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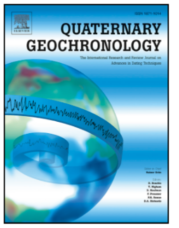

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Guidelines for reporting and archiving ^{210}Pb sediment chronologies to improve fidelity and extend data lifecycle

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ABSTRACT

Radiometric dating methods are essential for developing geochronologies to study Late Quaternary environmental change and ^{210}Pb dating is commonly used to produce age-depth models from recent (within 150 years) sediments and other geoarchives. The past two centuries are marked by rapid environmental socio-ecological changes frequently attributed to anthropogenic land-use activities, modified biogeochemical cycles, and climate change. Consequently, historical reconstructions over this recent time interval have high societal value because analyses of these datasets provide understanding of the consequences of environmental modifications, critical ecosystem thresholds, and to define desirable ranges of variation for management, restoration, and conservation. For this information to be used more broadly, for example to support land management decisions or to contribute data to regional analyses of ecosystem change, authors must report all of the useful age-depth model information. However, at present there are no guidelines for researchers on what information should be reported to ensure ^{210}Pb data are fully disclosed, reproducible, and reusable; leading to a plethora of reporting styles, including inadequate reporting that reduces potential reusability and shortening the data lifecycle. For example, 64% of the publications in a literature review of ^{210}Pb dated geoarchives did not include any presentation of age uncertainty estimates in modeled calendar ages used in age-depth models. Insufficient reporting of methods and results used in ^{210}Pb dating geoarchives severely hampers reproducibility and data reusability, especially in analyses that make use of databased palaeoenvironmental data. Reproducibility of data is fundamental to further analyses of the number of palaeoenvironmental data and the spatial coverage of published geoarchives sites. We suggest, and justify, a set of minimum reporting guidelines for metadata and data reporting for ^{210}Pb dates, including an IEDA (Interdisciplinary Earth Data Alliance), LiPD (Linked Paleo Data) and generic format data presentation templates, to contribute to improvements in data archiving standards and to facilitate the data requirements of researchers analyzing datasets of several palaeoenvironmental study sites. We

analyze practices of methods, results and first order interpretation of ^{210}Pb data and make recommendations to authors on effective data reporting and archiving to maximize the value of datasets. We provide empirical evidence from publications and practitioners to support our suggested reporting guidelines. These guidelines increase the scientific value of ^{210}Pb by expanding its relevance in the data lifecycle. Improving quality and fidelity of environmental datasets broadens interdisciplinary use, lengthens the potential lifecycle of data products, and achieves requirements applicable for evidenced-based policy support.

Keywords: data curation; geochronology; lead-210; metadata; radiometric dating; radionuclide; reproducibility; transparency

1. Introduction

1.1 Context

Palaeoenvironmental studies are instrumental for understanding how environments have varied through time and how anthropogenic effects and climate variability modify the environment and ecosystem processes. To illustrate, soil and palaeolimnological studies have been used to examine how landscapes have evolved over time, determine how land-use activities have led to declines in water quality, and to assess how rates and patterns of environment change have varied (ex. Gaillard et al., 1991; Walling et al., 2003). Importantly, this information can be used to inform land management decisions and can provide a fundamental understanding of ecosystem function as well as provide context for examining valuations of ecosystem services. The accumulation of sediments and environmental signals detectable in those sediments used to build numerical age-depth relationships to understand historical environmental variability and relate it to other processes, other locations, or historical events that are known with varying chronological precision (ex. Parnell et al., 2008). The absence of robust geochronological controls can limit the applicability of sediment profiles in understanding local or regional processes within a system. The centrality of geochronological data in understanding past environmental processes (Harrison et al., 2015) means that data availability is critical to peer review and validation, study repeatability and reproducibility, and data archiving and access (Konkol et al., 2018; Konkol and Kray, 2018). Geochronological data and information is especially relevant to field-based sciences, such as geology, ecology, and archaeology and other sciences that inform and promote public environmental and heritage related policy formulation development, implementation, and continual environment policy assessment and improvement (McNutt et al., 2016).

Lead-210 dating is a radiometric technique that can be applied to recent sediment stratigraphies (Appleby and Oldfield, 1978; Appleby, 2001; Gale, 2009; Schmidt and Cochran, 2010) making it useful to build age-depth models (Blaauw and Heegaard, 2012) that examine changes during a period of intensifying anthropogenic modifications to ecosystems. The technique as a geochronological tool was presented by Golberg (1963) and developed throughout the 1970s (Appleby et al., 1978, 1979; Oldfield et al., 1978, 1980; Appleby and Oldfield, 1983) with further advancements following (Appleby et al., 1986; Binford et al., 1990; Schelske et al.,1994; Blais et al., 1995; Appleby, 1997; Sanchez-Cabeza and Ruiz-Fernández, 2012; Davies et al., 2018) and we direct readers to textbook descriptions of the environmental mechanisms and dynamics fundamental to the theory of the dating technique (Appleby, 2001; Lowe and Walker, 2014). The technique estimates sedimentation rates and to model of calendar ages, which can then be used in conjunction with other geochronological information. The utility of ^{210}Pb geochronologies and the proliferation of data repositories for (paleo)environmental data necessitates a minimum defined structure for reporting and archiving data. Defined documentation practices facilitate new multidisciplinary research and engagement with non-specialist end users. Increasingly, academic publishers require appropriate data archiving alongside publications and funding agencies that demand open-access data repository solutions as a part of project outcomes. In certain instances, these requirements need to be outlined at the project proposal stage. Recommendations for the reporting of radiocarbon dates have been established since the introduction of the American Journal of Science: Radiocarbon Supplement (Deevey and Flint, 1959) and many journals have specific author instructions for reporting radiocarbon data. Reporting guidelines have evolved in response to writing modes and the data (re)use needs of the research communities (Stuiver and Polach, 1977; Stuiver, 1980; Millard, 2014). More recently, recommendations for uranium series geochronological measures have also been published (Dutton et al., 2017) and continue the movement toward improving data transparency, fidelity, access, reuse, and interoperability of archived environmental data (McNutt et al., 2016). Such developments contribute to the potential for geosciences in automated learning methods and computational thinking (Wolfram, 2002; Peters et al., 2014; Ma, 2018) and multidisciplinary applications.

Reporting recommendation for ^{210}Pb dating are useful for writing and reviewing publications applying the dating technique. Here we use approximately 50 years of published peer-reviewed literature featuring ^{210}Pb dating of sediments archives across approximately 90 journals to identify patterns of reporting and to identify deficiencies. We identify and justify the minimum information useful for effective data transparency and reproducibility by balancing the data input requirements necessary to recreate ^{210}Pb calendar ages and thus published age-depth models. Finally, we present reporting guidance and a template for ^{210}Pb geochronologies and suggest data fields for curated data repositories that rely on this dating technique.

1.2 Importance of archiving ^{210}Pb data

Data availability in a findable, accessible, and readable format is critical to peer review, validation, reproducibility, and data archiving (Wilkinson et al., 2016). Even with existing ^{14}C reporting recommendations (Millard, 2014), a variety of reporting styles continues in the published literature, and access to published data range from data being effectively unavailable for further scientific enquiry, to openly distributed, ad hoc data files distributed by the primary (or uploader) author (or a curator), or archived within structured databases (for an example of the latter see Chaput and Gajewski, 2016).

Reproducibility and replicability of research results is a key axiom of the scientific approach with current efforts, such as the Geoscience Paper of the Future (Yu et al., 2016), pushing these ideas to the fore (Arzberger et al., 2004; Cassey and Blackburn, 2006; Buck, 2015; Nosek et al., 2015). Reproducibility of a study using published datasets, computer code, and techniques relies on a complete description of the method and access to the numerical evidence. Specific to sediment core studies that rely on geochronological data and age-depth model creation, reproducing a study requires access to the raw data and the manipulated data in order to re-analyse the data. Reproducibility may also include re-analyses with some changes to the original study (Drummond, 2009), using an updated radiocarbon calibration curve (Reimer et al., 2009; 2013), novel age-depth modelling techniques (Bronk Ramsey, 1995; Blaauw, 2010; Blaauw and Christen, 2011; Aquino-López et al., 2018), or measuring a new proxy from the archived sediment cores that had been previously studied (Vermaire and Cwynar, 2010). Reporting complexity increases when multiple dating techniques are used but the use of multiple sediment dating techniques reduces uncertainty through convergence of evidence and produces more robust age-depth relationships.

The economic cost of losing primary data useful for future analyses has yet to be estimated. In some cases re-digitising data from tables and graphics in publications can be automated, semi-automated, or manually (Brewer and Peltzer, 2017; Brewer, 2017). It remains challenging to estimate errors between the original dataset underlying the table or graphics and the new re-digitised data product. For example, Courtney Mustaphi et al. (2017a; 2017b) re-digitised loss-on-ignition data from a sediment core (Karlén, 1985) without any quantitative data quality control or assessment checks, and presently there are no guidelines or standards to follow to streamline such (re)uses of data. Similarly, re-digitisation of published ^{210}Pb data may introduce or perpetuate errors and quality control and assurance practices have not been adequately defined. In short, it is far simpler and effective to adequately report underlying ^{210}Pb data and associated errors and metadata than to reconstruct this information for use in future studies.

Meta-analyses using large-scale re-analyses of palaeoenvironmental data examine regional and global scale patterns of past environmental change but requires the capacity to reconstruct age-depth models with consistency among records (Giesecke et al., 2014; Dawson et al., 2016). However, ^{210}Pb modeled dates are frequently reported with only the calendar date products and even less frequently with the associated Gaussian (symmetrical) estimates of age uncertainties. This provides enough information to replicate the age-depth model used to plot data in a given published study; but is not enough information to recalculate the ^{210}Pb-derived calendar dates with new techniques or even simply to reproduce the values in the original study. The common practice of inadequate reporting ^{210}Pb and other sediment data in single site studies has long been discussed (Blais et al., 1995; Smith, 2001). Inadequate reporting choices by authors, in part due to a lack of community agreement on reporting requirements, has resulted in the loss of crucial environmental data collected at significant cost and resources; thus, reducing scientific reproducibility and data lifecycle through loss of opportunities for additional analyses by the research community. The lost innovation and educational potential may exceed the financial losses of insufficient data reporting and archiving of ^{210}Pb dating data. Rigorous and transparent standards are required for data to be used as supporting evidence for policy formulation, decision making and judicial proceedings; reducing the potential impact studies may achieve due to incomplete reporting.

2. Materials and methods

2.1. Literature review

A keyword search of peer-reviewed scientific literature and related grey literature was undertaken to review patterns in the reporting of ^{210}Pb based geochronologies and age-depth models. The search engines used included Google Scholar and Thomson Reuters Web of Science. Searches also included the varved sediments database for studies that used ^{210}Pb dating (Ojala et al., 2012) but searches through data housed in other open-access databases were not specifically conducted – because of inabilities to query for ^{210}Pb-dated chronologies and because it is common for final calendar date age estimates to be archived in repositories. Keywords were decided upon at the Cyber4Paleo (C4P) Community Development Workshop, 20 June 2016, at National Center for Atmospheric Research, Boulder, CO, USA, and were single word or combination searches for: accumulation, accumulation rates, atmospheric, ^{210}Pb, basin, bog, core, date, dated, dating, deposition, deposition time, depositional environment, environment, environmental change, firn, fluvial, flux, geoarchive, geochronology, glacial, glacier, influx, lake sediments, lacustrine, lakes, lead-210, lead isotopes, sediment, sediments, sedimentology, marine, palustrine, peat, palaeoenvironments, paleolimnology, paleoecology, radiometric, radionuclide, reconstruction, unsupported, soil, snow, swamp. Regional modifier terms included: arctic, alpine, Antarctic, coastal, Great Lakes, montane, mountain, mountainous, oxbow, paraglacial, periglacial, subalpine. This approach does bias the results toward *a priori* awareness of the body of literature to the investigators and toward English-language sources; although, these biases likely do not heavily detract from the patterns that emerge from results. A template spreadsheet was designed to categorize and organize the specific details of what was reported in the studies that employed ^{210}Pb dating by the investigators. These details included several main categories of information:

- Publication metadata (year, journal title, reference, DOI or permalink or similar)
- A breakdown of relevant study site metadata and field-based sampling information
- Descriptions of laboratory sampling methods (such as sediment subsampling intervals)

- Description of the ^{210}Pb radioactivity measurements (pretreatments, laboratory analysis, standards, quality checks)
- Documentation of the modeling of ^{210}Pb activity counts to produce calendar ages
- Characterization of how the final ^{210}Pb age estimates and errors were presented
- Documentation on how all other geochronological determinations were integrated to produce age-depth models for sediment cores (or other types of geoarchives)
- How the underlying data and derived age-depth model products were presented

2.2. Questionnaire

An online anonymous questionnaire was developed using the web-based Qualtrics platform to survey present day expert perceptions on the use and reporting of ^{210}Pb dating data in the peer-reviewed scientific literature. The questionnaire was disseminated by a URL hyperlink to the research community through direct emails and canvassing for volunteer participants through topical email listservers used by researchers in geoscience fields (CANQUA, CAGlist, PALEOLIM, ECOLOG, AGU earth-space-science-informatics, Yorkshire Palaeo Group), and social media (Twitter: @neotomadb). The questionnaire was available from January to April 2017 and asked participants 25 multiple choice or fixed-scale ranking questions and two open-ended questions for users to respond with text.

2.3 Examining reporting patterns and distilling recommendations

Publication dates permitted an examination of trends in reporting styles evident in the literature review. Minimal criteria for reporting and archiving ^{210}Pb data and metadata were primarily distilled from the theoretical framework of the geochronological approach and equations necessary to establish calendar ages from measured radioactivities. The survey questionnaire also helped to highlight some aspects of measurement and reporting that often remains less clear, such as the importance of recording fieldwork dates when cores are collected, core barrel dimensions, sediment dry density, and how users define the sampling depth down a core (top, mid-level depth, and/or bottom), the type of radioactivity counting, and how data should be presented. Some of these aspects were *a priori* identified by data users who have experience in collating Holocene palaeoenvironmental datasets for archiving or research purposes. Together these streams of information informed our judgements of key criteria for reporting ^{210}Pb results.

3. Results

3.1. Reporting patterns in the literature

A total of 271 publications were found through the manual literature review (SM1). Most studies dated marine or lacustrine sediments (87.0%) and peat (9.6%). Other geoarchives studied were speleothem (1%), glacial ice or firn (1%), soil (<1%), and coral (<1%). Studies of lacustrine sediments were the most numerous, followed by marine sediments, and included sediments from artificial reservoirs (example: Sikorski and Goslar, 2003). Data appeared in 90 different peer-reviewed journals and additionally there were <5 from other academic sources - such as published reports or book chapters. Publications were predominantly in geosciences journals and general science journals with fewer papers in ecology, environmental sciences, archaeology, radiation and radionuclide journals (physics subdisciplines) (Table 1). The most frequent journals used to publish ^{210}Pb results were Journal of Palaeolimnology (9.2%) and Science of the Total Environment (5.5%) (Table 1). Publication years ranged from 1964 to 2017 and the number of studies reporting the use of the dating technique has increased to present (Fig. 1).

Metadata and core collection: Reporting of the core collection date during fieldwork was frequently missing (36.9%) or presented as month (or season) and year (36.9%). Presenting just the year of coring was common (18.5%) and explicit day, month year was rather infrequent (7.7%). Coring or site coordinates were clearly presented in over half of the publications (52.0%) or, alternatively, the site was presented on a map (35.0%) or simply by stating the site name (12.9%). The corer used to collect the core was usually described or named (55.7%) but often not reported (44.3%).

Core subsampling: Detailed descriptions of subsampling are discouraged in publications and often subsampling details can be deduced supplementary information or in shared datasets. In our review of published literature, subsampling information was clearly presented in tables or supplementary data in 43% of papers. Subsampling was presented as either depth ranges (21.0%), intervals (equal depth ranges and contiguous, 13.3%), midpoints of an interval range (n=5.2%), subsample tops (3.0%) or subsample bases (<1.0%, n=2). Frequently, such information could only be estimated (or digitized) from graphs (29.9%) or was not discussed (26.9%). Dry sediment weights or densities were seldom reported either as tables or graphs (as tables: 6.6%, 11.4%; as graphs only: 3.0%, 8.5%; respectively). Some studies mention collecting dry weights (or density) measurements but did not report the results (17.3%, 11.4%); leaving many studies not mentioning these measures (73.0%, 68.6%), even though these measurements are needed for estimating sediment influx values and deriving calendar ages from the radioactivity counts in some models (such as CRS).

Radioactivity counting: The laboratory used to measure the radioactivities and often provide the final calendar dates was not stated in 68.6% publications; although, in a few cases the laboratory could be discerned if operated by the author(s). The radiation counting technique (α and/or γ) was not reported in 36% of publications; but could be ascertained based on the laboratory if presented. The most pertinent radioactivity derivations (total and unsupported) were reported in just over half of the publications and was presented as graphs and/or tables (56.4%, 50.2% respectively; Table 2). Whether or not background activities in down core samples was reached was clearly discussed in 21 (8%) publications, partially described in 22 (8%), and ignored in 228 publications (84%).

Calendar dates and age-depth modeling: In 31 (11%) publications, calendar date ages were not estimated but radioactivities were measured. The most common technique to model ages from counts was the Constant Rate of Supply (CRS) type (49%), multiple models (11.4%), CF:CS (4.8%), Constant Initial Concentration (CIC, 2.2%) or other (1.1%); but was not reported in 17% of papers. Final ^{210}Pb modeled calendar date errors were not always explicitly presented in the paper (63.8%). When errors were explicit (36% of papers), the values were presented solely in a graph (18%) or explicitly in tables (18%). The modeled calendar ages were used in combination with other geochronological determinations (^{137}Cs, radiocarbon dates, marker beds, or others) to create age-depth models was presented in 103 studies (38%) and studies that combined with other geochronological techniques has increased through time (Fig. 2). We made no assessment on the character or quality of reporting for other geochronological measurements.

The total number of publications that used ^{210}Pb dating techniques in a given year has increased since the 1960s (Fig. 1). The number of publications that used ^{210}Pb in combination with other dating techniques to generate sediment geochronologies has increased, particularly over the past ten years (Fig. 2). This highlights the growing interest in combining different dating techniques to obtained better chronologies and the necessity for sharing all underlying data to reproduce chronologies.

Table 1 Top 10 journals used to publish ^{210}Pb dating results from the manual literature search. Journal Impact Factors (JIF) from the 2016 Journal Citation Reports® (Clarivate Analytics, 2017).

Journal title	5-year IF	Avg. JIF percentile	Count
Journal of Paleolimnology	2.309	64.974	25
Science of the Total Environment	5.102	90.611	15
Journal of Quaternary Science	2.980	63.257	10
Quaternary Science Reviews	5.227	94.168	10
The Holocene	2.733	54.741	10
Environmental Science and Technology	6.960	93.918	9
Geochimica et Cosmochimica Acta	4.847	94.643	9
Quaternary Geochronology	2.720	61.705	9
Earth and Planetary Science Letters	4.966	92.262	8
Quaternary Research	2.500	48.043	8

Table 2 Frequency of ^{210}Pb radioactivity counts reported in the literature review. Counts are presented with equivalent percentage in parenthesis (count out of 271 total studies).

	Total activities	Supported activities	Unsupported activities
Graph only	67 (24.7%)	16 (5.9%)	64 (23.6%)
Table with errors	57 (21.0%)	21 (7.7%)	49 (18.1%)
Table without errors	29 (10.7%)	16 (5.9%)	23 (8.5%)
Not reported	118 (43.5%)	218 (80.4%)	135 (49.8%)

3.2. Questionnaire results

The original questionnaire and results from 83 respondents are available in Appendix A (SM2 and SM3). Most responses came from researchers with >6 years of experience in their field, including 33 respondents with >20 years, and 5% with <5 years of experience. Careerists, either permanent academic staff (37%) or career researchers (34%) were the most frequent respondents; and 11% of respondents identified as graduate students. Job roles were predominantly research focused (48%) and academic teaching/research (40%).

Self-declared level of knowledge of ^{210}Pb in the environment and its use as a radiometric dating technique was moderately high and there were a few respondents at expert level. 90% of respondents had been introduced to the theory behind ^{210}Pb as a dating tool, 65% had submitted samples to a laboratory for dating, and 86% had used ^{210}Pb derived dates in generating an age-depth model for a sediment stratigraphy. 39% of respondents had experienced reuse of published ^{210}Pb dates by extract dating information from papers and 29% extracted dates from databases. Seventy one respondents (85.5%) planned to use ^{210}Pb in future studies. 65% of respondents had submitted (co-)authored papers with ^{210}Pb dating results and 71% had peer-reviewed papers with such data. A quarter of the respondents (25%) had worked on improvements to the dating technique and 22% had participated in establishing a ^{210}Pb dating facility.

Primary research areas identified were palaeo-sciences (59%), other geosciences (15.6%) and environmental sciences (13%), and ecology/biogeography (7%). Twenty-four (29%) respondents identified as a current or past editor of a journal. Only 18% of respondents believed reporting of ^{210}Pb results in peer-reviewed publications was inadequate and a further 45% believed some details were often missing. Roughly 30% believed reporting was satisfactory for review or validation and only 1% believed results were overly detailed. Perceptions were split on reporting and sharing of palaeoenvironmental data as an ongoing challenge to the research community – with the overall sentiment being passive. Respondents tended to believe that there should be minimum reporting recommendations for ^{210}Pb dating and that these data are needed for re-plotting and re-use of data with 73% of respondents promoted its usefulness to reviewers and editors. Over half of the participants felt that a guidance document would be a useful contribution to the research community (53%). Although we did not explicitly ask about participants beliefs for making geoscientific data open access, only one respondent stated that published data should be deposited into online open-access databases through their open question response.

Two optional questions were open written responses that asked about 1) respondents' practice reporting ^{210}Pb results in manuscripts and 2) about their experience re-plotting and working with previously published data. Fifty-eight of the 64 responses (91%) contained appropriate information for the first open question – with 19 respondents (22.9%) opting to leaving no response. Respondents converged on many details that should be reported, notably how samples were taken, core collection date, core subsampling, (total) activities, calendar age model used, and often believed discussion on how well the model fit and a qualitative description of robustness. Some respondents described looking at comparable papers to decide on what details to include – suggesting reporting trends are influential.

Thirty of the 61 responses (50%) contained appropriate information for the second open question about re-using published data. 24 respondents commented directly about efforts of re-using published data: 3 individuals found it satisfactory for their purpose, 7 responses were neutral or mixed experiences, and 14 described frustration and challenges. Many of those who experienced challenges were adamant about the lack of access to appropriate details to be critical of the presented models or to be re-used for their purpose, often for numerical analyses, including one respondent who found these challenges even when accessing data from databases. A single respondent also found that asking authors directly during peer-review for further ^{210}Pb related data was met by refusal or dismissal of the recommendation in the final accepted publication. Three respondents stated they had reused ^{210}Pb date determinations at face value from published data and one respondent mentioned that they had reused published radiocarbon dates but had not reused published ^{210}Pb dates - indicating missed value and opportunities for ^{210}Pb dated results.

4. Discussion

The literature review, while not comprehensive of the complete body of literature, is indicative of what information is often presented or excluded in published studies using ^{210}Pb dated sediments. It also presents a summary of the literature that researchers would be exposed to and the context for designing, peer reviewing and editing new papers presenting ^{210}Pb dating results. In the literature, the presentation of methods and results varies based on the focus of the multiple research uses of ^{210}Pb measurements and reflects decisions made by authors, reviewers and editors. Our survey of research community perspectives on ^{210}Pb reporting and data reuse and our review of 271 publications using ^{210}Pb dated geoarchives illustrated the variation in reporting styles. It also contextualizes the opportunity for future publications to present and preserve the crucial minimum information required to improve study repeatability and reproducibility, while also extending the data lifecycle for future reanalyses, which will likely become more automated. The proliferation of associated large supplementary material and open-access data repositories permits a readily and associable medium to disseminate underlying measurement values without cluttering the primary aspects of the studies.

While many studies on palaeoenvironments use ^{210}Pb dating to model calendar ages for recent (uppermost) sediments, other (and novel) parallel or potential research applications in environmental isotopes and age model improvements are missed when crucial information is not presented or accessible. In fact, missing information from palaeoenvironmental studies reduces the reuse potential of the data, data fidelity if not fully archived in a repository, and is a constraint on reproducibility. It is also a missed opportunity for achieving data standards reliable for informing decision making and policy formulation. Each explicit example from the second open ended question that relied on adequate sharing of ^{210}Pb results was also a loss in scientific exploration and innovation. Respondents felt that method and result descriptions in scientific manuscripts was generally satisfactory for peer-review purposes; but with nearly 40% of respondents stating that they have reused published ^{210}Pb dating information for new analyses, and 13 (16%) of respondents venting frustration with combing the literature for adequate ^{210}Pb dated sediment quantities to use in new analyses suggests that some improvements in reporting are necessary to give further scientific value to the data.

5. Recommendations

Here we build upon previous recommendations for presenting geochronological data (Stuiver and Polach, 1977; Millard, 2014; Dutton et al., 2016) and specifically ^{210}Pb data for re-calculation and verification (Smith, 2001). Minimum reporting guidelines described here are intended to increase data transparency and reproducibility. In addition, the template provided within IEDA (Interdisciplinary Earth Data Alliance) and LiPD (Linked Paleo Data; McKay and Emile-Geay, 2016) formats serve as both a guideline for creating user-specific data reports and as a potential platform for researchers to comply with the data reporting requirements outlined by some granting agencies (SM4, SM5). Table 3 and SM6 summarize checklists of suggested minimum information to include when reporting ^{210}Pb dating results. Finally, providing information that allows others to interpret or reuse data only acts to increase the value and significance of a study within its respective discipline.

Following Sanchez-Cabeza and Ruiz-Fernández (2012), there are few essential pieces of information needed to reproduce published CRS models; depth (m), dry mass (kg), ^{210}Pb excess concentration (or activities) – and in addition, coring date is also important. Excess is determined by subtracting the supported activity (^{210}Pb that is produced by ^{226}Ra) from the total activity, because of this reporting the supported activity becomes important. On the other hand, the depth and dry mass are later transformed into dry bulk densities (kg m^{-3}), and considering that the implementation of ^{210}Pb to chronologies in combination with other geochronological information has become more popular, explicit depth in (cm or m) becomes essential. The bare minimum variables and information we suggest reporting that uses ^{210}Pb for dating purposes are; Excess Activity or Total and Supported activity, sediment dry density, and subsampling depth intervals (base and top). Essential metadata include date and location of coring, corer type (for calculating sediment recovery volumes), radioactivity counting technique, and a first order interpretation if background was reached in the core and the age-depth model results.

5.1 Site metadata

5.1.1 Location of core (GPS coordinates)

Only 31% of papers provided site coordinates and 24% presented a map. Precise coring coordinates and coordinate systems are useful for data reuse and for site reinvestigations. This is because reconstructing a coring location from illustrations and descriptions is fraught with difficulties; hydronym use, complex terrain, multiple similarities between sites within close proximity and hydronym synonyms. We recommend that latitude and longitude of the coring location are provided to the highest possible precision in large lakes and add that precision in small lakes with simple bathymetries or wetlands is also important for repeating studies that emphasize within-in basin spatial complexity (see Beaudoin and Reasoner, 1992; Koff and Vandel, 2008; Courtney Mustaphi et al., 2016; Farquharson et al., 2016). In such cases, the spatial error reported by GPS is worth publishing in the publication(s) or at least the accompanying dataset. Even a best estimate of the coring location by the primary authors is preferable to a forensic reconstruction by future analysts.

5.1.2 Date of coring

^{210}Pb radioactive decay is a continuous process that continues after sediment coring and thus a correction must be applied once radioactivities are eventually measured from the sediments. Ideally, the date (day, month and year) of coring should be presented so that ^{210}Pb age reconstruction and synthesis analyses can be performed. Reporting the date of coring as precise as possible is important for correcting the decay offset between core collection and radioactivity counts (Joshi et al., 1992). When absent, analysts must replace a precise date with an estimate when a full date cannot be provided; leaving the choice to individual laboratories that may not be presented in publications. For example, if only the month and year are provided, an analyst may opt to use the first or last day of that month as default, but this detail will only be reported in the ^{210}Pb dating results that become inaccessible to future researchers. It is also useful to clearly report because it almost always used as the stratigraphic top age when re-running age-depth models. This avoids a top core age assumption, such as using the publication date plus-minus an error estimate, as has been done in data synthesis studies (Goring et al., 2012). Coring dates can be sufficiently recorded in the methods section or in the results as the core top is geochronological data point used in the age-depth model.

5.2 Core data and subsampling methods

5.2.1 Subsample volume and dry bulk density

At a minimum, the subsample volume should be provided as these values relate the sediment accumulation with the radioactivity measurements and reporting the corer type (or dimensions) can be used for calculating the volume of collected sediments and a useful consideration for future fieldwork by other researchers. This, along with dry sediment density data, will allow other users of the published data to re-calculate sedimentation rates and or re-run the data using certain or even alternative ^{210}Pb models and age-depth models. In cases where the entire sediment level was dried and then radioactivities measured, the sediment volume values can be estimated if the type of corer used was reported. A description of core collection locations and techniques used for aligning parallel cores in a composite core (master chronology) should also be included.

5.2.2 Sediment subsampling intervals (depth$_2$ to depth$_1$)

There are several techniques for subsampling a sediment core and precise reporting is useful. Subsampling for ^{210}Pb is usually not instantaneous measurements and requires a subsampling depth interval that can be contiguous or discontinuous. Reporting styles vary in the literature from contiguous uniform intervals (e.g. 1-2, 2-3 cm) or interval ranges, (2.6-5.1, 5.5-6.0 cm), top depths only, midpoint depths, or even base depths. Presenting interval depths with lower and upper bounds is the clearest and most readily reusable data for users – notably for reproducing age-depth relationships in the dataset. If a single depth is described the thickness of samples should also be mentioned and also what the single depth represents (for example, top or midpoint depths). If presented as a graph the sampling depths should be in the accompanying supplementary information or data repository. The inclusion of depth dimensions associated with age determinations will be required as numerical approaches to calendar age modeling and for age-depth modeling continue to be refined (Bronk Ramsey, 1995; Buck et al., 1999; Blaauw, 2010; compare: Boreux et al., 1997; Telford et al., 2004a; Haslett and Parnell, 2008; Blaauw and Christen, 2011). Without presenting the upper and lower depth interval, the age determination is reduced to a single point; thus, some information is lost to future analysts.

5.2.3 Laboratory sampling methods

The method used to subsample sediments, both in the field by extrusion (Glew, 1988; Verschuren, 1993) and in the laboratory using a calibrated volumetric sampler (such as a syringe, or water displacement), should be reported. Anecdotally, our review found that subsampling is frequently not described in methods, yet this can influence the precision of results. The choice is often dependent on the sediment type and character and equipment availability. Subsampling in the field sampling can improve accuracy because it avoids mixing of surface sediments during core transport. However, extrusion and scraping can blend sediment intervals because downwarping of sediment can occur near the core barrel. In these cases, subsampling can offer greater precision. Either way, reporting the sediment character and subsampling method can provide critical information to the scientific and management community that seek to use the published data, either as a management tool or for data integration and re-analysis.

5.3 ^{210}Pb radioactivity counting

5.3.1 Radioactivities and precision

The technique for drying sediment should be stated (oven drying, time and temperature; or freeze drying). Reporting which method is used to measure levels of ^{210}Pb is of great importance. Precision from both techniques (alpha and gamma spectrometry) varies, with alpha spectrometry providing a more precise measurement, precision from the resulting chronology will be directly affected by the measurement's precision. On the other hand, gamma spectrometry provides measurements from other environmental isotopes, such as ^{226}Ra and ^{137}Cs, as ^{226}Ra can be used as a proxy for supported levels of ^{210}Pb. When alpha spectrometry is used, levels of supported ^{210}Pb are inferred by obtaining measurements from depths at which the sediment's unsupported ^{210}Pb has completely decayed. This information is crucial for replicating dating models, such as the CRS, CIC and CF:CS, because these models use the unsupported ^{210}Pb data.

Reporting the measured levels of ^{210}Pb is one, if not the most, important variables to report for replication. Reporting this measurement should always be accompanied by the related uncertainties (standard deviations). Reporting the uncertainties allows for replication of not only the chronology but the uncertainty related to it. This is important given that the CRS uncertainties can be calculated using different methods (see Binford, 1990; Appleby, 2001; Sanchez-Cabeza et al, 2014). Reporting uncertainties is crucial for new approaches such as that introduced by Aquino-López et al. (2018).

5.4 Age-depth models

5.4.1 First order interpretation of the ^{210}Pb profile

If not mentioned by the authors, the geologic law of superposition of sediments is often assumed and a discussion of any effects of mixing, bioturbation, or instantaneous deposits are rarely explored (Benninger et al., 1979; Smith, 2001; Suckow et al., 2001; Arnaud et al., 2002). It is also useful to briefly discuss the relationship of sedimentation to basin characteristics (Bennet and Buck, 2016); especially, in the context of the ^{210}Pb results. We argue that this should be presented and moreover, reviewers/editors should make allowances for this to be presented and discussed, especially in geological and palaeoenvironmental journals. This practice is more commonplace for radiocarbon analyses where studies discuss age reversals or other departures from idealised conceptual models of superposition. This type of first order interpretation of the ^{210}Pb profile was not presented in 84% of papers; but is very useful to inform future users of the data. In addition, we encourage authors to explore regional (or environmental) comparisons of ^{210}Pb profiles to contextualize their new results. Results of such comparisons can be discussed to support interpretations of the profile (Appleby, 2000; 2008). Ancillary radioactivities of other radioisotopes used for interpreting the sediment profile should also be presented with errors and commented on if such use comeplements an understanding of sedimentation rates at the study site.

Furthermore, a description of at what depth background ^{210}Pb activities were reached downcore is crucial for recreating published ^{210}Pb models and useful within the first-order descrition of sedimentation by the study author(s). An idealised distribution of unsupported ^{210}Pb in a sediment stratigraphy is exponential, resulting in no true 0 measurement value – but CRS models set a 0 value where background levels are detected by subtracting an amount of total activity from all measurements (Binford, 1990). Corrections to the old-date error should also be reported a this information could prove to be useful for re-running models and applying newer models developed in the future. This is important for reruns because it guides the establishment of the oldest ^{210}Pb estimated age possible and helps to reinterpret the values of supported activity in the sediment. The inferred levels of supported ^{210}Pb directly affect the resulting chronology given that most models, with one exception (Aquino-López et al., 2018) use unsupported levels of ^{210}Pb and an overestimation of the unsupported ^{210}Pb leads to an underestimation of supported ^{210}Pb (and vice versa). Explicit documentation of model choices and the depth that background activities were measured are necessary to ensure replicability because many models use the supported ^{210}Pb inferred from ^{210}Pb inventories in the core.

5.4.2 ^{210}Pb chronologies and calendar ages, age-depth models, and uncertainties

Authors are encouraged to report the ^{210}Pb dating method used and cite the publication describing the method – just as with ^{14}C dates, it is necessary to state the calibration curve used. Unlike radiocarbon dating where each measurement is independent (but superpositioned in an undisturbed stratigraphy), ^{210}Pb dates heavily depend on the dating model used and; in the case of the CRS dates, cannot be considered independent, as the cumulative activities are used (see Appleby, 2001). As previously mentioned, there are different techniques for calculating ^{210}Pb uncertainties – meaning the chosen method must also be mentioned to reproduce the study. Properly reporting both the dating model and uncertainty calculation becomes more important in studies that combine ^{210}Pb dates with other dates to create an age-depth model, as most age-depth modeling techniques consider the dates as independent and make full use of age uncertainties to infer the age-depth models (ex. Blaauw and Christen, 2011).

The literature review revealed that the majority of publications (64%) did not report ^{210}Pb calendar ages with uncertainties. Further, there is increased use of combining ^{210}Pb dates with other dating techniques such as radiocarbon. Most age-depth modeling techniques (including Bayesian approaches) require a measurement of uncertainty. The relationships between different types of age determinations also relies on uncertainty estimates, especially when combining ^{210}Pb profiles with modern radiocarbon measurements (for example see: Rinta et al., 2016).

Table 3. Summary of recommended reporting for ^{210}Pb dated sediments.

Section	Information to report	Style	Justification
5.1.1	Coring location coordinates	Highest precision (with error) possible	^{210}Pb from atmosphere varies by latitude; with-in basin spatiality of sedimentation
5.1.2	Coring date	Day/month/year	Top sediment date when ^{210}Pb input ended
5.2.1	Sediment dry densities	or core barrel internal diameter	To calculate accumulation rates and relate sedimentation with radioactivities. Inventory estimates are used for some ^{210}Pb models
5.2.2	Sediment subsampling	lower and upper depth interval values	Needed for establishing ages and amount of temporal aggregation
5.2.3	Sediment subsampling methods	description in methods section	To increase precision
5.3.1	Radioactivities and precision	In the methods or figure/table captions	Precision varies by counting technique and calculations chosen to establish calendar ages and uncertainties
5.4.1	First order interpretation of the ^{210}Pb profile	In age-depth model methods or results	To document the variability by primary authors and define (quantify) when background was reached
5.4.2	^{210}Pb chronologies and calendar ages	Results section, tables, graphs, supplementary information	Count measurements and derived ages for reproducing studies and reusing data
5.5	Data archive	In the publication, data statement, or in relevant databases	Data and computer code to derive modeled results to improve data transparency, fidelity, reuse potential and data lifecycle

5.5 Grading the literature

We used our minimum ^{210}Pb relevant information categories to grade the publications identified in out literature review. If the minimum information category was clearly presented in text or table format we graded it as adequate and categorized as a ‘’pass’’ (green, Fig 3), and if the information could be used to estimate values (for example, corer type can be used to estimate core dimensions for inventory calculations) or if the data was presented in a figure that could re-digitised for quantities we graded it ''estimate-able'' (yellow, Fig 3), and if the information or data was not presented it was graded a ''fail'' (red, Fig 3). The type of information frequently unreported varies by category, with site locations being well reported or have a high likelihood for being estimated and information on background rates and where in the core (depth) it was reached are rarely reported (Fig. 3). A total of 63% of respondents believed some useful ^{210}Pb information was missing or inadequately reported in the published studies. This is corroborated by our literature review and enquiry of what and how ^{210}Pb-relevant information is presented. The review revealed that 50% of papers explicitly present only 2 of our minimum reporting information categories and 80% present less than four. No publications clearly presented all ten (or even nine) (Fig. 4, SM1). When we apply our minimum reporting guidelines to filter the publications from the literature review we find that no paper explicitly presents all of the data to maximize the further use of the ^{210}Pb data and 42 papers did not present any minimum information (Fig. 4, SM1). Within the literature it is possible to trace propagation of incomplete presentation of ^{210}Pb results. One example is a study by Courtney Mustaphi et al (2015) that presented a ^{210}Pb, ^{14}C, and tephra dated lake sediment core, which scored 0 passes, 3 estimate-able, and 7 failures, to present the 10 minimum information categories; partly because the study relied on citing a previous study for the geochronology (Courtney Mustaphi and Pisaric, 2013); which, itself was graded 4 passes, 3 estimate-able, and 3 failures to present the information. These examples demonstrate the need to improve reporting and represents a significant challenge for automated data scrapes of the literature. The recommended guidelines presented here facilitate improved reporting and encourage authors to maximize the value of datasets produced.

5.6 Archiving, repositories, and accessibility

If all of the data is not in the publications, then where is it? We did not follow the trail of each paper to uncover whether or not the raw and derived ^{210}Pb data was freely available, but anecdotal information from our literature review found 8 publications that presented useful ^{210}Pb data in the supplementary information that accompanied the publication, 1 study stated that the deposited data was in the PANGEA repository (Sabatier et al., 2014), at least one study explicitly stated that the ^{210}Pb data presented in the study relied on unpublished data (Romero-Viana et al., 2008), and one case where the ^{210}Pb data cites a third party report that presents ^{210}Pb data in significant detail; but the cited report is not easily obtainable (Turner, 1995; Courtney Mustaphi and Gajewski, 2013). Archiving publication writing, datasets, and computer code adds value, lengthens data lifecycle, and improves multidisciplinary reuse opportunities for studies producing and using ^{210}Pb data. We have presented rationale and recommendations for reporting ^{210}Pb measurements and geochronological data. We also have provided a template for ^{210}Pb raw data through the IEDA data archive and in the Supplementary Information (SM4). Standardized templates and archiving platforms are readily available to the research community that have the capacity to include ^{210}Pb information (such as IEDA, Neotoma, Global Charcoal Database, repositories at NOAA, amongst others) and our recommendations can guide authors for which data to include. Our recommendations also guide authors who choose to use other repositories that intake bespoke data archives (such as the Harvard Dataverse, Figshare, Dryas and others). Further guidance on reporting the full data report of radioactivity detections are available from the Centre National de la Recherche Scientifique (CNRS) of France that coordinated the development of a common way to present short-lived radionuclides data, such as ^{210}Pb, and produced a document guiding the needed information for storing data in a repository. Making geoscientific data more Findable, Accessible, Interoperable and Readable (FAIR; Wilkinson et al., 2016) prolongs the data lifecycle and data fidelity and thus its scientific value.

6. Conclusions

The presentation of ^{210}Pb data for geosciences varies widely in the literature and decisions by authors, reviewers, and editors can optimize the usefulness and data lifecycle of the underlying data. The theory behind the technique is well established and new instruments continue to be developed and put into operation, namely at research institutions but also commercial laboratories. This paper charaterises some patterns of reporting by researchers and highlighted the heterogeneity in presentation, which has led to the minimum reporting guidelines recommended here. Ultimately, the onus remains with authors, editors, peer reviewers, and learned societies to foster and maintain a culture of adequate reporting of results and the wider use of ^{210}Pb data in the geosciences. Interestingly, evidence suggests that examples set by senior scientists influence the reporting culture in a given discipline (Fuller et al., 2015). To facilitate this culture within the paleoenvironmental and geosciences, we have produced and shared a template for ^{210}Pb data archiving within the IEDA data archive (SM4). Acknowledging and participating in current demands of the research data lifecycle and maintenance of a high level of scientific integrity and ethics is crucial to the process of scientific publication and data curation (Gundersen, 2017; Hanson, 2017).

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Author contributions

CJCM, JB, MA-L, SG, AN, and JC designed the research; CJCM designed and implemented the questionnaire, all authors participated in researching and analyzing data, and all authors wrote the paper.

Conflicts of interest

Authors declare no competing interests.

Data and materials availability

All data is available in the main text or the Supplementary Materials.

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List of figure captions

Fig. 1. Histogram of number of publications per year reporting the use of ^{210}Pb dating of sediments or other geoarchives from the literature review.

Fig. 2. Percentage of publications per year with studies of ^{210}Pb-dated sediments in combination with other geochronological determinations (^{14}C, ^{137}Cs, ^{241}Am, varves, tephrochronology, etc.) to generate age-depth models.

Fig. 3. Publications for the literature review and reporting of minimum information of metadata, methods, and ^{210}Pb activities and calendar age estimate results in publications from the literature review (*n*=271 publications). Green, counts of publications with adequate reporting (nominally 'passes'); yellow, publications that present graphics or text that can be used to estimate or reconstruct the information; red, reporting is inadequate; grey, publications where that information category does not apply (for instance, when calendar ages were not modeled and only mean sedimentation rates were presented). Categories: Site location (section 5.1.1); coring data (5.1.2); Core dimension, type of corer used (5.2.1); sediment subsampling interval (5.2.2); Sediment dry densities (5.2.1); ^{210}Pb radioactivity counts and measurement errors (5.3.1); description or line in graphic presenting if background was reached and at which depth (5.4.1); and the estimated calendar ages and errors (5.4.2).

Fig. 4. The counts of publications (n=271) that explicitly presented categories of minimum required information in the main publication document or accompanying supplemental material (with the journal article).

List of table captions

Table 1 Top 10 journals used to publish ^{210}Pb dating results from the manual literature search. Journal Impact Factors (JIF) from the 2016 Journal Citation Reports® (Clarivate Analytics, 2017).

Table 2 Frequency of ^{210}Pb radioactivity counts reported in the literature review. Counts are presented with equivalent percentage in parenthesis (count out of 271 total studies).

Table 3. Summary of recommended reporting for ^{210}Pb dated sediments.

Appendix A. List of Supplementary Material

SM1_210Pb_Literature_Review_Reporting.xlsx

Spreadsheet of the literature review of ^{210}Pb dated geoarchives and the categorical information collected from each publication (n=271).

SM2_Lead-210_users_survey.docx

Complete original survey that was circulated online from January to April 2017 and received 83 respondents (see SM2).

SM3_Lead-210_user_survey_Qualtrics_Default_Report.pdf

Complete raw results from 83 respondents of the survey questionnaire (SM2).

SM4_IEDA_Lead210_Sample_Template.xlsx

IEDA formatted spreadsheets for inputting, archiving, finding and sharing ^{210}Pb dated sediments.

SM5_LiPDv1.2_template_210Pb_Results_Reporting.xlsx

Linked Paleo Data (LiPD; McKay and Emile-Geay, 2016) format spreadsheet presenting the minimum suggested reporting information for ^{210}Pb dating results.

SM6_Spreadsheet_210Pb_Results_Reporting_Suggestions_in_Text_and_Tables.xlsx

A generic spreadsheet for presenting the minimum suggested reporting information for ^{210}Pb dating results.

Tab	Tab name	Explanatory note
1	README	Table of contents for spreadsheet tabs in this file
2	Suggested Table report format	Column headers for variables to report in tables presenting 210Pb results in scientific manuscripts and reports, and dat
3	Suggested text to report	Suggested quantitative and qualitative information on 210Pb dating results to include in manuscript text, supplementa

Unique Sar	Depth (TOF	Depth (BAS	Dry sedime	Total 210Pl	Total 210Pl	Supported	Supported	Unsupport	Unsupport	Estimated (	Estimated calendar age error

Section in	Category	Notes
5.1.1	Coring latitude, longitude, elevation	With highest precision possible; error estimates if possible
5.1.2	Coring date	Can also be included in table of geochronological data
5.2.1	Corer shape and dimensions	Barrel size and thus original collected core dimensions
5.2.2	Sediment subsampling	A comment on subsampling down the core for 210Pb dating; i.e. Continuous in
5.2.3	Sediment subsampling method	Wet or dry subsampling using calibrated subsampler, or water displacement, o
5.4.1	First order interpretation of the 210Pb profile	Author interpretation of profile and designate depth at which 210Pb radioactiv
5.4.2	210Pb chronologies and calendar ages	Type of model used to estimate calendar ages using the 210Pb radioactivities

ıtervals, irregular intervals, depth interval ranges, systematic, randon
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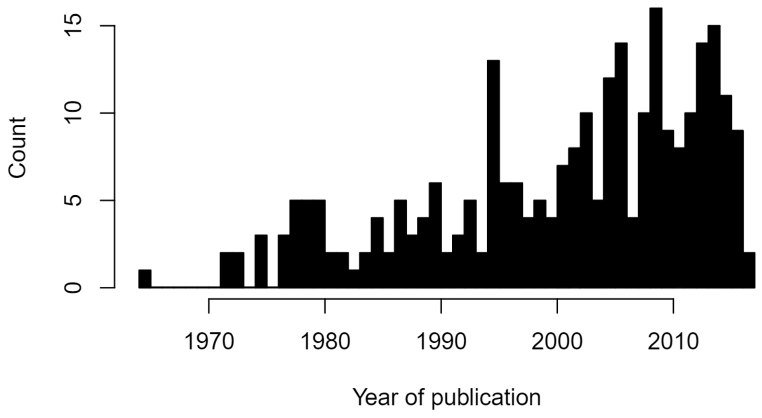
ıities reached "background'



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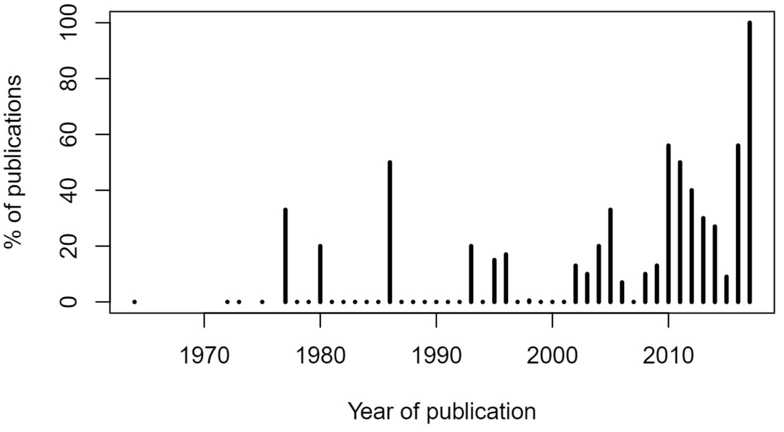
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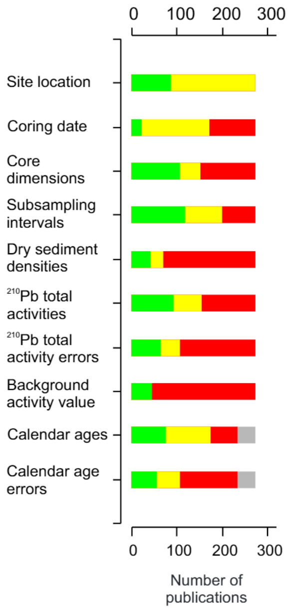
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Dry sediment densities
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Background activity value
Calendar ages
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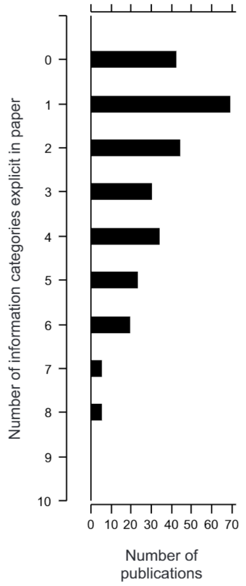
Number of publications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