

An open source database for the synthesis of soil radiocarbon data: ISRaD version 1.0

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Abstract. Radiocarbon is a critical constraint on our estimates of the timescales of soil carbon cycling that can aid in identifying mechanisms of carbon stabilization and destabilization, and improve forecast of soil carbon response to management or environmental change. Despite the wealth of soil radiocarbon data that has been reported over the past 75 years, the ability to apply these data to global scale questions is limited by our capacity to synthesize and compare measurements generated using a variety of methods. Here, we present the International Soil Radiocarbon Database (ISRaD, soilradiocarbon.org), an open-source archive of soils data that include reported measurements from bulk soils; distinct soil carbon pools isolated in the laboratory by a variety of soil fractionation methods; samples of soil gas or water collected interstitially from within an intact soil profile; CO₂ gas isolated from laboratory soil incubations; and fluxes collected *in situ* from a soil profile. The core of ISRaD is a relational database structured around individual datasets (entries) and organized hierarchically to report soil radiocarbon data, measured at different physical and temporal scales, as well as other soil or environmental properties that may also be measured and may assist with interpretation and context. Anyone may contribute their own data to the database by entering it into the ISRaD template and subjecting it to quality assurance protocols. ISRaD can be accessed through: (1) a web-based interface, (2) an R package (ISRaD), or (3) direct access to code and data through the GitHub repository, which hosts both code and data. The design of ISRaD allows for participants to become directly involved in the management, design, and application of ISRaD data. The synthesized dataset is available in two forms: the original data as reported by the authors of the datasets; and an enhanced dataset that includes ancillary geospatial data calculated within the ISRaD framework. ISRaD also provides data management tools in the ISRaD-R package that provide a starting point for data analysis; and as an open-source project, the broader soils community is invited and encouraged to add data, tools, and ideas for improvement. As a whole, ISRaD provides resources to aid our evaluation of soil dynamics across a range of spatial and temporal scales. The ISRaD v1.0 dataset (Lawrence et al., 2019) is archived and freely available at <https://doi.org/10.5281/zenodo.2613911>.

1 1. Introduction

2 The study of soil organic matter (SOM) dynamics is essential to an improved understanding of
3 terrestrial ecosystem dynamics and the Earth's carbon cycle (Oades, 1988; Heimann and
4 Reichstein, 2008). Current evaluations suggest that SOM accounts for up to 2770 Pg of organic
5 carbon in the top 3 m of soil (Jackson et al., 2017; Le Quéré et al., 2018), which makes it one of
6 the largest actively cycling terrestrial carbon reservoirs and an important modulator of climate
7 change (Sulman et al., 2018). However, the lack of clarity about which fraction of that reservoir
8 will respond to ongoing environmental changes (i.e. timescales of years to centuries) and which
9 will respond only on millennial timescales (He et al. 2016) makes it imperative to improve our
10 understanding of the controls on soil carbon cycling. Additionally, many studies and models focus
11 on only the top 0.5 m of soil or less, despite deeper soils contributing a significant proportion of
12 SOM storage by way of low carbon concentrations but large deep soil mass (Rumpel and Kögel-
13 Knabner, 2010). There is an urgent need to synthesize a wide variety of soils data to model the
14 role of soil in the climate system (Bradford et al., 2016), to develop more data-driven estimates of
15 soil health (Harden et al., 2017), to inform policy and land management plans that preserve and
16 enhance soil carbon storage (Minasny et al. 2017; Poulton et al. 2018), and to extend our detailed
17 understanding of soil developed from observations made at the profile scale to both regional and
18 global extents. Here we describe a new open-source database for the synthesis of soils data with a
19 particular focus on soil radiocarbon data.

20
21 Radiocarbon (i.e., ^{14}C) content of SOM is a useful tool to estimate the timescales of SOM cycling
22 including the turnover time, residence time, or mean age of carbon in soil - defined as the time it
23 has been isolated in soil from the atmosphere (Sierra et al., 2017; Manzoni et al., 2009; Trumbore,
24 2006). Although it was recognized very early on that radiocarbon measurements could provide a
25 useful measure of the stability of soil carbon (Broecker and Olson 1960; Tam and Ostlund, 1960),
26 the need for several grams of carbon for decay-counting methods meant that there were relatively
27 few publications before the mid-1980's (e.g., Scharpenseel 1971; O'Brien & Stout, 1978). Many
28 of these papers only published bulk soil radiocarbon for the same reason (with some exceptions,
29 e.g., Martel and Paul, 1974; Goh et al. 1977). These early papers indicated that carbon in soils is
30 heterogeneous and made up of a range of different aged materials that could be separated

31 chemically (Martel and Paul, 1974). Several of these studies use models of the uptake of bomb
32 carbon (Goh et al. 1977, Cherinski 1981, O'Brien, 1984; Balesdent, 1987). In the 1980's the
33 advent of accelerator mass spectrometry, a method that measures ^{14}C atoms in a sample by
34 accelerating them to high energy, allowed for radiocarbon analysis using milligrams of carbon
35 instead of grams, while simultaneously increasing sample throughput (Trumbore, 2009). This
36 development enabled analysis of small amounts of archived soils to track the incorporation of ^{14}C
37 derived from atmospheric testing of nuclear weapons over time, as well as making it far easier to
38 analyze physically and chemically isolated soil fractions (e.g., Trumbore 1993). These applications
39 have led to an explosion in the number of publications with radiocarbon measurements from soil,
40 increasing from a few dozen papers annually during the 1980's to more than 150 per year in the
41 last decade (based on papers with "soil" and "radiocarbon" as keywords). The database presented
42 here is an attempt to provide an archive for all the previously published data but also a repository
43 for organizing new data as it is published.

44
45 Two recent soil radiocarbon synthesis efforts demonstrate the utility of these data for improving
46 predictions of SOM dynamics (He et al., 2016; Mathieu et al., 2015). Bulk soil radiocarbon
47 measurements, if not part of repeated time series, provide only an approximation of the time
48 elapsed since carbon in the soil was fixed from the atmosphere. In other words, soil carbon age as
49 measured by radiocarbon is defined as the age of carbon stored in the soil, since the time it enters
50 until a time of observation. However, this mean value is not representative of how fast soil carbon
51 will respond to a change in inputs, as it has been repeatedly demonstrated that SOM is not
52 homogeneous, and that carbon stabilized by different physical, chemical or biological mechanisms
53 cycles at different rates. Models can be used to explain time series of bulk radiocarbon or
54 physically and chemically separated SOM fractions, but this requires model structures with
55 multiple pools cycling on different timescales to simultaneously explain the rate of bomb ^{14}C
56 uptake and the mean ^{14}C signature of SOM (Gaudinski et al. 2000; Baisden et al 2002a; 2013;
57 Sierra et al. 2012; Schrumpf et al. 2013). Partitioning SOM into pools is easily implemented in
58 models, but in reality, measuring these pools is both challenging and dependent on the techniques
59 used to fractionate the bulk soil (Moni et al., 2012) or to track throughput of bomb-derived carbon
60 through repeat measurements (Baisden et al., 2013; Baisden and Keller, 2013). A second measure
61 of carbon cycling rates in soils is the transit (residence) time, which is defined as the time it takes

62 carbon to pass through the soil system, since the time it enters until it is observed in an output flux
63 (Sierra et al., 2017). The modeled transit time can be constrained by measurements of the
64 radiocarbon signature of carbon in these output fluxes, which include respired CO₂ or dissolved
65 organic carbon (DOC) leached from the soil. Critically, most approaches using radiocarbon to
66 estimate the timescales of carbon cycling in soils require multiple measurements of carbon in
67 distinct soil reservoirs (Trumbore, 2000) or a time series of measurements made over the course
68 of several years (Baisden et al., 2013; Baisden and Keller, 2013). As the assumptions required for
69 modeling radiocarbon data can lead to confusion in the terminology and concepts of SOM
70 dynamics, it is imperative that we archive radiocarbon measurements in order to preserve the
71 ability to reevaluate calculations and compare data across different modeling frameworks.

72
73 Ongoing study of soils has led to shifting conceptual views of the controls on SOM dynamics
74 (Blankinship et al., 2018; Golchin et al., 1996; Lehmann and Kleber, 2015; Oades, 1989; Schmidt
75 and Torn et al., 2011). Current conceptual views that emphasize the protection of SOM from
76 microbial decomposition via physical isolation or sorption to soil mineral surfaces (Lehmann and
77 Kleber, 2015) and within anaerobic microsites (Keiluweit et al., 2016) have largely replaced earlier
78 paradigms of humification, selective preservation, and progressive decomposition. Three of the
79 fundamental questions currently driving SOM research are: (1) what are the controls on the
80 partitioning of organic inputs between soil reservoirs cycling over different timescales; (2) what
81 factors determine rates at which SOM in each reservoir is lost, retained, or transferred within the
82 soil; and (3) which mechanisms contribute to transformation of SOM to stabilized or more
83 protected forms? To address these questions, researchers typically measure the concentration or
84 mass content of organic carbon along with other properties, including molecular composition,
85 isotopic ratios, and the distribution of SOM between conceptually or operationally defined pools
86 (e.g., Basile-Doelsch et al., 2009) or a time series of samples collected over the course of decades
87 (e.g., Baisden et al, 2002a).

88
89 Soil fractionation is the operationally defined separation of soils into distinct pools or “fractions”
90 through a variety of physical, chemical, and biological approaches. Soil fractionation is generally
91 intended to isolate soil fractions that reflect SOM in different physico-chemical states or
92 mechanisms of SOM protection (Trumbore and Zheng, 1996); these mechanisms may operate on

93 distinct temporal scales (e.g., Khomo et al., 2017). For example, density fractionation of SOM is
94 a commonly applied technique (Golchin et al., 1994; 1995; Crow et al., 2007; Sollins et al., 2006;
95 2009; Swanston et al. 2005). The “light” fraction of soil material that floats in a dense solution
96 (e.g., sodium polytungstate) or gets picked up by electrostatic attraction (Kaiser et al., 2009) is
97 sometimes used as a proxy for rapidly-cycling SOM, as this material is generally observed to have
98 a shorter mean residence time compared with the bulk soil average, while the “heavy” or dense
99 material is used as a proxy for mineral-associated SOM, which is assumed to cycle more slowly
100 (e.g., Sollins et al., 2009). In some cases, sonication of the suspension may be used to further
101 isolate occluded SOM, i.e., organic material in soil aggregates (Golchin et al., 1994; Kasier and
102 Berhe, 2014). Other methods for isolating SOM with different cycling rates in the soil include, but
103 are not limited to, physical separation of aggregates by size and water-stability (Jastrow et al.,
104 2006; Plante et al., 2006; Six and Paustian, 2014) or of different-sized soil particles (Desjardins et
105 al., 1994), biological incubation of soils (Torn et al., 2005; Trumbore, 2000; Paul, et al., 2001),
106 and chemical extractions (Heckman et al., 2018; Masiello et al., 2004).

107
108 Comparing the mass and radiocarbon signature of the carbon leaving or entering the soil system
109 (fluxes) with those of specific soil fractions provides insight into the rates of transfers between
110 pools and provides a means for differentiating between various measures of dynamics ranging
111 from mean age to the transit time of carbon for the whole soil, a given depth increment, or a given
112 SOM pool (Gaudinski et al., 2000; Baisden et al., 2002a; 2002b; 2003; Sierra et al., 2014; Ohno
113 et al., 2017; Ziegler et al., 2017; Szymanski et al., 2019). Similarly, measurements of interstitial
114 soil carbon (i.e., in soil water or gases collected from within an intact soil profile) and its isotopic
115 signature provide key information about the dynamics of the carbon present in the soil solution
116 (Sanderman et al., 2008). Soluble carbon is believed to be the dominant pathway for vertical
117 transport of organic carbon (Kaiser and Kalbitz, 2012; Angst et al., 2016), and also an intermediate
118 stage through which carbon exchanges from being vulnerable to microbial decomposition to being
119 stabilized on mineral surfaces (Jackson et al., 2017; Leinemann et al., 2018).

120
121 Measurements of bulk soils as well as soil fractions are evaluated in the context of other soil
122 properties to better understand the controls on SOM preservation. However, the diversity of soil
123 fractionation methods makes it difficult to compare measurements across soils or to evaluate best

124 practices (e.g., Trumbore and Zheng, 1996). Combining radiocarbon measurements of soil carbon
125 fractions, time series, incubations, interstitial observations, and fluxes has proven useful in
126 resolving the contribution of different soil carbon persistence mechanisms in a site-specific
127 modeling context (Braakhekke et al., 2015), but the application of this approach beyond the site-
128 scale has thus far been limited due to the lack of globally synthesized data.

129
130 With a changing paradigm for SOM dynamics and ever-evolving SOM models, it is more
131 important now than ever that we synthesize existing soil radiocarbon measurements *and* provide a
132 central repository for new data. There have been previous efforts to develop a soil radiocarbon
133 database (Becker-Heidmann, 1996; 2010; Trumbore et al. 2011), separately or integrated with a
134 general-purpose soil carbon database (Harden et al., 2017). However, a challenge remains: to
135 compile and organize soil radiocarbon data that has been collected in many different and complex
136 ways (e.g., using various fractionation methods or including fluxes as well as organic matter
137 pools). Addressing this challenge will provide new opportunities to leverage existing soil
138 radiocarbon data for critical research such as developing practical and theoretical insights into the
139 information contained in various fractionation methods and how they relate to one another. This
140 will expand our understanding of controls on soil carbon dynamics, and facilitate broader
141 integration of radiocarbon constraints on soil carbon turnover in Earth system models. For
142 example, He et al. (2016) leveraged a synthesis of bulk-soil radiocarbon data to better constrain
143 the age of carbon in five Earth system models, demonstrating that without this added constraint,
144 these models overestimate soil carbon sequestration potential by an average of 40%.

145
146 Here, we present a flexible database spanning broad spatial scales and capturing a range of data
147 types including diverse soil fractionation methods, incubations, fluxes, interstitial measurements
148 and spanning a range of spatial scales. Our goal is to provide an open-access data resource that
149 will encourage the scientific community to apply the database for a variety of synthesis studies or
150 metaanalyses, and also contribute data to the repository.

151

152 2. The International Soil Radiocarbon Database (ISRaD)

153 The International Soil Radiocarbon Database (ISRaD) is designed to be an open-source platform
154 that (1) provides a repository for soil radiocarbon and associated measurements, (2) is able to
155 accommodate data collected from a large variety of soil radiocarbon studies, including the
156 diversity of fractionation techniques applied to soils as well as repeated bulk measurements made
157 over spatial or temporal gradients, and (3) is flexible and adaptable enough to accommodate new
158 variables and data types. Although ISRaD was specifically developed with soil radiocarbon
159 measurements in mind, it is well suited for synthesizing other soil measurements, including stable
160 carbon and nitrogen isotopes. Importantly, we currently focus only on natural abundance isotopic
161 measurements and therefore exclude data from isotopic tracer studies. The ISRaD v1.x data is
162 archived and freely available at <https://doi.org/10.5281/zenodo.2613911> (Lawrence et al., 2019).
163 Access to additional information as well as the various ISRaD resources described below is
164 provided through the ISRaD website (soilradiocarbon.org).

165

166 2.1 Database and Dataset Structure

167 In its most general form, ISRaD is an implicitly relational database. It consists of a linked
168 hierarchical list of tables that contain soil measurements, i.e. variables (Fig. 1). The fundamental
169 unit of organization in ISRaD is the *entry*, which corresponds to a unique dataset i.e., a dataset
170 with a digital object identifier (DOI), while each subordinate table corresponds to data from that
171 entry with a particular spatial or temporal dimension.

172

173 Transparency and traceability are fundamental tenants of ISRaD. Accordingly, each entry, whether
174 ingested individually or as a compilation, must have a DOI. For data from published studies, the
175 DOI of the publication is acceptable. Data from unpublished studies must be registered for a DOI
176 through a DOI registration agency (e.g., zenodo.org, www.pangaea.de, etc.) prior to ingestion into
177 ISRaD. As it is equally important to be able to reconstruct prior data compilations e.g., synthesis
178 studies, the specific references for individual datasets making up a synthesis are ingested as part
179 of the synthesis entry and the entry is flagged within the database with an additional reference to
180 the synthesis study itself. For example, several of the major data sources added to ISRaD were
181 synthesis studies (e.g., He et al., 2016; Mathieu et al., 2015), and users can generate reports of data
182 from these prior syntheses by constructing a query that utilizes this synthesis flag.

183

184 Each ISRaD release will be available in two forms: (1) a raw version of data (*ISRaD_data*),
185 containing only values that were reported in the original source of each data entry and (2) an
186 expanded version of the database (*ISRaD_extra*). The *ISRaD_extra* version of the dataset includes
187 additional parameters that have either been calculated or imported based on site coordinates, such
188 as geospatially referenced climate information. Table 2 includes examples of some of the new
189 variables included in *ISRaD_extra*; a more detailed list of this growing list of variables can be
190 found on the ISRaD website in the *ISRaD_extra* Information File. Both versions of the database
191 follow the general data hierarchy outlined below.

192

193 2.2 Data Hierarchy

194 The ISRaD data hierarchy consists of eight levels of information (Fig. 2). The top level of the data
195 hierarchy is the metadata table (1), which includes information describing the source of data for a
196 particular entry. The remainder of the hierarchical levels can be defined by the spatial extent of the
197 information included in each table. The site (2), profile (3), layer (4), and fraction (5) tables
198 represent information captured from decreasing spatial extents: from the scale of the study area to
199 individual mass fractions isolated from a single soil sample. Special cases of the last three spatial
200 extents further accommodate the temporal context of repeated measurements: (6) fluxes, (7)
201 interstitial, and (8) incubations. In the sub-sections below, we provide overviews and examples of
202 the types of information reported at each level, and for each of the tables that occupy these levels
203 (Fig. 2).

204

205 The data hierarchy is maintained across tables through the use of unique keys, or linking variables
206 (noted with a "*" in the following descriptions) that are required in each record (row) of data in
207 each table. In addition to the table-specific key, each subordinate table in the hierarchy must also
208 contain the key variables of the above tables. For example, in addition to a unique *layer_name**,
209 each record in the layer table must also be associated with an *entry_name**, *site_name**, and
210 *pro_name** (profile name) i.e., the key variables for the metadata, site, and profile tables.

211

212 ISRaD provides basic quality assurance/quality control (QA/QC) protocols (described below) and
213 expert review that are applied prior to ingesting entries. These protocols are used to ensure required

214 variables are complete, that the key variables match across levels of the hierarchy (more detail
215 below), and data entered match the specified data type and range for a given variable. Variables
216 that are not designated as required need only be completed if those data are available. The ISRaD
217 template and a detailed description containing the full list of variables along with instructions for
218 populating the template can be downloaded or viewed from the “Contribute” page of the web-
219 interface (soilradiocarbon.org).

220
221 For all variables across all hierarchical levels, it is important to observe the acceptable data types
222 (character, numeric) and units. Variable names, descriptions, and reporting conventions are given
223 in the heading columns of the ISRaD template file (*ISRaD_Template.xlsx*) and more detailed
224 information is provided in the data dictionary (*ISRaD_Template_Info.xlsx*). Allowed values
225 include unrestricted text, controlled text, or numeric variables with or without defined ranges.
226 Unrestricted text is generally limited to naming and note data fields, while controlled text fields
227 are implemented for certain variables in an attempt to standardize the data and simplify data
228 analysis. In the event that desired variables are not included in the current version of ISRaD, users
229 may submit a request to add new variables. This process is initiated by posting an issue at the
230 ISRaD GitHub repository and is described in more detail in section 3.4.

231
232 **2.2.1 Metadata Table**
233 The metadata table provides information for the characterization of the entry itself. Required
234 metadata includes the entry name (i.e., *entry_name**), the DOI, the data curator (the person who
235 oversees template entry), and their contact information. The entry name is the key variable used to
236 match the entry with measurements reported at the other data levels.

237
238 **2.2.2 Site Data Table**
239 Site-level data are limited to the geospatial details defining the coarsest scale of the study area(s)
240 included in each entry. We define a site as a spatially defined location that includes one or more
241 soil profiles. By convention, we define a site as having ≥ 5 km radius, i.e., samples collected within
242 5 km of each other should be grouped under the same “site” designation. However, the 5 km radius
243 is a convention only, as the distinction between site and profile may be study-specific, and
244 geospatial data at this resolution is not always available for legacy datasets. Spatial coordinates are

245 required to designate a site, and thus the required fields at the site level are limited to the site name
246 (*site_name**), latitude, and longitude. Every entry must specify a minimum of one site location,
247 but can include multiple sites that do not need to be located in close proximity. For entries that do
248 not report spatial coordinates, the data curator may estimate latitude and longitude based on the
249 description of the study area using any of the widely acceptable mapping software (e.g., Google
250 Earth, Google Maps, etc.). The site table does not include fields for reporting site properties. Such
251 directly measured variables are reported at the profile level. The intended purpose of the site level
252 data is to provide at least coarse-scale geospatial coordinates for extracting consistently sourced
253 parameters from geospatial datasets, which can then be compared against the range of
254 measurements reported at the profile level.

255

256 2.2.3 Profile Data Table

257 Profile-level data includes details pertaining to specific sampling locations. If available, profile-
258 scale spatial coordinates should be provided in addition to site-scale coordinates.

259

260 Many variables that may initially appear to belong at the site level are instead included at the
261 profile level to facilitate accurate representation of spatial heterogeneity at a finer scale than the
262 site level (e.g., for multiple profiles observed at the same site). Examples include local mean annual
263 temperature and precipitation, soil taxonomic classification, vegetation type, land cover, depth to
264 bedrock, and parent material composition. Other than the entry name and site name, the only
265 additional required variable at the profile-level is the profile name (*pro_name**).

266

267 2.2.4 Flux Data Table

268 Soil flux data present a special case of observations that correspond to the profile level of the
269 database hierarchy. Flux-level data allows for reporting of temporally explicit measurements of
270 mass or energy transfer occurring at the profile scale. Both gas and liquid analytes (e.g. CO₂, CH₄,
271 dissolved OC, particulate OC, etc.) may be reported in flux data. In addition to the profile name,
272 records with flux data must also include the observation date (*flx_obs_date*). Data measured at
273 multiple time points in a single location will have identical profile names but unique temporal data.

274

275 2.2.5 Layer Data Table

276 Layer-level data corresponds to measurements made for a specific depth increment collected from
277 a soil profile. The required variables at the layer level include layer name (*lyr_name*), depth of
278 layer top, and depth of layer bottom. The latter two variables describe the upper and lower range
279 of the sampling depth, respectively, in units of centimeters. We use a depth reporting system where
280 the top of the mineral soil is denoted as zero and subsequent depths below that point are reported
281 with incrementally increasing positive values. Organic horizons are thus reported as negative depth
282 intervals. Special indicator fields (e.g., *lyr_all_org_neg*) are used when the depth to the mineral
283 soil is unknown, e.g. for deep organic horizons or peats. The layer level is where most common
284 measurements of soil physical, chemical, and/or biological properties are reported. As such, there
285 is an ever-increasing list of variables that may be reported in the layer table. Users should consult
286 the up-to-date template instruction file for the complete list of accepted variables.

287

288 2.2.6 Interstitial Data Table

289 The interstitial level is a special case of layer-level data. Specifically, interstitial data refers to
290 measurements made on material occupying the interstices of the soil structure. In most cases, this
291 material can be thought of as being mobile relative to the rest of the soil matter. Some common
292 examples include gases, liquids, and colloids. Like flux data, the interstitial data table
293 accommodates repeated measurements of these properties through time and as such, the
294 observation date must be recorded for each record in the interstitial table. Because interstitial
295 records may not correspond to the same depth increments defined for solid phase analyses, separate
296 depth reporting is used in the interstitial table distinct from what is reported in the layer table. Both
297 sampling methodology as well as the properties of interstitial samples are reported in the interstitial
298 table.

299

300 2.2.7 Fraction Data Table

301 Compared with most other soil databases, the fraction data table of ISRaD is unique. The fraction
302 data fields are designed to accommodate and allow for fair comparison of the wide-ranging
303 methodologies utilized to partition soils into discrete fractions. As such, there are more required
304 fields for the fraction level compared with the other hierarchical levels. These required fields
305 include fraction name (*frc_name**); the input source (*frc_input*), which can be the name of another

306 fraction or bulk (unfractionated) soil layer fraction scheme (*frc_scheme*), which is a controlled set
307 of terms describing the general class of fractionation procedure used; the fractionation agent
308 (*frc_agent*), which provides additional detail for methods that have multiple options; the upper and
309 lower boundaries (*frc_lower* and *frc_upper*), which allow for description of the fractionation
310 thresholds used in the fractionation procedure; and finally the fraction scheme units
311 (*frc_scheme_units*), which describes the units of reference for the cut-off thresholds.

312
313 For example (see figure 3), most soil density fraction (*frc_scheme* = density) procedures starts with
314 bulk soil from the layer in question (*frc_input* = bulk). The first distinct fraction, “free light”, is
315 isolated by floating the soil in a heavy solution, e.g. sodium polytungstate (*frc_agent* = SPT). If
316 the density of the sodium polytungstate used in density separation step was 1.6 g cm^{-3} , *frc_lower*
317 for the “free light” fraction = 0, and *frc_upper* = 1.6 (indicating that anything with a density less
318 than 1.6 was included), and *frc_scheme_units* = g cm^3 . In addition to these required fields, the
319 fraction-level data may include many of the same data fields that are reported for the layer-level
320 data. Ideally the fraction data also includes the mass percentage of the total sample represented by
321 the fraction as well as the specific carbon concentration and carbon isotopic composition of the
322 fraction, which are critical for relating bulk and fraction level observations.

323

324 2.2.8 Incubation Data Table

325 Flux rates and isotopic signatures of laboratory-incubated samples are reported in the incubation
326 table. Sample processing data (e.g., whether or not roots have been removed from samples prior
327 to incubation) are recorded, as well as incubation conditions (e.g. temperature, moisture, duration).
328 Repeat measurements, such as incubation time series, can also be recorded. Incubation records
329 must be linked either to a layer or both a fraction and a layer, e.g. roots isolated from a specific
330 bulk layer sample.

331

332 2.3 Radiocarbon Data – Reporting Conventions

333 Radiocarbon measurements of environmental samples have a long history, much of which is
334 reviewed in Trumbore (2009) including common units. Radiocarbon data ingested to ISRaD are
335 required to adhere to some basic reporting conventions. First, measurements of radiocarbon may
336 be reported in units of either fraction modern (FM) or $\Delta^{14}\text{C}$. Within the *ISRaD_extra* version of

337 the database, values reported in one or the other accepted units are internally converted and filled
338 across all entries, so that either unit may be used for analyses of the full dataset. Other units are
339 not supported at this time – for example, calibrated radiocarbon dates are not accepted, as the
340 calibration curves are evolving over time. Such calibrated ages make sense only for certain
341 fractions (e.g. macrofossils found in soils), and do not make sense in the context of most soil
342 organic matter, which is an open system for carbon, with inputs that vary in $\Delta^{14}\text{C}$ over time. For
343 datasets where radiocarbon is reported in units other than FM or $\Delta^{14}\text{C}$ (e.g. percent modern carbon
344 or conventional radiocarbon age), it is up to the data curator or original author of the dataset to
345 convert the reported values to one or both of the permitted units. Second, the year of measurement
346 for each radiocarbon value must also be reported so that values may be internally converted
347 between the two accepted units. In addition to these basic requirements, there are several other
348 optional fields pertaining to radiocarbon data. These include the radiocarbon laboratory; the
349 laboratory number, a unique identifier issued by each AMS facility; the analytical error reported
350 for each measurement reported by most laboratories; and the environmental standard deviation of
351 replicate samples (if analyzed). These variables are not required for data submission but should be
352 included if they are available.

353

354 2.4 Data Ingestion

355 New data entries are added, or ingested, into ISRaD through a user-initiated process. The most
356 common means of ingesting entries is via the template provided on the ISRaD website
357 (*ISRaD_Master_Template.xlsx*). The template is intended to be used in combination with the data
358 dictionary (*ISRaD_Template_Info.xlsx*). These files and other supporting documentation (user
359 guide and FAQ) are also available at the website (soilradiocarbon.org). Completed entries that
360 have been formatted for ingestion must also pass the automated QA/QC test before the ingestion
361 process can proceed. Users can initiate QA/QC using the ISRaD-R package (described below), or
362 directly from the ISRaD website. If the entry fails QA/QC, the report from the test can be used as
363 a guide to make corrections. Once an entry passes QA/QC, it can be submitted for the final two
364 steps of the ingestion process: expert review and final ingestion.

365

366 Data templates that have passed QA/QC should be submitted via email to ISRaD at
367 info.israd@gmail.com. These templates are then distributed to ISRaD expert reviewers who

368 inspect template files to ensure proper completion of the more complex aspects of the template,
369 such as classification of soil fractionation methods. If problems are identified with a submitted
370 dataset during the expert review process, reviewers will work with the data curator to ensure these
371 problems are corrected. Once the expert reviewer signs off on a submitted template, it will be
372 ingested into the database.

373 3. Database Infrastructure

374 3.1 ISRaD v1.x

375 The current version, v1.4, of ISRaD includes a total of 212 individual data entries and 550 sites
376 spanning the globe (Fig. 3). The current distribution of data across the various levels of the
377 database hierarchy are shown in Table 1, and a full list of data entry references is provided in
378 Supplemental Table 1.

379

380 Users may access ISRaD and its supporting information three ways: (1) the website, (2) the ISRaD-
381 R package, and (3) the GitHub repository. Each of these access points is described in more detail
382 below.

383

384 3.2 The ISRaD Website

385 Most simply, users can access ISRaD data and associated resources by way of the website
386 (<http://soilradiocarbon.org>). From the website users can download pre-compiled versions of the
387 database in a simple file format (.xlsx or .csv), which can be easily ingested into graphical or
388 database software. The website also provides access to the most recent versions of the ISRaD entry
389 template, the template information file, an up-to-date list of the datasets included in the latest
390 version of ISRaD, the QA/QC tool, and a variety of other resources for assisting with filling out
391 data templates and interacting with ISRaD data.

392

393 3.3 Accessing ISRaD within the R computing environment and the ISRaD-R package

394 ISRaD has been designed for ease of use in the R computing environment (R Foundation for
395 Statistical Computing, Vienna, Austria) in order for users to be able to take advantage of the full
396 suite of R capabilities and functionality to manipulate and analyze ISRaD data. Many of the basic
397 functionalities such as loading current versions of the ISRaD data objects can be performed in the

398 R environment without installation of the ISRaD-R package. A number of vignettes including R
399 scripts for some commonly used data manipulations or plotting are given on the website.

400
401 Users who need to locally compile a version of ISRaD (e.g. using their own templates) or who
402 want access to the full suite of reporting functions can access these features by installing the
403 ISRaD-R package (also called *ISRaD*, which is available at the CRAN repository, [http://cran.r-](http://cran.r-project.org/)
404 [project.org/](http://cran.r-project.org/)). The ISRaD-R package primarily consists of the code that is used to assemble the
405 database and perform the QA/QC checks for the ISRaD datasets. Users may ingest their own data
406 within a local version of the ISRaD dataset by running the function `ISRaD::compile()`. This
407 functionality is intended to allow researchers to interpret their own new or unpublished data in the
408 context of ISRaD data. Additionally, the ISRaD-R package provides simple tools to download and
409 quickly import the most recent ISRaD data into the R environment, and produce basic data
410 summaries and visualizations for the full dataset or user-defined subsets using report functions.

411 412 3.4 The ISRaD GitHub Repository

413 The source code for the ISRaD-R package is hosted under version control on the GitHub repository
414 ISRaD (<https://github.com/International-Soil-Radiocarbon-Database/ISRaD>) (GitHub Inc., San
415 Francisco, CA). This platform is used to facilitate the open-source collaborative development of
416 ISRaD data and additional database tools. Through the GitHub interface, users may (1) access data
417 entries included in the compiled database; (2) evaluate and suggest modifications of the underlying
418 code used for compilation, QA/QC, and calculation of the additional variables included in either
419 the compiled ISRaD data object (*ISRaD_data*) or in the augmented data product (*ISRaD_extra*);
420 and (3) report problems, questions, or other issues.

421 422 3.5 The Soil Carbon Information Hub

423 For students or non-experts interested in learning more about the science behind the data, we have
424 developed the Soil Organic Carbon Information Hub (SOC-Hub). SOC-Hub ([https://international-](https://international-soil-radiocarbon-database.github.io/SOC-Hub/)
425 [soil-radiocarbon-database.github.io/SOC-Hub/](https://international-soil-radiocarbon-database.github.io/SOC-Hub/)) is a set of articles in the form of blog posts
426 providing background information on soils, radiocarbon, the terrestrial carbon cycle, and soil
427 models. A large portion of the content for this site was created by students, and whenever possible
428 uses non-technical language to describe topics pertinent to ISRaD. Technical editing of the SOC-

429 Hub is facilitated through the ISRaD GitHub repository. Users are welcome and encouraged to
430 contribute to or improve the content in SOC-Hub. We will update the SOC-Hub annually.

431 4. Database Operations

432 4.1 Accessing data entries

433 Individual data entries (i.e., completed templates, or templates output from ingested compilations)
434 that have passed QA/QC and the expert review process are hosted in the “ISRaD_data_files” folder
435 of the GitHub repository. Users may download these entries in order to add new data or to make
436 corrections to existing data if problems are discovered. Corrected files can be resubmitted to
437 ISRaD once they pass QA/QC by emailing the updated template and a text file of the QA/QC
438 report to the ISRaD editor (info.israd@gmail.com), and will be reingested after passing the expert
439 review process. This process of user-initiated revision of existing data entries is particularly useful
440 when large data compilations are ingested into ISRaD from previously published syntheses (e.g.,
441 He et al., 2016; Mathieu et al., 2015) or when publications report treatment means. Depending on
442 the scope of the synthesis efforts, entries ingested into ISRaD this way may omit data available
443 from the original studies, and the entry modification process allows those data to be added or
444 corrected as needed.

445

446 4.2 Accessing code

447 Access to the source code underlying the ISRaD database compilation and calculations allows for
448 users to check for errors and contribute to the functionality of ISRaD. Users with a registered
449 GitHub account are invited to write code that adds to or improves upon the existing database tools.
450 Using standard GitHub tools, users will submit a “pull request”, and following code testing and
451 evaluation of utility to the ISRaD community, user-submitted code will be incorporated into the
452 ISRaD-R package.

453

454 4.3 Reporting Issues, making suggestions, and asking questions.

455 One of the most important tools available to ISRaD users is the ability to post questions, report
456 issues, or make suggestions, including requests to incorporate new variables. We use issue tracking
457 tools provided by GitHub to track and categorize user input including: suggestions for
458 improvements; problems or errors with website, the R-package, code, or any other aspects of

459 ISRaD; requests for new variables or issues related to existing variables (e.g., incorrect acceptable
460 ranges used in QA/QC); or asking questions related to template entry or any other aspect of ISRaD.
461 While the GitHub issue-reporting functionality is the preferred means for reporting questions or
462 issues with the database or process, it does require that users register a GitHub account. Users who
463 do not wish to or are not able to register with GitHub, can also submit issues or questions via an
464 email to the ISRaD editor (info.israd@gmail.com), however, the response time may be slower.

465

466 4.4 Database Versioning and Archiving

467 Versioning of ISRaD datasets will be tracked on two levels: official releases and regular
468 updates. Official releases of the ISRaD datasets (e.g., ISRaD v1.0) will be issued
469 periodically, following major changes to the codebase or after the ingestion substantial new
470 data. For each official release, a DOI number will be issued and the data will be archived
471 at Zenodo (<https://zenodo.org/>) and at the USGS Science Base repository. These archives
472 will be maintained into perpetuity to facilitate reproduction of any analyses conducted
473 using a past version of the database. Regular updates correspond to minor changes in
474 development version of ISRaD. These regular updates occur anytime the codebase is
475 rebuilt or when new data is ingested. Regular updates will be archived and available
476 through the GitHub repository, but they will not be issued DOI numbers. The most current
477 version of the ISRaD datasets are always available from the ISRaD website and the GitHub
478 repository. To ensure repeatability of analyses and accurate citations, users accessing the
479 ISRaD dataset should always record version number of the data. The names of ISRaD data
480 files reflect the dataset versioning using the following standardized structure: (*data*
481 *name*)(*vX*)(*date*).(format), where *data name* reflects the file type and structure (e.g.,
482 ISRaD_extra_flat_layer), *vX* refers to the most recent official release version number
483 (*X*), *date* corresponds to date of the most recent regular update of the database in the
484 GitHub repository, and *format* is the file type.

485

486 Versioning of the ISRaD codebase and the ISRaD-R package are tracked separately from ISRaD
487 data. The codebase versioning is tracked via Git but can be linked back to the data version using

488 the *date* identifier from the data file names. The ISRaD-R package versioning is tracked via the
489 Comprehensive R Archive Network (CRAN) and is independent of the ISRaD data versioning.
490 Thus, when using the ISRaD-R package it is useful to record the version installed from CRAN
491 but users must also remember to record which version of the data they have accessed.

492

493 4.5 Citing ISRaD

494 Users citing ISRaD should cite this publication as well as the most recent official data release at
495 the time that they accessed the data. In their citation of the official release, users should also
496 reference the version of the data they used (e.g., v1-2019-09-09).

497

498 4.6 Data Sharing Between Soil Databases

499 ISRaD is not the only soils database available to the international research community. The
500 primary niche of ISRaD is the ability to synthesize soil radiocarbon data and provide a framework
501 for comparing soil carbon fraction data. For other purposes, there may be other soil databases that
502 are more applicable. However, as a benefit of adding data to ISRaD, we facilitate sharing of data
503 ingested into ISRaD with other databases developed by the soil science community. At present,
504 ISRaD has a reciprocal agreement with the International Soil Carbon Network (ISCN), which is
505 focused on soil carbon content and related variables from bulk soils (i.e., no isotope or soil fraction
506 information). As per this agreement, the ISCN retrieves bulk soil data from ISRaD, and is
507 responsible for filtering duplicate entries and incorporating any new data into the ISCN database.

508 5. Database Governance

509 ISRaD is a community effort with multiple contributors operating at different levels. Governance
510 of ISRaD is required in order to ensure continuity of services and to plan for the future evolution
511 of this data repository. The governance structure of the ISRaD is pyramid shaped (Fig. 5). The
512 ISRaD *scientific steering committee* (SSC) consists of a rotating group of 7 scientists and data
513 managers. The committee members are nominated and voted into service by a majority vote of the
514 existing steering committee. The role of the steering committee is to determine the feasibility of
515 major changes to ISRaD proposed by the community; to oversee data management, archiving, and
516 establishment of cooperative agreements; and to coordinate activities and funding of affiliated
517 institutions.

518

519 Database *maintainers* oversee the development and maintenance of the technical resources
520 underlying ISRaD. For example, these individuals are responsible for overseeing GitHub pull
521 requests and managing major changes in the ISRaD data template and/or data structure. The ISRaD
522 associate editor is a special case of maintainer, whose role also includes assigning submitted
523 templates to expert reviewers (described below) and periodically rebuilding the database with new
524 entries that have passed the expert review process.

525

526 Data *contributors* are users who contribute data to ISRaD. Anyone can be a data contributor
527 provided they agree to the terms of use and follow the proper steps for contributing data to ISRaD.
528 Within the pool of data contributors, individuals with significant experience working within the
529 ISRaD structure may be designated, either by the steering committee or database maintainers, as
530 *expert reviewers*. These individuals are tasked to assist maintainers and oversee peer review of
531 contributed entries. Although the automated QA/QC tools are designed to catch many common
532 errors in the data ingestion process, review by these expert contributors ensures the integrity of the
533 data within ISRaD.

534

535 Finally, ISRaD *data users* are individuals who are accessing ISRaD or ISRaD-supported resources
536 to utilize data and other resources rather than to contribute data. Anyone can be a data user
537 provided they agree to the basic user guidelines and terms of use described in the next section.

538

539 Although the structure of the ISRaD governance pyramid is oriented around individual users, the
540 nature of scientific research is often more group-focused. For example, teams of researchers
541 generally work together to seek out funding and to conduct research. Thus, in some cases a group
542 or team of individuals may seek to utilize or modify ISRaD for their purposes. Such groups can
543 petition the scientific steering committee to be formally designated as an ISRaD organization. This
544 process should be followed when groups seek to leverage the ISRaD resources beyond the scope
545 of a basic user or contributor. The steering committee will consider the scope of the work proposed
546 by the group and, when appropriate, provide a letter of support for funding proposals. Approved
547 organizations should nominate a member to serve on the steering committee and, in the case of

548 organizations making large changes or additions to ISRaD, a data maintainer to coordinate the
549 technical aspects of that work.

550 6. Database Availability and User Guidelines

551 As detailed above, ISRaD is an open source project that provides several ways for participation.
552 ISRaD v1.0 data (Lawrence et al., 2019) is archived and freely available at
553 <https://doi.org/10.5281/zenodo.2613911> Anyone may share or adapt the ISRaD dataset provided
554 they do so in accordance with the Creative Commons Attribution 4.0 International Public License
555 (<https://creativecommons.org/licenses/by/4.0/legalcode>), also referred to as CC-By. In addition,
556 we strongly encourage ISRaD users to follow two simple guidelines for use:

- 557
- 558 (1) When utilizing the resources provided by ISRaD, including the complete dataset,
559 individually curated entries, or value-added calculations included in the R-package, users
560 should cite this publication and reference the version of ISRaD that was used for their work
561 (see section 3.6 above). Additionally, if users leverage individual data entries from the
562 database, they should also cite the original source dataset and/or paper.
 - 563 (2) When users interpret their own data in the context of data accessed from ISRaD, they
564 should submit those new data for inclusion in ISRaD after they have published their results
565 and/or obtained a DOI for their dataset.

566 7. Conclusions and Outlook

567 ISRaD is an interactive open source data repository specializing in radiocarbon data associated
568 with measurements of soils spanning a broad range of spatial scales. The ISRaD dataset is unique
569 in that it includes not only measurements of bulk soils but also measurements of soil water, gases,
570 and the wide diversity of soil pools isolated through different fractionation methodologies. Most
571 of the studies summarized in ISRaD were conducted with a goal of understanding the factors
572 controlling timescales of carbon cycling in specific sites, regions or biomes. ISRaD is an attempt
573 to gather the data from these individual studies in one place and in the same format to facilitate
574 comparisons and synthesis activities. There are three ways through which potential users can
575 access ISRaD: (1) the web-interface enables users to download of the most recently compiled
576 report formatted as a .csv file, (2) the ISRaD-R package provides access to the compiled reports

577 as well as visualization tools and R-based querying tools, or (3) the GitHub repository provides
578 direct access to the source code for the ISRaD-R package, as well as data from individual entries
579 and the compiled database. Currently, the ISRaD dataset contains ~8500 radiocarbon analyses,
580 which, at a typical cost ~\$500 each, represent over US \$4,250,000 dollars of research investment.
581 By providing a useful platform for existing data, we hope to encourage the community to increase
582 the effectiveness of that investment, and to use the ISRaD platform as a repository to increase the
583 impact of new results. Many opportunities exist for applying ISRaD data for improving our
584 understanding of controls on soil carbon dynamics, for comparing different methodologies of
585 characterizing soils, or for constraining soil processes in models ranging from profile to global
586 scales.

587 8. Author Contribution

588 The creation of ISRaD was a community effort. The initial concept to build ISRaD started with
589 the USGS Powell Center working group on Soil Carbon Storage and Stability but benefited greatly
590 from early efforts of the International Soil Carbon Network and other individual efforts to compile
591 soil fraction or radiocarbon data. Scientists from the Max Planck Institute for Biogeochemistry
592 joined forces with the Powell Center group to greatly expand the scope and technical complexity
593 of ISRaD. CL, JBM, AH, GM, CS, SS, KH, JB, SC, GMc, and ST designed and built ISRaD as
594 well as led the preparation of the manuscript. PL, OV, KTB, CR, CHP, CS, KM, and SD provided
595 technical contributions, including coding, to the creation of the database as well as assisted with
596 the ingestion of data. CH, YH, CT, JH, MT, and CEA provided large datasets or data compilations.
597 AAB, MK, AK, EMS, AP, AT, JS, LV, SFvF and RW contributed to the conceptual framing of
598 ISRaD and assisted with data ingestion. All authors read and commented on the manuscript.

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607 Any use of trade, firm, or product names is for descriptive purposes only and does not imply
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Tables

Table 1. The number of data points currently included at each hierarchical level in ISRaD v1.0.

Entries	Sites	Profiles	Layers	Fractions	Incubations	Interstitial	Fluxes
212	550	1854	7734	3910	1978	353	2119

Table 2. Details of some core calculations included with ISRaD_extra. Additional variables will be regularly added to ISRaD_extra, an up-to-date list can be found at soilradiocarbon.org.

Operation	Purpose	Output
fill_dates	Radiocarbon calculations and unit conversions often require the year of measurement.	If no date is reported for fraction and/or incubation observation dates, this function replaces those empty cells with the mandatory layer observation date.
fill_14c	In some studies, only fraction modern (FM) units are reported	If no $\Delta^{14}\text{C}$ values are reported, they are calculated from FM and the measurement date.
fill_coords	Spatial coordinates are required to plot soil profiles and to extract geospatial data. Profile level coordinates are often not reported in publications.	If no spatial coordinates are specified for a profile, this function fills those cells with the site coordinates, which are required for template ingestion.
delta_delta	Delta-delta ($\Delta\Delta$) is the offset between the $\Delta^{14}\text{C}$ ratio of the atmosphere and that of a sample during the year of collection and is a useful way to compare radiocarbon data across a range of collection years.	This function calculates the $\Delta\Delta$ values for all radiocarbon measurements in the database, using the profile coordinates and the year of observation to extract an atmospheric radiocarbon value for the region of sample collection. The output is appended as a new variable, e.g. <code>lyr_dd14c</code> .
fill_FM	In some studies, only $\Delta^{14}\text{C}$ values are reported.	If no FM values reported, they are calculated from $\Delta^{14}\text{C}$ values.
CStocks	Measurements of carbon concentration are not, on their own, good estimates of the mass of carbon in soils. Bulk density and soil layer depth information is also needed.	If not measured directly, organic carbon concentration is filled with total carbon concentration (carbonates are accounted for only if reported). Then, with user-supplied bulk density, these values are used to calculate the mass of carbon in each soil layer (i.e., C stocks).
fill_expert	In some cases, data measured at one extent may be reasonably substituted at another extent for the purposes of conducting comparisons across incomplete datasets	Original reported data can be merged with expert suggested data to provide unreported bulk layer values. These estimates are not from original studies, and may be approximations, but they are useful for large-scale global analyses.

geospatial.climate	Across a wide range of datasets, basic climate variables are inconsistently measured and reported. The purpose of this function is to fill separate, geospatially-estimated, climate parameters with a consistent source and scale.	This function uses the site coordinates to pull climate, meteorological, soil and other parameters from known global scale source datasets. At present, we use climate data from WorldClim v1.4 (http://www.worldclim.org/bioclim) and soil classification and characteristics from ISRIC (https://www.isric.org/explore/soilgrids)
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Figure Captions

Figure 1. Conceptual diagram of an entry in the database. Each box represents a table in an entry; the horizontal bars distinguish the hierarchical levels of the database. Arrows show the hierarchical relationship between and among levels of the database. Time is considered at the profile level, as this is the coarsest spatial scale for which observational data are reported. Every time a profile is sampled a unique profile identifier must be generated, consisting of the profile name combined with the profile observation date, which is then linked to all measurements made at or below the profile level of the hierarchy.

Figure 2. An entity relationship diagram for the International Soil Radiocarbon Database (ISRaD). A short description of the required variables for each entity are shown along with the field name used in the database and the variable data type. Crow's foot connections with a straight line indicate mandatory daughter entities (one or more), whereas a crow's foot with an open circle indicates optional (zero or more) daughter entities. The "*" indicates entries indicate keys, or linking variables, which are repeated at each successive level of the ISRaD hierarchy. The "^" indicates conditionally required values. A full list of non-required variables is available in the Template Information File.

Figure 3. One key feature of the ISRaD structure is the ability to classify and categorize data generated from diverse methods for fractionating soils. The ISRaD approach requires specification of the fractionation scheme applied, which may include but is not limited to: density (A), aggregate (B), and/or particle size (C) separations. In each of these examples, the fraction data is linked to a specific soil layer. Classification of the fractionation scheme along with several other fields that specify the nature of the fractionation method allow for an accurate partitioning of mass between the individual fractions, such that the total mass of the soil layer can be reconstructed. A proper accounting of mass attributable to each soil fraction, which in some cases may be derived from more complicated multistep or sequential fractionations (D), is essential in order to compare measurements across these diverse methods.

Figure 4. Geographic location of sites currently included in ISRaD v1.0. Circles that appear darker in color indicate multiple overlapping sites at the resolution of the map.

Figure 5. A simplified depiction of the ISRaD governance pyramid, where the scientific steering committee is responsible for approving major management decisions and data maintainers are responsible for implementing broad changes, but data contributors and users are the primary drivers of the evolution of the data product.

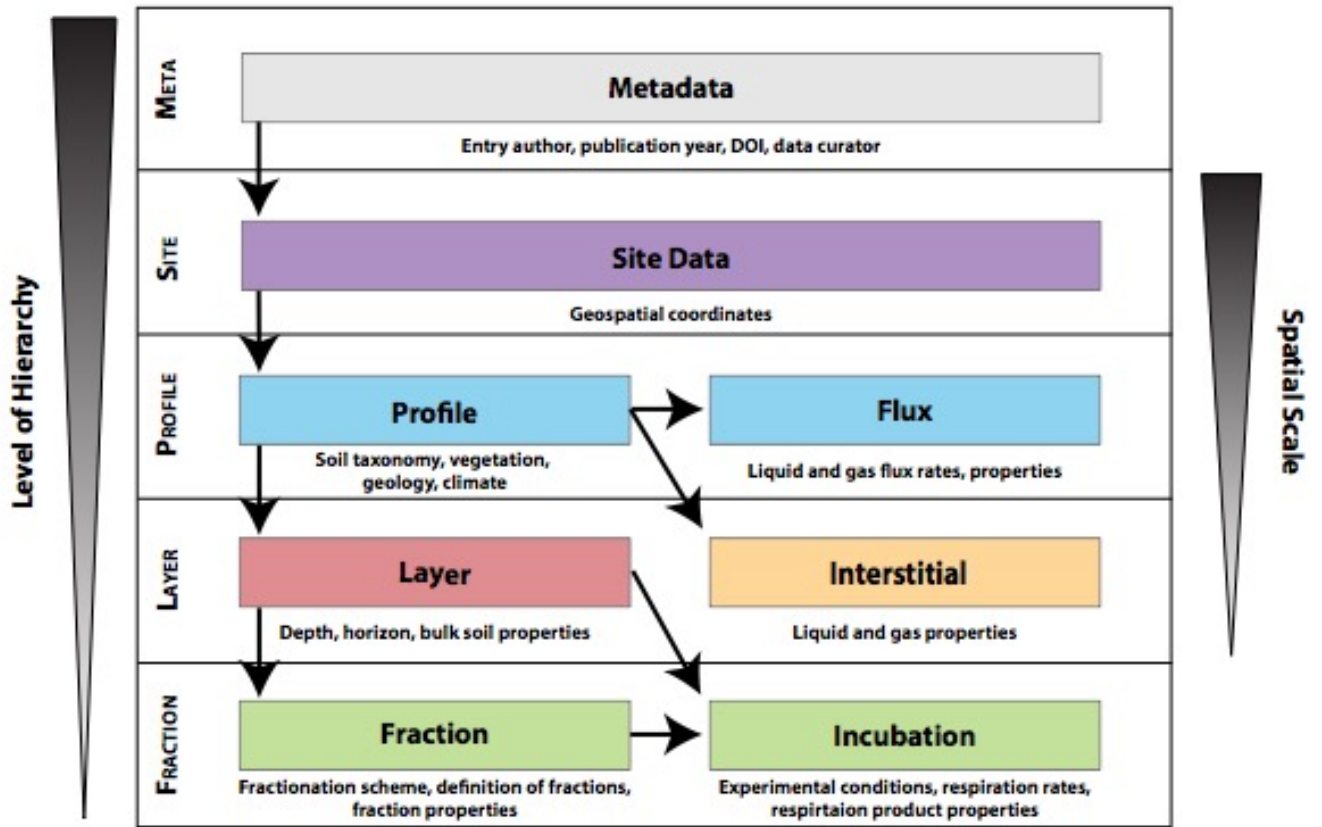


Figure 1.

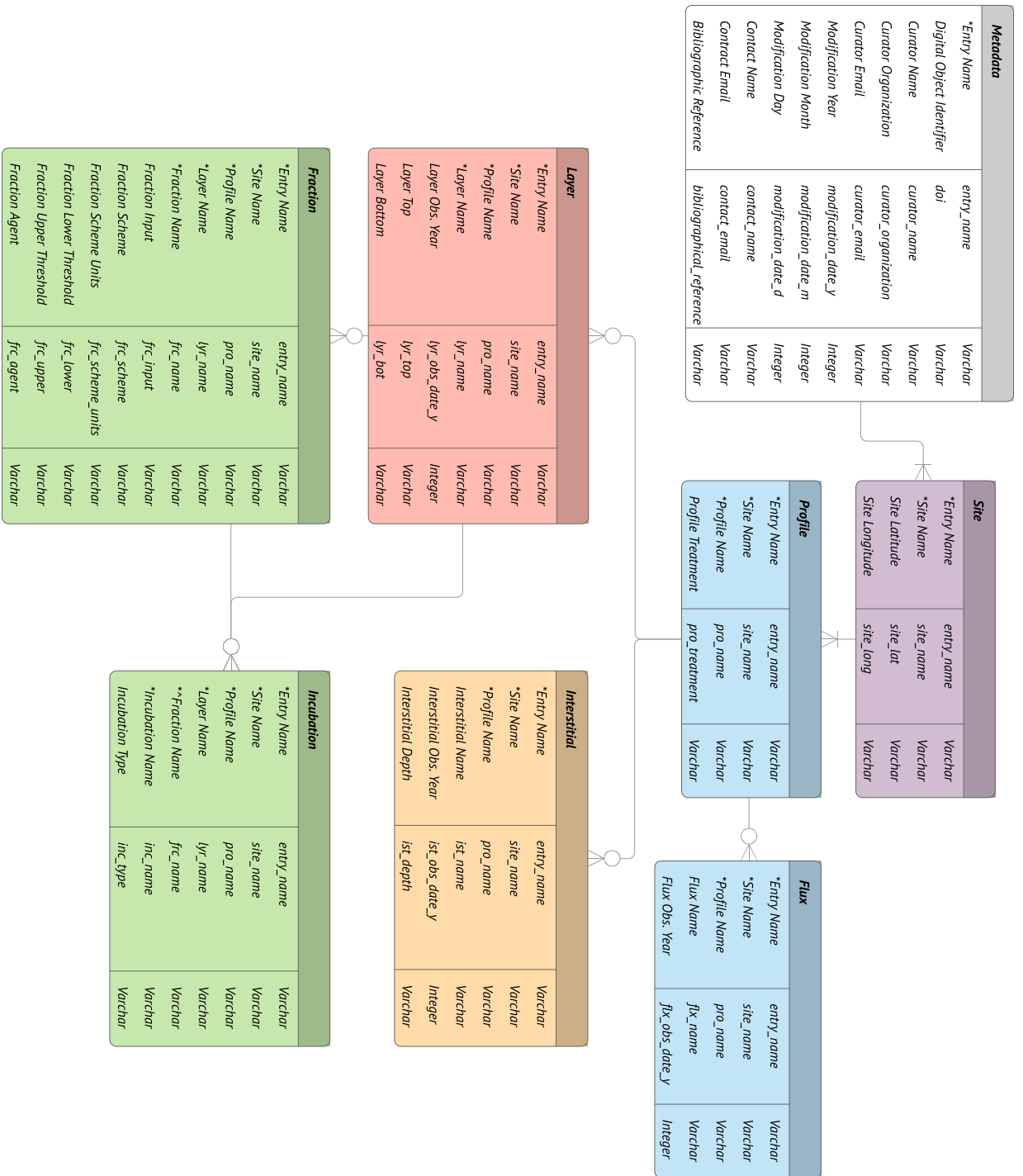


Figure 2.

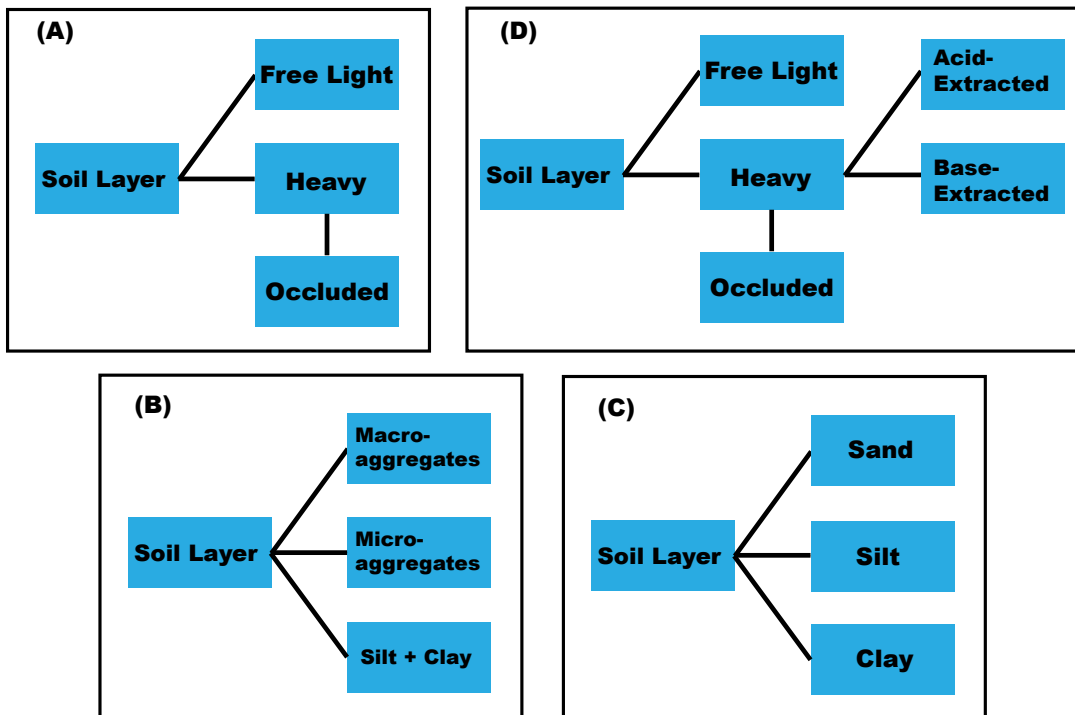


Figure 3.

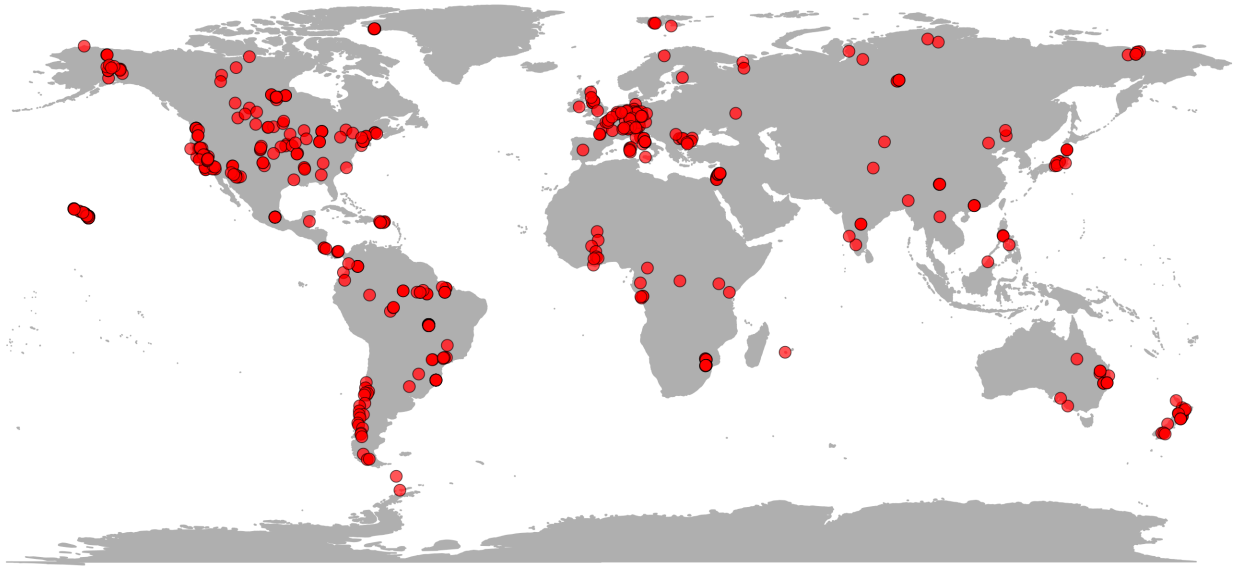


Figure 4.

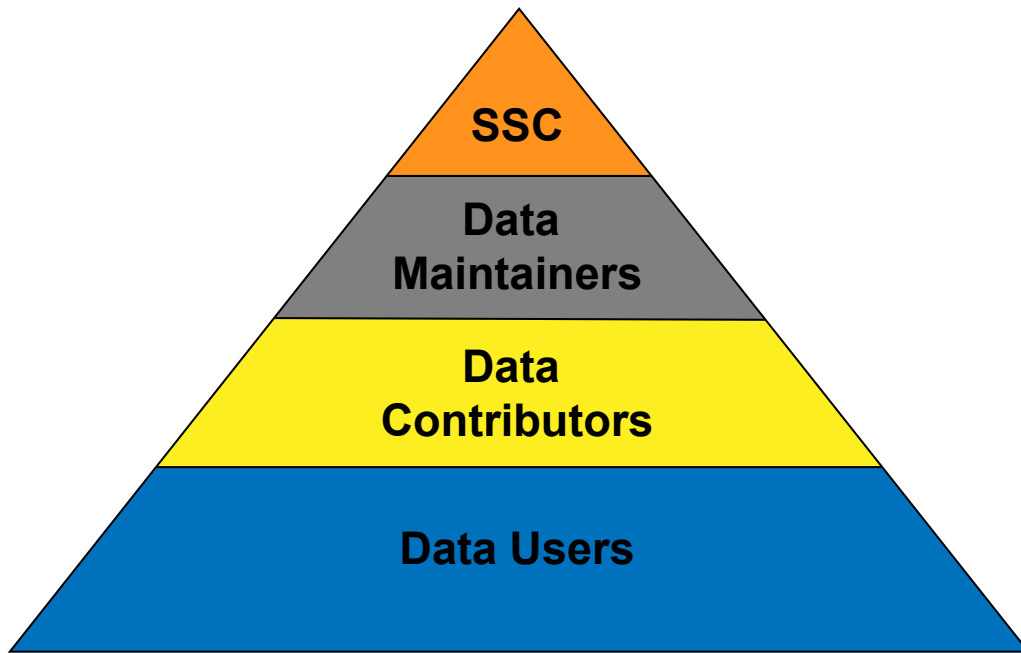


Figure 5.