Received: 22 October 2021 | Accepted: 22 December 2021 | Published online: 16 February 2022

DOI: 10.1002/saj2.20372

Soil Science Society of America Journal

SHORT CRITICAL REVIEWS OR ESSAYS

Time in a bottle: Use of soil archives for understanding long-term soil change

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Assigned to Associate Editor Craig Drury.

Abstract

Soil archives preserve a snapshot of soils from a specific time and location, allowing researchers to re-evaluate soils of the past in the context of the present for an improved understanding of long-term soil change. To date, the extent of soil archive use in the peer-reviewed literature is poorly inventoried. Here, we document the characteristics and distribution of global soil archive use, as found in 245 publications, following an exhaustive search of English language journals. Soil archive use has increased substantially since 1980, reaching 59 publications between 2016 and 2020. The age of soil archives across the compilation ranged from 5 to 160 yr, with mean and median archive ages of 48 and 37 yr, respectively. Publications using soil archives originated mostly from countries in the northern hemisphere, with the top five reporting countries including the United States (61), United Kingdom (52), New Zealand (21), Canada (18), and China (14). Land uses associated with soil archive publications were dominated by agroecosystems, specifically land planted to annual crops. Forty-seven percent of investigations focused on changes in soil C, N, or organic matter, whereas investigations of other subjects did not exceed 20% each. The compilation is publicly available online. As demands on soils increase, archives will serve as an invaluable tool for understanding long-term soil change in the Anthropocene era. Multiregional coordination and increased investment in curation and retention of soil archives are recommended to preserve these irreplaceable resources.

1 | INTRODUCTION

Soil archives are an exceptionally valuable resource for measuring impacts of management practices over time, providing unique data for informing decisions impacting sustainable food production and key ecosystem services (Dolfing & Feng, 2015). Moreover, archived soil samples provide researchers an essential resource to advance their understanding of soil change as analytical methods are developed and refined (Boone et al., 1999; Janzen, 2016). Despite these apparent benefits, systemic investment in the curation and retention of soil archives is lacking. Accordingly, there is a

Abbreviations: LTSE, long-term soil experiment.

pressing need to document and communicate the utility of soil archives for addressing critically important questions related to long-term soil change. Threats of soil degradation and climate change, coupled with accelerating demands for food, feed, fiber, and fuel, bring focus to this urgent need (Manter et al., 2017).

The value of long-term soil experiments (LTSEs) as an important resource for the scientific community is widely recognized (e.g., Richter et al., 2007). The International Soil Carbon Network maintains an inventory of global LTSEs; however, less than half of all LTSEs archive soil (International Soil Carbon Network, 2021; Richter & Yaalon, 2012). Previous efforts to tally and compile information related to soil archives have revealed an uneven distribution globally with limited accessibility (Pool & Laney, 2021; Richer-de-Forges et al., 2021). Whereas some soil archives excel in their documentation of metadata, experimental data, and ongoing research (e.g., NEON Megapit Soil Archive and Rothamsted Sample Archive) (Ayres, 2019; Perryman et al., 2018), efforts to compile and categorize key information related to the use of soil archives in the scientific literature is lacking. Such information could increase the value of soil archives for understanding long-term soil change, highlight notable gaps, and suggest approaches to enhance future use and accessibility.

Given this context, we evaluated peer-reviewed publications for use of soil archives in original experiments and extracted and compiled key metadata. Insights from compiled metadata were then used to suggest possible paths forward to increase investment in the development, curation, and retention of soil archives.

Core Ideas

- Archived soil samples facilitate an improved understanding of long-term soil change.
- A literature review was conducted to compile metadata documenting soil archive use.
- Since 1980, there has been an accelerating use of soil archives in research.
- Research is primarily focused on soil organic matter change in agroecosystems.
- Resources are needed to support soil archives, especially in developing countries.

2 | METHODS

2.1 Search methodology and selection criteria

Peer-reviewed publications with documented use of soil archives were identified through a literature search using the USDA National Agricultural Library's Digitop search engine (USDA, 2021), supplemented with results from Wageningen University & Research Library search (Wageningen University & Research Library, 2021) and Google Scholar (Google, n.d.). Core search terms included "archive soil," "soil archive," "old stored soil," and "stored soil samples." A complete list of search terms can be found in Supplemental Table S1. All search results from Digitop and the Wageningen University & Research Library were screened, as well as the first 50 results in Google Scholar searches (after this point search results were found to be redundant or irrelevant). References in identified publications were further screened for additional publications relating to use of archived soils. Articles cited in applicable review papers were also included in the search (e.g., Ayres, 2019; Dolfing & Feng, 2015; Richer-de-Forges et al., 2021; Richter et al., 2007). For this study, only publications in English or with English abstracts were considered.

Identified publications were vetted to ensure archived soils were experimentally used in each study. Opinion pieces, review papers, and publications without direct analysis of archived soil were omitted. For purposes of this compilation, archived soils were designated as those that had been stored for five or more years. A total of 245 papers met these criteria. A subset of papers with archives not meeting the age criteria addressed effects of storing and archiving soils, and while these were excluded from analysis here, they were set aside as an additional tab in a document available online (Bergh & Liebig, 2021).

To place our findings in context, we conducted an additional Digitop search of peer-reviewed publications using the keyword "soil" in the abstract, title, or keywords and recorded the number of publications per year for the period 1910–2020.

2.2 Data categorization and analysis

Each publication was reviewed for key metadata, including publication year, age of oldest sample, and sample collection location. For presentation purposes, publication year and soil archive age were grouped in 5-yr increments. Land use associated with archived soil, along with the subject of each investigation, were also recorded. Land planted to annual crops was identified as "annual cropland," whereas "grassland" was defined as having native vegetation (may or may not be grazed) and "pasture" as having planted vegetation for grazing. Trees and palms grown for timber or food were placed in a separate category ("orchards and palms") as they were neither annual cropland nor natural forests. If samples within one publication were from multiple locations with different land uses, all locations and land uses were recorded. Additionally, if investigations addressed multiple subject categories (e.g., soil organic matter, macronutrients, pH, etc.), all were recorded. As indicated above, select papers specifically

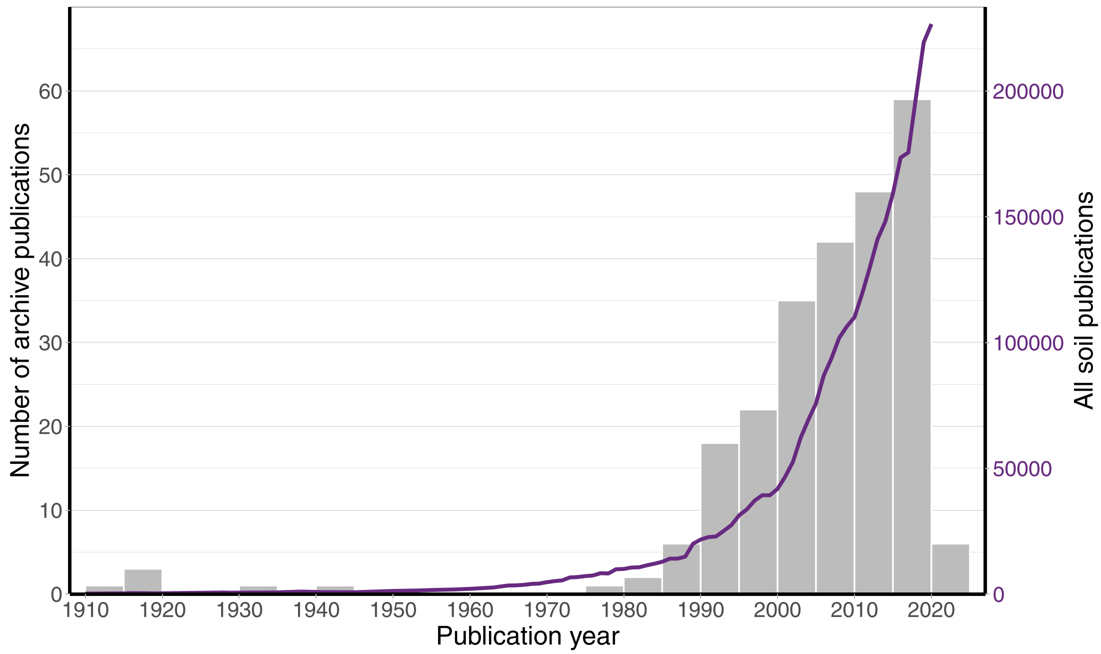

FIGURE 1 Distribution of publication year for identified publications using soil archives, grouped in 5-yr increments (grey, left *y* axis), and number of total soil publications per year from 1910–2020 (purple, right *y* axis)

investigated effects of soil storage and archiving. These 29 publications were additionally tagged with "effects of archiving" for future reference.

Metadata were summarized and visualized using R 4.0.5 and the suite of tools in "tidyverse 1.3.0" (R core team, 2019; Wickham et al., 2019).

3 | RESULTS

The 245 papers spanned 106 publication years (1915–2021), with a mean publication year of 2006 and a median of 2009 (Figure 1). The search methods used in this study identified only seven publications prior to 1980 that used soil archives. The number of publications after 1980 increased markedly, peaking at 59 publications between 2016 and 2020. This trend was similar to the pattern for total number of soil science publications (Figure 1).

The age of soil archives reported in the publications ranged from 5 to 160 yr, with mean and median archive ages of 47 and 35 yr, respectively (Figure 2). Archived soil 25–34 yr in age was used most frequently, comprising 20% (48) of compiled publications. Notably, almost all studies using soil archives >100 yr of age were from the Rothamsted Experimental Station (Figure 2). Established in 1843, the Rothamsted long-term experiments are among the longest continuous cropping system studies in the world, supplemented by extensive archives of soil, grain, and straw, with samples collected as early as 1846 (A. Johnston & Poulton, 2018).

English-language publications using soil archives originated largely from countries in the northern hemisphere, with the United States and United Kingdom accounting for almost half of total compiled publications (61 and 52 publications, respectively; Figure 3). Other countries using soil archives in publications included New Zealand (21), Canada (18), China (14), Australia (12), Denmark (12), Russia (12), France (11), and Sweden (11). Regions without publications using soil archives included most of Africa (especially North and West Africa), the Middle East, Latin America, Southeast Asia, and land masses largely covered by ice (Greenland, Antarctica). In total, 49 countries were represented.

The distribution of land uses associated with soil archive publications highlighted the prevalence of annual cropland studies, which were included in 54% of recorded evaluations (Table 1). Twenty-four percent of recorded evaluations using soil archives included forests, followed by grasslands (19%) and pasture (13%). Less than 6% per category of recorded evaluations included bare fallow, urban, desert–shrubland, orchard–palm groves, industrial, or other land uses. Almost half of soil archive investigations focused on C, N, or soil organic matter (47%; Table 2), followed by investigations of trace elements (16%), macronutrients (15%), and soil microorganisms (13%).

When land use and subject category were combined (Figure 4), nearly a quarter of compiled publications addressed C, N, or soil organic matter in annual cropland systems (55 of 245 publications). Generally, the spectrum of investigations across annual cropland and forest systems was broad, whereas other land uses were associated with ≤10

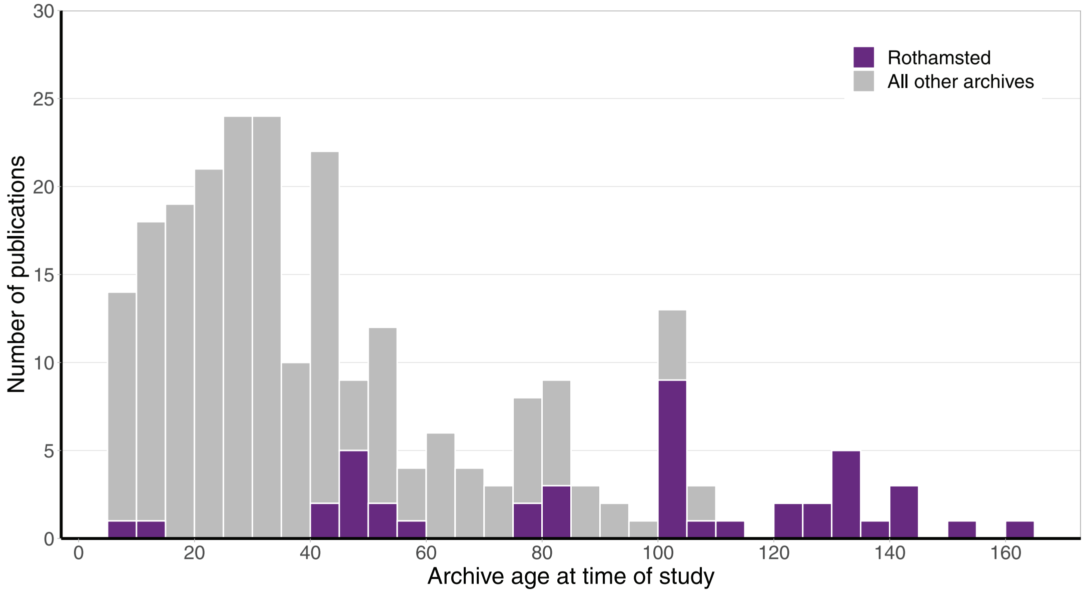

FIGURE 2 Distribution of soil archive age reported in publications, grouped in 5-yr increments

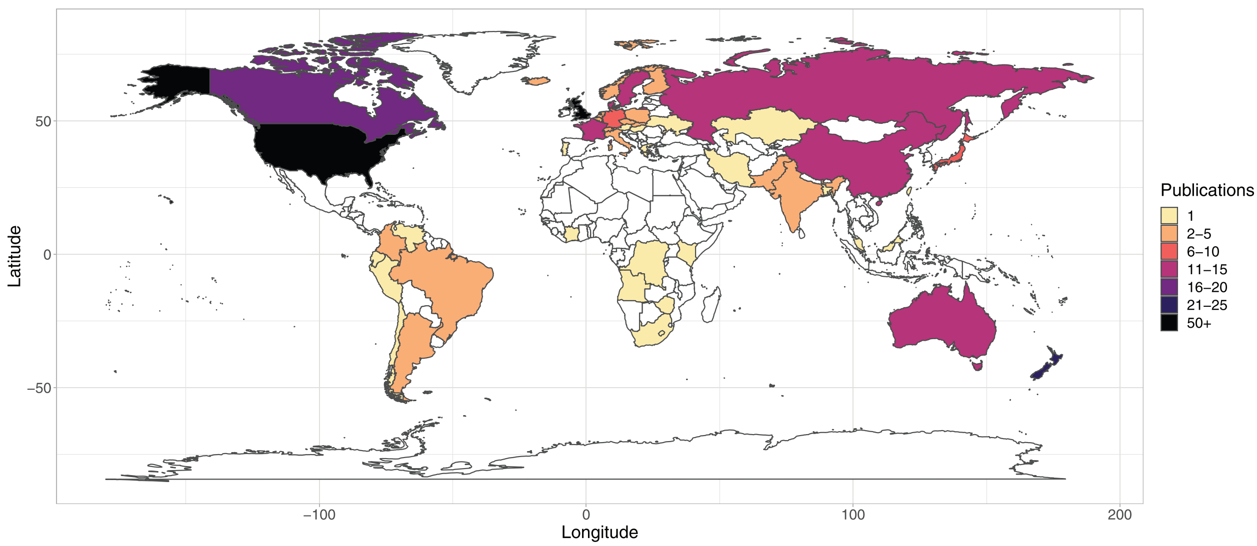

FIGURE 3 Map of soil archive locations. For publications using archive soils from multiple countries, all countries were included

publications across subject categories. Notable gaps in investigations within land uses were apparent by omission (e.g., trace elements in grassland systems). The inclusion of some land uses appeared to serve as an experimental control (e.g., C, N, or soil organic matter in bare fallow).

4 | DISCUSSION

Compiled publications highlighted the emerging use of soil archives for research primarily focused on soil organic matter change in agroecosystems in developed countries. We acknowledge our compilation may be incomplete given the focus on English language journals and abstracts and the reliance on online search results. Moreover, it is likely that many researchers using soil samples in storage for five or more years may not use the term "archive" to describe them. In both cases, this compilation would underrepresent soil archive use. Despite these caveats, we feel the analysis improves our understanding of soil archive use globally and can identify possible paths forward to improve support and access to these valuable scientific resources to address current questions in soil science, ecology, and climate change research.

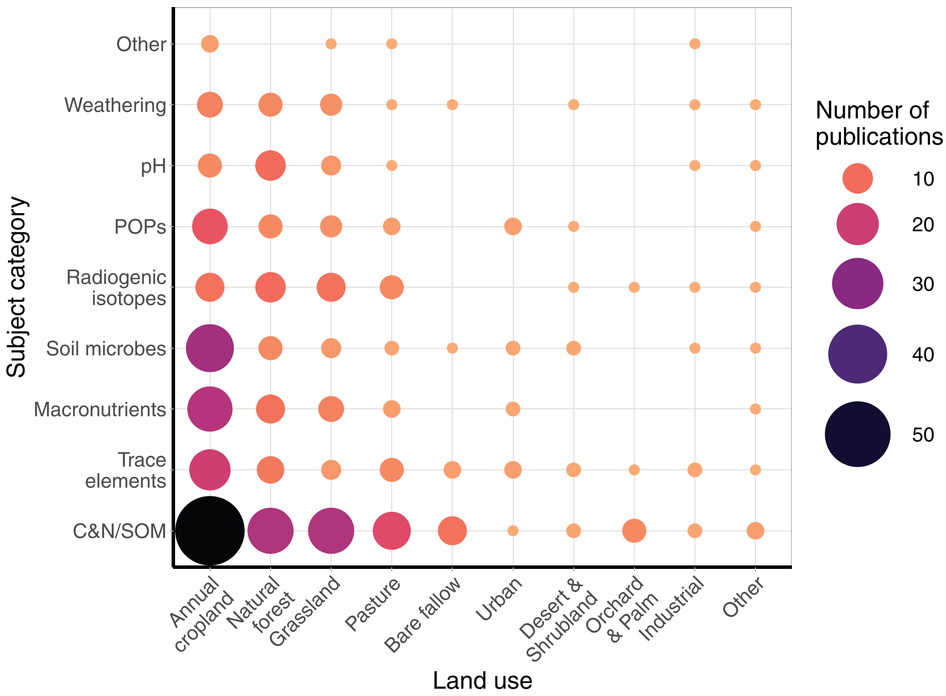

FIGURE 4 Bubble plot documenting the number of publications using soil archives expressed by land use (*x* axis) and subject category (*y* axis). Subject categories were arranged in descending order based on total number from 0,0. C&N/SOM, C and N/soil organic matter; POPs, persistent organic pollutants

TABLE 1 Land uses associated with archived soils across compiled publications

Land use	Number of publications[a]
Annual cropland	132
Natural forest	59
Grassland[b]	47
Pasture	31
Bare fallow	13
Urban	10
Desert and shrubland	8
Orchard and palm	7
Industrial	6
Other[c]	9

[a]Totals include publications with multiple land uses in each relevant category.
[b]Rothamsted park grass included under grassland.
[c]Land uses included in Other: arctic (3), coral island (1), lakebed (1), volcanic island (1), wetland (2), and unknown (1).

TABLE 2 Number of publications using archived soils organized by subject category

Subject category	Number of publications[a]
C and N/soil organic matter	115
Trace elements	38
Macronutrients	36
Soil microorganisms	31
Radiogenic isotopes	25
Persistent organic pollutants	22
pH	20
Weathering	16
Other[b]	4

[a]Totals include publications with multiple subjects in each total.
[b]Categories included in Other: lipids and proteins (3) and magnetic susceptibility (1).

The current trajectory of publications since 1980 suggests an accelerating interest in the use of soil archives for addressing contemporary research questions. Questions framed by themes of climate change, soil pollution, and soil health were represented in the compiled literature, inferring the important role of soil archives for informing issues related to sustainable land management and environmental quality (Manter et al., 2017). Additionally, the recent increase in publications can be partially attributed to the development of new laboratory and analytical techniques for analyzing soils. For example, modern molecular methods have allowed researchers to quantify the presence of antibiotic resistance genes in soil over time (Dolfing & Feng, 2015). The increase in archive publications lagged slightly behind the overall pattern for soil science literature, which increased beginning in 1960 as indicated in this review and in Hartemink (2019). However, it is unclear if this delay is an artifact of our search methods or is representative of a later start in archive soils research.

The age of soil archives used in publications highlighted a limited understanding of soil change of a half-century or longer, with the notable exception of land uses evaluated at the Rothamsted Experimental Station. The Rothamsted experiments are central to our understanding of long-term soil change due to their age, consistency in experimental design, and extensive sample archive (A. Johnston & Poulton, 2018), but extrapolation of findings is limited to agroecosystems with similar climatic, edaphic, and management attributes. Reliance on younger soil archives in publications was much more common, with the 25–34 yr archive age range used most frequently for investigating long-term soil change. Accordingly, there is currently a systemic lack of knowledge concerning the extent of soil change over the average human lifespan (73 yr in 2019) (WHO, 2021).

The geographical distribution of publications using soil archives revealed a substantial disparity between developed and developing nations. This contrast likely reflects differences in stable research funding given the importance of continuous resources to curate and maintain soil archives, in addition to the support needed for long-term research from which archived samples are often derived. Addressing the geographical knowledge gap in long-term soil change is critical moving forward and future efforts to expand soil archive use in developing nations will require strong local engagement, collaborative research alliances, and long-term resource commitments (Gobezie et al., 2021; Minasny et al., 2020; Van Groenigen & Stoof, 2020). These challenges are not unique to soil archive research, or even soil science, but the long-term nature of soil archives exacerbates pre-existing differences.

An additional contrast emanating from the geographical distribution of publications was the paucity of archived samples from sites in tropical countries, currently home to approximately 40% of the world's human population (State of the Tropics, 2021). This may be associated with the limited number of long-term soil experiments in these areas, specifically in Africa and South America. Long-term soil experiments are also concentrated in relatively few soil orders, with over 50% of sites being located on Alfisols, Mollisols, and Vertisols (Richter & Yaalon, 2012).

Compiled publications were disproportionately focused on soil change in agroecosystems. Such emphasis is understandable given the importance of maintaining soil functions to support the myriad of ecosystem services in agricultural production systems necessary for human survival. The number of publications focusing on C, N, or soil organic matter in agroecosystems was particularly noteworthy, underscoring the value of those metrics for addressing research questions related to climate change and soil fertility. However, other fertility-related metrics (e.g., macronutrients and trace elements) were less represented in the compilation, despite their importance to the maintenance of productive agroecosystems and linkages to environmental quality.

Fifty-nine percent of compiled publications using soil archives from pasture were from New Zealand, suggesting a dominance of long-term soil change information related to pastures under a temperate oceanic climate. An additional imbalance of information was also noted for forested sites, for which changes in soil pH and organic matter attributes were often the focus of study. Expanding knowledge of long-term soil change under pastures, grasslands, and forests across a broader spectrum of metrics is warranted. Whereas ongoing monitoring efforts in Australia (R. Johnston et al., 2003) and the United States (Ayres, 2019) aim to address knowledge gaps for these land uses, additional efforts are needed. Moreover, investigations of long-term soil change under desert and shrubland ecosystems, orchard and palm production systems, industrial sites, and urban environments appears to be an unexploited research opportunity.

5 | CONCLUSIONS

The compilation of publications shared in this article provides a platform for a broadened understanding of long-term soil change. The accelerating pace of soil archive use for scientific investigations suggests the emergence of a subdiscipline in soil science focused on the understanding of soil change over decadal or longer timescales. While traditionally placed under the rubric of "long-term" or "observational" research, we recommend an explicit designation for investigations using soil archives given their capacity to provide critical insights into changes in soil physical, chemical, and/or biological attributes; and, more importantly, what those changes imply toward the maintenance of ecosystem services and status of environmental health. The increased use of soil archives also suggests the need for a global archive network to facilitate increased information and sample sharing among researchers. Such a network could offer a more inclusive collection of archive metadata, guidelines for sample access and data availability, and address the geographical gaps revealed by the present review. Finally, resources are urgently needed to support the curation and maintenance of soil archives in regions where the current absence of archives co-occur with projections of intensified soil resource use.

ACKNOWLEDGMENTS

We thank Henry Janzen for his vision and encouragement to reveal the many important stories offered by archived soils. The USDA prohibits discrimination in all its programs and activities on the basis of race, color, national origin, age, disability, and where applicable, sex, marital status, familial status, parental status, religion, sexual orientation, genetic information, political beliefs, reprisal, or because all or part of an individual's income is derived from any public assistance program. (Not all prohibited bases apply to all programs.)

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AUTHOR CONTRIBUTIONS

Emma L. Bergh: Data curation; Formal analysis; Investigation; Methodology; Writing – original draft. Andrea K. Clemensen: Writing – review & editing. Lisa Durso: Writing – review & editing. Jed O. Eberly: Writing – review & editing. Jonathan J. Halvorson: Writing – review & editing. Virginia L. Jin: Writing – review & editing. Andrew J. Margenot: Writing – review & editing. Catherine E. Stewart: Writing – review & editing. Scott Van Pelt: Writing – review & editing. Mark A. Liebig: Conceptualization; Investigation; Methodology; Project administration; Supervision; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The dataset of 245 soil archives publications is publicly available at https://doi.org/10.6084/m9.figshare.16652890. Each publication has associated citation information (title, abstract, authors, year, journal etc.), as well as tagged information used in this review (land use, subject category, country of origin for archives). Additionally, papers omitted from the review because they investigated effects of archiving are included in another tab.

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How to cite this article: Bergh, E. L., Calderon, F. J., Clemensen, A. K., Durso, L., Eberly, J. O., Halvorson, J. J., Jin, V. L., Margenot, A. J., Stewart, C. E., Van Pelt, S., & Liebig, M. A. (2022). Time in a bottle: Use of soil archives for understanding long-term soil change. *Soil Science Society of America Journal*, *86,* 520–527. https://doi.org/10.1002/saj2.20372