Institution: University of Liverpool		
Unit of Assessment: 10 – Mathematical Sciences		
Title of case study: Radiometric dating at the Environmental Radioactivity Research Centre changes environmental policy in Norway and Canada and redirects commercial resources		
Period when the underpinning research was undertaken: June 2000 – September 2019		
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:**
Prof Peter Appleby Dr Gayane Piliposyan	Professor of Applied Mathematics Senior Lecturer in Applied Mathematics	1966 - Present 2001 - Present
Period when the claimed impact occurred: September 2016 – September 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Techniques for dating environmental records in natural archives such as lake sediments using mathematical models of the fallout radionuclide ^{210}Pb have been pioneered and refined at the Environmental Radioactivity Research Centre (ERRC), Department of Mathematical Sciences, University of Liverpool. These techniques have become essential tools for international decision-makers studying the effects of pollution and climate change. Recent impacts on policy, environment and commerce include:

- Climate change mitigation strategy incorporating first-of-its-kind localised carbon budget (Canada, 2020);
- Government guidelines for classifying the ecological status of water bodies (Norway, 2018);
- Re-allocation of industry resources tackling oil sands pollution (Canada, 2017).

2. Underpinning research

The Environmental Radioactivity Research Centre (ERRC), led by Dr Piliposyan and Prof Appleby from the University of Liverpool's Department of Mathematical Sciences is a world leading centre for excellence in ^{210}Pb dating. The current ^{210}Pb dating methodology is underpinned by a substantial body of ongoing mathematical research conducted by Prof Appleby and Dr Piliposyan on ^{210}Pb in the environment, and also on radiometric techniques for determining fallout **[3.1-6]**.

^{210}Pb is a naturally occurring fallout radionuclide created in the atmosphere by the decay of radon (^{222}Rn) gas. ^{210}Pb atoms are quickly attached to fine atmospheric aerosols and deposited on the landscape, principally during rain. A fraction of this fallout ^{210}Pb is incorporated in sediments accumulating for example on the bed of a lake. Over time each new layer is buried by later deposits and its initial concentration reduced by radioactive decay. By comparing present-day concentrations with estimates of the original concentrations made using mathematical models pioneered and refined by the research group of Prof Appleby and Dr Piliposyan, including PhD student P. Semertzidou **[3.3, 3.4]**, it is possible to calculate the age of each sediment layer and hence of the environmental records contained within it. The 22-year half-life of ^{210}Pb makes it ideal for studying sediment records spanning the past 150 years, the period of greatest impact of human activity on the environment.

The Constant Rate of Supply (CRS) model developed by Prof Appleby is the most widely used ^{210}Pb dating method **[3.1]**. Recent modelling of the atmospheric **[3.3]** and terrestrial **[3.4]** pathways by which ^{210}Pb reaches the bed of a lake have led to a much better quantitative understanding of the processes governing the supply of fallout ^{210}Pb to the sediment record. This has been coupled with work on testing and validating the models using dates determined independently from records of ^{137}Cs fallout **[3.5, 3.6]**. ^{137}Cs is an artificial radionuclide originating from the atmospheric testing of nuclear weapons, and nuclear accidents such as Chernobyl.

The ERRC also pioneered the use of gamma spectrometry for determining radionuclides in environmental samples. Mathematical models developed for improving the accuracy of the technique **[3.2]** have been incorporated into a sophisticated software package for analysing ^{210}Pb and ^{137}Cs data from the University of Liverpool Environmental Radiometric Laboratory, established by Prof Appleby. This package has been used to develop and manage a database of radiometric records from the many hundreds of cores from around the world analysed by the ERRC. The combination of state-of-the-art analytical techniques, highly developed environmental models, and associated software and database have been key in the widespread uptake of the technique and involvement of the ERRC in numerous projects with significant environmental impacts such as those described in section 4. All rely on the capability of the ERRC to mathematically model and date analyse records of environmental change stored in a range of different natural archives including salt-marshes and peat bogs as well as lake and marine sediments.

3. References to the research

3.1. Appleby PG (2001). Chronostratigraphic Techniques in Recent Sediments. In: Last W.M., Smol J.P. (eds) Tracking Environmental Change Using Lake Sediments. Developments in Paleoenvironmental Research, vol 1. Springer, Dordrecht. doi:10.1007/0-306-47669-X_9

3.2. Appleby PG and Piliposyan GT (2004). Efficiency corrections for variable sample height in well-type germanium detectors. Nucl Instrum Meth B 225(3): 423-433. doi:10.1016/j.nimb.2004.05.020

3.3. Semertzidou P, Piliposian GT and Appleby PG (2016). Atmospheric residence time of ^{210}Pb determined from the activity ratios with its daughter radionuclides ^{210}Bi and ^{210}Po. J Environmental Radioactivity 160:42-53. doi:10.1016/j.jenvrad.2016.04.019

3.4. Appleby PG, Semertzidou P, Piliposian GT, Chiverrell RC, Schillereff DN and Warburton J (2019). The transport and mass balance of fallout radionuclides in Brotherswater, Cumbria (UK). J Paleolimnology 62(4):389-407. doi:10.1007/s10933-019-00095-z

3.5. Semertzidou P, Piliposian GT, Chiverrell RC and Appleby PG (2019). Long-term stability of records of fallout radionuclides in the sediments of Brotherswater, Cumbria (UK). J Paleolimnology 61(2):231-249. doi:10.1007/s10933-018-0055-7

3.6. Davies LJ, Appleby PG, Jensen BJ, Magnan G, Mullan-Boudreau G, Noernberg T, Shannon B, Shotyk W, van Bellen S, Zaccone C et al. (2018). High-resolution age modelling of peat bogs from northern Alberta, Canada, using pre- and post-bomb ^{14}C, ^{210}Pb and historical cryptotephra. Quaternary Geochronology 47:138-162. doi:10.1016/j.quageo.2018.04.008

4. Details of the impact

Environmental policy globally is crucially dependent on good evidence of the past and present status of the environment, and the extent to which changes are driven by human activity. Cores retrieved from natural archives such as accumulating sediments and peat bogs contain a wealth of information on environmental pollution, climate and their changes through time. Radiometric dating methods developed by Prof Appleby and Dr Piliposyan at Liverpool's Environmental Radioactivity Research Centre (ERRC) **[3.1-4]** are key to putting a reliable timescale on these changes. Three recent examples of where these dating techniques have generated important policy, environmental and commercial impacts across Canada and Norway are given below, in chronological order **[4.1-3]**.

4.1 First-of-its-kind carbon budget (Canada)

The Lake Simcoe Region Conservation Authority (LSRCA) NGO initiated research designed to inform a pioneering Climate Change Mitigation Strategy for the Lake Simcoe watershed in 2016. This is a recreational area near Toronto with one of the most rapidly expanding populations in Canada. An important part of the investigation was the critical role natural features (forests and wetlands) play in offsetting carbon emissions. Since historical rates were also important, the ERRC was asked to provide a chronological framework by dating wetland soil cores using ^{210}Pb **[5.1, 5.2]**. An analysis of ^{210}Pb and ^{137}Cs records in these cores showed that they contained a true chronological sequence that could be dated using the methods outlined in **[3.1]**. Results of this project enabled the LSRCA to model possible future carbon budgets taking account of both sequestration and emissions **[5.2]**, and develop the Climate Change Mitigation Strategy published in September 2020 **[5.1]**. The LSRCA's General Manager of Integrated Watershed Management explains how Prof Appleby's "*isotope analysis was essential for us to understand what the multidecadal sequestration rates are…*" **[5.2]**.

The strategy and associated carbon budget are the first of their kind in tackling climate change across a geographical rather than political boundary **[5.1]**. This is at the forefront of a shifting paradigm in Canada to prioritise climate change, which is mainly addressed at a provincial level. The policy applies to all industry in the area, covering more than 3,400km^2 and approximately 600,000 residents **[5.1]**.

4.2 Government guidelines on the classification of ecological water status (Norway)

Sediment cores were ^{210}Pb dated by the ERRC between 2016 and 2018 for a project funded by the Norwegian Environmental Agency **[5.3]**. This provided the first environmental data on water bodies for the period prior to industrial fish farming, important for making judgements as to the current ecological status. As part of this study, results based on the ERRC's dating led to development of a fossil foraminifera-based index for determining baseline conditions that has been incorporated into national government recommendations **[5.3]**. These guidelines, published by the Norwegian government in 2018 for classifying the ecological status of water bodies across Norway, are used to manage the impact of industry on the environment **[5.4a]** and are needed in order to comply with the EU Water Framework Directive **[5.3, 5.4a]**.

The guidelines are mandatory, enabling the government to monitor ecological status as temperatures and pollutants increase. Our collaborator at the University of Oslo explains how Prof Appleby's modelling, using techniques in **[3.1]** that are cited directly in the government guidelines and appendix **[5.4a-c]**, "*…played a significant role in the results generated by our research and subsequent impact. Your dating was essential and without it this work could not have been carried out. The dating was instrumental in the development and testing of a foraminifera-based multimetric index that was used for governmental environment recommendations…Dating of these sediments is essential for this method to work.*" **[5.3]**.

4.3 Redirecting industry resources (Canada)

The Alberta oil sands industry, which produces the majority of Canada's oil, is benefitting from a more efficient use of resources as a result of Prof Appleby's research on ^{210}Pb dating **[3.1, 3.6]**. The oil sands cover a land mass larger than England and are Canada's biggest export earner. The 120 extraction projects are licensed to major oil companies in Canada, the U.S. and China. Since the early 2000s there has been much controversy over the extent of environmental contamination caused by the extraction processes. A major concern was trace metal pollution. Calculations carried out by Prof Appleby were essential to a study carried out between 2013 and 2017 on Alberta peat cores showing that atmospheric deposition of these substances has in fact declined in recent decades, concluding this longstanding debate **[5.5a, 5.5b** and **5.6]**.

The study lead at the University of Alberta explains Liverpool's contribution: "…*Your work on ^{210}Pb age dating was key to all of that…we needed the best person on the planet to help us date those cores…our work has been a game changer* [to industry]" **[5.6]**. The findings have enabled the oil sands industry, which spends around USD150,000,000 (04-2019) annually on environmental monitoring **[5.7]**, to redirect resources towards more pressing environmental issues **[5.8]**.

The Director of Canada's Oil Sands Innovation Alliance (COSIA) explains why the aerial deposition analysis was so important, including the '*enormous*' costs saved as a direct result: "*Prior studies suggested that these* [trace elements] *deposits were from coke piles or stack emissions and further, that these* [trace elements] *were bioavailable and potentially damaging the environment. If this was true or if key decision makers like government and regulatory bodies thought this was true, the cost to the oil sand for source mitigation could be enormous… The impact on COSIA and COSIA members…is significant simply because we cannot afford to spend time, energy and money on problems that either don't exist or that are natural rather than anthropogenic* [caused by industrial activity]".

5. Sources to corroborate the impact

5.1. Lake Simcoe Region Conservation Authority (LSRCA). 2020. [Climate Change Mitigation Strategy for the Lake Simcoe Watershed.]() *Last accessed: 17th December 2020*. First-of-its-kind status (p.1); Size and population of area (p.6); Results from Prof Appleby's isotope analysis for historical rates of wetland carbon accumulation (pp.40-3).

5.2. Email from the General Manager (Integrated Watershed Management), of the Lake Simcoe Region Conservation Authority (LSRCA) explaining how Prof Appleby's isotope analysis was essential for their Climate Change Mitigation Strategy in [5.1].

5.3. Letter from project lead for the foraminifera-based index at the University of Oslo, explaining the critical contribution of Prof Appleby's dating in their own research and resulting government guidelines in [5.4].

5.4. Government guidelines for the classification of ecological water status in Norway (2018).
a) Direktoratsguppen vanndirektivet 2018. Veileder 02:2018 Klassifisering av miljøtilstand i vann (Norwegian). See p.217 for citation of Prof Appleby's research [3.1] and section 1, p.168 for recommendation on resulting foraminifera-based index.
b) Appendix to guidelines [5.4a]. Vedlegg til veileder 02:2018. (Norwegian). See section 9, p.131 for description of how Prof Appleby's methods [3.1] are used for radiometric dating of sediments.
c) English translation of relevant sections of [5.4a] and [5.4b] provided by the project lead at the University of Oslo, September 2019.

5.5. Major environmental publications from the Alberta peat cores study, led by the University of Alberta and underpinned by Prof Appleby's calculations, showing effectively zero (declining) atmospheric Pb contamination. These concluded a longstanding debate on trace metal pollution in the Alberta oil sands region.

a) Shotyk W, Appleby PG, Bicalho B, Davies L, Froese D, Grant-Weaver I, Krachler M, Magnan G, Mullan-Boudreau G, Noernberg T, Pelletier R, Shannon B, van Bellen S, Zaccone C, (2016). Peat bogs in northern Alberta, Canada reveal decades of declining atmospheric Pb contamination. Geophys. Res. Lett. 43(18):9964-9974. doi:10.1002/2016GL070952

b) Shotyk W, Appleby PG, Bicalho B, Davies L, Froese D, Grant-Weaver I, Magnan G, Mullan-Boudreau G, Noernberg T, Pelletier R, Shannon B, van Bellen S, Zaccone C, (2017). Peat bogs document decades of declining atmospheric contamination by trace metals in the Athabasca Bituminous Sands region of northern Alberta, Canada. Env Sci & Tech 51(11):6237-6249. doi:10.1021/acs.est.6b04909.

5.6. Email from project lead of the Alberta oil sands research at the University of Alberta, explaining the key role of Prof Appleby's ^{210}Pb dating in his own research and the subsequent impact on industry.

5.7. Leahy, S. This is the most destructive oil operation – and it's growing. National Geographic. 11th April 2019. *Last accessed 17th December 2020*. Executive vice president of the Canadian Association of Petroleum Producers indicates annual spend by the industry on environmental monitoring.

5.8. Letter from the Director of Water for Canada's Oil Sands Innovation Alliance (COSIA) on how the Alberta peat cores study has led to oil sands producers redirecting significant resources.