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The International Soil Radiocarbon Database (ISRaD) version 2: Synthesis, data gaps, and future directions of soil radiocarbon data

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Abstract

Soil radiocarbon (^{14}C) measurements are crucial for understanding soil carbon cycling over timescales ranging from years to millennia. However, the global synthesis and comparison of radiocarbon data has been limited due to the variety of measurement methodologies and data formats. The International Soil Radiocarbon Database (ISRaD) is an open-access, community-driven archive designed to compile soil radiocarbon data and facilitate large-scale research on soil carbon dynamics. Here, we present ISRaD version 2 (v2), which has grown significantly since its initial release in 2020. It now contains data from 515 unique studies spanning 1,669 sites globally, with over 20,000 radiocarbon observations across multiple hierarchical levels, including bulk soil layers, soil fractions, laboratory incubations, interstitial carbon in soil pores, and in situ fluxes of CO_2 and CH_4. Major updates include expanded metadata structures to capture emerging measurement techniques and an improved soil fractionation template to better capture diverse methods. There has also been a substantial increase in data from underrepresented ecosystems, including urban and cultivated soils, as well as wetlands. Despite this growth, significant geographic and data-type gaps persist. Tropical and arid regions, soils deeper than 100 cm, and certain types of measurements, including incubation, interstitial, and flux, are severely undersampled. We discuss the scientific advances enabled by ISRaD v1 and the major updates to the database and data representation. We also explore future opportunities for ISRaD and the soil radiocarbon community. ISRaD v2 continues to serve as a living archive and dynamic platform for the soil radiocarbon research community. It

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supports synthesis efforts that are critical for predicting how soil carbon will respond to environmental and climatic changes.

1. Introduction

Soil carbon (C) is the largest terrestrial C reservoir, serving as an important climate regulator. Soil organic matter provides crucial benefits to people and nature, including improved soil water retention, crop yield, nutrient availability, microbial activity and biodiversity, and long-term ecosystem productivity and resilience (Bossio et al., 2020; Jenkinson et al., 1991; Natali et al., 2021). With ongoing environmental and climatic change threatening these benefits, there is a need to understand how soil C will respond. Models used to predict how organic matter responds to environmental changes often treat soil C as a homogeneous pool. However, observational evidence, including radiocarbon data, suggests that soil C dynamics are better explained by models that treat soil C as separate pools (or fractions) that cycle on different timescales. These different soil C fractions cycle across a range of timescales (Heckman et al., 2022), and natural abundance radiocarbon (^{14}C) allows us to evaluate timescales ranging from multi-annual to millennial. Combining ^{14}C measurements of C that represent different parts of this age spectrum provides insight into the mechanisms that drive the transformation and persistence of soil C (Ahrens et al., 2015; Lawrence et al., 2020). Given the complexity of soil organic matter, characterizing the age spectra of multiple forms of C, including soil fractions of different physical or chemical properties, interstitial C in soil pores, and C losses through respiration and lateral fluxes, provide critical constraints for testing hypotheses about mechanisms underlying C persistence and models of soil organic matter dynamics.

The production of atmospheric ^{14}C from nuclear weapon testing in the 1950s and 1960s (i.e., 'bomb' ^{14}C) has provided a useful tool for tracing C exchange between the atmosphere and soil C over annual to decadal timescales (Trumbore, 2009). Much of the subsequent decline observed in atmospheric ^{14}C has been due to mixing of this excess 'bomb' ^{14}C into long-term terrestrial and marine C reservoirs. In recent decades, acceleration of fossil fuel burning has become the largest cause of ^{14}C decline in atmospheric CO_2. Since 2020, the ratio of $^{14}C/^{12}C$ of northern hemisphere CO_2 has dropped below pre-industrial levels, such that newly synthesized organic matter has ^{14}C values equal to those last experienced before 1950 (Graven, 2015). With increased access to ^{14}C measurement capabilities and more researchers utilizing ^{14}C, there is a unique opportunity to understand changes in the C cycle over the next decade. There is special value associated with radiocarbon measurements made in reservoirs, such as soils collected in the last 60 years. This opportunity is provided by a coordinated effort to synthesize current and past measurements of soil ^{14}C as part of an overall effort to quantify past and present ^{14}C distributions across Earth's C reservoirs, i.e. an 'International Decade of Radiocarbon' (Eglinton et al., 2023).

Here, we present the second version of the International Soil Radiocarbon Database (ISRaD v2). ISRaD fills a critical gap in soil C research by offering the first open-access, on-going, and comprehensive archive of soil radiocarbon data, with particular emphasis on diverse soil fractions, fluxes, and interstitial measurements (Lawrence et al., 2020). ISRaD is a community-driven effort that continues to evolve in response to the needs and interests of its contributors and user community. In this manuscript, we briefly describe the scientific rationale of the database structure, review scientific insights enabled by ISRaD v1, detail major updates since its initial release, present the geographic and thematic distribution of data in ISRaD v2, and conclude with some proposals of future directions for soil radiocarbon research and synthesis efforts.

2. Scientific rationale for ISRaD's data structure

ISRaD is organized hierarchically around individual datasets (entries; Figure 1a), with data reported at multiple spatial and temporal scales: from site-level geospatial information through profile-level characteristics to layer-specific measurements, individual soil fractions, and observations of fluxes, interstitial samples, and laboratory incubations (Lawrence et al., 2020). This structure accommodates the diversity of radiocarbon measurement methodologies while

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maintaining the capacity for accurate comparison across studies. The ISRaD hierarchical data model incorporates principles established in international soil information standards (e.g., GLOSIS) while extending these frameworks to capture the temporal complexity and isotopic specificity required for radiocarbon measurements. Below, we describe the scientific rationale for this diverse data architecture and how these multiple measurement types contribute to understanding soil C cycling. For more details about the general structure of ISRaD we refer to Lawrence et al. (2020).

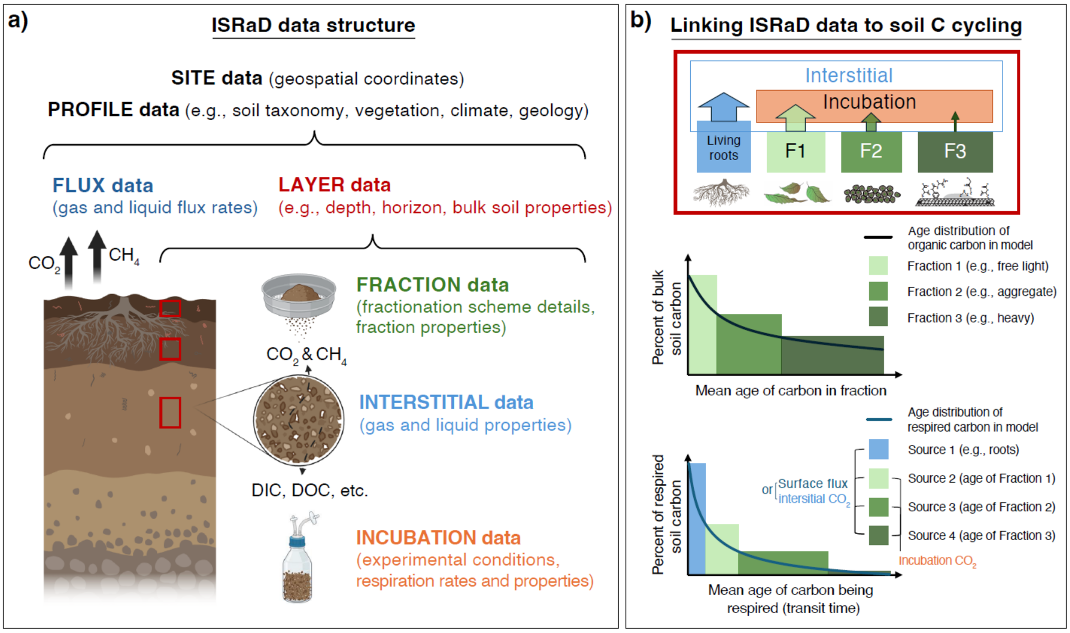

Figure 1: Conceptual figure of a) the data types in ISRaD and b) how these different measures can link to biogeochemical representations of soil carbon cycling. Abbreviations: DIC = dissolved inorganic carbon; DOC = dissolved organic carbon.

One of the primary objectives of initiating ISRaD was to synthesize soil radiocarbon data to improve our understanding of the factors that influence the age and transit time distributions of C in soils. Additionally, this effort aimed to establish benchmarks to evaluate models of soil C dynamics (Sierra et al., 2018). For instance, combining sequential physical, density and chemical isolated fractions of organic matter with increasing ^{14}C ages (Figure 1b) provides information on the timescales associated with different stabilization mechanisms. Multi-pool models of soil C dynamics will also predict age distributions within soil organic matter, which can be compared with the distributions of observed C stocks and radiocarbon-derived ages (Figure 1b). One ongoing area of research is to identify the fractionation schemes that best approximate the pools used for models. Comparisons of the age (or ^{14}C) distributions provide a metric for comparing even for complex model structures (Metzler et al., 2020).

Measurements of ^{14}C being respired or leached from soils provide an estimate of the transit time of C in ecosystems–the time elapsed from C fixation by photosynthesis to its loss by plant respiration, exudation, decomposition, or leaching. Measurements of C emitted from the soil surface (‘flux’), or in soil pore space (‘interstitial’), include contributions from living roots, as well as the decomposition of C pools with faster turnover (Figure 1b). CO_2 respired in soil incubations reflects the age of microbially available C substrates and tends to be younger than the bulk soil C. This is because bulk soil C age is mass-weighted and dominated by larger, slower-cycling fractions, while respired C is weighted by fluxes and dominated by the fastest cycling fractions (Trumbore 2006). Soil C models also predict the distribution of ages in respired C, providing an additional constraint for understanding the dynamics of the faster-cycling soil C fractions (Fekete et al., 2021). Since the radiocarbon signatures of C derived from living-roots (CO_2,

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root exudates) often differ from those derived from microbial decomposition (CO_2, CH_4, or dissolved organic carbon (DOC)), the radiocarbon signature of fluxes that combine these sources (surface fluxes, interstitial C) can be used to partition their relative contributions (Chanton et al., 2008; Cisneros-Dozal et al., 2006; Gaudinski et al., 2000; Phillips et al., 2013; Wilson et al., 2016).

Understanding vertical patterns in soil C age requires measuring C age across multiple soil compartments simultaneously. Approximately 30–60% of the global variation in bulk ^{14}C is explained by systematic aging with depth (Shi et al., 2020; von Fromm et al., 2024). This depth pattern is likely driven by a combination of factors including microbial availability, root density, and differences in decomposition kinetics (Henneron et al., 2022; Sierra et al., 2024). However, multiple processes could influence the age distribution of soil C, such as rates of vertical transport and pre-aging of C litter pools, in addition to simple aging mechanisms..

Understanding these depth-dependent patterns requires diverse measurement approaches. ISRaD archives extensive data from traditional physical and chemical fractionation methods that try to characterize the age structure of bulk organic matter. The new version of ISRaD also incorporates emerging approaches, such as ramped thermal oxidation, which directly link C ages to chemical composition and mineral association (Grant et al., 2019; Stoner et al., 2023). Other resources in ISRaD include data from experimental manipulations, for example how radiocarbon in soil organic matter or respired CO_2 changes with soil warming or nitrogen fertilization (e.g., McFarlane et al., 2024; Nowinski et al., 2009; Qin et al., 2023). An increasing number of the studies in ISRaD deal with manipulations of cropping or pasture management (e.g., González-Sosa et al., 2024; Min et al., 2025; Sanderman et al., 2017; Spohn et al., 2023; Stoner et al., 2021). Collectively, these diverse measurement types enable mechanistic understanding of soil C cycling across spatial and temporal scales, precisely the synthesis opportunity that ISRaD facilitates.

3. Science enabled by ISRaD v1

Since its initial release in 2020, ISRaD has been widely cited and used to enable diverse scientific advances. These advances span quantifying soil C turnover, benchmarking soil models, and identifying depth, mineral, and climate controls on soil C persistence from local to global scales. Studies found that soil C age is strongly depth-dependent. Subsoils contain old C (^{14}C depleted) that has accumulated over centuries to millennia, highlighting the importance of accurately representing deep soil processes in models (e.g., Shi et al., 2020; Sierra et al., 2024; von Fromm et al., 2024; Wang et al., 2024). Nevertheless, soil CO_2 efflux is dominated by young C despite substantial old soil C stocks (Xiao et al., 2022). Studies also found that vertical transport processes influence apparent soil C ages, but their relative importance varies. While advection and bioturbation can significantly shape ^{14}C soil profiles in some regions (e.g., Amundson et al., 2024), the balance between root inputs and C decomposition (mediated by microbial activity) may be equally or more important than physical transport processes in controlling soil C profiles elsewhere (Sierra et al., 2024; Wang et al., 2021). ISRaD data also served as an important model benchmark, suggesting a likely underestimation of SOC persistence in Earth system models. Specifically, comparisons of modeled bulk and fraction ^{14}C values with observations highlight overestimation of ^{14}C content (underestimation of C persistence) in some new-generation soil models and motivate depth-explicit, process-rich, isotope-enabled modeling frameworks (e.g., Brunmayr et al., 2024; Chen et al., 2019). Studies using ISRaD also supported the existing hypothesis that climate and soil properties jointly regulate SOC persistence, albeit with noticeable and important regional differences (e.g., Chai et al., 2023; Huang et al., 2023; von Fromm et al., 2023, 2024; Wang et al., 2023). ISRaD enabled an analysis of global patterns of C accumulation in tropical peatlands (Hedgpeth, 2024), which are among the Earth's most C-dense ecosystems (Winton et al., 2025). Fraction-resolved ^{14}C indicated that mineral-associated organic matter and particulate organic matter have distinct C ages, turnover rates, and environmental sensitivities (e.g., Hansen et al., 2024; Heckman et al., 2022; Jia et al., 2023; Li et al., 2023). Recent studies also demonstrate that geogenic C from sedimentary parent materials (e.g., kerogen, lignite) can contribute to ^{14}C depletion and should be considered when interpreting soil radiocarbon (e.g., Copard et al., 2025; Grant et al., 2023; Williams & Lawrence, 2025). Taken as a whole, these studies comprise a substantial increase in our understanding of soil C dynamics, illustrating the power of ISRaD v1 to enable new and innovative science.

Beyond these scientific advances, ISRaD also facilitated community development around soil research. ISRaD users and developers meet regularly both virtually and at international conferences to discuss research and data priorities, with particular focus on advancing land surface modeling through radiocarbon constraints and isotope-enabled frameworks (e.g., Billings et al., 2021; Camino-Serrano et al., 2019; Cotrufo & Lavallee, 2022; Derrien et al., 2023; Doetterl et al., 2025; Frischknecht et al., 2022; MacBean et al., 2022; Malhotra et al., 2019; Raoult et al., 2024; Riley et al., 2022; Todd-Brown et al., 2022; Van de Broek et al., 2025; Vickery et al., 2025). Various soil-related data syntheses cite ISRaD as a key reference for good data practices (e.g., Bond-Lamberty et al., 2020; Crystal-Ornelas et al., 2022; Fujisaki et al., 2023; Ke et al., 2022; Malhotra et al., 2019; Schädel et al., 2020; van der Voort et al., 2021; Wieder et al., 2021). Many of the science lessons enabled by ISRaD have contributed to a more nuanced understanding of the potential caveats and pitfalls of using soil radiocarbon to better understand soil C dynamics. ISRaD v2 will further deepen these insights with its expanded data coverage.

4. Major structural updates since ISRaD v1

The first version of ISRaD (v1) was released in 2020 (Lawrence et al., 2020). Since then, substantial growth in community contributions and improvements to the database have motivated the release of ISRaD v2. The most recent version of ISRaD incorporates 186 new unique studies, expanding the database by more than half, from 329 to 515 entries (Table 1). Data increased substantially across all hierarchical levels, with particularly large growth in bulk layer (+143%) and fraction data (+96%), reflecting the growing emphasis on understanding soil C dynamics at depth and across different C pools. Geographically and ecosystemically, the expanded dataset now provides improved representation across major climate zones, soil orders, and land-cover types, with notable growth in understudied ecosystems including wetlands. This growth underscores the increasing importance of radiocarbon as a tool for constraining soil C dynamics. Additionally, it reflects the critical need for a centralized, open-access database that standardizes and facilitates comparison of radiocarbon measurements across diverse methodologies and spatial scales. In the following sections, we will highlight some of the major updates since the initial release of ISRaD.

Table 1: Number of data points included at each hierarchical level in ISRaD v1.2.3.2019-12-20 and ISRaD v2.9.9.2025-08-14. Note: Not every entry has radiocarbon measurements.

	Entries	Sites	Profiles	Fluxes	Layers	Interstitial	Fractions	Incubations
ISRaD v1	329	807	2,530	3,923	17,242	835	4,266	2,203
ISRaD v2	515	1,669	5,531	4,597	41,823	1,219	8,351	3,002

4.1. Improvements in the representation of different soil fractionation schemes

Methods for partitioning bulk soil into distinct parts, or fractions, are fundamental to radiocarbon-based quantification of soil C age and transit time distributions (Trumbore et al., 2009). While soil incubations warrant a separate structure within ISRaD due to their unique temporal dynamics, most other soil fractionation methods are recorded in the fraction table. The broad diversity of methods used for soil fractionations, as well as subtle variations in the implementation of specific methods, complicate inter-study comparisons and were one of the primary reasons for initiation of the ISRaD database. During analysis of synthesized fraction data in ISRaD v1 (Heckman et al., 2022), we became aware that the initial template structure could not adequately capture the various fractionation schemes used in soil science. This motivated us to restructure the fraction table in v2 to better capture the specifics of different soil fractionation techniques, as well as to make data entry and analysis more consistent.

The updated template for entering fraction data includes two new mandatory fields, frc_aba and frc_aggregate_dis, to record information about macrofossil pretreatment (e.g., acid-base-acid) and aggregate dispersion, respectively. Controlled values available for selection in the fractionation scheme (frc_scheme), agent (frc_agent), and property

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(frc_property) fields were also expanded and reorganized. Accepted fractionation approaches now fall into one of the following schemes: density, particle size, aggregate, chemical, physical (other), thermal, and compound-specific methods. This expansion enables capture of emerging techniques such as ramped thermal oxidation and compound-specific radiocarbon analysis, which were not represented in ISRaD v1.

In concert with these changes, the ISRaD template has been updated to incorporate dynamic lists to aid in selection of fractionation details. Through this approach, only fractionation agents and properties that correspond with the selected fractionation scheme are available for selection. This should minimize confusion and encourage consistency in the reporting of fractionation data. As before, additional controlled values can be added to capture novel fractionation methods that are not currently available.

All fraction data ingested into the ISRaD database prior to implementation of these changes has been manually inspected and updated for consistency with the revised template structure. More detailed information about how to enter soil radiocarbon fraction data is provided on the ISRaD website (https://www.soilradiocarbon.org/).

4.2. Improved accessibility of the database

ISRaD's primary objective is twofold: to serve as a central repository for soil radiocarbon data and to equip users with the tools necessary to analyze the data they collect. To this end, ISRaD offers a comprehensive R package and tutorials, as well as a website that provides valuable information on the database and on soil radiocarbon in general. The R package was first publicly released in 2020 and has since been updated and improved iteratively (Beem-Miller et al., 2025). All data and code can also be found in the ISRaD GitHub repository (https://github.com/International-Soil-Radiocarbon-Database/ISRaD) The ISRaD website has been completely redesigned (https://www.soilradiocarbon.org/) and includes links to an updated R tutorial to help first-time users get started analyzing ISRaD data (https://www.soilradiocarbon.org/user-manual). Additionally, we have developed an interactive data portal (R ShinyApp) that allows users to explore the database online, and to filter and download targeted data directly (https://www.soilradiocarbon.org/integrated-interactive). In the future, we aim to increase the amount of soil radiocarbon information to assist those less familiar with the nomenclature and use of soil radiocarbon data.

4.3. Governance and community involvement

ISRaD operates as a community-driven initiative, currently without dedicated funding or formal governance structures. Instead of adhering to pyramid-style governance outlined in the initial ISRaD release (Lawrence et al., 2020), ISRaD v2 evolved organically through contributions from the international soil radiocarbon research community. This approach reflects how open-source, collaborative scientific databases often function in practice. The ISRaD GitHub repository and associated resources are currently maintained by a dedicated group of contributors from the authoring team and broader community. Major decisions regarding database structure, new data types, or template modifications are made collaboratively through GitHub discussions, during regular self-funded workshops, and are informed by community feedback and emerging research needs.

While this community-driven approach has proven effective for fostering engagement and rapid development, it does present some challenges. For example, the reliance on volunteer efforts and self-funded workshops means that critical maintenance tasks or major infrastructure improvements may be delayed if community capacity is limited. We recognize that securing stable institutional or funding partnerships would strengthen the database's long-term capacity to serve the growing research community.

Anyone wishing to contribute data, suggest improvements, report issues, or participate in database development is encouraged to reach out directly to any member of the authoring team or post issues on the ISRaD GitHub repository (https://github.com/International-Soil-Radiocarbon-Database/ISRaD). ISRaD's continuous growth over the past five years demonstrates the value of community-maintained open-source databases for synthesizing scientific data. This flexible approach has facilitated the substantial growth in data and community engagement since ISRaD v1 was

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released in 2020. To ensure continued evolution and maintenance of ISRaD, we encourage the community to contribute not only data but also technical expertise, funding support, and institutional support as available.

5. Major data updates since ISRaD v1

The geospatial distribution of all data types in ISRaD v2 reveals substantial variation across climate zones, land-cover types, and soil orders (Figure 2). Across climate zones (Figure 2a), arid environments (B climate zones) consistently represent the smallest percentage of observations (1–7%) within each data type, while cold climates (D climate zones) dominate most data types (34–74%). Flux measurements are particularly skewed toward cold regions (D and E climate zones: 88%). The database exhibits a strong bias toward forest ecosystems, comprising approximately 43% of observations across all data types (Figure 2b). In contrast, bare and urban soils remain critically undersampled. Cultivated soils (2–7%) and shrublands (2–9%) are also underrepresented across most data types, though cultivated soils account for 12% of bulk layer data. Certain land-cover types show pronounced biases within specific data types. For example, wetlands constitute 22% of interstitial data but only 8% of incubation data. Tundra represents 32% of flux measurements but merely 3% of bulk layer data. Range-/grasslands comprise 18% of bulk layer observations yet only 5% of interstitial data.

Soil order representation mirrors the above-described climate-related patterns, with Aridisols being among the least sampled soils in the database (Figure 2c). Interstitial and flux data are particularly limited, with observations being heavily dominated by Gelisols (63% and 76%, respectively) and many soil orders lack any records in these categories. Incubation data likewise concentrate on Gelisols (40%), followed by Inceptisols (20%), with the latter being the most represented soil order in both bulk layer (13%) and fraction (17%) data. Temporally, the database shows limited observations prior to 1985, with the vast majority of data collected in the past two decades (Figure S1). This trend is also reflected in increased soil radiocarbon research activities (Figure S2).

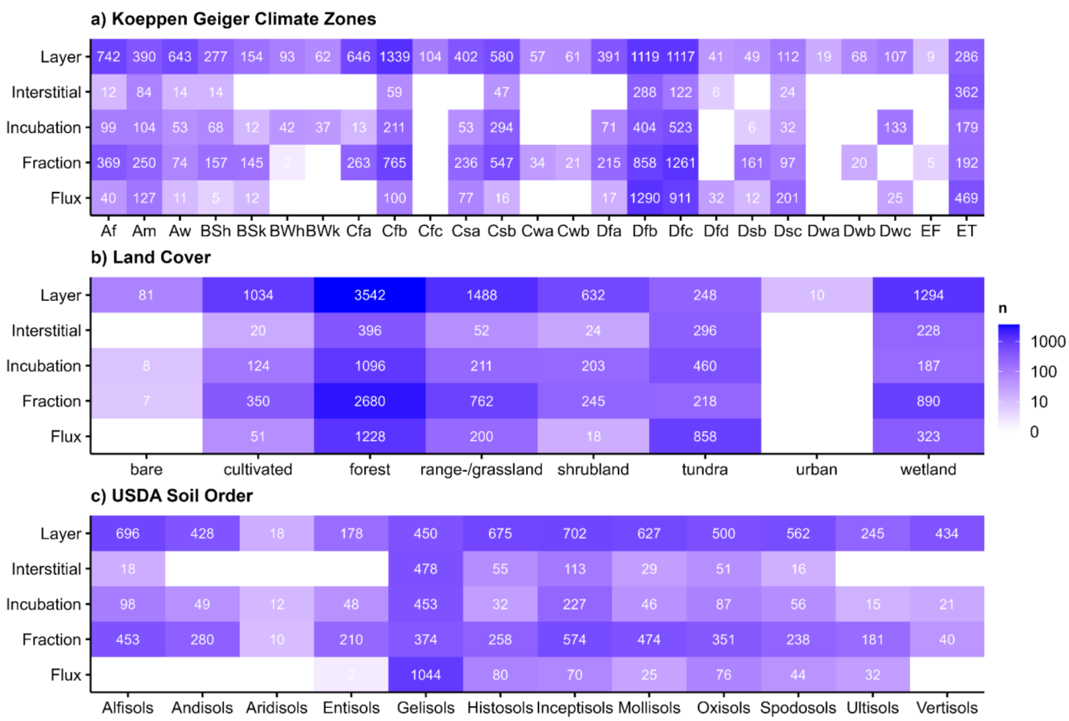

Figure 2: Total number of ^{14}C observations by data type and a) Koeppen-Geiger Climate Zones (after Beck et al., 2023; key for each climate zone code can be found in Table S1). Capital letters indicate the main climate zone: A - tropical, B -

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arid, C - temperate, D - cold, E - polar. b) by land cover (as reported in original studies; excluding NA's). c) by USDA soil order (as reported in original studies; excluding NA's).

5.1. Bulk layer

Bulk layer data correspond to measurements made for a specific depth increment collected from a soil profile as described in more detail in Lawrence et al. (2020). Since the initial release of ISRaD, the updated template for entering bulk layer data has four more columns that allow the user to specify if a buried organic horizon was sampled, the International Geo Sample Number (IGSN), the density of the coarse fraction, and to specify if the sample is the basal layer of a peat profile. The number of bulk layer data has increased by about 143%, totalling 41,823 observations from 479 unique studies, from 1,549 different sites, and 4,935 individual profiles. This makes the bulk layer measurements by far the most common data type in ISRaD. Most of these samples have been collected from topsoils in temperate and cold climate zones (Figure 3).

The vertical distribution of bulk layer ^{14}C measurements reveals strong sampling biases towards surface mineral horizons (Figures 3b, 4a). Approximately 60% of all ^{14}C measurements come from the upper 30 cm of soil, with data density declining exponentially with depth and for surface litter layers. Despite the critical importance of subsoils for long-term C storage and contribution to global SOC stocks (Jobbágy & Jackson, 2000), deep soil horizons (>100 cm) remain severely undersampled across all climate zones, soil orders, and land-cover types (Figures 3c, S3, S4). This sampling bias is particularly problematic given that bulk soil $\Delta\Delta^{14}$C values (i.e., measured - atmospheric Δ^{14}C) show the greatest depletion (oldest ages) and widest variability below 50 cm depth (Figure 4a), highlighting the need to expand deep soil sampling to better constrain estimates of C persistence and vulnerability (Hicks Pries et al., 2023).

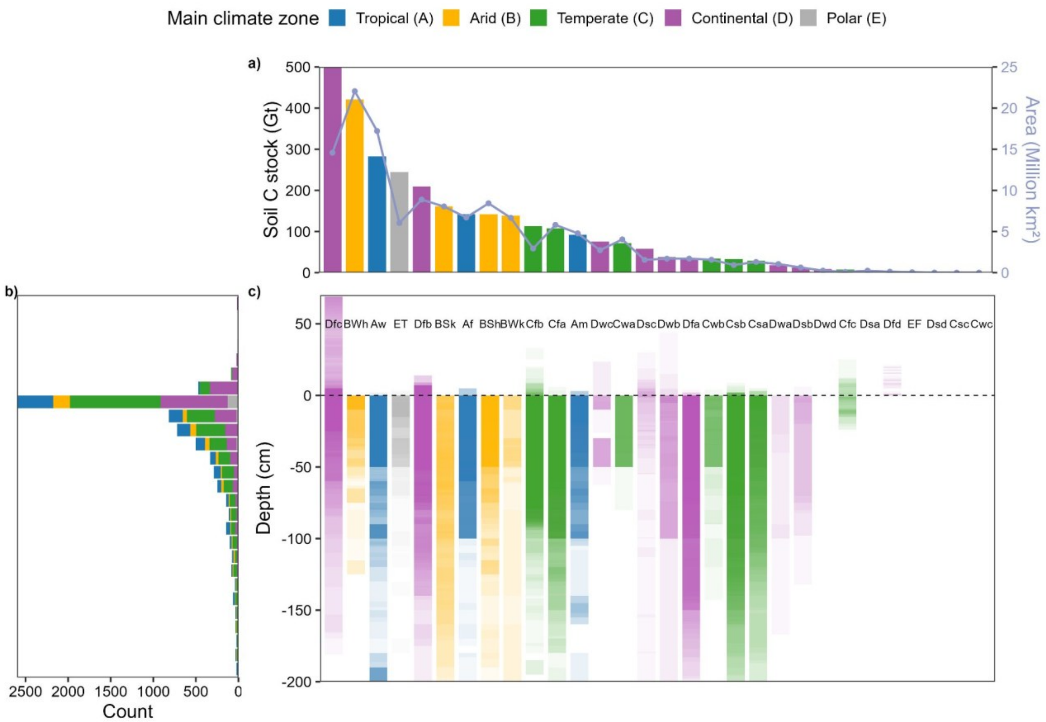

Figure 3: a) Area-weighted total soil organic carbon stocks down to 200 cm (SoilGrids 2.0; Poggio et al. 2021) for each Koeppen-Geiger Climate Zone (Beck et al., 2023; key for each climate zone code can be found in Table S1) and total land area (excluding ice) covered by each climate zone; b) Number of bulk soil radiocarbon measurements for each 0.1 m depth interval; c) Data distribution of bulk soil radiocarbon measurements with depth (limited to 200 cm and excluding wetlands

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and peatlands; positive depth values refer to litter layers above the mineral soil) across each Koeppen-Geiger Climate Zone (code for each climate zone is shown above each bar). The darker the color, the more data points are present in a given depth range. Colors in each panel refer to the main climate zones as indicated by the capital letter.

Climate-specific patterns reveal substantial heterogeneity in both sampling intensity and depth coverage (Figure 3). Bulk layer ^{14}C measurements in temperate (C) and cold (D) climate zones dominate, collectively accounting for approximately 72% of all layer observations. These zones also show the most comprehensive depth profiles, with measurements extending to 200 cm (Figure 3c). In contrast, tropical (A) and arid (B) climates are underrepresented, together comprising about 26% of observations despite storing substantial SOC stocks globally (Figure 3a). Tropical regions show moderate sampling in surface layers but minimal deep (>50 cm) soil coverage, while arid systems lack comprehensive depth profiles entirely. Polar (E) climate zones are the least represented, accounting for less than 3% of all layer ^{14}C data. These climate-related sampling biases in layer ^{14}C measurements are mirrored in soil order representation, with Aridisols accounting for less than 1% of observations despite covering ~12% of global land area, and tropical Ultisols and Oxisols showing particularly poor deep soil coverage (Figure S3). Similarly, land cover analysis demonstrates extreme bias toward forested ecosystems (~51% of observations), while cultivated soils represent only ~15% of layer ^{14}C data and urban soils remain essentially absent (Figures S4). When accounting for both land area and SOC stocks (Figure 3a), the underrepresentation of tropical and arid systems, along with cultivated and degraded lands, represents critical gaps that limit our ability to understand C dynamics in regions experiencing rapid climate and land-use change.

5.2. Incubation

Incubation data include C gas production rates (CO_2 or CH_4) and C isotopic signatures of laboratory-incubated samples as described in more detail in Lawrence et al. (2020). Since the initial release of ISRaD, the updated template for entering incubation data has two more columns that allow the user to specify the incubation analyte (CO_2 or CH_4) and if the incubation was performed under anaerobic conditions. The number of incubation data has increased by about 36%, totalling 3,002 observations, from 79 unique studies, 273 different sites, and 896 individual profiles. So far, of the reported incubation ^{14}C measurements (n = 2,334), zero have CH_4 reported as an analyte. The majority of ^{14}C measurements from incubations have been carried out on 'root-picked soils' (n = 1,333), followed by 'soils with dead roots' (n = 601), 'litter' (n = 174), 'live roots only' (n = 116), and 'soils with live roots' (n = 110). Given this data distribution, we will highlight some insights based on incubated 'root-picked soils'.

The majority of the incubated 'root-picked soil' samples exhibit relatively fast C cycling, albeit with a strong depth trend: incubated soils from deeper depths tend to release slower-cycling C (Figure 4b). Since C fluxes from incubated 'root-picked soil' samples are dominated by microbially derived C, this suggests that the C age of the substrate increases with depth. However, interpreting incubation ^{14}C data requires careful consideration of multiple factors. First, it is unclear how much the measured ^{14}C fluxes are influenced by methodological differences (e.g., incubation duration, temperature, moisture conditions), which vary substantially across studies in ISRaD (Beem-Miller et al., 2021). Systematic comparison of these methodological variations would strengthen our ability to draw robust conclusions about the age of microbially-derived C from incubation data. Additionally, incubation-derived $^{14}CO_2$ measurements may be influenced by inorganic C sources from carbonates, particularly in soils derived from calcareous parent materials or in systems receiving carbonate amendments (e.g., limed agricultural soils). Co-measurement of $^{13}CO_2$ alongside $^{14}CO_2$ can help identify and quantify inorganic C contributions to respired CO_2 fluxes.

In terms of data coverage, 28% and 9% of the incubated 'root-picked soil' samples are from Gelisols and Inceptisols, respectively. For 43% of the incubations, the soil type was not reported. Additionally, 48% and 30% of the data are from forest and tundra ecosystems, respectively. Furthermore, 49% and 22% of the data are from cold climate zones with no dry season (Dfa, Dfb, and Dfc) and temperate climate zones with dry summers (Csa, Csb, and Csc), respectively. More data from other soil types, land covers (including wetlands), and climate zones are needed to draw

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robust conclusions at larger scales (Figure 2). In addition, to improve our understanding of actively cycling C, more depth-resolved data of incubated 'living roots' or 'soils with living roots' are needed, as they are currently limited to a few studies and only down to 20 cm.

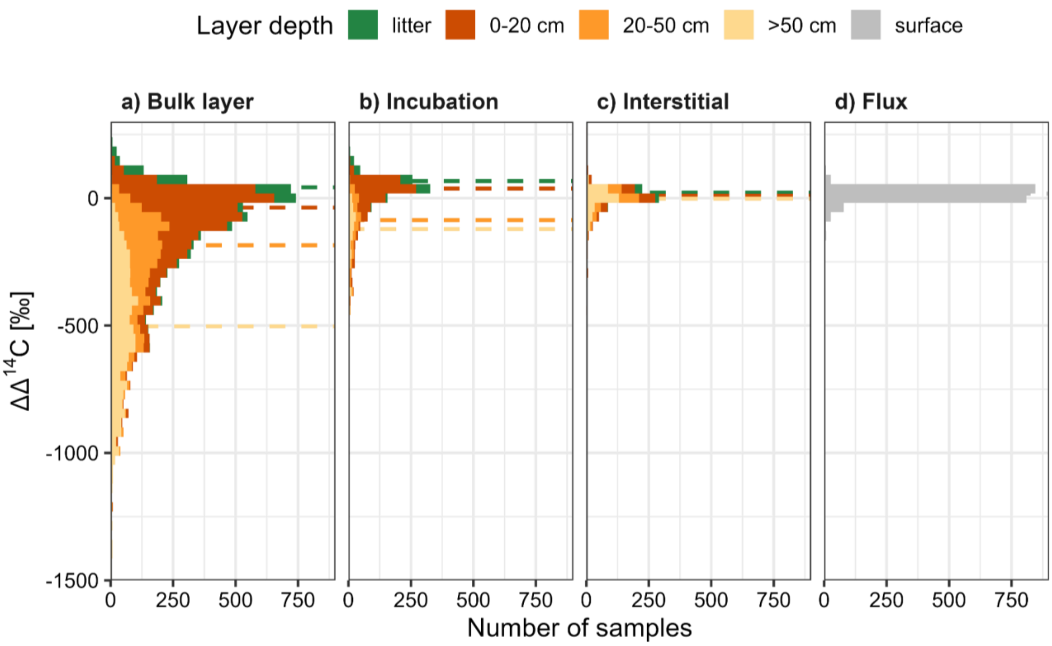

Figure 4: All $\Delta\Delta^{14}C$ (measured - atmospheric $\Delta^{14}C$) measurements for a) layer data, b) incubation data from 'root-picked soil', c) interstitial data of CO_2, and d) soil flux data of ecosystem CO_2 soil emissions. Dashed lines refer to median values. Peatland and wetland studies are excluded.

5.3. Interstitial data

Interstitial data (CO_2, CH_4, dissolved inorganic C (DIC), DOC, or particulate organic carbon (POC)) refer to measurements made on material (gas, liquid, or frozen) occupying the interstices of the soil structure, as described in more detail in ISRaD v1 (Lawrence et al., 2020). Since the first release of ISRaD, the updated template for entering interstitial data contains two new columns that allow the user to enter other stable isotope measurements in addition to $\delta^{13}C$, namely $\delta^{18}O$ and $\delta^{2}H$. The number of interstitial data has increased by about 46%, totaling 1,219 observations, from 34 individual studies, 59 unique sites and 136 different profiles. The vast majority of entered ^{14}C interstitial data are CO_2 measurements (n = 820), followed by DOC (n = 159), CH_4 (n = 70), and POC (n = 6). Thus, we will highlight some insights based on CO_2 measurements and provide suggestions for future sampling efforts.

Measurements of interstitial $^{14}CO_2$ in mineral soils indicate that the majority of gaseous C in soil pores cycles on timescales of years to a few decades, independent of sampling depth (Figure 4c). This suggests that interstitial CO_2 data are a mix of much younger root respiration mixed with microbial decomposition of other organic matter that supplies the CO_2 released in incubations (Figure 4b). Future work should further investigate the source of interstitial CO_2 throughout a soil profile by combining radiocarbon with stable isotope measurements. It is important to note that current ^{14}C data from interstitial CO_2 are limited in their coverage of climate zones, ecosystems, and different soil types. Most data originate from forest (45%) and tundra (36%) ecosystems and the majority were collected in cold climate zones with no dry season (Dfb, Dfc, Dfd; 42%) and polar climate zones (ET; 34%). In addition, the diversity of soil types represented is limited: 44% of the measurements come from Gelisols, 14% from Inceptisols, and 27% are not classified. This indicates that broader and more diverse data coverage is needed to draw robust conclusions at larger

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spatial scales (Figure 2). In addition, to improve our understanding of the timescales of C transport and mobilization through a profile, more depth-resolved DOC and POC data is urgently needed. This sampling effort should also be extended to wetlands, where radiocarbon measures of interstitial C may be used to interpret changes in soil C cycling with climatic or land-use changes (Wilson et al., 2021), or to understand the age of laterally transported C (Bowen, Hoyt, et al., 2024). Finally, future work could also further investigate how interstitial ^{14}C data compare with other soil ^{14}C measurements to provide a more holistic understanding of the different rates of soil C cycling.

5.4. Flux data

Flux data refer to temporally explicit measurements of mass or energy transfer occurring at the profile scale. These measurements include both gas (e.g., CO_2 or CH_4) and liquid (e.g., DIC, DOC, or POC) analytes. The definition of flux data is described in more detail in ISRaD v1 (Lawrence et al., 2020). Since the initial release of ISRaD, the updated template for entering flux data has six new columns. These new columns allow users to enter flux analyte concentrations, flux analyte discharge rates, flux analyte pH, and conductivity (if aquatic). Users can also enter additional stable isotope measurements of $\delta^{18}O$ and $\delta^{2}H$. The number of flux data has increased by about 17%, totaling 4,597 observations from 79 individual studies, 163 unique sites, and 587 different profiles. The vast majority of the entered ^{14}C flux data are CO_2 measurements (n = 2,894), followed by lateral DOC (n = 251), CH_4 (n = 167), and lateral POC (n = 44) analytes. The distribution of the most common flux analytes is also reflected in the most abundant flux pathways, including 'soil emission' (n = 2,694), 'bubble ebullition' (n = 272), 'dissolved' (n = 251) and 'suspended' (n = 44). The ecosystem components most represented by flux measurements are 'ecosystems' respiration (i.e., net fluxes from soils; n = 1,972), 'heterotrophic' respiration (n = 544), and 'aquatic' (n = 299). Given this data distribution, we will highlight insights based on CO_2 fluxes representing net ecosystem soil emissions (n = 1,962).

The majority of ecosystem CO_2 soil emission fluxes cycles on fast timescales (years to a few decades; Figure 4d). This suggests that ecosystem CO_2 soil emission flux data are most likely dominated by C that has recently entered the soil system, reflecting a combination of root-respired and decomposition derived C. Comparison of the ^{14}C in CO_2 in surface soil respiration and soil pore spaces to its component sources can be used to partition soil respiration into younger and older C sources (Chanton et al., 2008; Gaudinski et al., 2000; Taylor et al., 2015; Trumbore, 2006). These component sources include recently fixed C from root respiration and decomposed organic matter that is often fixed years to decades earlier. Changes in the age of respiration sources can indicate disturbances that destabilize older C and make it available for decomposition, for example as a result of thawing permafrost (Estop-Aragonés et al., 2020; Schuur et al., 2023), deforestation and conversion to agriculture (Drake et al., 2019; Minich et al., 2025), peatland drainage and fires (Bowen, Hoyt, et al., 2024; Wiggins et al., 2018), or changes in snow cover (Lupascu et al., 2018; Pedron et al., 2023).

It is important to note that about 23% of the current ecosystem $^{14}CO_2$ soil emission measurements in ISRaD are from Gelisols, while 67% of the measurements have no soil type reported. In addition, 52% and 23% of the data are from forest and tundra ecosystems, respectively, and about 89% are from cold climate zones with no dry season (Dfa, Dfb, and Dfc). More data from other soil types, land covers, climate zones and ecosystem components are needed to draw robust conclusions at larger scales (Figure 2). In addition, to improve our understanding of the timescales of C fluxes across ecosystems, seasonally resolved data, CH_4 fluxes from wet soils, as well as DIC, DOC and POC data from aquatic systems (e.g., wetlands and peatlands) are urgently needed. Finally, future work could also investigate how C fluxes are related to the ratio of particulate organic matter to mineral-associated matter fractions, as well as how the age of upland C fluxes compares to wetland C fluxes.

5.5. Fraction data

Since its initial release, the fraction data template in ISRaD has been updated and is now designed to accommodate the wide range of methodologies used to partition soils into discrete fractions and allow for fair comparison (see Section

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4.1). The number of fraction data has increased by approximately 96%, totaling 8,351 observations from 218 individual studies, 481 unique sites, and 1,324 different profiles. The majority of fraction data are from density separations (n = 3,991), followed by physical separation of distinct particles such as macrofossils, charcoal or roots (n = 1,849), chemical separations (n = 1,446), and particle size fractions (n = 850). More narrowly applied fractionation schemes include thermal fractionation (n = 315), separation by aggregate classes (n = 162), and compound-specific analyses which currently include lipids only (n = 64).

The currently compiled fraction data suggest significant variation among fractionation schemes regarding their efficacy in separating pools of contrasting ^{14}C concentration (Figure 5). Density fractionation has historically been the most commonly employed approach, reflected in the much higher number of these fractions in ISRaD (n = 3,991). Particle-size and chemical fractionation schemes seemingly yield fractions with greater ^{14}C heterogeneity. These operationally-defined separations, particularly density fractionation (which isolates heavy from light fractions) and particle size fractionation (which isolates coarse from fine fractions), are increasingly being interpreted as isolating mineral-associated and particulate organic matter pools (Heckman et al., 2022; Lavallee et al., 2020; Leuthold et al., 2024). ISRaD data reveal substantial variation in C ages within these conceptual pools, with many mineral-associated fractions exhibiting young ^{14}C signatures, suggesting these pools contain significant proportions of actively cycling C (Feng et al., 2016; Jilling et al., 2025; Leuthold et al., 2024).

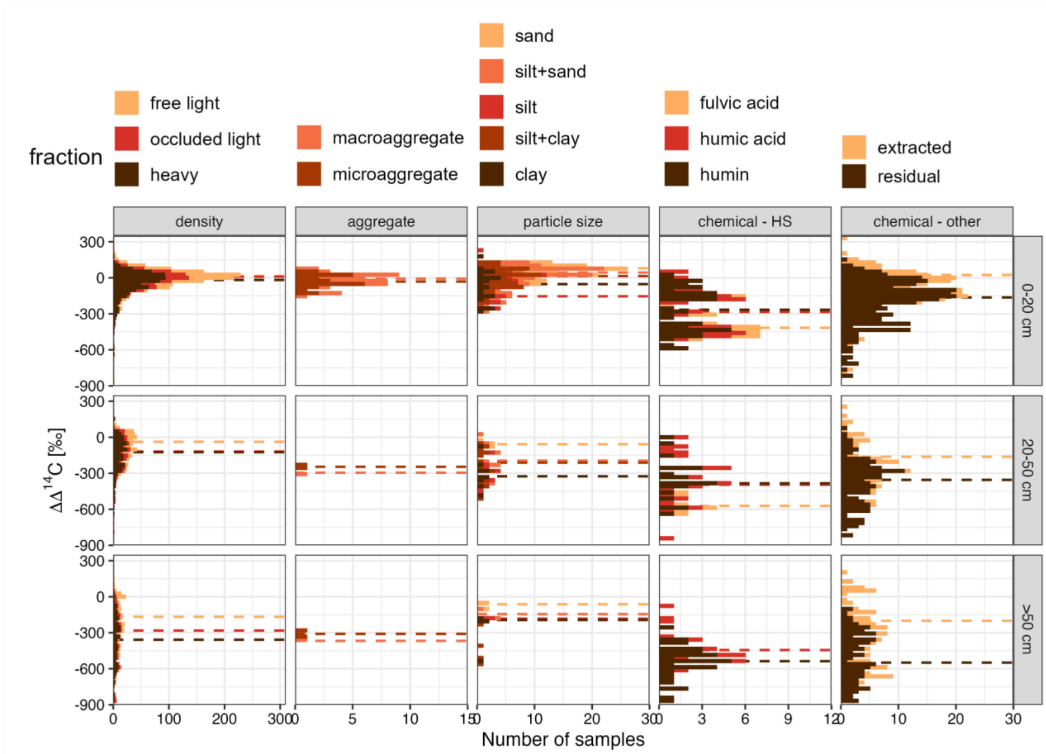

Figure 5: $\Delta\Delta^{14}C$ (measured - atmospheric $\Delta^{14}C$) measurements for selected types of fraction data from different depths. Dashed lines refer to median values. Peatland and wetland studies are excluded. HS = humic substances. Note the different scales for the x-axes.

Chemical fractionations, based on solubility or other chemical properties, also effectively separate C into pools of contrasting ^{14}C ages (Figure 5; Heckman et al., 2018; Martel & Paul, 1974; Paul et al., 1997, 2001; Yanai et al., 2024). However, the mechanistic basis for these separations remains unclear, and the resulting pools do not map directly onto

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the persistence mechanisms central to soil C modeling. Thermal fractionation, represented by a smaller but growing number of ISRaD datasets (n = 315), shows promise for distinguishing thermally labile versus stable pools, highlighting potential directions for future methodological development (Grant et al., 2019; Stoner et al., 2023). Overall, ISRaD data underscore that fractionation approaches each capture distinct aspects of soil C cycling; the choice of fractionation method reflects both scientific objectives and assumptions about soil C persistence mechanisms.

The diversity of fractionation approaches in ISRaD creates both opportunity and challenge. Investigating soil fractions aids in interpreting bulk soil data given the underlying heterogeneity of soil C. On one hand, having multiple fractionation methods applied to the same soils and profiles enables comparison of what each method reveals about C age structure. On the other hand, the lack of standardized fractionation protocols complicates cross-study synthesis. Nevertheless, connecting operationally-defined fractions with conceptually-defined pools in soil C models provides important constraints that can help refine models and minimize parameter equifinality (Ahrens et al., 2020; Brunmayr et al., 2024; Van de Broek et al., 2025).

Despite substantial growth in fraction data since ISRaD v1, important gaps remain. An underexplored question is whether different fractionation approaches preferentially isolate plant-derived versus microbial-derived soil C components. Additionally, the mechanistic basis for chemical fractionations remains poorly characterized in the radiocarbon literature. These gaps represent important opportunities for future data collection and synthesis through ISRaD. More broadly, ISRaD's expanded fraction database demonstrates both the power and the limitation of current fractionation approaches: while diverse methods reveal the complexity of soil C age structure, the continued lack of consensus on 'best-practice' fractionation highlights fundamental questions about which soil C characteristics are most relevant to understanding ecosystem-scale C cycling and climate feedbacks.

5.6. Wetlands

Wetlands are important components of the global terrestrial C system. They store 520–710 Pg of soil organic C (Poulter et al., 2021), which is roughly one-third of the global soil organic C pool. This C storage occurs on just 6% of the land surface (Stewart et al., 2024). Of the different types of wetlands, peatlands store twice as much C than that of global forests (~350 Pg of soil organic C; Dargie et al., 2017; Hugelius et al., 2020), while coastal wetlands, including mangroves and salt marshes, store approximately 2.73–9.75 Pg of soil organic C globally (Macreadie et al., 2021). Historically, radiocarbon measurements in wetlands have had paleoecological applications (e.g., MacDonald et al., 2006). More recently, radiocarbon has become a key tool to investigate mechanisms of soil C accumulation and avenues of soil C loss (Bowen, Hoyt, et al., 2024; Cooray et al., 2025; Hamada et al., 2024, 2025; Maher et al., 2017). Despite the importance of wetlands and the increase of wetland studies using radiocarbon measurements, the v1 database contained disproportionately low amounts of ^{14}C data from wetland ecosystems (Lawrence et al., 2020; Figure 6).

To address this in v2, we have added more data from wetlands compared to v1, especially from peatlands, saltmarshes and mangroves. These wetlands now account for one-third of all entered studies in ISRaD. Currently, the ISRaD data template includes wetland as a category of land cover, with a separate column dedicated to the presence of peat. This column designates peatland sites and tracks whether organic horizons are present. Users should note that peatland designation adopts author-reported nomenclature and that depth reporting conventions differ between systems with superficial organic layers (negative depths) and thick organic-dominated soils (organic horizons at zero depth). Detailed guidance for interpreting wetland data metadata is available on the ISRaD website.

The largest category of data from wetland soils is in the layer data with 128 individual studies covering 215 unique sites and 512 different profiles (Figure 6). The next largest category for wetland soils is the fraction data, which has 91 individual studies covering 149 unique sites, and 325 different profiles. The majority of the fraction data are from physical separation of distinct particles such as macrofossils (i.e., pollens), charcoal, roots, or non-root plant material (n = 1,023), followed by density separations (n = 93), particle size fractions (n = 81), chemical separations (n = 78),

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and very narrowly applied fractionation schemes of thermal fractionation (n = 10) and compound specific analyses that only include lipids (n = 6). ISRaD wetland data reflect important methodological considerations. Among fraction data, macrofossil separations dominate, followed by density fractions, suggesting researcher preference for these approaches in wetland ecosystems. This distribution likely reflects recognized challenges: bulk ^{14}C analysis has limitations in wetlands due to mixed C sources with varying turnover times (Komada et al., 2022; Sefton et al., 2022), while macrofossils in peatlands provide more reliable paleoenvironmental records compared to bulk material which may represent inputs spanning centuries (Holmquist et al., 2016; Monacci et al., 2009; Woodroffe, Long, Milne, et al., 2015; Wüst et al., 2008). Notably, density fractionation has shown greater success than particle-size fractionation for resolving different C sources in coastal wetlands, which may explain the relative abundance of density-separated samples in ISRaD (Hamada et al., 2024, 2025; Kemp et al., 2019; Komada et al., 2022; Sefton et al., 2022; Van de Broek et al., 2018; Woodroffe, Long, Punwong, et al., 2015).

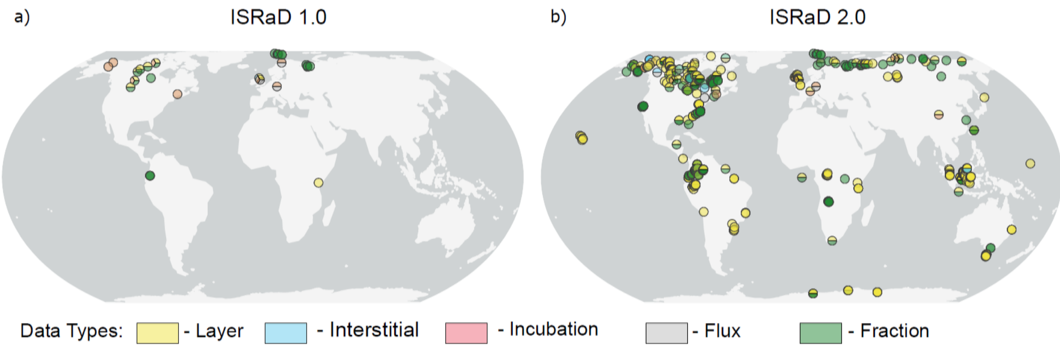

Figure 6. Geographical location of all wetland samples (pro_land_cover == "wetland" or pro_peatland == "yes") in ISRaD v1.2.3.2019-12-20 and v2.9.9.2025-08-14 colored by data types

Given that many wetlands have faced extensive management and land-use changes, there has been a growing number of studies collecting flux and interstitial radiocarbon data to understand wetland responses to disturbance and to restoration efforts (Bowen, Hoyt, et al., 2024; Houston et al., 2024; Van de Broek et al., 2018; Wang et al., 2021). Yet, despite these efforts, flux, incubation, and interstitial data remain low in abundance for wetland soils in ISRaD, covering 68, 60, and 35 different profiles, respectively, each with less than 15 individual studies and less than 20 unique sites. For example, for incubation data, there are currently only three studies in peatlands that utilize radiocarbon and only one study in coastal wetland ecosystems, the latter which had results following findings from other ecosystems that young soil C is preferentially respired over aged soil C (Houston et al., 2024). For flux data, nearly all correspond to soil fluxes of CO_2 or CH_4. With the close proximity of coastal wetlands to the ocean and the loss of coastal wetlands to anthropogenic disturbance and sea-level rise, there has also been increased use of radiocarbon to understand the lateral fluxes of dissolved organic and inorganic C (Bowen, Wahyudio, et al., 2024; Maher et al., 2017; Nakamura et al., 2025). Because ISRaD now includes DOC and DIC in the column designating the species for the flux measured, future efforts should focus on integrating aquatic radiocarbon datasets (e.g., Dean et al., 2025; Marwick et al., 2015) into ISRaD.

6. Database availability and user guidelines

As detailed above, ISRaD is an open-source project that provides several ways for participation. ISRaD v2 data (Beem-Miller et al., 2025) are archived and freely available at https://zenodo.org/records/17860507. Anyone may share or adapt the ISRaD dataset, provided they do so in accordance with the Creative Commons Attribution 4.0 International Public License (https://creativecommons.org/licenses/by/4.0/legalcode, last access: 26 November 2025), also referred to as CC BY. In addition, we strongly encourage ISRaD users to follow two simple guidelines for use:

i. When utilizing the resources provided by ISRaD, including the complete dataset, individually curated entries, or value-added calculations included in the R-package, users should cite this publication, the R package, and reference the version of ISRaD that was used for their work. Additionally, if users leverage individual data entries from the database, they should also cite the original source dataset and/or paper.

ii. When users interpret their own data in the context of data accessed from ISRaD, they should submit those new data for inclusion in ISRaD after they have published their results and/or obtained a DOI for their dataset.

7. Conclusion and Future Directions

The International Soil Radiocarbon Database has evolved into an important resource for understanding soil C dynamics across spatial and temporal scales. Since its initial release in 2020, ISRaD v2 has doubled in size and demonstrated its usefulness to enable diverse scientific advances. Nonetheless, substantial opportunities remain to expand ISRaD's coverage, improve metadata specificity, and strengthen its integration with complementary data systems and modeling frameworks. The following sections outline priority directions for the continued evolution of ISRaD and the soil radiocarbon community.

7.1. Leveraging time-series to navigate declining atmospheric radiocarbon

As atmospheric ^{14}C concentrations continue to decline from their 'bomb'-spike maximum into a 'post-bomb' era, interpreting single-point radiocarbon measurements from soils become increasingly challenging (Graven et al., 2020; Sierra, 2018). We now observe $\Delta^{14}C$ values at or below the initial values of the 'bomb'-spike (~0 ‰), meaning that CO_2 fixed by plants today has a similar ^{14}C value to C fixed in the 1950s. However, this emerging challenge underscores a critical strength of ISRaD: utilizing time-series radiocarbon data.

The analytical power of ^{14}C measurements is derived from changes in the atmospheric signal combined with modeling approaches that track C movement through soil pools over time. The 'bomb'-spike made it possible to characterize soil C dynamics at a finer temporal resolution (~1–10 years) than natural abundance ^{14}C (~100–1,000 years). Although the 'bomb'-spike dilutes over time due to the burning of fossil fuels, the resulting decline in the atmospheric ^{14}C signal continues to provide a measurable and predictable tracer. As long as atmospheric ^{14}C values are changing, time-series measurements are uniquely powerful for distinguishing between fast- and slow-cycling carbon pools and for constraining turnover rates, far more so than single-point measurements alone.

Several studies already in ISRaD demonstrate the power of combining temporal measurements with modeling (e.g., Baisden et al., 2013; González-Sosa et al., 2024; Sanderman et al., 2017; Sierra et al., 2012; Spohn et al., 2023; Stoner et al., 2021; Trumbore et al., 1996; von Fromm et al., 2025). These studies show that revisiting sites over years to decades, and resampling archived soil collected decades ago, can improve our ability to better constrain soil C cycling. Alternatively, accreting systems like organic peatland or permafrost soils can preserve atmospheric ^{14}C with depth via annual C inputs (e.g., Hicks Pries et al., 2012). Thus, we encourage the scientific community to focus on i) systematic resampling of existing sites, ii) analysis of archived samples, and iii) leveraging natural archives (i.e., peatlands, wetlands, and permafrost soils).

7.2. Best practice for collecting, reporting, and sharing soil radiocarbon data

The growth of ISRaD v2 and synthesis studies leveraging the database have highlighted both the value of comprehensive data archiving and the importance of consistent, high-quality metadata. To maximize the scientific utility of soil radiocarbon data and facilitate meaningful cross-study comparisons, we recommend the following best practices for the soil radiocarbon community:

Minimum metadata requirements: every soil radiocarbon measurement should include the following core information to ensure accurate attribution, reproducibility and comparability:

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i. **Geographic location:** Sampling site coordinates (latitude, longitude) at the highest possible precision, preferably at the individual profile level rather than regional generalizations. Accurate geolocation is essential for linking radiocarbon data to climate, soil, and land-use variables and for identifying candidate sites for resampling.
ii. **Depth intervals:** Precise reporting of sampling depths (e.g., 0–10 cm, 10–30 cm) with clear notation of reference levels (e.g., mineral soil surface, peat surface, or litter surface). Standardized depth notation is critical for depth-dependent analyses and for comparing data across studies.
iii. Both the **year of sample collection** and the **year of radiocarbon analysis** must be reported. This is essential because changes in atmospheric ^{14}C content, particularly during and after the 'bomb' period, directly affect the interpretation of measured ^{14}C values. This distinction is particularly important for archived samples analyzed years or decades after collection.
iv. **Sample description:** Clear identification of the material analyzed (e.g., bulk soil, specific fraction, roots, incubation, interstitial CO_2), including pretreatment methods if applicable (e.g., acid-base-acid for macrofossils).
v. **Laboratory information:** Laboratory code/reference number, and reported uncertainties (Δ^{14}C or Fm, with associated standard deviation).

While ISRaD captures the core radiocarbon measurements and basic soil properties, several types of supplementary data significantly strengthen the interpretive power of radiocarbon studies but are often incompletely reported: i) soil mineralogy and texture, ii) soil chemistry, iii) microbial and biological indicators, iv) management and disturbance history. We recognize that not all studies will have access to comprehensive soil characterization data. However, when such data are available, we strongly encourage their inclusion in ISRaD submissions or as supplementary information linked to database entries.

7.3. Future Directions for ISRaD

Despite substantial growth in ISRaD v2, significant geographic and data type gaps remain that limit our ability to understand soil C dynamics at global scales. Tropical and arid regions remain severely undersampled relative to their global soil C stocks, and agricultural and urban soils are critically underrepresented. Depth-resolved sampling is particularly biased toward surface mineral horizons; a critical limitation given that deep soils contribute substantially to long-term C storage. Beyond geographic gaps, several data types remain limited: interstitial DOC and POC measurements (especially from wetlands and peatlands), CH_4 measurements from anaerobic systems, living root incubations deeper than 20 cm, and seasonally-resolved flux measurements. A major untapped opportunity exists to reanalyze archived soil samples collected decades ago from well-documented sites, which would enable the construction of radiocarbon time series to constrain ages and transit times and test model predictions of soil C dynamics during the declining 'bomb' radiocarbon era. Addressing these sampling gaps will require not only expanded data collection but also improved metadata reporting in ISRaD. We encourage researchers who publish radiocarbon data, especially those who have benefited from ISRaD, to contribute their measurements to the database. Community participation is essential for addressing sampling gaps and advancing our understanding of soil C dynamics.

ISRaD continues to evolve in response to emerging research priorities and community needs. One area for improvement is the classification of land-cover types and capture of disturbance and restoration history, particularly for ecosystems with rapidly growing radiocarbon research. Wetlands are increasingly recognized as critical components of the global C cycle, yet current ISRaD metadata do not adequately capture the diversity and disturbance history within these systems. Beyond wetlands, agricultural soils under different management regimes (conservation vs. conventional tillage, liming, fertilization history) represent another critical gap, as do disturbed systems affected by fire, erosion, or land-use change. We recognize that developing robust classification schemes for disturbance is challenging since disturbances vary in type, severity, timing, and recovery trajectory. Rather than prescribing a single solution, we invite

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the community to contribute ideas, data, and expertise on how best to capture this information. Proposed improvements might include: hierarchical ecosystem classifications that distinguish management states and disturbance types; metadata fields for disturbance type, timing, and intensity; or linkages to external land-use change databases. We encourage contributions on these topics and welcome collaborative efforts to refine ISRaD's capacity to represent the full complexity of terrestrial C cycling and beyond in a rapidly changing world.

Another emerging research area is understanding the fate of soil-derived C once it leaves terrestrial systems and enters aquatic pathways. There is a growing body of literature demonstrating that streams, canals, and rivers transport and emit substantial quantities of aged soil C to the atmosphere, highlighting the importance of lateral C fluxes in global C budgets (Bowen, Wahyudio, et al., 2024; Dean et al., 2025; Galy et al., 2015; Marwick et al., 2015; Townsend-Small et al., 2007). Expanding ISRaD to systematically link soil radiocarbon measurements with riverine C observations at shared locations would provide critical constraints on how soil C ages and sources translate into aquatic C dynamics, ultimately providing a full picture of the avenues of which terrestrial C is transferred to the atmosphere. Beyond improved ecosystem representations, broader integration with complementary data systems and modeling frameworks would amplify the utility of ISRaD data across disciplines. Realizing these collaborative opportunities and expanding ISRaD's capacity will require sustained effort and resources; while ISRaD has demonstrated resilience in continuing without dedicated funding, maintaining and advancing the database remains challenging without institutional or financial support.

While ISRaD provides a centralized repository for soil radiocarbon measurements, substantial opportunities exist for the broader soil science and modeling communities to develop deeper integrations with complementary databases and create model-ready data products. Linking ISRaD with other soil information systems, aquatic C databases, and climate datasets could unlock powerful cross-disciplinary research on soil C dynamics and fate. Similarly, developing standardized formats and pre-processed data products tailored to the needs of land surface modelers would greatly enhance the utility of radiocarbon constraints for model parameterization and validation. Such integration efforts require coordinated development and community engagement beyond the scope of a single database. We invite the soil science, modeling, and aquatic C communities to collaborate on defining priorities for these integrations and to contribute technical expertise and resources toward building the necessary linkages and products. These collaborative efforts would strengthen the scientific value of radiocarbon data across disciplinary boundaries and improve our ability to predict soil C responses to environmental change.

Code and Data availability

The International Soil Radiocarbon Database (ISRaD) v2.9.8 data (Beem-Miller et al., 2025) is archived and freely available at https://zenodo.org/records/17860507. In addition, the development version of the database can be accessed directly from GitHub (https://github.com/International-Soil-Radiocarbon-Database/ISRaD). All code to reproduce the analysis and figures presented in this publication (von Fromm, Winton, et al., 2025) are available at https://zenodo.org/records/17859527 and at https://github.com/International-Soil-Radiocarbon-Database/ISRaD-v2-analysis.

Author contributions

SvF, RSW, DRV, JCB, ST, KJ, JS, OV, SWS, MC, AM, AAW, KH, DW, LIM, KEG, CECP, KJM, AA, CL, and JBM contributed to data curation. SvF lead the formal analysis with contributions from DRV, JCB, ST, OV, SWS, AM, AAW, AMH, KG, DW, LIM, KEG, CEHP, KJM, and AA. SvF lead the writing with contributions from all co-authors.

Competing interests

All authors declare that they have no competing interests.

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