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A global database of soil respiration data

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Abstract

Soil respiration – R_S, the flux of autotropically- and heterotrophically-generated CO_2 from the soil to the atmosphere – remains the least well-constrained component of the terrestrial C cycle. Here we introduce the SRDB database, a near-universal compendium of published R_S data, and make it available to the scientific community both as a traditional static archive and as a dynamic community database that will be updated over time by interested users. The database encompasses all published studies that report one of the following data measured in the field (not laboratory): annual R_S, mean seasonal R_S, a seasonal or annual partitioning of R_S into its sources fluxes, R_S temperature response (Q_{10}), or R_S at 10 °C. Its orientation is thus to seasonal and annual fluxes, not shorter-term or chamber-specific measurements. To date, data from 818 studies have been entered into the database, constituting 3379 records. The data span the measurement years 1961–2007 and are dominated by temperate, well-drained forests. We briefly examine some aspects of the SRDB data – mean annual R_S fluxes and their correlation with other carbon fluxes, R_S variability, temperature sensitivities, and the partitioning of R_S source flux – and suggest some potential lines of research that could be explored using these data. The SRDB database described here is available online in a permanent archive as well as via a project-hosting repository; the latter source leverages open-source software technologies to encourage wider participation in the database's future development. Ultimately, we hope that the updating of, and corrections to, the SRDB will become a shared project, managed by the users of these data in the scientific community.

1 Introduction

Soil respiration – R_S, the flux of carbon dioxide from the soil surface to the atmosphere – comprises the second-largest terrestrial carbon (C) flux (IPCC, 2001; Raich and Potter, 1995); at 75–100 Pg C yr^{-1}, it is an order of magnitude larger than anthropogenic

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fossil fuel combustion (Boden et al., 2009), implying that ∼10% of atmospheric CO_2 cycles through the soil annually (Reichstein and Beer, 2008). This large flux comes from a large pool – globally, soils store twice as much C as is in the atmosphere (Tarnocai et al., 2009; Post et al., 1982) – and given that climate models predict mid- and high-latitude warming throughout this century (IPCC, 2007), a critical question is whether enhanced R_S will constitute a significant climate feedback (Jenkinson, 1991; Knorr et al., 2005; Davidson and Janssens, 2006). Such a feedback would have significant consequences for the global C cycle and rates of climate change (Jones et al., 2003; Rustad et al., 2000) and affect policy decisions based on the valuation of terrestrial C fluxes (Wise et al., 2009).

The spatial variability of R_S, and our inability to measure it remotely, remain significant constraints to regional and global evaluations of this feedback potential; modeling efforts linking observations at different scales are critical to future progress in this arena (Reichstein and Beer, 2008). Because of its high variability, inaccessibility of the soil medium, and high cost of measurement instruments (Savage et al., 2008), R_S remains the least well constrained component of the terrestrial C cycle (Trumbore, 2006; Davidson et al., 2006). As the integrated result of a broad spectrum of autotrophic and heterotrophic respiratory processes operating under wildly varying environmental constraints, the temporal and spatial dynamics of R_S remain difficult to model or predict (Zobitz et al., 2008).

A better understanding of R_S flux dynamics will come from elucidating the integrated effects of environmental constraints on soil biotic and abiotic processes, based on the kinetic properties of soil organic compounds (Davidson and Janssens, 2006). It is also important, however, to leverage the thousands of R_S observations made over decades (Singh and Gupta, 1977; Raich and Schlesinger, 1992; Schlesinger, 1977; Chen and Tian, 2005; Hibbard et al., 2005). This is particularly important for understanding R_S, as it has been almost 20 years since the last comprehensive R_S data collection and meta-analysis was published (Raich and Schlesinger, 1992); 80% of R_S studies have appeared since that time (Fig. 1), a number large enough to deter or limit most data collection projects. Nonetheless, a global, community R_S data set would be useful both on its own and in conjunction with remote sensing, eddy covariance, soils and other databases that either exist or are being assembled, opening the possibility of identifying large-scale patterns that are not – or only rarely (Epron et al., 2004) – visible in individual studies. Such meta-analyses can result in unexpected or interesting results, even if they are sometimes subject to particular statistical issues, e.g., the "file drawer" problem (Rosenthal, 1979). For example, a database recently assembled to support a meta-analysis of C balance in relation to stand age (Luyssaert et al., 2007) led to a provocative hypothesis about the controls on forest C sequestration (Luyssaert et al., 2008). Other reviews and meta-analyses have drawn similarly broad, if tentative, inferences on ecosystem structure and function (Elser et al., 2007; LeBauer and Treseder, 2008; Lusk and Warton, 2007; Rustad et al., 2001; Wan et al., 2001; Hanson et al., 2000).

Meta-analyses are thus not new, but recent efforts to assemble large shared data sets in the earth system sciences make use of Internet-facing databases and modern computational tools, allowing for a vastly expanded pool of potential users, increased analytical power, and increased public trust (Anonymous, 2009). New data-sharing models can also be applied; in particular, technologies such as version control, developed and exploited by the open-source software movement (Raymond, 2001), enable a "living" database that is continually expanded and improved by its users. These new technologies drive the goals of this study: to assemble a near-universal database of all published R_S data and make it available to the scientific community, both as a traditional static archive and as a dynamic community database.

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2 Methods

2.1 Data sources and inclusion criteria

We collected all available studies in the peer-reviewed scientific literature reporting R_S measured in the field; lab incubation studies were not included. The ISI Web of Science™ constituted the primary source of published studies; search terms used included "soil respiration", "soil CO_2 evolution", etc., and were conducted through the 2008 publication year. We used each study's title and abstract to decide whether to acquire it; ~40% of the almost 4700 studies were acquired and examined. To qualify for inclusion, a study had to report at least one of the following data:

- Annual R_S
- Mean seasonal R_S
- Annual or seasonal partitioning of R_S sources
- Q_{10} and associated temperature range
- R_{10} (R_S at 10 °C)

If at least one of these data was reported, or could be calculated with few or no assumptions, e.g., easily estimated from points in a figure, the study was entered into the database. Short-term experiments (i.e., R_S measurements made over less than 1–2 weeks) were not entered unless the study authors extrapolated their results to seasonal or annual values; the database is in general not designed to accommodate instantaneous or short-term measurements. In general we did not do additional research to find older publications that might not be listed in the Web of Science. Data were however crosschecked against a number of other R_S data collections and meta-analyses (Hibbard et al., 2005; Chen and Tian, 2005; Burton et al., 2008; Sotta et al., 2004).

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2.2 Database structure

The database ("SRDB") is composed of two separate data files: a "studies" file, listing the publication information for all studies acquired, examined, entered or rejected, etc., and a "data" file, holding the acquired R_S data. An index number is used to map entries between the two files. The primary R_S units used were $g\,C\,m^{-2}\,yr^{-1}$ (for annual fluxes) and $\mu mol\,m^{-2}\,s^{-1}$ (for mean seasonal fluxes); values were converted as necessary from those given by study authors. A variety of ancillary data were also entered when reported, including site-related and experimental data, information on ecosystem structure and function, methods used, etc.; we assumed a 12:44 ratio of C to CO_2 molecular weights, and that biomass was 50% C (unless specified otherwise in the study). Temperate-response functions were categorized following table 10.1 in Luo and Zhou (2006) and Reichstein et al. (2008). The primary data file includes 104 fields; these are summarized in Table 1, and fully documented in included metadata files. A Google Earth (http://earth.google.com/) data layer is included with the database for easy geographic visualization of the included studies.

2.3 Quality control

Some basic quality control has been performed on the data. Map plots were used to identify incorrectly entered location or climate information, and histograms of the primary variables of interest used to flag outliers for special attention. We have also attempted to check for basic data incompatibilities (e.g., cases where R_S > total ecosystem respiration), and to identify duplicate entries. Two metadata fields are used to alert SRDB users to records that are duplicates, or that contain potential problems. It should be emphasized, however, that many errors undoubtedly remain in the database (see Sect. 4.2 below).

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3 Results and discussion

In total, 1932 studies were marked for acquisition, 1853 acquired and examined, and 818 entered into the SRDB database, spanning the publication years 1963–2008 and measurement years 1961–2007. As of this writing the 818 studies resulted in 3379 records (a single study generates multiple records if, e.g., there are multiple years of data, or different sites reported, or different experimental treatments). The countries most frequently represented include USA (1404 records), Canada (308), China (273), Finland (179), Japan (162) and Germany (115); Fig. 2 shows the spatial distribution of the collected data. Temperate-biome studies dominate the database (2373 records), with boreal (415) and tropical (353) also significant. Data from forest (2198 records), grassland (460) and agricultural (453) ecosystems are most frequently reported; upland systems (3084 records) far outnumber wetland ones. A majority of studies took place in unmanipulated ecosystems (2382 records), but data from thinned, burned, CO_2-increase, warmed and fertilized plots are represented as well.

Below we outline, rather than analyze in depth, a few characteristics of the SRDB data and suggest some potential lines of research that could be explored using these data.

3.1 Observed annual fluxes

Mean (± standard deviation) annual R_S fluxes were 109±109, 383±228, 749±426 and 1286±633 g C m^{-2} yr^{-1} for unmanipulated Arctic, boreal, temperate and tropical ecosystems respectively (Fig. 3). Three variables – mean annual temperature, precipitation, and leaf area index – explained ∼41% of the observed variability in annual R_S, in line with previous meta-analyses of these drivers (Raich and Schlesinger, 1992; Reichstein et al., 2003). The annual data also exhibited an increasing temporal trend, driven primarily by air temperature anomaly (Bond-Lamberty and Thomson, 2010). Annual fluxes were correlated with a number of commonly measured C pools and fluxes (Fig. 4); most of these relationships have been noted in previous studies, e.g., that between litterfall and R_S (Raich and Nadelhoffer, 1989; Raich and Schlesinger, 1992; Davidson et al., 2002) or gross primary production and R_S (Hibbard et al., 2005). Some of these correlations raise the possibility of estimating R_S, with an associated error range, from airborne and satellite observations; the lack of such large-scale, observation-driven R_S estimates is a major problem in constraining regional- to global-scale C fluxes (Qi et al., 2002; Rayner et al., 2005; Jones et al., 2003).

3.2 Spatial and temporal variability

The high variability of R_S constitutes a major reason why its measurement and modeling remain so difficult, as it responds to a suite of drivers including temperature, moisture, and vegetation productivity, all at different spatial and temporal scales (Reichstein et al., 2003; Rochette et al., 1991; Rodeghiero and Cescatti, 2008; Saiz et al., 2006; Vincent et al., 2006; Webster et al., 2008). Two measures of variability are defined in the SRDB: interannual variability (the standard deviation of a series of annual R_S values at one place) and spatial variability (the standard deviation of a group of concurrently-measured annual R_S values). The latter poses an analytical problem in that the spatial scale is not defined, although for most studies this should be considered plot-to-plot error, operating on a scale of tens to hundreds of meters. The mean coefficient of variability (standard deviation divided by the mean) in the SRDB is 15–16% for both variables. Spatial and interannual variability are distributed differently, however, with the latter reaching much higher values in some systems (Fig. 5). Ecosystem variability does not scale linearly to regional or global variability, and estimates of the interannual variability of large-scale R_S fluxes are much smaller than these means (Potter and Klooster, 1998; Raich et al., 2002; Bond-Lamberty and Thomson, 2010).

3.3 Temperature sensitivity

Ambient temperature constitutes the dominant – but not only – short-term control on R_S in most boreal and temperate ecosystems, at most points in time (Chen and Tian, 2005); temperate deserts and other dry areas constitute only one of many exceptions to this generalization (Parker et al., 1983; Zhou et al., 2009; Sponseller and Fisher, 2008; Tang et al., 2005). Our understanding of R_S and ecosystem respiration generally (Trumbore, 2006) is less advanced than that of photosynthesis, and most biogeochemical models still use simple, constant-Q_{10} models (originating from van't Hoff, 1898) that – among other problems – have been shown to overestimate low-temperature R_S (Lloyd and Taylor, 1994).

An interesting question to which the SRDB could be applied is how R_S temperature sensitivity changes with temperature, and whether a general temperature-dependent model exists for R_S; if this is the case, most large-scale R_S models, which use a constant Q_{10} response, could be shown to be considerably biased (Chen and Tian, 2005; Tjoelker et al., 2001). The SRDB records the temperature-response model used by individual studies as well as Q_{10} values (the relative R_S change over 10 °C) for a variety of temperature ranges, as this parameter is reported so frequently in the R_S literature. Mean Q_{10} values in the database are 3.3±1.5 for 0–10 °C, 2.9±1.2 for 5–15 °C, 2.6±1.1 for 10–20 °C, and 3.0±1.1 over the entire 0–20 °C range; these means exclude a few extreme (Q_{10}≥10, ∼1% of the data) reported values. This decline is interesting but must be treated with caution for several reasons. First, these values are "apparent" (Davidson and Janssens, 2006) temperature sensitivities, as they are observed in the field and thus constrained by ambient environmental conditions (Zhou et al., 2009), rather than "intrinsic" or theoretical sensitivities. Second, they are not based on a statistically random sample. Finally, the Q_{10} values in the database, already stratified by temperature range, do not further vary with mean annual air temperature, although soil temperature may have a stronger effect on Q_{10} variability than does air temperature (Chen and Tian, 2005).

3.4 Source fluxes of soil respiration

Partitioning R_S into its autotrophic (R_A) and heterotrophic (R_H) source fluxes is important for assessing plant physiology, C allocation, ecosystem C balance, and the climate feedback potential of changes in R_S. The relative responses of R_A and R_H will strongly affect the terrestrial climate feedback under future conditions, at scales from the ecosystem to the globe (Burton et al., 2008; Boone et al., 1998; Curiel Yuste et al., 2007; Lavigne et al., 2003). Broad means have been computed for the relative contribution of R_S source fluxes (Hanson et al., 2000); in addition, Bond-Lamberty et al. (2004) noted a highly significant (R^2=0.8, P<0.001) relationship between R_S and R_H, permitting the estimation of the latter from annual estimates of the former. The much larger data set collected here allows us to re-examine this relationship (Fig. 6); it remains fundamentally the same as that found in Bond-Lamberty et al. (2004), although these data show considerably more scatter. We also note that a few studies examine mycorrhizal (Moyano et al., 2007; Heinemeyer et al., 2007) and geological (Andrews and Schlesinger, 2001) contributions to R_S, although these sources are not broken out in the current database.

4 SRDB access and future development

The SRDB database described here is being released to the scientific community and other interested users, and is available immediately online.

4.1 Database access

A static version of these data is permanently archived at the Oak Ridge National Laboratory's Distributed Active Archive Center (ORNL-DAAC): http://daac.ornl.gov/

There is also a dynamic version of the database, hosted as of this writing on Google Code: http://code.google.com/p/srdb/

The latter version uses version control software (Subversion, http://subversion.tigris.org/), so that researchers can use (check out) current as well as previous versions of the database. It also features online wiki documentation, a mailing list, and other aspects typical of any open-source project. Both archives include the database itself, metadata, and usage notes. Initially the two repositories will hold identical copies, but we anticipate that the dynamic version will be expanded and change with time. For this reason we recommend that citations to this database always include a version number, URL, and download date.

4.2 Weaknesses of the current database

This database is flawed and incomplete, and should be viewed as a "1.0" release. First, there are inevitable data entry mistakes – in unit conversion, language translation, etc. – that will be discovered and corrected. Second, data can be added: new studies appear frequently (91 studies published in 2008 alone were entered, and a similar number have been published in 2009), and missed older ones found. In particular, we suspect that there is substantial data in the Russian- and Chinese-language scientific literatures not currently entered in SRDB. Finally, there are undoubtedly better ways to structure the existing data, and new fields or calculations could be added (for example, the R_S soil moisture response is only cursorily treated in the current database; no error terms are included for Q_{10} and R_{10} estimates; R_S partitioning is limited to a crude autotrophic and heterotrophic separation; Q_{10} estimates are not recorded separately by source flux; etc). For all these reasons, we intend to update the dynamic version of this database, and hope that such updating and corrections will ultimately become a shared project driven by interested users of these data; this will make it a true community database that over time could be linked with other, similar projects.

5 Conclusion

The SRDB is designed to capture and make available for analysis the large number of R_S studies published over the last four decades. It will also, we hope, be one of the first such databases in the earth sciences to leverage open-source software technologies, resulting in a dynamic, shared, and more powerful data resource for interested users.

The science community will determine how, and if, it changes in the future, and the uses to which these data will be put.

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Table 1. Categories of database fields and examples of data included for the soil respiration (R_S) database's main "data" file. A separate "studies" file contains bibliographic information for all studies, indexed by a study number common to both files.

Category	Example fields
General site information	Country; latitude and longitude; elevation; biome; ecosystem type; time since disturbance; species; leaf habit; soil type and drainage; mean annual climate
Measurements	Study year; years of data; site name; manipulation performed; CO_2 measurement method
R_S data	Annual R_S; plot error; interannual error; source flux contributions; seasonal means; R_S at 10 °C
Temperature response	Response direction; model form; temperature depth in soil; Q_{10} values for various temperature ranges
Moisture response	Response direction
Ancillary pools and fluxes	Major carbon pools and fluxes; leaf area index; basal area; nitrogen deposition; methane flux
Record metadata	Record number; entry date; study number; data contributor; problem flag; duplicate flag; notes

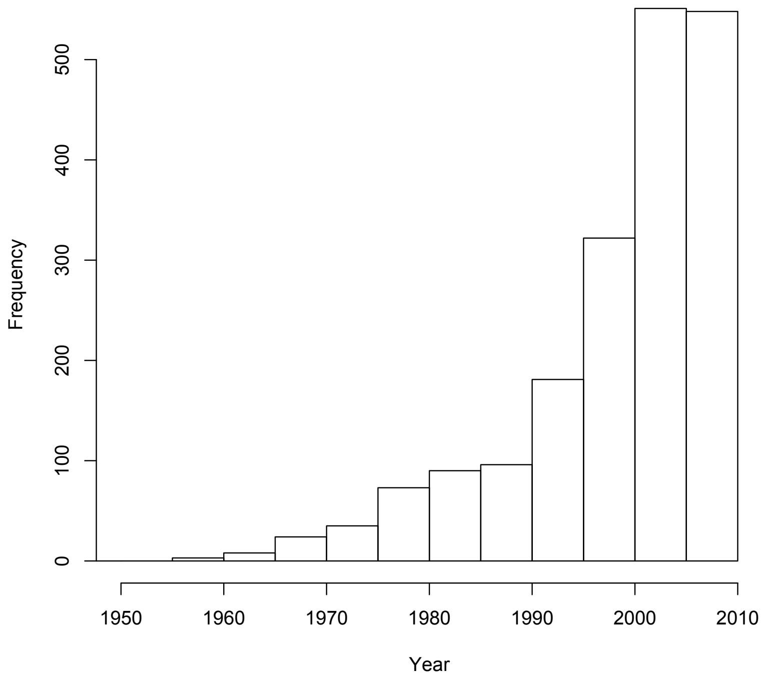

Fig. 1. Soil respiration studies over time, from the ISI Web of Science™ database.

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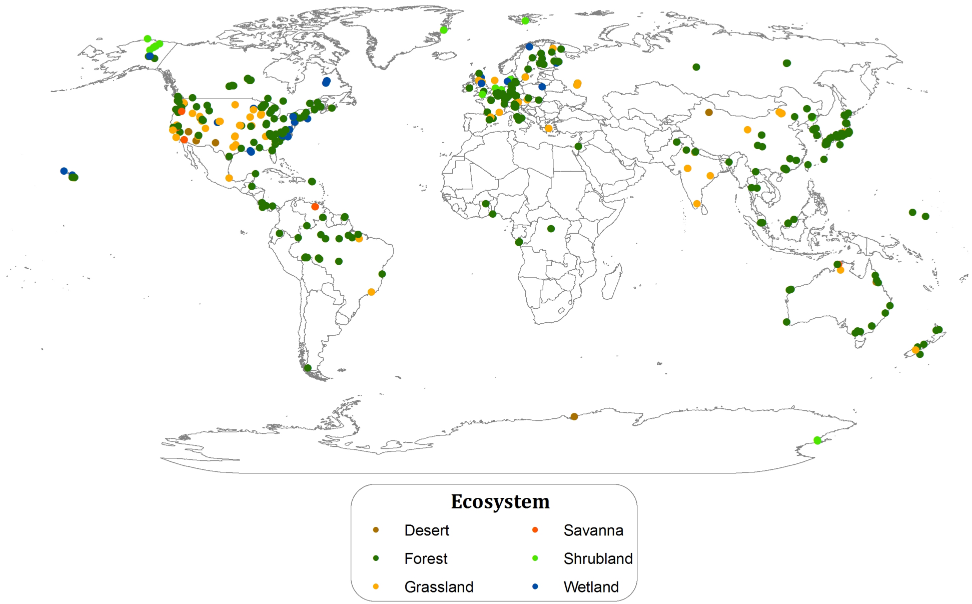

Fig. 2. Location of SRDB database observations (dots), by ecosystem type. A Google Earth™ data layer is included with the database for more detailed spatial views.

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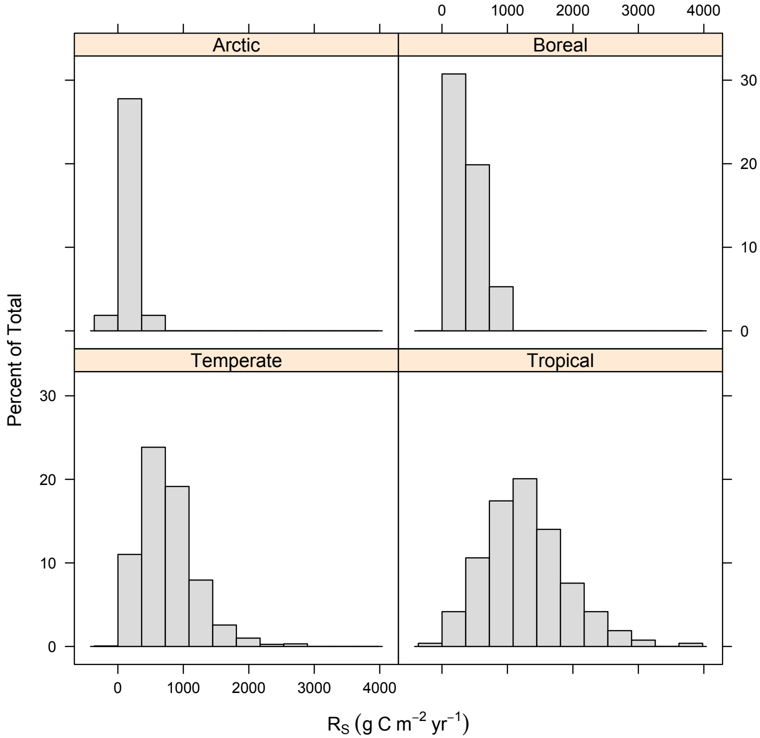

Fig. 3. Annual soil respiration (R_S) fluxes observed in the field, unmanipulated plots only, by biome. Relative histograms are shown; total observations are N=54, 322, 1598 and 264 for Arctic, boreal, temperate and tropical, respectively.

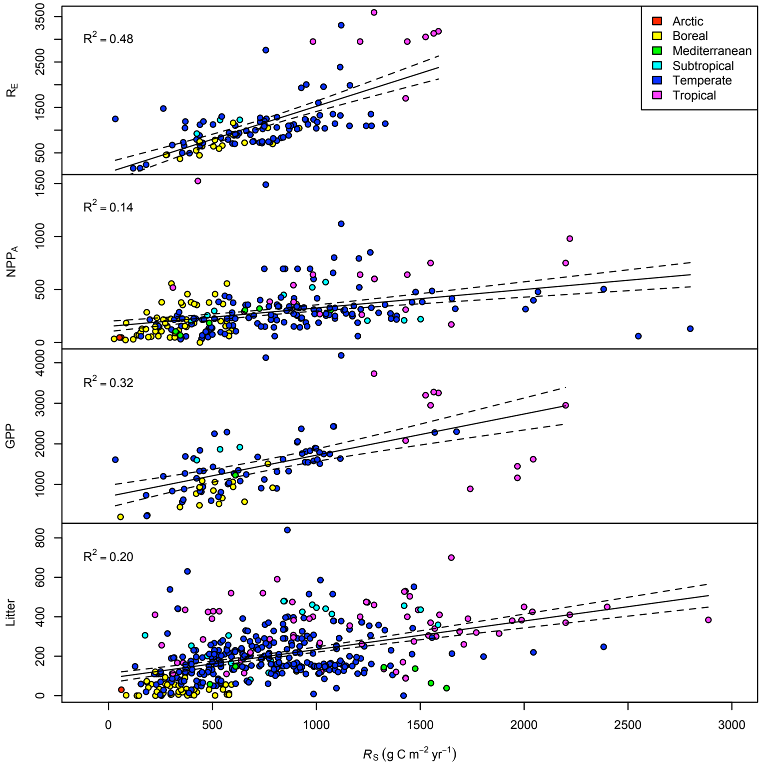

Fig. 4. Correlation between annual soil respiration (R_S) ecosystem carbon fluxes, by biome, unmanipulated field studies only. Fluxes include total ecosystem respiration (R_E), aboveground net primary production (NPP_A), gross primary production (GPP), and aboveground litter flux; all are $g\,C\,m^{-2}\,yr^{-1}$. Solid lines show linear regression fit (model adjusted R^2 given in each panel); dashed lines are 95% confidence intervals.

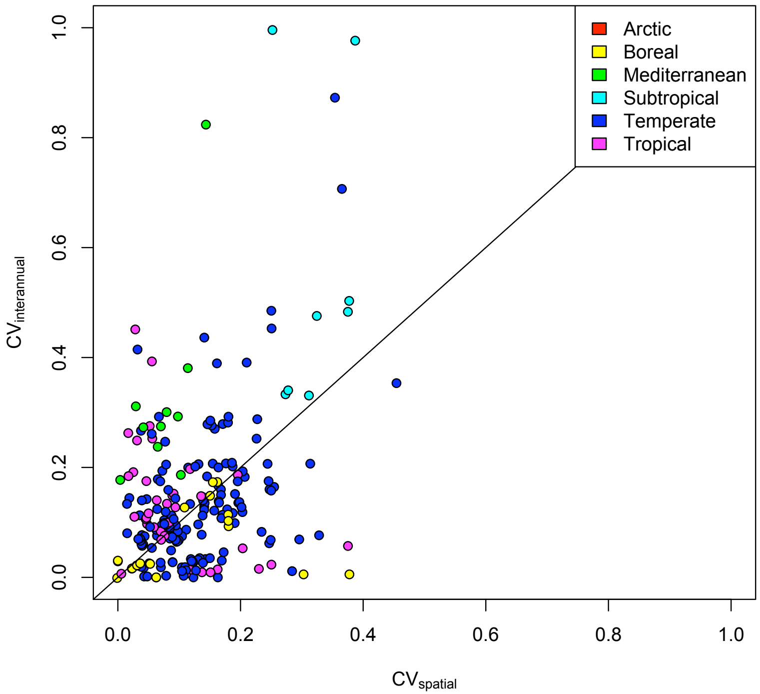

Fig. 5. Spatial versus interannual variability in soil respiration, by biome. Data are displayed as coefficients of variability (CV); solid line shows the 1:1 relationship.

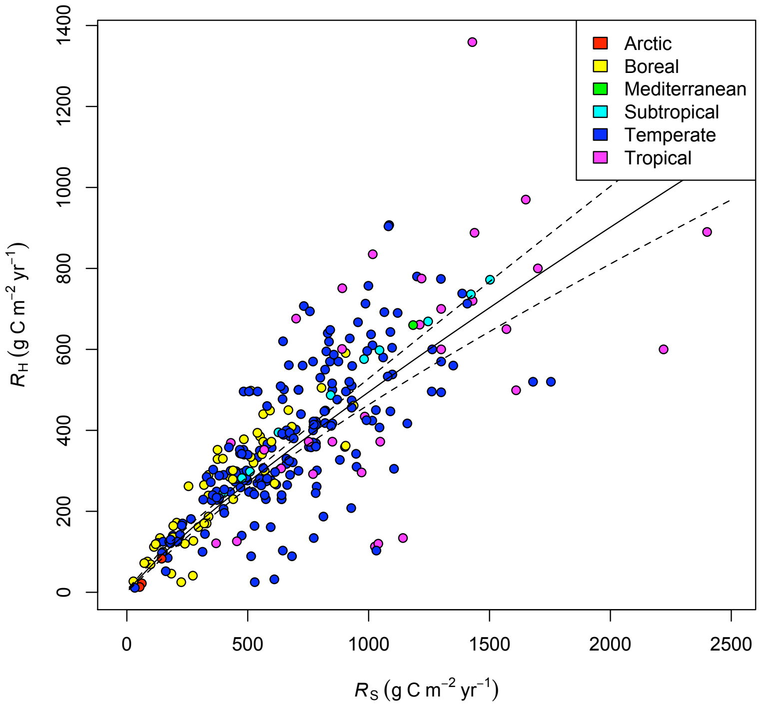

Fig. 6. Relationship between soil respiration (R_S) and heterotrophic soil respiration (R_H) in the database, by biome, following Bond-Lamberty et al. (2004). Fitted model shown (solid line) is $\ln(R_H)=0.22+0.87\ln(R_S)$, $R^2=0.64$, $P<0.001$; dashed lines show 95% confidence interval. Two studies (Grier and Logan, 1977; Thierron and Laudelout, 1996) in the database were excluded from this figure based on a Cook's influential outlier test (R Development Core Team, 2009).

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