

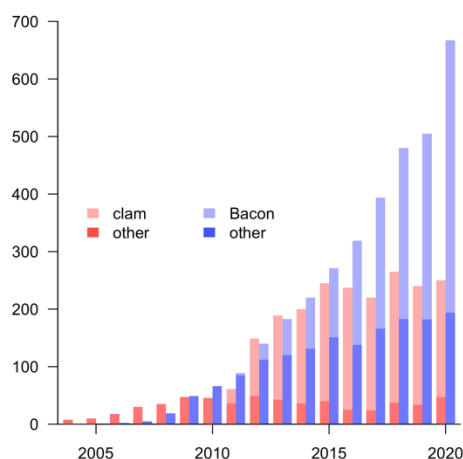
Institution: Queen's University Belfast		
Unit of Assessment: 15		
Title of case study: Providing a unified timescale to our past: the global impact of Queen's radiocarbon chronological techniques		
Period when the underpinning research was undertaken: 2010-2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Paula Reimer, Maarten Blaauw	Professor Reader	2004 – present 2007 – present
Period when the claimed impact occurred: 2004 - 2020		
Is this case study continued from a case study submitted in 2014? N		
1. Summary of the impact		
<p>Radiocarbon (^{14}C) is an essential tool for reconstructing past ages, but only after calibration and age-modelling of raw measurements onto the calendar scale. Reimer initiated the IntCal Working Group in 2001, leading an international team to construct refined ^{14}C calibration curves used for >92% of worldwide ^{14}C calibrations. Impacts include:</p> <ul style="list-style-type: none"> • Use by major commercial ^{14}C laboratories generating approx. GBP45,000,000 annual revenue • Released ^{14}C age-model approaches which have become worldwide standards • Scientific Basis of 5th IPCC report (the roadmap for the Paris Agreement) • UNESCO World Heritage status for Chauvet Cave's (oldest European figurative cave art) • Dating the earliest inhabitants in Ireland 		
2. Underpinning research		
<p>Chronological techniques are essential to provide a unified timescale for archaeological and environmental changes in the past. Raw measurements/dates need to be translated into meaningful calendar dates to be understood by a wider audience. Ever since the development of ^{14}C dating in the 1950s, it has been known from ^{14}C dating of historical objects that atmospheric radiocarbon concentrations have varied over time. These fluctuations cause ^{14}C ages to deviate from calendar time by up to 10-15%, requiring correction (calibration) to calendar years using curves constructed from known-age samples such as tree-rings.</p> <p>Radiocarbon calibration</p> <p>In 2001, Paula Reimer initiated the IntCal Working Group (IWG) through funding she secured from the Leverhulme Trust, assembling and leading a team of international experts to evaluate the available data from a variety of independently dated archives (for example, tree-rings, corals, speleothems). The IWG developed criteria for selection of calibration-quality data and improved statistical techniques. This allowed us to construct robust calibration curves back to 26,000 years before present [R1]. Reimer received NERC funding in 2006 allowing the IWG, under her direction, to extend the marine and terrestrial (both northern and southern hemisphere) calibration curves back to the ca. 50,000 year limit of radiocarbon dating [R2], which meant, for example, that for the first time calibrated radiocarbon dates on the last known Neanderthals could be compared to the timing of climate changes recorded in the Greenland ice cores.</p>		

With increased understanding of the global carbon cycle, the IWG was able to greatly improve the calibration curves by applying archive-specific variability, e.g., modelled marine reservoir correction changes over time [R3]. Reimer was awarded the **Lyell Medal** by the **Geological Society of London** in 2013 for her work on radiocarbon calibration. Of all Scopus papers citing ^{14}C calibration curves since 2004, 92.3% cite IntCal.

Age-modelling software

Because the calibration curves are non-linear, software is needed to make the conversion between radiocarbon ages and calendar year estimates as reliable as possible. Additional information such as stratigraphy can be included using Bayesian models. Blaauw developed innovative open-source software for chronological modelling such as *clam* [R4] and *Bacon* [R5]. *Bacon* and other Bayesian age-depth models help the community produce more realistic chronologies with reliable precision estimates, even with few dates [R6] and on any timescale (e.g., sites dating to the 65Ma mega-extinction event; Sprain et al *Science* 10.1126/science.aav1446). *Bacon* and *clam* have rapidly become adopted by the global palaeo-community; they are standard age-modelling tools of the NSF-funded neotomadb.org database which contains millions of global fossil data, have been downloaded >50,000 times as packages of the open-source statistical software R, and are the most popular classical and Bayesian age-models (Fig. 1) with a large increase in the use of Bayesian models. CALIB and CALIBomb (calib.org) developed by Reimer are highly popular on-line tools for calibrating ^{14}C dates, and are accessed worldwide on average 1,000 times per month.

Fig. 1. Google Scholar citations to published age-depth modelling tools show *clam* and *Bacon* as most-used approaches among classical (red) and Bayesian (blue), respectively.



3. References to the research

[R1] Reimer PJ, Baillie MGL, Bard E, Bayliss A, Beck JW, Bertrand CJH, Blackwell PG, Buck CE, Burr GS, Cutler KB, Damon PE, Edwards RL, Fairbanks RG, Friedrich M, Guilderson TP, Hogg AG, Hughen KA, Kromer B, McCormac G, Manning S, Ramsey CB, Reimer RW, Remmele S, Southon JR, Stuiver M, Talamo S, Taylor FW, van der Plicht J, Weyhenmeyer CE 2004. IntCal04 terrestrial radiocarbon age calibration, 0-26 cal kyr BP. *Radiocarbon* 46:1029–58. [3114 citations, Scopus 22 Jan 2021] <https://doi.org/10.1017/S0033822200032999>

[R2] Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Cheng H, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Hafliðason H, Hajdas I, Hatté C, Heaton TJ, Hoffmann TL, Hogg AG, Hughen KA, Kaiser KF, Kromer B, Manning SW, Niu M, Reimer RW, Richards DA, Scott EM, Southon JE, Staff RA, Turney CSM, van der Plicht J 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* 55:1869–87. [7772 citations]

https://doi.org/10.2458/azu_js_rc.55.16947

Across all disciplines, this was the most cited paper published by UK authors in 2013, and the 6th most cited published by US authors in 2013.

[R3] Reimer PJ, Austin WEN, Bard E, Bayliss A, Blackwell PG, Bronk Ramsey C, Butzin M, Cheng H, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Hajdas I, Heaton TJ, Hogg AG, Hughen KA, Kromer B, Manning SW, Muscheler R, Palmer JG, Pearson C, Van Der Plicht J, Reimer RW, Richards DA, Scott EM, Southon JR, Turney CSM, Wacker L, Adolphi F, Büntgen U, Capano M, Fahrni SM, Fogtmann-Schulz A, Friedrich R, Köhler P, Kudsk S, Miyake F, Olsen J, Reinig F, Sakamoto M, Sookdeo A, Talamo S2020. The IntCal20 Northern Hemisphere radiocarbon calibration curve (0-55 cal kBP) Radiocarbon 62:725–57. [94 citations] <https://doi.org/10.1017/RDC.2020.41>

[R4] Blaauw M, 2010. Methods and code for 'classical' age-modelling of radiocarbon sequences. Quaternary Geochronology 5:512–8. [1335 citations] <https://doi.org/10.1016/j.quageo.2010.01.002>

[R5] Blaauw M, Christen JA 2011. Flexible paleoclimate age-depth models using an autoregressive gamma process. Bayesian Analysis 6:457–74. [1465 citations] <https://doi.org/10.1214/11-BA618>

[R6] Blaauw M, Christen JA, Bennett KD, Reimer PJ, 2018. Double the dates and go for Bayes – impacts of model choice, dating density and quality on chronologies. Quaternary Science Reviews 188:58–66. [40 citations] <https://doi.org/10.1016/j.quascirev.2018.03.032>

4. Details of the impact

Radiocarbon research at Queen's has been **instrumental** to the work of commercial dating labs, provided the **scientific evidence for climate change** policies, contributed to the **safeguarding of world-renowned cultural heritage sites** and shed new light on the lives of past civilisations including the **earliest figurative cave art** discovered in France and the **earliest inhabitants** in Ireland.

Commercial Laboratories

Calibration is an essential part of the carbon dating process, placing radiocarbon dates on a unified timescale. IntCal calibration is free and the software is open-source. It is used by all major commercial radiocarbon laboratories (for example, Beta Analytic **[5.1]**).

The President of Beta Analytic, reported that Intcal is “*the recognized standard*” *not only for researchers around the world, but also ...in the provision of commercial dating services*”.

“...Radiocarbon Dating remains a relevant and vital tool for researchers of ...interdisciplinary fields..., as well as allowing for over a million previous Radiocarbon ages to be reviewed and updated to the most recent and relevant calibration scenarios... related to the history of mankind...”

Radiocarbon dating acts as a source of revenue for commercial laboratories. Based on published laboratory codes from 14 major radiocarbon dating laboratories worldwide, we estimate that **over 135,000 samples are radiocarbon dated annually**, at a cost of around GBP350 each – this means **>GBP45,000,000 per year is generated through radiocarbon dating**. **Over 92% of these samples are then calibrated using the IntCal curves**.

Radiocarbon dating changing public understanding

Beyond commercial labs, public and private sector practitioners such as those with the responsibility to care for and promote the historic environment use calibration curves. For

example, Historic England [5.2], Historic Scotland, and the NI Historic Environment Division all base calendar dates (for excavations and published reports) on IntCal.

The National Head of Research at Historic England has reported that *"Knowledge is critical to public enjoyment of the Historic Environment and is often underpinned by accurate radiocarbon dating. For example, recent ground-breaking research using IntCal and performed by Historic England enabled the development of a new and improved timeline for the story of Stonehenge (Darvill et al 2012)and fed directly into the presentation of the site through a new £27 million visitors' centre and an accompanying recreation of Neolithic houses, both opened in December 2013, which receive more than 1.5M visitors annually."*

In Northern Ireland, the archaeology team at Queen's worked with the Derry Tower Heritage Group, to date a tower previously thought to be a windmill dated circa 1700. The innovative application of radiocarbon dating to mortar samples enabled the true date of the monument to be established, indicating that this was the remains of an Early Medieval monastic round tower and, as such, the last remaining upstanding vestige of the city's Medieval fabric.

"A, member of The Derry Tower Heritage Group and teacher at Lumen Christi College said: "The new discovery is set to change our understanding of the early history of Derry. The textbooks will certainly need to be revised. Up to now we had no upstanding medieval fabric surviving in our city – now we have a round tower." [5.3]

In Ireland, Reimer worked with a team from IT Sligo and National Museums Ireland to date a bear bone with butchery marks discovered in a cave in County Clare. Dating of the bone established that humans were in Ireland some 12,500 years ago – 2,500 earlier than previously believed.

"Archaeologists have been searching for the Irish Palaeolithic since the 19th century, and now, finally, the first piece of the jigsaw has been revealed. This find adds a new chapter to the human history of Ireland" [5.4]

Internationally, IntCal has been used to date cave art found in the Cave of Pont d'Arc in Ardeche, France, to 32,000-30,000 years BP [5.5]. These ages are much older than previously expected, revealing the art to be the **earliest currently known pictorial drawings in Europe**. The cave was granted UNESCO World Heritage Status in June 2014 with radiocarbon dating used as one of the measures of authenticity [5.6]. A replica cave (costing EUR55,000,000), designed to preserve the original drawings, opened in April 2015 and received **1 million** visitors and generated EUR**25,000,000** for the local region in the first two years after opening [5.7].

Impact on international policy development

The Intergovernmental Panel on Climate Change (IPCC) is the United Nations body for assessing the science related to climate change. The work of the IPCC includes providing policymakers with regular scientific reports on climate change, its implications and potential future risks, as well as to put forward adaptation and mitigation options.

In 2013, a working group of 259 experts from 39 countries published "**Climate Change 2013: The Physical Science Basis**" (PCB), an assessment which formed the scientific basis for the full 5th IPCC report (published in 2014). The governments of all IPCC member countries agreed the findings [5.8]. **80 publications cited in PCB relied on IntCal / Bacon / clam to produce calendar dates** and for use in models relating ¹⁴C records to solar irradiance.

The lead author of Chapter 2 of the 6th IPCC report (due out in 2021) states that

"the IntCal calibration curves have been critical for providing a perspective on past climate

which is essential for our understanding of the climate system, and a baseline for modelling future changes. A large number of studies of past climate change that were referenced in the earlier IPCC Assessment Report 5 report utilized the IntCal curves” [5.9]

The Chair of the IPCC stated that the 5th IPCC report provided the “**roadmap**” to the **Paris Agreement** and that “*the scientific document provided by the authors becomes the essential reference that is used throughout the entire world*”. [5.10]

5. Sources to corroborate the impact

[5.1] Testimonial R. E. Hatfield, President of Beta Analytic

[5.2] Testimonial from Historic England

[5.3] Report in the Medievalists website <https://www.medievalists.net/2018/10/medieval-round-tower-discovered-in-northern-ireland/>

[5.4] BBC news article <https://www.bbc.co.uk/news/science-environment-35863186>

[5.5] Quiles, A. et al. 2016. A high-precision chronological model for the decorated Upper Paleolithic cave of Chauvet-Pont d’Arc, Ardèche, France. Proc. Natl Acad. Sci. USA 113, 4670–4675 <https://doi.org/10.1073/pnas.1523158113>

[5.6] UNESCO Webpage on Inscription of Chauvet-Pont d’Arc <https://whc.unesco.org/en/list/1426>

[5.7] Visitor numbers to Ardeche Replica Cave see page 5 of pdf provided

[5.8] Climate Change 2013: The Physical Science Basis, released online on 30th January 2014 – <https://www.ipcc.ch/report/ar5/wg1/>

[5.9] Testimonial from Professor Darrell Kaufman

[5.10] Rajendra Pachauri, Chair of the IPCC, states that the 5th IPCC report provided the “roadmap” to the Paris Agreement <https://www.climatechangenews.com/2014/10/27/ipcc-report-is-roadmap-to-paris-climate-deal-pachauri/>