers have been members since 2001. The key research that gave rise to the impact was undertaken at the University of Sheffield, between 2001 and 2014, by Professor Caitlin Buck, and Professor Paul Blackwell and Dr Tim Heaton (UoA 10). It involved development of a fully probabilistic modelling framework for estimating radiocarbon calibration curves and a suite of Bayesian implementation methods that can be extended as new data structures become available.

Sheffield models and methods have been used for all IntCal curve updates since 2004. The group produces three regularly updated curves dependent upon the environment where the object to be dated obtained its carbon: IntCalXX (where XX represents the year of release) for the Northern Hemispheric atmosphere, SHCalXX for the Southern Hemisphere, and MarineXX for the world's oceans. These updates (in 2004 **[R1]**, 2009 **[R2]**, 2013 **[R3]**) replaced the previous curves and were made as our understanding of the Earth system advanced and new data sets, such as tree rings, plant macrofossils, or corals, became available. Each update provided new challenges for the Sheffield team members as the unique elements of the calibration data led to modelling complexity. These required bespoke solutions and close collaboration with co-authors to ensure their expert knowledge was incorporated. The 2009 update provided an extension of the calibration curves back from 24,000 (their previous limit) to 50,000 years before present, allowing calibration for the full limit of the radiocarbon technique for the first time. This required Sheffield to provide a careful statistical synthesis of a variety of new reference data sources and novel uncertainty quantification **[R4, R5]**. For the 2013 curves, Sheffield identified previously unconsidered sources of uncertainty in the reference data and developed new approaches to quantify and incorporate them **[R6]**.

The IWG crosses interdisciplinary boundaries and key to the construction of all the curves are the modelling and statistical analyses, by Sheffield researchers, which are required to combine the diverse data sets, each with their own specific attributes, into each of the IntCalXX, SHCalXX and MarineXX curves.

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

**R1.** Reimer, P.J., Baillie, M.G.J., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., **Blackwell, P.G., Buck**, C.E., Burr, G.E., 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., McCormac, G., Manning, S., … Weyhenmeyer, C.E. (2004). IntCal04 terrestrial radiocarbon age calibration, 0-26 cal kyr BP. (2004). *Radiocarbon*, *46*(3), 1029–1058. https://doi.org/10.1017/s0033822200032999

**R2.** 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., … Weyhenmeyer, C. E. (2009). IntCal09 and Marine09 Radiocarbon Age Calibration Curves, 0–50,000 Years cal BP. *Radiocarbon*, *51*(4), 1111–1150. https://doi.org/10.1017/s0033822200034202 [3,831 citations, Scopus 28 May 2020]

**R3.** Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., **Blackwell, P. G.**, Ramsey, C. B., **Buck, C. E.**, Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Haflidason, H., Hajdas, I., Hatté, C., **Heaton, T. J.**, Hoffmann, D. L., Hogg, A. G., Hughen, K. A., … van der Plicht, J. (2013). IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0–50,000 Years cal BP. *Radiocarbon*, *55*(4), 1869–1887. https://doi.org/10.2458/azu_js_rc.55.16947. [6,739 citations, Scopus 28 May 2020]

*Across all disciplines, this was the most cited paper published by UK authors in 2013, and the sixth most cited published by U.S. authors in 2013.*

**R4.** **Buck, C. E.**, & **Blackwell, P. G.** (2004). Formal Statistical Models for Estimating Radiocarbon Calibration Curves. *Radiocarbon*, *46*(3), 1093–1102. https://doi.org/10.1017/s0033822200033026

**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*(4), 1151–1164. https://doi.org/10.1017/s0033822200034214

**R6.** **Niu, M., Heaton, T. J., Blackwell, P. G., & Buck, C. E.** (2013). The Bayesian Approach to Radiocarbon Calibration Curve Estimation: The IntCal13, Marine13, and SHCal13 Methodologies. *Radiocarbon*, *55*(4), 1905–1922. https://doi.org/10.2458/azu_js_rc.55.17222

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

All radiocarbon dating requires calibration to transform $^{14}C$ measurements into calendar ages. IntCal curves are the internationally agreed standard for the radiocarbon calibration - everyone in the world who uses radiocarbon dating depends upon the IntCal curves to calibrate their radiocarbon dates. There are currently at least 141 laboratories around the world with facilities for radiocarbon dating, all of which use IntCal13, SHCal13, and Marine13 calibrations [S1]. Published laboratory codes from 14 major labs indicate that over 120,000 samples were dated per year between 2013 and 2018. Of these, over 93% are calibrated using IntCal curves. There are currently no competitors to the curves provided by the IntCal Working Group and without curves the laboratory results are not interpretable as dates. At a cost of £350 per date this equates to over £42 million per annum generated for commercial laboratories. Without the curves the revenue generated for commercial laboratories by radiocarbon dating would be considerably lower.

The ability to obtain accurate and precise dating is fundamental, as it informs many of the economic and professional decisions relating to the protection, conservation, and understanding of the Historic Environment. As the global standard for radiocarbon dating, the IntCal curves provide a consistent chronology that enables accurate measurements and verification of findings across the globe. They provide validity and enable cross checking and comparison of dates and discoveries. IntCalXX delivers "*robust, reliable, and readily comparable chronologies between, and within, projects*" **[S1].**

The President of Beta Analytic, the largest commercial radiocarbon laboratory in the world, describes the IntCal curves as "*the recognized standard for radiocarbon age calibrations*" and recommends recent updates "*as the primary (and preferably only) curves used for radiocarbon dating calibrations*" **[S2].** Time and monetary constraints would not otherwise allow for such robust statistical methodology and curve refinement within the commercial environment without the findings from the IWG **[S2]**. In addition, the frequent updates to the IntCal curves have generated improved understanding by allowing for over a million previously produced radiocarbon ages to be reviewed and updated, thus producing 'new and exciting interpretations' of historic events **[S2].**

Accurate and reliable radiocarbon dates calibrated with IntCal09 and IntCal13 have therefore had an impact in a wide range of different social and economic areas since 2013. The following examples have been chosen to demonstrate the variety of fields in which these dating methods are used, and the breadth of impacts that have affected a diverse range of beneficiaries.

**Impact on global climate change policy**

A precise understanding of our past climate is needed to understand, predict, and mitigate potential, current, and future changes. The IntCal curves enable the comparison of environmental records on radiocarbon timescales with other key independent timescales (e.g. ice-cores).

The Intergovernmental Panel on Climate Change (IPCC) is the United Nations body responsible for assessing climate change science. Used by policy makers to understand risks, and plan adaptations and mitigations, its reports are the most authoritative documents influencing understanding of international climate change. In September 2013, 259 experts from 39 countries published 'Climate Change 2013: The Physical Science Basis', a comprehensive assessment of evidence of climate change. 80 publications cited in this assessment relied on the IntCal curves for their calendar dates **[S3]**.

This assessment formed the scientific basis for the 5th IPCC report (published in 2014 and agreed by governments of all IPCC member countries). This was described by the vice-chair of the IPCC's Working Group 3, which deals with measures to mitigate climate change, as "*the most important report the IPCC has ever produced*" **[S4]** as it underpinned the United Nations climate talks in Paris in 2015. These talks led to the formation of the Paris Agreement, the first-ever universal, legally binding global climate change agreement, adopted December 2015 and formally ratified by the EU in October 2016 **[S5]**.

Regents' Professor, Northern Arizona University, and lead author of Chapter 2 of the 6th IPCC report testifies that the IntCal curves have "*been critical for providing a perspective on past climate […] essential for our understanding of the climate system, and a baseline for modelling future changes*". IntCal curves are "highly relevant" to policy development as they provide new understanding on the carbon cycle and the processes in the Earth's climate system **[S6].**

**Impact on developers and practitioners in the protection and appreciation of the historic environment**

The IntCal curves provide a reliable, rigorous, international, industry-wide standard that is vital to the commissioning and delivery of commercial archaeology **[S1].** The comparability and consistency provided by the IntCal curves, together with improvements in the precision and accuracy of these curves, ensures clear value for money for the construction and land development industry. This funds the great majority of archaeological investigation (a market currently worth an estimated £200 million annually in England, and €2 billion annually across Europe) **[S1].**

The Bayesian approach used to compile the IntCal curves allows integration with the standard use of Bayesian chronological modelling in the archaeological sector. Within the archaeological sector, calibrated radiocarbon dating, using the IntCal curves, is frequently a required step in the planning process when archaeological work is commissioned for new construction development including large-scale projects **[S1]**. The National Head of Research at Historic England states that radiocarbon dating and calibration using the IntCal curves, in combination with Bayesian chronological modelling are "*fundamental elements of archaeological specifications issued as part of the planning process*" **[S1]**.

Thus, the IntCal curves provide essential infrastructure that enables developers to commission archaeological work to standards that meet regulatory guidance in the UK and beyond **[S1].**

**Increased public awareness in the historic environment**

The Heritage Sector is an important economic sector. In England, in 2019, it directly provided £14.7 billion GVA and 206,000 jobs. Knowledge is critical to public enjoyment of the Historic Environment and is often underpinned by accurate radiocarbon dating. In England it provided new insights into the construction of Stonehenge. This knowledge has been incorporated into displays in the Stonehenge visitors' centre and accompanying recreation of Neolithic houses, both opened in December 2013. IntCal09 enabled "*novel insight*" that "*fed directly into the presentation of the Stonehenge site*" **[S1].**

In China, IntCal13 provided evidence for the earliest water-management site in Liangzhu City. IntCal13 calibrated dates were subsequently used in its application, and 2019 inscription, to UNESCO's World Heritage List. Having a site inscribed on the World Heritage List increases the prestige of the site and helps raise awareness among citizens and governments for the preservation of that site. This increased awareness facilitates a rise in the level of the protection and conservation given to heritage properties. Countries can also apply for financial assistance and expert advice from the World Heritage Committee to support activities for the preservation of its sites.

The site provides new insights into Chinese history by '*authentically and credibly demonstrating the degree of development of the rice-cultivating civilization […] in the Neolithic'* **[S7]**. Use of IntCal13 on artefacts from Liangzhu City provided scientific confirmation for the first time that '*Chinese are the inheritors of a 5,000-year-old unbroken cultural tradition'* **[S7]**. These results are used in 2019-20 Chinese history and mathematics textbooks, an act the president of the Chinese Archaeological Society states helped '*foster a cultural confidence among young people'* and improved '*their awareness of cultural protection and heritage'* **[S7]**.

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

**S1.** Letter from National Head of Research Historic England

**S2.** Letter from the President of Beta Analytics

**S3.** Climate Change 2013: The Physical Science Basis https://www.ipcc.ch/report/ar5/wg1/

**S4.** The Conversation article, dated 2nd November 2014, describing the importance of the 5th IPCC Report as it underpinned the formation of the Paris Agreement (https://theconversation.com/ipccs-most-important-report-sets-stage-for-paris-climate-talks-33713).

**S5.** European Commission web page describing the importance of the Paris Agreement (https://ec.europa.eu/clima/policies/international/negotiations/paris_en#:~:text=The%20Paris%20Agreement%20sets%20out,support%20them%20in%20their%20efforts).

**S6.** Letter from Regents' Professor Northern Arizona University and lead author of Chapter 2 of the 6th IPCC report

**S7.** Combined sources to corroborate impact on dating of Chinese artefacts, public awareness and education.