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Title

Twelve years of TRY – towards a third generation of plant trait data assimilation and sharing

Running title

The TRY plant trait database revisited

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Abstract

Plant traits – the morphological, anatomical, physiological, biochemical and phenological characteristics of plants – determine how plants respond to environmental factors, affect other trophic levels, and influence ecosystems properties and the derived benefits and detriments to people. Plant trait data thus represent the essential basis for a vast area of research spanning from evolutionary biology, community and functional ecology, to biodiversity conservation, ecosystem and landscape management, restoration, and biogeography and earth system modelling. Since its foundation in 2007, the TRY database of plant traits has grown continuously. It now provides unprecedented data coverage under an open access data policy and is the main plant trait database used by the research community worldwide. Increasingly the TRY database also supports new frontiers of trait-based plant research, including the identification of data gaps and the subsequent mobilization or measurement of new data. To support this development, in this article we evaluate the extent of the trait data compiled in TRY and analyse emerging patterns of data coverage and representativeness. Best species coverage is achieved for categorical traits. For example, we have achieved almost nearly complete global coverage of 'plant growth form'. However, most traits relevant for ecology and vegetation modelling are characterized by intraspecific variation and trait-environmental relationships; therefore, for many purposes, these traits have to be measured on individual plants in their respective environment. Despite unprecedented data coverage, we observe a humbling lack of completeness and representativeness in many aspects. Due to the sheer amount of data in the TRY database, machine learning for trait prediction is promising - but does not add new data. We, therefore, conclude that reducing data gaps and biases in the TRY database requires a coordinated approach to data mobilization and in-situ trait measurements. This can only be achieved in collaboration with other initiatives.

Keywords:

Plant traits, TRY plant trait database, data integration, data coverage, data representativeness, functional diversity

Introduction

Plant traits – the morphological, anatomical, physiological, biochemical and phenological characteristics of plants measurable at the individual plant level (Violle et al., 2007) – reflect the outcome of evolutionary and community assembly processes responding to abiotic and biotic environmental constraints (Valladares, Gianoli, & Gomez, 2007). Traits and trait syndromes (recurrent coordinated expressions of multiple traits) determine how plants perform and respond to environmental factors (Grime, 1974; Wright et al., 2017), affect other trophic levels (Lavorel et al., 2013; Loranger et al., 2012; Loranger et al., 2013), and provide a link from species richness to functional diversity, which influences ecosystems properties and derived benefits and detriments to people (Aerts & Chapin, 2000; Díaz et al., 2004; Díaz et al., 2007; Garnier & Navas, 2011; Grime, 2001, 2006; Lavorel et al., 2015; Lavorel & Garnier, 2002). In the context of the Global Earth Observation Biodiversity Observation Network (GEO BON) species traits are considered an Essential Biodiversity Variable (EBV) to inform policy about biodiversity change (Kissling et al., 2018; Pereira et al., 2013). A focus on traits and trait syndromes, therefore, provides a crucial basis for quantitative and predictive ecology, ecologically informed landscape conservation and the global change science-policy interface (Díaz et al., 2016; McGill, Enquist, Weiher, & Westoby, 2006; Westoby & Wright, 2006). To fully realize this potential, plant trait data not only need to be available and accessible in appropriate quantity and quality but also representative for the scales of inference and research questions at hand (König et al., 2019). With an increasing number of studies with large geographic and broad taxonomic scope, the latter becomes particularly challenging. Here we analyse where the TRY plant trait database stands with respect to representativeness and coverage after 12 years of operation. We further review the mechanisms and emergent dynamics helping to increase both.

A global database of plant traits – a brief history

Several research groups have developed major plant trait databases with remarkable success, e.g. the Ecological Flora of the British Islands (Fitter & Peat 1994), the Seed Information Database (Royal Botanical Gardens KEW, 2001), BIOPOP (Poschlod, Kleyer, Jackel, Dannemann, & Tackenberg, 2003), GLOPNET (Wright et al., 2004), BiolFlor (Klotz, Kühn, & Durka, 2002), LEDA (Kleyer et al., 2008), BROT (Paula & Pausas, 2009), USDA PLANTSdata (Green, 2009), BRIDGE (Baraloto et al., 2010). However, these databases have either been focused on particular regions (Biolflor, LEDA, BIOPOP, USDA Plants, Ecological Flora of the British Islands, BRIDGE) or specific traits (GLOPNET, SID). A 'database of databases' had been in discussion for some time, but funding was difficult. Finally, at a joint workshop of the International Geosphere-Biosphere Program (IGBP) and DIVERSITAS, the TRY database was proposed with the explicit assignment to improve the availability and accessibility of plant trait data for ecology and earth system sciences. The Max Planck Institute for Biogeochemistry (MPI-BGC) offered to host the database and the different groups joined forces for this community-driven program. Two factors were key to the success of TRY: the support and trust of leaders in the field of functional plant ecology submitting large databases and the long-term funding by the Max Planck Society, the MPI-BGC and the German Centre for Integrative Biodiversity Research (iDiv) Halle-

Jena-Leipzig, which has enabled the continuous development of the TRY database (Kattge et al., 2011a) (https://www.try-db.org).

At the time of the foundation of TRY, data sharing was not yet a common practice (Kattge et al., 2011a; Reichman, Jones, & Schildhauer, 2011). This was an important obstacle for scientific progress. The first important step of the initiative was, therefore, to jointly develop a data sharing policy. This was based on permission of dataset owners and a 'give-and-take' system: the right to request data was coupled to data contribution to keep the TRY database growing. Exceptions were data requests for vegetation modelling projects, as modellers typically do not own plant trait data. At an open sDiv workshop of the TRY initiative in 2013, the members decided to offer the opportunity to make data publicly available and trait data contribution was no longer a requirement for data access. In 2014 this decision was implemented in the TRY Data Portal and was immediately followed by an 'explosion' of the number of data requests (Figure1a): TRY started to serve more than 1000 requests per year, so that as of July 2019 about 700 million trait records accompanied by 3 billion ancillary data have been released for 7000 requests. Since 2019 the TRY database is open access under a Creative Commons Attribution license (CC BY 4.0, https://creativecommons.org/licenses/by/4.0): anyone can use and redistribute data received via TRY under the only condition of appropriate citation of the TRY database and the references of contributing datasets. Restriction of data access now is the exception and limited to 2(+2) years, after which the datasets become public.

Since 2014 the TRY Data Portal (https://www.try-db.org/TryWeb/dp.php) has become the central access point of the TRY database: the portal organizes data uploads, searches, and requests. In addition, it provides accounts for dataset custodians (the individual who directly contributed the dataset) and principal investigators of data requests, enables interaction of data contributors, management and users, and provides precise bookkeeping for dataset custodians about the use of their trait data via TRY. The TRY Data Portal also provides a link to the TRY File Archive (https://www.try-db.org/TryWeb/Data.php), which offers climate and soil data for TRY measurement sites, and standardized categorical traits relevant to attribute species to plant functional types. In addition, the TRY File Archive provides the opportunity to publish plant trait datasets and receive a DOI.

As of July 2019 trait data via TRY contributed to about 250 scientific applications and publications (Figure1a), among these 202 peer-reviewed publications in 83 different scientific journals, covering a broad range of topics, from 'Landscape and Urban planning' to 'Geoscientific Model Development'. A cluster analysis of keywords from the peer-reviewed publications shows eight clusters around the central keywords 'plant traits', 'climate change', 'diversity', 'biodiversity', 'functional diversity', 'vegetation' and 'ecology' (Figure 2). This seems to reflect the expectation that improved knowledge of plant functional diversity, mediated by plant traits, will help to better understand vegetation feedbacks to climate change and drivers and consequences of plant biodiversity loss. Citations of publications using trait data via TRY have increased exponentially, leading to about 10,000 citations and an h-factor of 46 for the TRY database (Figure 1b).

The TRY database comprises 602 datasets from 765 data contributors (as of July 2019, Figure 1a, Table 5). The dynamics of the number of datasets in TRY indicates an increasing success of calls to the scientific community for data contribution in 2007, 2013 and 2019. When the manuscript was submitted, data contributions responding to the call in 2019 were not yet fully integrated into the TRY database. Therefore all analyses presented in this paper are based on versions 1 to 5 of the TRY database (Table 1). TRY version 5, published on 26 March 2019, contains 387 datasets providing 11.8 million trait records, accompanied by 35 million ancillary data, for 2091 traits and 280,000 plant taxa, mostly at the species level (Table 2). Data coverage is still driven by a few large (often integrated) databases, but increasingly small datasets (mostly primary data) contribute to the overall coverage (Figure 3a). Plant trait data in TRY can be traced to >10,000 original sources. This highlights the breadth of data integrated in the TRY database and its nature as database of databases, a 'second generation of data pooling' (M. Westoby, pers. comm.).

We now observe a tendency that new trait-based research is increasingly planned against the background of the TRY database. Coverage and availability of trait data in TRY stimulate trait-based research, which then often leads to the identification of unexpected data gaps. This often motivates data mobilization and/or new measurements, which improve the availability of plant trait data for the research community, and - if contributed to TRY - help the database grow. Examples for such a 'feed-forward data assimilation loop' are provided in Box 1.

To support this process, in this article, we take stock of the data compiled in the TRY database and present emerging pattern of data coverage and representativeness with a focus on the identification of principal and systematic gaps. Finally, we discuss ways forward and the potential future role of the TRY initiative for the research community.

Table 1: TRY database versions

Version	Data acquisition & import			Data release			Status
1	Oct 2007	–	Jul 2009	Oct 2008	–	Apr 2011	restricted, give-and-take
2	Jul 2009	–	Apr 2011	Apr 2011	–	Dec 2014	restricted, give-and-take
3	Apr 2011	–	Apr 2014	Dec 2014	–	Jul 2017	optionally open access
4	Apr 2014	–	Feb 2017	Jul 2017	–	Mar 2019	optionally open access
5	Feb 2017	–	Mar 2019	Mar 2019	–		open access
6	Mar 2019	–					open access

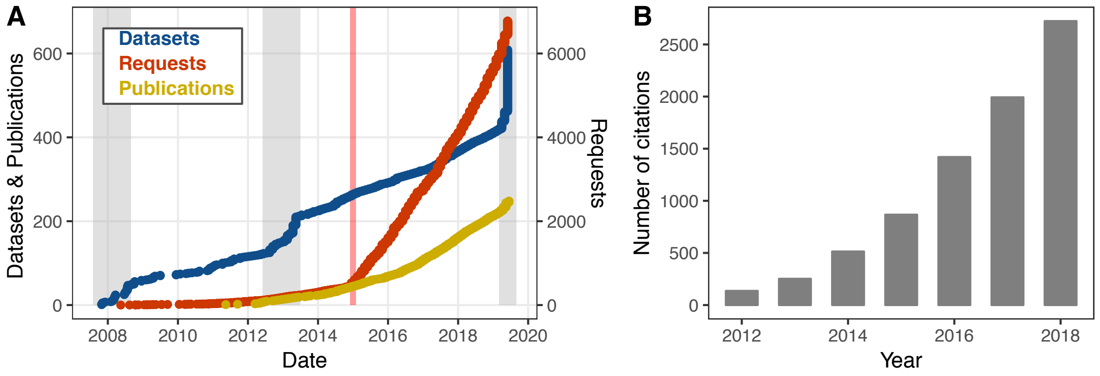

Figure 1: TRY performance statistics, status 1 July 2019: (A) cumulative numbers of datasets and publications (left axis) and data requests (right axis); light grey vertical bars indicate calls for data contribution, the red vertical bar indicates the date of opening TRY to the public. (B) Number of citations for publications using trait data via TRY (Google Scholar).

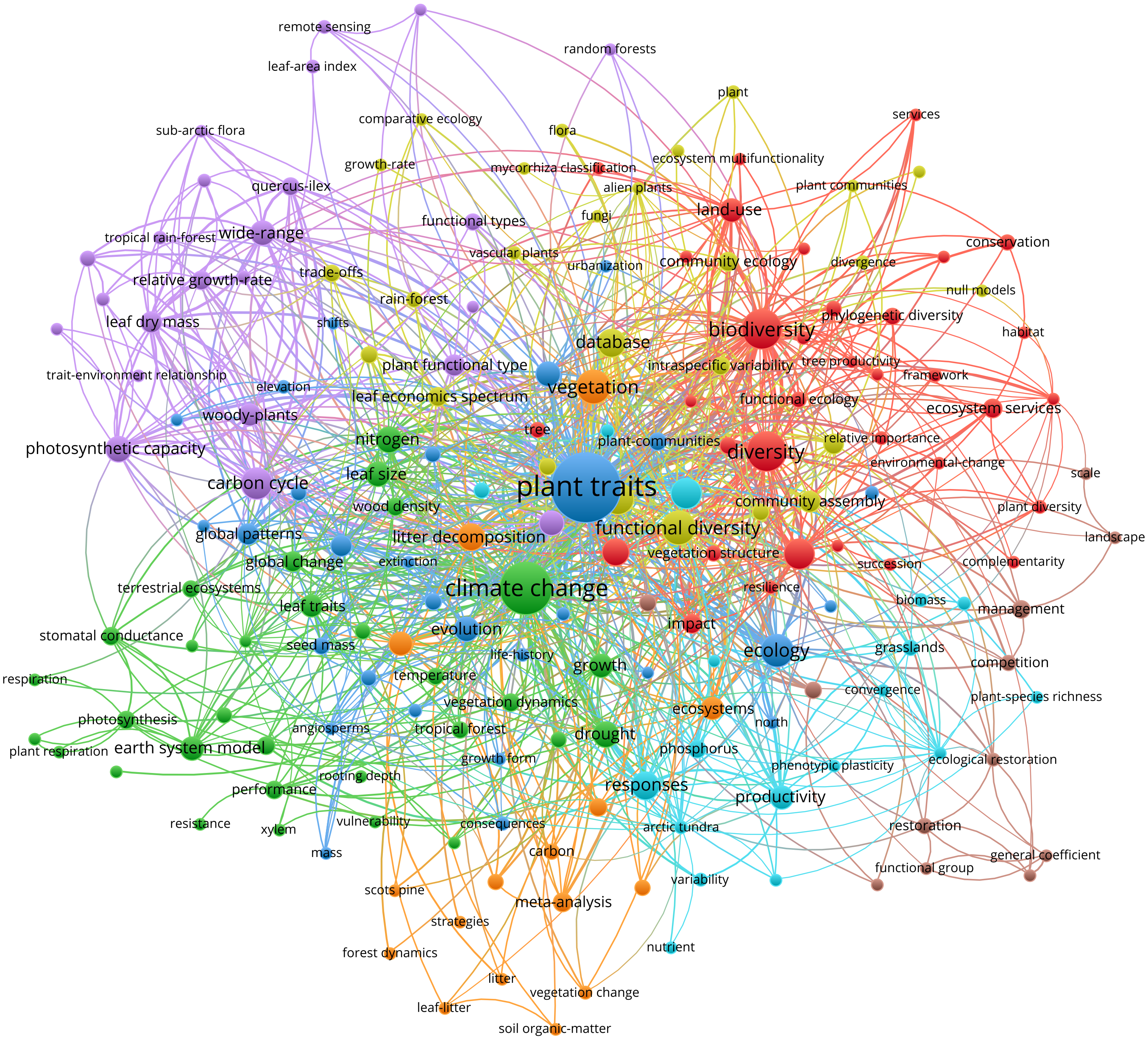

Figure 2: Cluster analysis of keywords from peer-reviewed publications using plant trait data via TRY. The size of the circles and letters indicates the frequency of the keywords, colours indicate the eight clusters. The analysis is based on 190 publications with DOI compiled by ISI Web of Science (https://clarivate.com/products/web-of-science). Keywords were provided by authors

and complemented by Clarivate. The analysis was performed with VOSviewer version 1.6.11 (https://www.vosviewer.com). The clustering technique used by VOSviewer is discussed by (Waltman, van Eck, & Noyons, 2010).

Box 1: Examples for the ‘feed-forward data assimilation loop’ observed in the context of the TRY database.

- Iversen et al. (2017) indicated that in the TRY database only 1% of trait records were related to roots. This motivated the development of the Fine Root Ecology Database (FRED) specializing in the mobilization of fine-root trait records from the literature (Iversen et al., 2017). In the meantime, the first versions of the FRED database have been contributed to the TRY database. The improved number and availability of trait data on roots allowed for a successful iDiv synthesis project proposal on root trait functionality in a whole-plant context (https://www.idiv.de/en/sdiv/working_groups/wg_pool/sroot.html). The project motivated additional mobilization of root trait data.
- The promising coverage of plant trait data from tundra regions in the TRY database encouraged the inclusion of plant traits in an analysis of tundra ecosystem change, scaling shrub expansion from site to biome (Bjorkman et al., 2018a). In the context of the project, a large number of additional trait data were mobilized by the Tundra Traits Team (Bjorkman, et al., 2018b), which have recently been contributed to the TRY database.
- Moreno-Martínez et al. (2018) estimated the worldwide variation of several leaf traits to improve the parameterization of global vegetation models and

remote sensing approaches predicting e.g. gross primary productivity. Due to the low representation of traits for crops in the TRY database, they could not provide estimates for major agricultural regions (see white spots in Moreno-Martinez et al. 2018, Figure 5). The identification of this gap motivated mobilization of trait data for crop plants and agroecosystems (Martin et al., 2018; Martin & Isaac, 2015), which were then contributed to the TRY database.

- Trait data on plant growth form (tree, shrub, herb, etc.) were compiled and consolidated by TRY, extended in the context of the BIEN initiative (Engemann et al., 2016; Enquist, Condit, Peet, Schildhauer, & Thiers, 2016) and then contributed to the development of the GIFT database (Weigelt, König, & Kreft, 2019). The upgraded plant growth form data were contributed again to TRY.
- Plant species richness is unequally distributed across the globe, with the highest species richness observed in the tropics (von Humboldt, 1817). The highest numbers of species with measurements in TRY are also found in the tropics, but as well the largest gap relative to reported species richness: less than 1% of estimated species richness was represented in TRY (Jetz et al., 2016). This principle and systematic mismatch of data coverage and representativeness has been used to suggest the development of a ‘global biodiversity observatory’ of in-situ measurements and space-born remote sensing that tracks temporal changes in plant functional traits around the globe to fill critical knowledge gaps, aid in the assessment of global environmental change, and improve predictions of future change (Jetz et al. 2016).

- TRY was also crucially involved in the sPlot initiative to establish a global vegetation-plot database (www.idiv.de/sPlot). sPlot supports the analysis of plant communities across the world's biomes by combining vegetation-plot data with traits from the TRY database (Bruelheide et al., 2019). This has resulted, for the first time, in global analyses of plant functional community data (Bruelheide et al., 2018). In contrast to single species measurements or trait values aggregated in grid cells, using vegetation-plot data allows understanding the role of traits for biotic interactions and community assembly processes. In turn, trait data measured in the context of sPlot plots are contributed to TRY - an important new source of trait data has become available to TRY.

Material and methods

Plant trait data in the TRY database

Plant traits can be classified to categorical (qualitative and ordinal) and quantitative (continuous) traits (Kattge et al., 2011b). Some traits are rather stable within species (mostly categorical traits), and some of these can be systematically compiled from species checklists and floras (Weigelt, König & Kreft 2019). However, most traits relevant to ecology and earth system sciences are characterized by intraspecific variability and trait-environment relationships (mostly quantitative traits). Both kinds of traits are compiled in the TRY database, but with a focus on continuous traits. These traits have to be measured on individual plants in their particular environmental context. Each of such trait measurements has high information content as it captures the specific response of a given genome to the prevailing environmental conditions. The collection of these quantitative traits and their essential environmental covariates is important but often tedious and expensive: researchers need to travel to the objects of interest – often to remote and dangerous places – or they need to develop experiments creating specific environmental conditions. While trait measurements themselves may be relatively simple, the selection of the adequate entity (e.g. a representative plant in a community, or a leaf on a tree) and obtaining the relevant ancillary data (taxonomic identification, soil and climate properties, disturbance history, etc.) may require sophisticated instruments and a high degree of expertise and experience. In addition, these data are most often individual measurements with a low level of automation. This not only strongly limits the number of measurements, but also causes a high risk of errors, which need to be corrected *a posteriori*, requiring substantial human work. The integration of these data from different sources into a consistent dataset requires careful workflow with sufficient data quality assurance (See Box 2: TRY data integration workflow).

These measurements of quantitative traits are single sampling events for particular individuals at certain locations and times, which preserve relevant information on intraspecific variation and provide the necessary detail to address questions at the level of populations or communities. Within individual field campaigns or experiments, researchers often aim at measuring complete sets of these data: all traits of interest for all individuals or species in the analyses. However, across studies and datasets and at large scales these data provide two challenges: data completeness and representativeness (König et al. 2019).

Box 2: The data integration workflow for the TRY database version 5.

Data acquisition

In the context of the TRY initiative data acquisition so far relies on active contributions by the community – datasets need to be sent by email or uploaded at the TRY website (https://www.try-db.org/TryWeb/Submission.php). From time to time (2007, 2013 and 2019) TRY sends out calls for data contributions to the community. But so far there was no systematic screening of public data repositories like DRYAD (https://datadryad.org*)* or PANGAEA *(*https://www.pangaea.de*)* for plant trait data.

Data integration

The basic principle of data integration in the TRY database is to preserve the original trait and ancillary data and annotate these with complementing and consolidated information. Data integration consists of three major components: data consolidation, complementation and quality assurance. We here provide a brief overview, a detailed description can be found in supplementary material and on the TRY website (https://www.try-db.org/TryWeb/Database.php).

Data consolidation: The data structure is transformed into the entity-attribute-value (EAV) model and the OBOE schema (Madin et al., 2007) used in the TRY database: a long table of trait records and ancillary data where all trait records and ancillary data measured on the same entity (most often an individual plant or plant organ) are linked by a unique identifier. Plant taxonomy is consolidated using the Taxonomic Names

Resolution Service (TNRS, Boyle et al. (2013), http://tnrs.iplantcollaborative.org) with a taxonomic backbone based on the Plant List (http://www.theplantlist.org), Missouri Botanical Garden's Tropicos database (http://www.tropicos.org), the Global Compositae Checklist (https://www.compositae.org/checklist), the International Legume Database and Information Service (http://www.ildis.org), and USDA's Plants Database (http://plants.usda.gov). Trait names and definitions are consolidated across all datasets, based on the TOP thesaurus of plant characteristics (Garnier et al., 2016) (http://top-thesaurus.org) or the plant trait handbook (Pérez-Harguindeguy et al., 2013), if possible. For continuous traits with more than 1000 records, units are standardized and trait values are recalculated if necessary. Most relevant ancillary data - geo-references, measurement date, exposition, maturity, and health - are consolidated across datasets and, if possible, to external standards, like the decimal representation of latitude and longitude, or ISO 8601 (YYYY-MM-DD) for the date.

Data complementation: After consolidation, additional trait values are derived from contributed trait data where possible, e.g. leaf nitrogen content per area from leaf nitrogen content per dry weight and specific leaf area (SLA) if both were measured on the same entity.

Data quality assurance: Continuous traits with >1000 records in the database are subject to a three-step process: (1) Systematic errors, like a wrong unit for a given trait for all records of a specific dataset, are identified across datasets with semi-automated procedures and corrected. (2) Z-scores are calculated for each standardized trait value to indicate outliers and potential errors of individual trait records. (3) Duplicate trait records are identified based on consolidated trait names, taxonomy, units, and values. Geo-references are checked against the ESA CCI Land Cover Map of Global Water Bodies (https://www.esa-landcover-cci.org/?q=node/162) to assure that the provided locations are on land.

After a dataset has been integrated into the TRY database the dataset custodian is asked for feedback, i.e. whether consolidated trait names are appropriate and consolidated values correct. Data are reformatted for data release and format errors (i.e. tabs and line breaks in database cells) are corrected. Finally, the original and consolidated data (incl. flags for outliers and duplicates) are released on request as tab-delimited text files.

Results

Data coverage

Compared to TRY database version 1 and the state reported in Kattge et al. (2011a), TRY' version 5 has substantially grown concerning the number of trait records, traits, species, entities, geo-referenced measurement sites and ancillary data (Table 2).

Trait records and entities

The numbers of trait records (individual trait measurements) and entities (individual plants or plant organs on which the measurements have been taken) increased by a factor of about 6 for trait records and 5 for entities from TRY version 1 (2.1 million trait records measured on 1.1 million entities) to TRY version 5 (11.8 million trait records measured on 5.0 million entities). The average number of trait records per entity increased from 1.9 to 2.4 (Table 2).

Traits

The number of traits has grown steadily from TRY version 1 to 5, apart from a steep step from TRY version 3 to 4 (Table 2). This step was caused by the contribution of the FRED database, which added about 700 new traits for roots. Data coverage across traits is characterized by long-tail distributions: a small number of traits is well covered by records and species, while the majority of traits has only very low coverage of records and species (Figure 3). However, the number of continuous traits with more than 1000 records (which are subject to intense data quality assurance during integration) has increased from about 200 in TRY version 1 to 600 in TRY version 5 (Figure 3b). The number of traits with data for more than 100 species has increased from 300 to 700 (Figure 3c). In parallel the number of records per trait and species ('intraspecific retakes') has increased from TRY version 1 to 5: from almost zero traits with on average more than 10 records per trait-species combination to more than 500 (Figure 3f).

The traits with best species coverage in TRY version 5 are mostly categorical (Table 3). The categorical traits most often used for the classification of plant functional types (PFT) - plant woodiness, plant growth form, leaf type, leaf phenology type, leaf photosynthesis pathway - are still among the best covered, whereas the number of species characterized for each of these traits has substantially increased from TRY version 1 to 5, most significantly for plant growth form from 31,327 to 263,357 species, supported by the contribution from the GIFT database (Weigelt, König & Kreft 2019).

The quantitative traits with the highest species coverage are still the six traits, which were already prominent in TRY version 1 and involved in the analysis of the global spectrum of plant form and function (Díaz et al. 2016): plant height, seed mass, leaf area, leaf area per dry mass, leaf nitrogen content and stem specific density. However, in general, the coverage of continuous traits already present in TRY 1 has substantially improved. This facilitates a more robust characterization of frequency distributions (Figure 4). In most cases, the range of observed trait values did not change much from TRY version 1 to 5, but the shapes of frequency distributions became more regular and pronounced, especially for multimodal trait spectra like height and leaf 13C. Noteworthy, examples in Figure 4 lack several kinds of traits because they are missing relevant numbers of trait records, like secondary metabolites, dead plant material (litter) or data related to trophic interactions.

Species

From TRY version 1 to 4, the number of species increased slowly, but almost doubled to version 5 due to the contribution of plant growth form data from the GIFT database, which added about 100,000 new species. As in the case of traits, the data coverage for species is characterized by long-tail distributions: few species are covered well by measurements and traits, while the majority of species has only very low data coverage (Figure 3d, e, f). The species characterized by most traits tend to be northern temperate trees or pasture species that have been sown all over the world (Table 4). 27 (90%) out of the top 30 species with the best coverage originate in Central or Northern Europe.

Table 2: Data coverage from TRY version 1 to 5.

Version	Trait records	Entities	Trait records per entity	Traits	Average number of records per trait	Species	Georeferenced trait records	Sites	Ancillary data
1	2,077,640	1,110,303	1.87	661	3,143	57,591	682,108	8,276	4,439,783
2	2,376,231	1,207,669	1.97	743	3,198	65,746	871,582	8,513	4,758,033
3	5,783,482	2,246,967	2.57	1,149	5,033	92,146	2,201,242	11,844	11,834,960
4	7,162,252	3,435,238	2.08	1,981	3,615	141,461	2,978,776	16,480	14,644,354
5	11,850,781	5,102,993	2.37	2,091	5,668	279,875	4,952,839	20,953	35,516,190

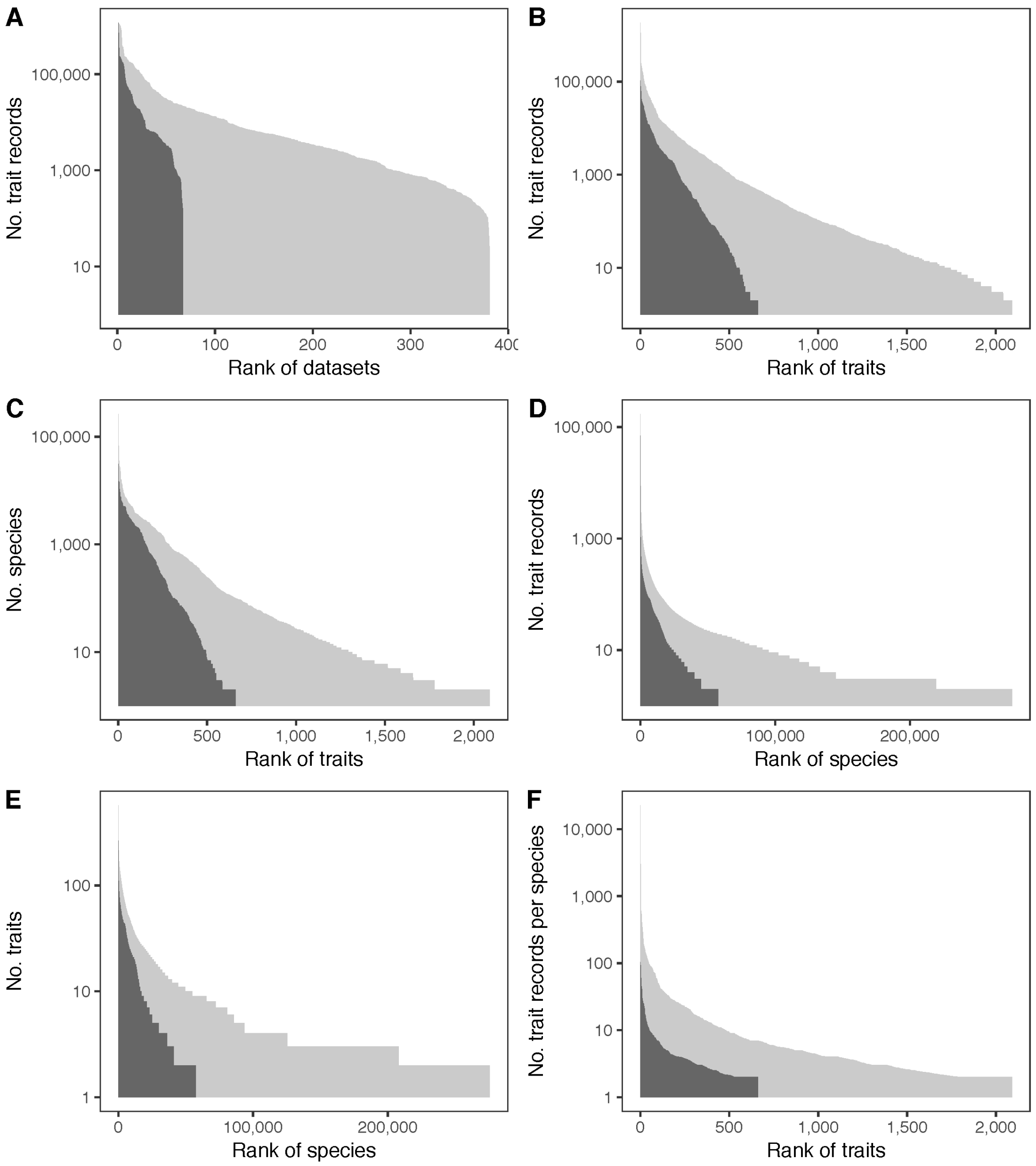

Figure 3: Trait data coverage of TRY version 1 (dark grey) and 5 (light grey). Data coverage in TRY is characterized by long-tailed rank-size distributions: (A) Rank of dataset by trait records, (B) rank of traits by number of records, (C) rank of traits by number of species, (D) rank of species by trait records, (E) rank of species by number of traits, (F) rank of traits by number of records per species (averaged by trait). Note: y-axes are log-scaled.

Table 3: Traits with best species coverage. The 30 traits covering the highest number of species in the TRY database version 5 and the number of species represented for these traits in TRY version 1. Data type: cat = categorical, con = continuous. Sorted by the number of species in TRY 5.

		Number of species	
Trait name	**Data type**	**TRY 1**	**TRY 5**
Plant growth form	cat	31,327	263,357
Plant woodiness	cat	14,628	79,298
Leaf type	cat	7,934	62,904
Leaf compoundness	cat	7,998	57,922
Leaf photosynthesis pathway	cat	15,609	37,315
Leaflet number per leaf	con	0	30,296
Plant height vegetative	con	13,899	28,944
Leaf phenology type	cat,con	14,622	28,514
Species tolerance to frost	cat,con	2,180	28,122
Seed dry mass	con	14,602	27,022
Species occurrence range: native versus invasive	cat	11,313	25,067
Plant lifespan	cat,con	7,617	24,712
Dispersal syndrome	cat	7,528	21,717
Plant nitrogen fixation capacity	cat	10,504	18,247
Plant resprouting capacity	cat	3,320	15,997
Seed germination rate (germination efficiency)	con	6,698	15,822
Plant life form sensu Raunkiaer	cat	7,710	15,766
Pollination syndrome	cat	4,064	15,631
Leaf shape	cat	3,191	15,594
Flower sex	cat	3,572	13,735
Leaf distribution arrangement type	cat	3,998	13,130
Leaf area per leaf dry mass (specific leaf area, SLA)*	con	5,230	13,101
Leaf nitrogen content per leaf dry mass	con	6,291	12,238

Leaf area**	con	6,318	11,149
Stem specific density	con	9,813	11,001
Flower colour	cat	4,747	10,507
Seed storage behaviour	cat	10,161	10,161
Fruit type	cat	3,644	9,573
Leaf margin type	cat	0	9,179
Wood growth ring distinction	cat	5,121	9,103

* undefined if petiole is in- or excluded;

**in case of compound leaves: leaflet, undefined if petiole is in- or excluded

Table 4: Species with best trait coverage. The 30 species with the highest number of traits in the TRY database version 5 and number of traits represented for these species in TRY version 1 and 5. Sorted by the number of traits in TRY 5.

		Number of traits	
Species	**Plant growth form**	**TRY 1**	**TRY 5**
Pinus sylvestris	tree	264	569
Fagus sylvatica	tree	237	517
Picea abies	tree	252	475
Quercus robur	tree	194	435
Acer saccharum	tree	139	430
Betula pendula	tree	265	429
Achillea millefolium	herb	209	403
Acer pseudoplatanus	tree	186	397
Trifolium pratense	herb	181	395
Quercus rubra	tree	190	388
Dactylis glomerata	herb	193	387
Plantago lanceolata	herb	156	386
Vaccinium vitis-idaea	shrub	189	382
Trifolium repens	herb	173	380
Fraxinus excelsior	tree	196	378
Acer platanoides	tree	186	378
Quercus petraea	tree	194	368
Poa pratensis	herb	195	366
Holcus lanatus	herb	178	364
Tilia cordata	tree	153	362
Calluna vulgaris	shrub	190	360
Lotus corniculatus	herb	153	360
Pseudotsuga menziesii	tree	141	356
Medicago lupulina	herb	145	351
Festuca rubra	herb	175	347

Sorbus aucuparia	tree	197	335
Phleum pratense	herb	179	335
Quercus ilex	tree	195	333
Betula papyrifera	tree	126	332
Vaccinium uliginosum	shrub	169	330

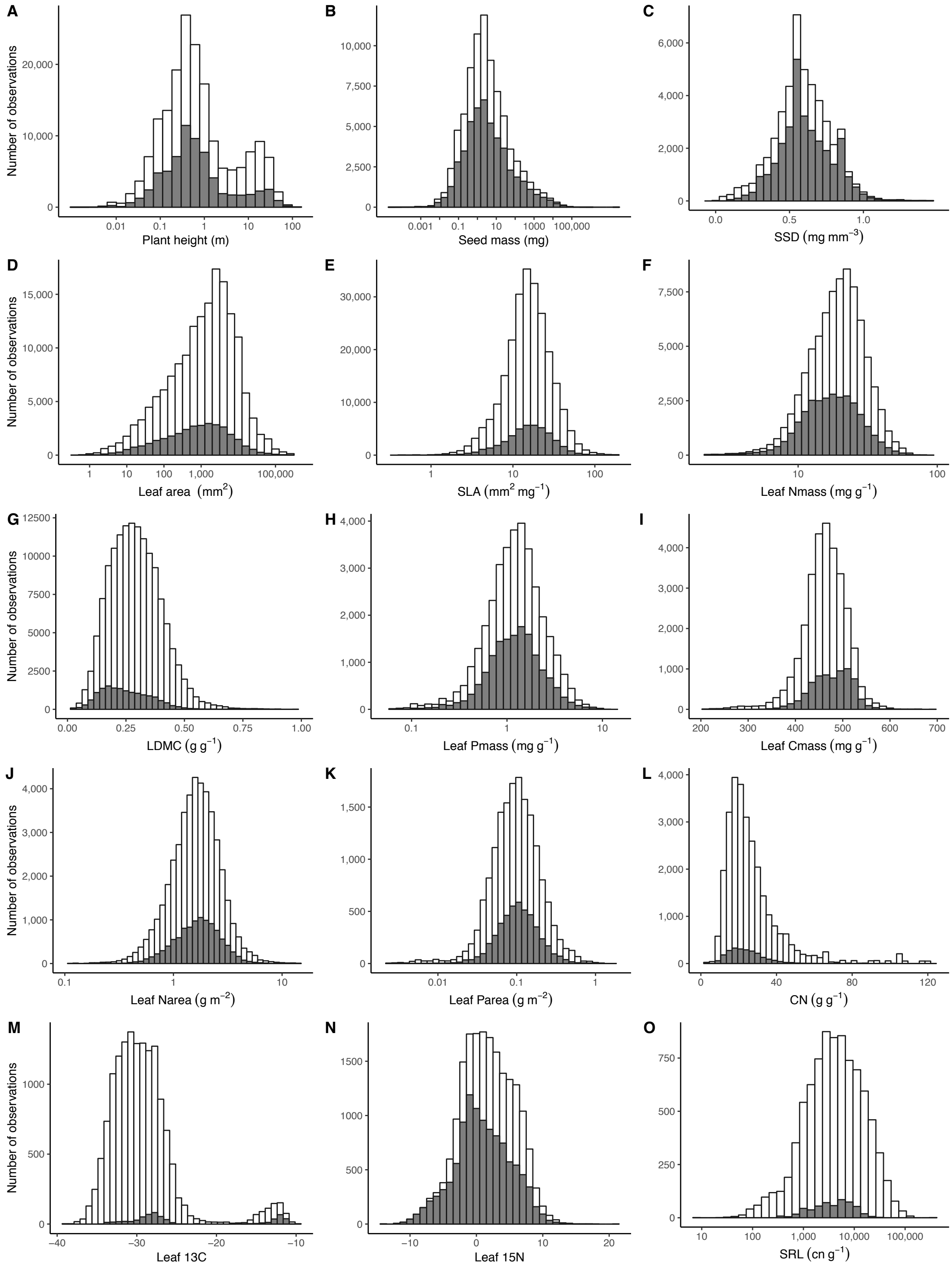

Figure 4: Frequency distributions of observations for 15 ecologically relevant and well sampled continuous traits from different plant organs. Grey: TRY version 1, white: TRY version 5. SLA: leaf area per leaf dry mass (specific leaf area); Leaf Nmass: leaf nitrogen content per leaf dry mass (leaf nitrogen concentration); LDMC: leaf dry mass per leaf fresh mass (leaf dry matter content); Leaf Pmass: leaf phosphorus content per leaf dry mass; Leaf Cmass: leaf carbon content per leaf dry mass; Leaf Narea: leaf nitrogen content per leaf area; Leaf Parea: leaf phosphorus content per leaf area; Leaf CN: leaf carbon content per leaf nitrogen content; Leaf13C: leaf 13C carbon isotope signature; leaf 15N: leaf 15N nitrogen isotope signature; SRL: root length per root dry mass (specific root length).

Entity×trait and species×trait matrices

The trait data in the TRY database can be represented by two two-dimensional matrices: the entity×trait matrix, with entities in rows and traits in columns, and the species×trait matrix, with species in rows and traits in columns. Both matrices can be characterized as large but sparse: high numbers of entities, species, and traits in TRY increase the size of the two matrices, but many cells in the matrices are empty. From TRY version 1 to 5 the size of the matrices has grown by a factor of 15, but at the same time the number of trait records to fill the cells increased only by a factor of about 5 and thus the matrices became even sparser: the fractional coverage decreased from 0.4% to 0.1% (entity×trait) and 1.4% to 0.4% (species×trait) (Figure 5a). This sparsity together with the observed long-tail distributions has consequences, especially for multivariate analyses. Given that on average only two to three traits of the 2091 traits in TRY version 5 are measured on an individual plant (entity), a multivariate analysis based on individuals is indeed practically impossible (as mentioned by Shan et al. (2012)). Even after aggregation at the species level, the decline of the number of species with complete trait coverage when adding a new trait, e.g. for multivariate analysis, is surprisingly high (Figure 5b). Additionally, the final number of species represented in the analysis is determined by the trait with the lowest species coverage. Therefore multivariate analyses with more than about six traits are still very much limited by the number of species. The same applies when species have to be classified by several categorical traits, like e.g. in the context of PFTs.

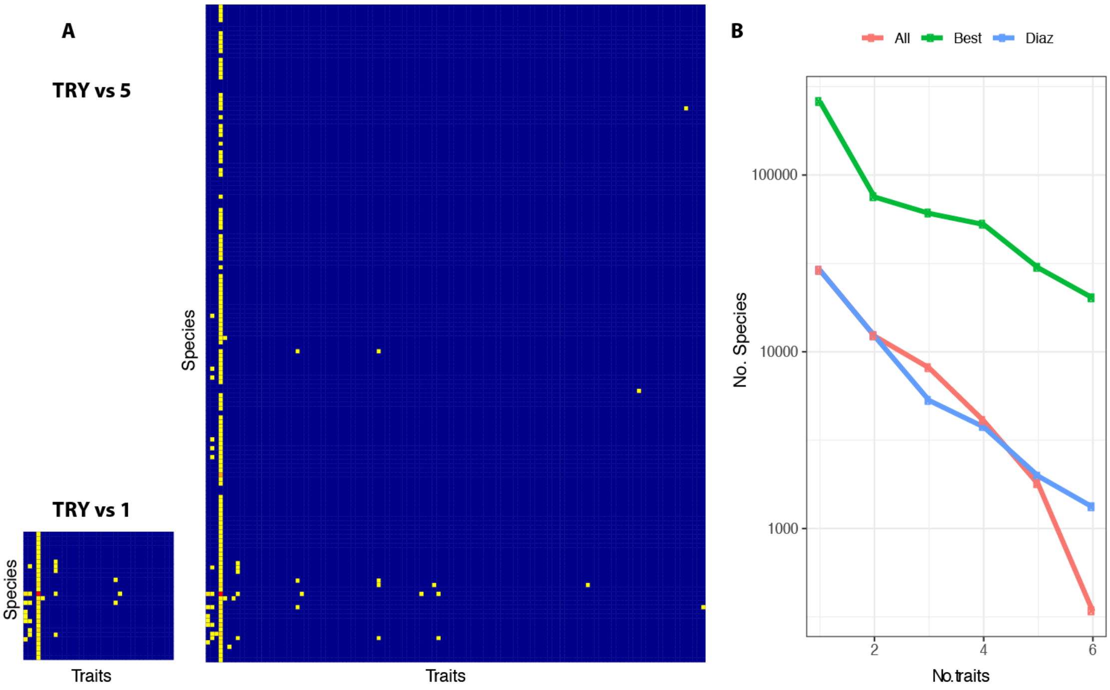

Figure 5: (A) Comparison of the species×trait matrix from TRY version 1 and version 5. The sizes of the blue boxes represent the numbers of species and traits. Blue: missing data, bright colour: the presence of data (yellow to red indicating an increasing number of measurements). For visibility, only 5% of traits and 0.05% of species are shown (randomly selected, with TRY version 1 as a subsample of TRY version 5; ordering of species and traits by submission date). (B) Multivariate

analyses: the decline of the number of common species with an increasing number of traits. Green: six best covered traits in TRY version 5 (categorical traits: plant growth form, plant woodiness, leaf type, leaf compoundness, leaf photosynthetic pathway, leaflet number per leaf), blue: six traits chosen in Díaz et al. (2016), red: the best covered quantitative traits representing each of the six plant parts (see Figure 6): shoot (plant height vegetative), reproductive organs (seed dry mass), whole plant (plant lifespan), leaves (SLA), roots (rooting depth) and dead material (litter decomposition rate).

Ancillary data

The numbers of ancillary data, georeferenced trait records and trait records with measurement date increased by a factor of almost 10 from TRY version 1 to TRY version 5 (Table 2). The ratio of ancillary data to trait records, therefore, increased from TRY version 1 to 5 from 2:1 to 3:1 and the fraction of geo-referenced trait records from about 33% to 42% (Table 2). The number of geo-referenced trait records with information on measurement date that could be standardized to year, month and day increased from 290,000 in TRY version 1 to 2.5 million records in TRY version 5. The increasing ratio of ancillary data to trait records indicates growing awareness for the relevance of environmental conditions during plant growth and trait measurements. In this context geo-references (and date) are crucial, as they allow trait records to be related to information on climate, soil, or biome type from external sources.

The geographic coverage of trait measurements has substantially improved from TRY version 1 (8,276 measurement sites representing 1,260 1°×1° grid-cells) to TRY version 5 (20,953 sites representing 3,320 1°×1° grid-cells, Table 2, Figure 6). Europe still has the highest density of measurement sites, but TRY version 5 also provides good coverage for, i.e., the USA and China. The number of sites has substantially improved for several other regions as well, e.g. Central America, Russia, Asia and parts of central Africa. However, there are still obvious gaps in boreal regions (Canada, East Russia) and some parts of the tropics and sub-tropics, particularly in Africa (Figure 6).

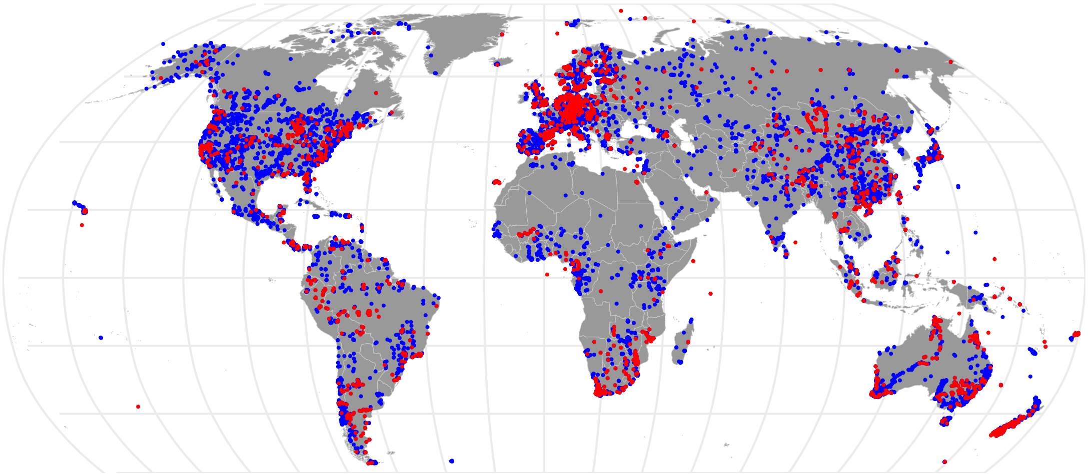

Figure 6: Geographic coverage. Measurement sites in TRY version 1 (red) and additional measurement sites in TRY version 5 (blue).

Data completeness and representativeness

To progress from a description of data coverage towards an analysis of representativeness, we need a baseline for comparison. At the global scale, this information has been lacking. Reference datasets have become available only recently for plant growth form (Weigelt, König & Kreft 2019) and phylogeny (S. A. Smith & Brown, 2018) representing about 260,000 and 356,000 of the 400,000 extant species.

Together with estimations for the global distribution of plant species richness (Kier et al., 2005), it seems now possible and timely to explicitly address representativeness of plant trait data in the TRY database along five key dimensions: (1) Are trait data in TRY well distributed among plant parts? (2) Are the species in TRY and for individual traits representative for global plant growth forms and functional types? (3) Are the species in TRY and for individual traits representative according to phylogeny? (4) Does the geographic distribution of species richness in TRY represent the estimated global species richness? (5) Is data coverage sufficient to represent intraspecific variation?

Distribution of trait records among plant parts

Trait records in the TRY database are very unequally distributed among different plant parts (Figure 7), forming three groups: leaves and the whole plant are well represented; shoot and reproductive organs are moderately represented; roots and dead material (morphological and chemical feature of litter and coarse woody debris, but also decomposition rates) are not well represented. This skewed distribution of trait records to the different parts of the plants has only changed little from TRY version 1 to 5, however, the fraction of records for root traits has substantially increased (from 0.7% to 2.0%), due to the contribution of the FRED database.

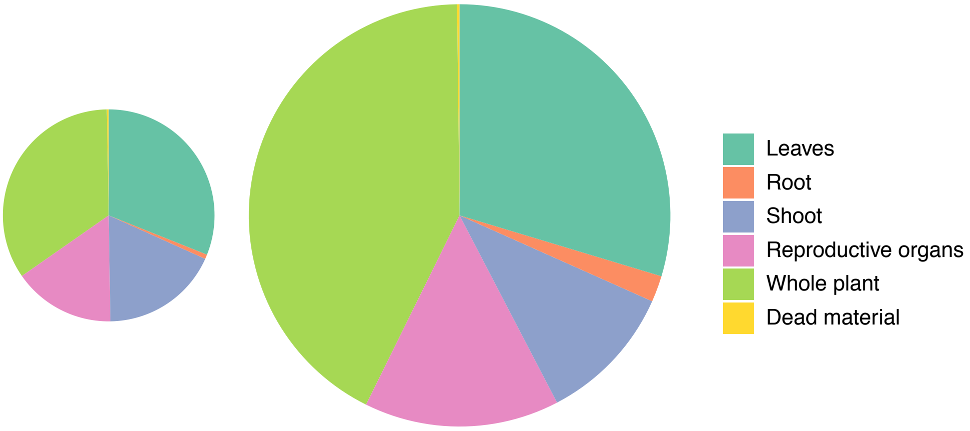

Figure 7: Distribution of trait records to plant parts. Different sizes of circles indicate different data coverage in TRY version 1 (left, 2.1 million trait records) and TRY version 5 (right, 11.8 million trait records).

Plant growth form and plant functional types

The most basic distinction of plant growth form used to describe vegetation is that among herbs, shrubs and trees. We here compare the fraction of the different plant growth forms for trait measurements in TRY version 5 to a comprehensive list of plant growth forms for >280.000 species, which is currently developed in the context of the GIFT database project. The comprehensive coverage of plant growth form in the GIFT database allows for the first time to make robust assumptions about the fractions of plant growth forms for all 400.000 estimated plant species worldwide.

In GIFT about 50% of species are currently assigned to herbs, 30% to trees and 20% to shrubs (Figure 8). This distribution is well reflected by the species in TRY (excluding data from the GIFT database). However, the six best covered continuous traits in TRY indicate that this distribution is very much trait-dependent, with a bias towards trees versus herbs, while the fraction of shrubs is surprisingly constant and close to the fraction in the GIFT database (Figure 8). The over-representation of trees is most obvious for SSD (stem specific density), which is not surprising because SSD is a more general concept derived from wood density, a trait relevant for forestry, timber industry and estimates of forest vegetation biomass. The tendency is also obvious for SLA, leaf nitrogen content per dry mass and leaf area. However, species for which we know plant height and seed dry mass are representative at the global scale with respect to plant growth form. For these, we can argue that species based frequency distributions are representative with respect to plant growth form (Figure 9). For specific root length (SRL), a relatively well-covered root trait, the growth form distribution is surprisingly close to the one observed in the GIFT database, just slightly underestimating the fraction of shrubs.

Apart from plant growth form, three additional categorical traits are relevant to determine PFTs commonly used in global vegetation models: leaf type (broadleaved - needle-leaved) and leaf phenology type (deciduous - evergreen) for tree species, and photosynthesis pathway (C3, C4, CAM) for herbaceous species. TRY provides leaf type for 62,904 species and leaf phenology type for 28,514 species. Of these 15,768 species and 11,853 species are attributed as trees. The photosynthesis pathway is provided for 37,315 species, 12,241 of these are herbs. TRY thus provides leaf type and leaf phenology type for about 10% of the estimated 130,000 tree species worldwide and photosynthesis pathway for about 6% of estimated 200,000 herb species.

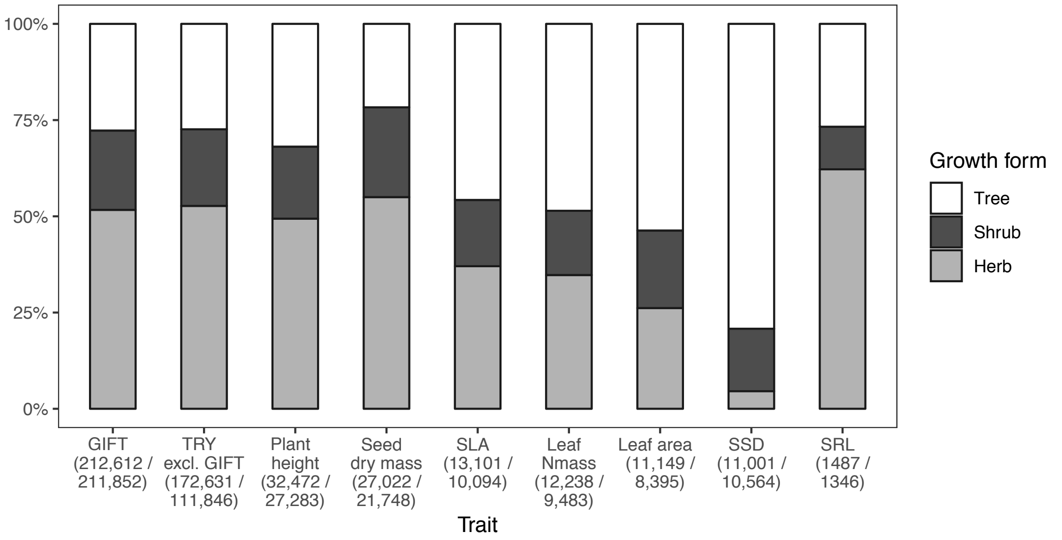

Figure 8: Fraction of species with plant growth forms herb, shrub and tree in the GIFT database, in TRY version 5 (excl. GIFT) and for the six best covered continuous traits in TRY version 5: plant height, seed dry mass, leaf area per leaf dry mass (SLA), leaf N per dry mass, leaf area and stem specific density (SSD), and one well covered root trait: specific root length (SRL). In brackets: the number of species with data for the trait and the number of species for which the growth form could be determined as tree, shrub or herb.

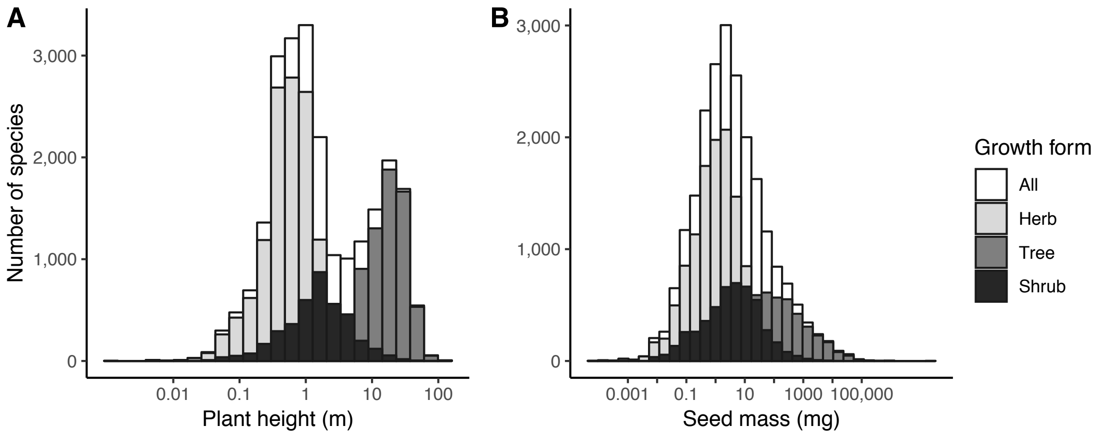

Figure 9: Frequency distributions of species maximum plant height (A) and maximum seed dry mass (B) with respect to basic plant growth forms.

Phylogeny

In 2018 Smith and Brown published a series of broadly inclusive seed plant phylogenies (Smith and Brown, 2018). We here chose the most comprehensive phylogeny (ALLMB), containing 356,305 taxa, as a baseline to visualize the coverage of TRY in a phylogenetic context. Taxa in ALLMB were cut to binomials and consolidated using the Taxonomic Name Resolution Service (TNRS) with TPL, GCC, ILDIS, TROPICOS, and USDA as the taxonomic backbone (the same approach as for TRY). After consolidation, we could match 208,406 of the 279,875 taxa in TRY (mostly species) to the taxa in the phylogeny. Higher-level taxonomy is based on (Zanne et al., 2014).

Visually, the 208,000 species with data in TRY are well distributed across the 350,000 species represented in the phylogeny of seed plants (Figure 10). An ancestral state reconstruction (ASR) of species trait number confirms that the long-tail distribution previously seen at the species level also holds in a phylogenetic context: some clades are covered very well (bright colours), while most clades have only lower data coverage (dark colours). The ASR additionally shows how deep in phylogeny data gaps are rooted. This indicates potential and limits for phylogeny informed gap-filling. Examples of high-coverage clades are (parts of) the Pinales, Poales and Asterales. When looking at the six best covered continuous traits individually, we find these to are well distributed across the phylogeny (Figure 10).

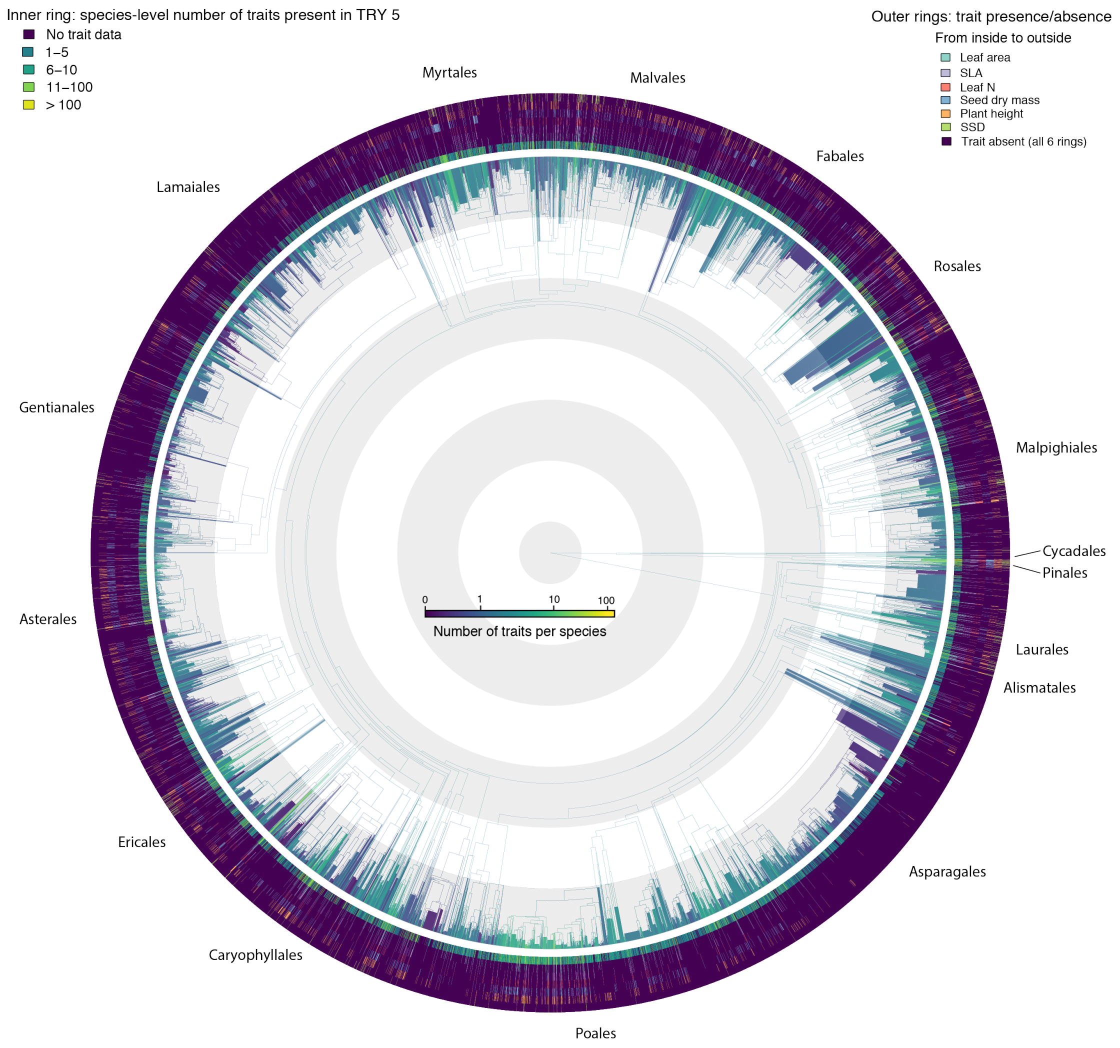

Figure 10: Trait coverage per species projected on a global phylogeny. The presence of trait data for plant species in the TRY database version 5 matched to the global ALLMB phylogeny published by Smith and Brown (2018). Rings surrounding the phylogeny indicate from inside outwards: (i) number of traits per species (innermost ring), (ii) presence of data for six best covered continuous traits, specifically: leaf area, SLA, leaf nitrogen per dry mass, seed dry mass, plant height and stem specific density. Colours of the phylogeny branches represent an ancestral state reconstruction of the number of traits per species. White and grey circles indicate periods of 50 million years. For visibility, only 5% of species (randomly selected) are presented (full figure in supplementary material).

Geographic distribution of species richness

Jetz et al. (2016) reported a latitudinal gradient for the gap between plant species with regional measurements in TRY and estimated species richness, with the largest gap observed in the tropics, because these are especially rich in species. To address this in more detail, we here ask if the TRY database provides trait information for a relevant number of plant species in the different regions worldwide. To characterize regions in an ecologically meaningful way we adopt the ecoregions introduced by (Olson et al., 2001), which are defined as relatively large units of land containing a distinct assemblage of natural communities and species, with boundaries that approximate the original extent of natural communities before major land-use change. The ecoregions are nested within biomes with biotic communities formed in response to a shared physical climate, most importantly temperature and rainfall. We compare the number of species, which have trait measurements in an ecoregion in TRY version 5 to estimated species numbers per ecoregion by Kier et al. (2005). This approach accounts to some extent for intraspecific trait variation, as it counts only species with a least one trait measurement in the given ecoregion.

The 839 ecoregions defined by Olson et al. (2001) are very different in size, from 6 km^2 (San Felix-San Ambrosio Islands temperate forests) to 4,639,920 km^2 (Sahara desert) with species numbers ranging from 0 (St. Peter and St. Paul rocks And the Maudlandia Antarctic desert) to 10,000 (Borneo lowland rain forests). The TRY database contains no trait measurements for 271 mostly small ecoregions and up to 1,400 species for some ecoregions in Europe (Alps conifer and mixed forests) and tropical South America (Napo moist forests, Tapajos-Xingu moist forests). In general, high absolute numbers of species with trait measurements for ecoregions are found in Europe, East Asia, Oceania, Australia, tropical South America, and the USA (Figure 11a). East Asia, Oceania, and tropical South America are also the regions with the highest numbers of species per ecoregions estimated by Kier et al. (2005) (Figure 11b).

The best relative coverage in TRY (Figure 11c) is provided for the Marielandia Antarctic tundra (2 species estimated and in TRY) and for a large Ecoregion in Central Russia (West Siberian taiga, 900 species estimated, 885 in TRY). The species in the Russian ecoregion are measured at several sites relatively well distributed across the ecoregion, but dominated by just one trait: 'mycorrhiza infection intensity' contributed by the Mycorrhizal Intensity Database (Akhmetzhanova et al., 2012). Some other ecoregions are also well covered with data for more than 50% of estimated species (Southeast Australia temperate savanna, Qaidam Basin semi-desert, Cordoba montane savanna). Apart from these special cases spread across the world, large parts of Europe are well covered, with trait data for about 30% of the species number estimated by Kier et al. (2005). Some ecoregions in East Asia, Australia, tropical South America, the Sahara, and the USA are also well covered, providing data for about 20% of estimated species richness. Very low relative coverage (<2%) is observed for major parts of Canada, Africa, western Asia (Iran, Iraq, Pakistan, Afghanistan) and major parts of India.

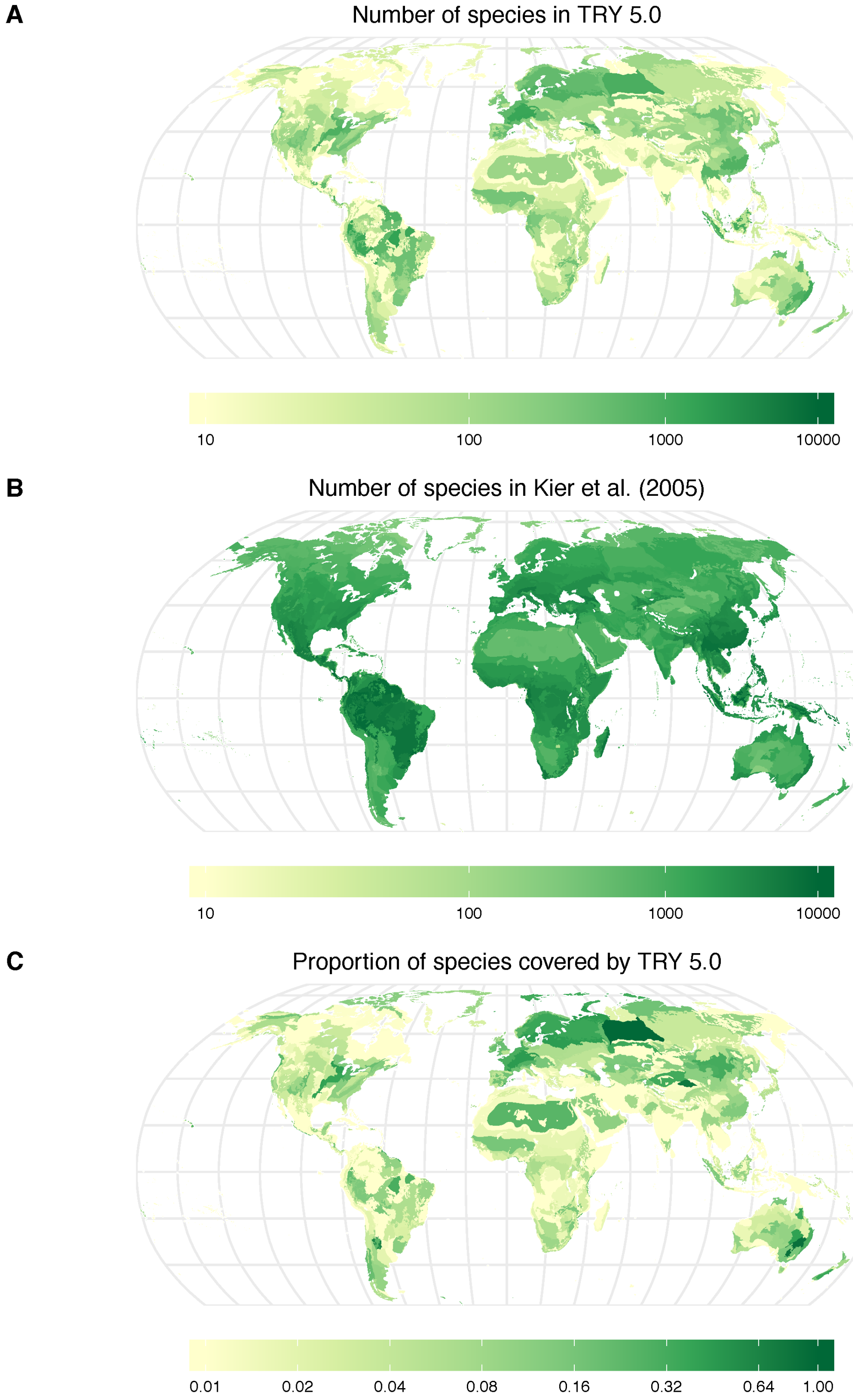

Figure 11: Geographic representativeness: A) the number of species with at least one trait measurement in an ecoregion in TRY version 5, B) number of species per ecoregion estimated by Kier et al. (2005), C) fraction (%) of species represented in TRY version 5 versus estimation by Kier et al. (2005).

Intraspecific variation

Understanding and prediction of intraspecific variation for a relevant number of traits and species is still in its infancy. Given that TRY is collecting trait measurements on individual plants, the TRY dataset might be suited to address these questions. A precondition for such analyses is a minimum number of measurements on different individual plants at different sites per trait and species. To assess this issue we plotted the number of species for which TRY version 5 contains a minimum number of individual measurements (Figure 12a) and measurements from a minimum number of different sites (Figure 12b) for the 15 best-covered continuous traits. With increasing minimum number of individuals or sites, the number of species available for analysis is decreasing steeply (more than exponential), whereas the exact slope is trait-specific. The characterization of intraspecific variation in Kattge et al. (2011a) relied on at least 20 individuals per species. Based on this criterion, TRY 5 provides information for hundreds to thousands of species for 14 out of the 15 traits (Figure 12a). Assuming a more realistic limit of 100 individuals per species, SLA and LDMC are sufficiently covered for about 300 species, four other traits for more than 100 species. Assuming a minimum number of 200 individuals per species, still, four traits allow for an analysis of 100 species, and nine traits for the analysis of intraspecific variation of more than 10 species. However, the numbers are more humbling if the environmental context is taken into account (Figure 12b). If we assume that a minimum of trait records from 50 sites per species is necessary to represent intraspecific variation, four traits are sufficiently covered for about 100 species. If 100 sites should be necessary, no trait is covered by data for more than 10 species.

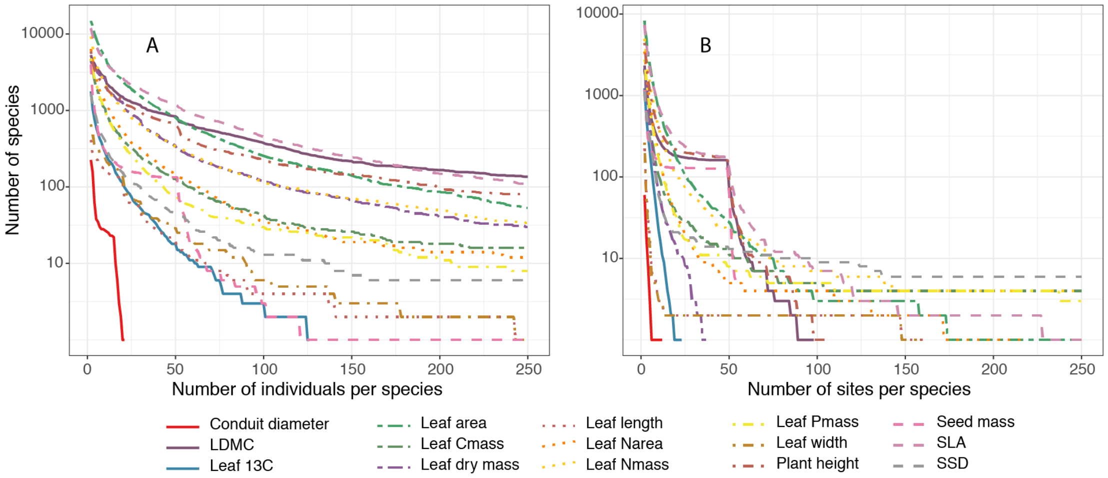

Figure 12: Data coverage to characterize intraspecific variation: Impact of the minimum number of individuals per species (a) and measurement sites per species (b) on the number of species available for analyses of intraspecific variation. Measurement sites were assumed different if they differed at least by 0.01 degrees in latitude or longitude. LDMC: leaf dry matter content; Leaf 13C: Leaf carbon (C) isotope signature; Leaf Cmass: leaf carbon content per leaf dry mass; Leaf Narea: leaf nitrogen content per leaf area; Leaf Nmass: leaf nitrogen content per leaf dry mass; Leaf Pmass: leaf phosphorus content per leaf dry mass; SLA: leaf area per leaf dry mass (specific leaf area); SSD: stem specific density.

Discussion

Plant trait data provide a wealth of information directly relevant in several scientific contexts, from conservation, ecology, and evolution to earth system sciences. To fully realize this potential the TRY initiative was initiated in 2007 as a ‘database of databases’ and leading groups in the field of functional plant ecology joined forces for this community-driven program. The TRY database now provides an unprecedented number of consolidated plant trait data, which have become easily accessible at the TRY Data Portal under an open access data policy.

TRY data coverage is characterized by four attributes: (1) long-tail distributions, (2) sparse matrices, (3) increasing number of ancillary data per trait record, and (4) increasing geographic coverage. So far the size of the two sparse matrices (entity×trait and species×trait) has increased faster than the number of trait records to fill the matrices. Therefore the sparseness of the matrices has increased from TRY version 1 to 5 (the fractional coverage declined). Rather than converging in a small number of traits, the scientific community continues to measure a large, diverse number of traits, following equally diverse motivations.

However, given the number of species has a natural limit and assuming the number of traits will continue to grow, but more slowly, once the most obvious ones have been covered, we expect that the sparseness of the entity×trait matrix will become stable: new data adding new rows for entities, but not many new columns for traits, while the sparseness of the species×trait matrix should actually decline in the future: new data will mostly contribute to filling the matrix and increasing the number of species per trait. This increasing number of species per trait and reduced sparseness of the species×traits matrix will systematically improve the applicability of trait data for macroecology and earth system modelling and will facilitate multivariate analyses for an increasing number of traits. In parallel the number of records per species-trait combination is increasing: from TRY 1 to 5 it has already doubled and will further increase in the future. This increasing number of records per species-trait combinations will improve data coverage for analyses of intraspecific trait variation and trait environment relationships accounting for intraspecific variation. Noteworthy, the matrix does not only fill up, but the traits will increasingly be able to inform each other: the 'usual suspects' might not be masters of all traits, they surely will be very useful as baseline traits and provide a background against which other - maybe more influential - traits can be analyzed for coverage, representativeness, orthogonality etc..

Data completeness and representativeness

Despite unprecedented and continuously growing data coverage, we observe a humbling lack of completeness and representativeness in many aspects. Best species coverage is achieved for categorical traits relevant to determine plant functional types commonly used in global vegetation models. For the traits ‘woodiness’ and ‘plant growth form’ even full species coverage is within reach, due to the contribution of data from the GIFT database. For the first time, this provides a global baseline for these traits, which are relevant to understand basic pattern of variation for several other traits (Díaz et al. 2016). For example, plant height extracted from the TRY database shows two bimodal frequency distributions: (1) with one peak representing mostly herbs and the other mostly trees, and (2) with respect to shrubs and trees (Figure 9, Kattge et al. 2011a, Scheffer et al. 2014). There has been debate on whether, the bimodal distribution of shrubs and trees is a meaningful ecological and ecophysiological pattern (Larjavaara, 2015; Scheffer et al., 2014; Scheffer et al., 2015) or rather an artefact caused by sampling biases in the TRY database, i.e. underrepresenting shrubs (McGlone, Richardson, Jordan, & Perry, 2015; Qian & Ricklefs, 2015). Based on the almost complete dataset for plant growth form, we can now argue that the bimodal frequency distributions of maximum plant height, now based on 27,000 species, are not an artefact caused by major sampling biases with respect to plant growth form. At the global scale, shrubs indeed appear to be comparatively less abundant than trees or herbs, rather than being misrepresented in TRY. This, however, may not be reflected in regional floras or by the realized plant height (McGlone et al. 2015, Qian and Ricklefs 2015).

Knowledge of the global baseline for relevant aspects, e.g. relevant categorical traits like plant growth form or plant functional type, well-covered continuous traits, species phylogeny, the global distribution of species, will facilitate dedicated stratification of plant trait data to improve representativeness. In the past, for global analyses, we were primarily aiming at improving data coverage, worrying about representativeness, but without means to seriously address this issue. Knowing the baseline for relevant aspects, in the future, we may favour representativeness over coverage (König et al. 2019). We, therefore, expect that the improving knowledge of baselines for different aspects will substantially contribute to better understand the global pattern of plant traits relevant for biodiversity and ecosystem function.

Most traits directly relevant for ecology and vegetation modelling are characterized by intraspecific variation and trait-environmental relationships: for these traits, completeness at the global scale is impossible and representativeness challenging. We find that in the current version of the TRY database, these traits are biased against roots and dead organic material. Plant growth forms and phylogeny are represented well in general, but there are significant biases for individual traits. The global distribution of species richness is only marginally reflected by trait measurements. We observe a general bias towards temperate biomes. In contrast to Jetz et al. (2016) the tropics do not stand out as especially underrepresented in our analysis: apart from

Europe, all continents contain major regions that are only very sparsely represented in TRY.

So far we addressed representativeness in a geographic context only based on species richness: the number of species observed in an ecoregion. To address representativeness in an ecological more meaningful context we should also take species identity and species abundance into account. Both aspects are relevant to community attributes and ecosystem function. There is ample evidence in the literature of the high influence, at the level of community structure and ecosystem dynamics, of species that represent a large proportion of the total local biomass (consisting of large individuals or and/or large total cover). Such species have a particularly large impact on the trait community weighted mean (CWM; (Garnier et al., 2004)). In addition (A. Ali et al., 2019) indicate that individual dominant large trees may overrule remaining trees' attributes. Initial evidence indicates that abundant species are better covered in TRY than rare species. (Bruelheide et al., 2019) show that the 25% most dominant or most frequent species compiled in the sPlot vegetation plot database are better represented by trait data in the TRY database than species observed on the plots overall. We also checked this for the 227 hyperdominant species of the Amazonia tree flora identified by (ter Steege et al., 2013). After the consolidation of species names via TNRS all 227 hyperdominant species are present in the TRY database, with on average 69 traits per species, which is far above average (see Figure 2e). We, therefore conclude that the coverage of trait data in TRY is biased towards the more abundant species in the respective ecoregions – which is reasonable for many kinds of analyses.

We have reported that intraspecific variation in space is increasingly well covered, but variation in time is hard to estimate. Nevertheless, intraspecific variation in time is relevant for several traits to characterize the seasonal variation of plant and ecosystem function (Xu & Griffin, 2006; Xu & Baldocchi, 2003) and long-term trends to inform policy about biodiversity change (Kissling et al., 2018). About half of the geo-referenced trait records have information on the sampling date that could be standardized to year, month and day, but systematic replicates over time ('time-series') are rare (but see e.g. the 'Photosynthesis Traits Database', Xu & Baldocchi, (2003)). In principle, 'non-time-series' data can also allow detection of trait changes over time (Craine et al., 2018), but these analyses are very challenging, as for most traits the variation in geographic space along climate and soil gradients is stronger than temporal changes. In addition, the variation of traits on different time scales (diurnal, seasonal, inter-annual variation and long-term trends) are superimposed and hard to disentangle. Apart from this, there is a need to collect and report repeated trait measurements from the same location or population to monitor biodiversity change and inform policy, e.g. in the context of GEO BON (Kissling et al., 2018).

In summary, we observe almost a bifurcation of plant traits into few well-represented traits ('leading traits') and a majority of traits with only few trait records (we may call them 'explorative traits). Leading traits are characterized by scientific community consensus about their information content and measurement feasibility. For some leading categorical traits global coverage - at least for the relevant species (e.g. photosynthesis pathway for herbaceous species) – is within reach or appears feasible. For leading continuous traits representativeness at global scale seems a realistic goal. In the best case, this coverage would allow estimating traits for each individual plant worldwide with sufficient robustness and accuracy based on taxonomy at the species level, representing the genotype, and geographic coordinates and sampling date to derive environmental information and resolve intraspecific variation. Explorative traits are characterized by low community consensus on relevance and/or measurement feasibility. For these traits, the best path is probably to explore their potential relevance and/or their links to leading, easily measurable and well-represented traits (which may serve as a baseline for these less common traits) than to aim for global coverage or representativeness**.**

Ways forward

Figure 1 shows the most obvious way to mobilize additional trait data: the TRY initiative should regularly send calls for data contribution to the wider scientific community, in combination with regular publication of respective reference papers. This can be combined with 1) a systematic collection of datasets from public data repositories, which has become possible since TRY is open access (according to the common open-access policies, it is not allowed to acquired open access data and then share them under restricted conditions); and 2) systematic extraction of trait data from the ecological literature, floras and herbarium specimen, which is a promising task, especially for its potential to open a window into the past. In parallel TRY should further support the 'feed-forward data assimilation loop' outlined above: using trait data via TRY, identifying gaps, mobilizing and/or measuring new data, contributing additional data to TRY. This has proven very effective for focused data mobilization. If relevant gaps are detected, TRY can also send specific calls to the community**.**

As TRY has been designed as a community cyber-infrastructure based on the idea of incentive-driven data sharing (Kattge et al. 2014), the collaboration and data exchange with other plant trait databases will continue to be the key to achieve a comprehensive representation of plant traits. TRY is, therefore, collaborating with many ongoing trait database initiatives, such as GLOPNET, FRED, GIFT, BIEN and the Tundra Trait Team, and since the early days of TRY - LEDA, SID, BiolFlor, BIOPOP, BROT, the Ecological Flora of the British Isles, eHALOPH, USDA PLANTSdata, BRIDGE and many others. Importantly, these collaborations provide mutual benefit. Based on these collaborations the TRY database may serve as a central node for plant traits in an overarching network of trait databases, currently emerging in the context of the Open Traits Network (Gallagher et al., 2019). Finally, new techniques and approaches are gradually becoming available which may substantially change how pant trait data are collected: remote sensing, citizen sciences, microbiological and molecular screening etc..

However, predicting the variation of continuous traits – especially based on individual plants - will remain an almost insurmountable challenge. Machine learning methods have become very powerful to predict trait values and fill gaps in the entity×trait matrix providing best trait estimates and uncertainties, e.g., based on probabilistic matrix factorization (Shan et al. 2012; Fazayeli, Banerjee, Kattge, Schrodt, & Reich, 2014; Schrodt et al., 2015) or random forest models (Moreno-Martinez et al. 2018). This is facilitated by the combination of phylogenetic trait conservatism and consistent trait-trait and trait-environment relationships. Gap filling is also alleviated by the long tail distributions observed in the trait data: some traits are much better covered by data than others – these then can be used as predictors. In addition, the average number of replicate individuals for each species×trait combination has doubled from TRY 1 to 5. Evidence for the efficiency of the gap-filling approaches is provided in Díaz et al. (2016), Moreno-Martínez et al. (2018) and Bruelheide et al. (2019). However, this predictive capacity refers to the overall accuracy – predictions of trait values for individual plants are still far from accurate and robust (Schrodt et al. 2015) and, therefore, the approach should not be taken as a "silver bullet" or a complete substitute for continued acquisition of empirical data. Importantly, where original data are too sparse the methods do not provide meaningful estimates at all (Moreno-Martinez et al. 2018) and machine learning does not provide new data after all. However, two other families of models, functional gradient descent and deep learning algorithms, have been quite successful in many applications, but not yet applied in the context of plant traits. It may, therefore, be interesting to explore these methods especially for traits where data are sparse.

Towards a third generation of plant trait data assimilation and sharing

We expect that the combination of (1) systematic involvement of the TRY community towards extraction and mobilization of legacy and recent trait data from public repositories, ecological literature, floras and herbaria, (2) facilitation of the 'feed-forward data assimilation loop', and (3) intensified collaboration of all plant trait-related initiatives, including new approaches and techniques, in combination with (4) improved machine learning for gap-filling and trait prediction will be effective towards a comprehensive representation of plant traits: a third generation of plant trait data assimilation and sharing.

Conclusion

TRY has received institutional support since 2007 and is still growing steeply in quantity and quality. While TRY may be generally considered a success and potentially a role model of future database initiatives by other scientific communities, it is important to realize that this development needed time and patience. It took until 2011 for the first TRY publication to appear because the early years of TRY were mostly devoted to organizing the community process towards a joint data sharing policy and to building trust. This process involved initially dozens and later hundreds of scientist when it came to agree on moving towards open access. These dynamics do not fit into three-year funding cycles as typically offered by national funding agencies. A key lesson of TRY is that the development of a database that is trusted by the community and accepted for its service and quality also needs the trust of the funders, i.e. long-term support, at the scale of decades rather than years. It also needs journals that are willing to accept long author lists and extended references lists to adequately acknowledge the original contributions that are the building blocks of community databases.

Table 5: Datasets contributed to the TRY plant trait database.

(THIS TABLE IS STILL WORK IN PROGRESS. IT NEEDS FINAL EDITING AND ADDING MISSING REFERENCES. PLEASE DO NOT COMMENT.)

ID	Dataset name	Custodian	Reference
1	Abisko & Sheffield Database	Johannes Cornelissen	(Cornelissen et al., 2004)
3	Australian Fire Ecology Database	Ross Bradstock	unpublished
4	BiolFlor Database	Ingolf Kühn	37
7	Cedar Creek Plant Physiology Database	Daniel Bunker	unpublished
10	Roots Of the World (ROW) Database	Joseph Craine	(Craine, Lee, Bond, Williams, & Johnson, 2005)
12	ECOCRAFT	Belinda Medlyn	(Medlyn et al., 1999)
20	GLOPNET - Global Plant Trait Network Database	Ian Wright	(Wright et al., 2004)
21	KEW Seed Information Database (SID)	Udayangani Liu	23
25	The LEDA Traitbase	Michael Kleyer	(Kleyer et al., 2008)
27	BROT Plant Trait Database	Juli Pausas	(Paula et al., 2009)
28	Global Seed Mass, Plant Height Database	Angela Moles	(Moles et al., 2005)
33	Tropical Rainforest Traits Database	Lourens Poorter	(Poorter & Bongers, 2006)
34	The RAINFOR Plant Trait Database	Jon Lloyd	(Fyllas et al., 2009)

35	Reich-Oleksyn Global Leaf N, P Database	Peter Reich	(Reich, Oleksyn, & Wright, 2009)
37	Sheffield Database	Johannes Cornelissen	(Cornelissen, Diez, & Hunt, 1996)
45	The VISTA Plant Trait Database	Eric Garnier	(Garnier et al., 2007)
47	South African Woody Plants Database (ZLTP)	William Bond	unpublished
48	Dispersal Traits Database	Steve Higgins	unpublished
49	Tree Tolerance Database	Ülo Niinemets	(Niinemets & Valladares, 2006)
50	Leaf and Whole Plant Traits Database	Bill Shipley	(Shipley, 2002)
51	Tropical Plant Traits From Borneo Database	Emily Swaine	74
52	Traits of Bornean Trees Database	Hiroko Kurokawa	(Kurokawa & Nakashizuka, 2008)
53	Chinese Leaf Traits Database	Jingyun Fang	(Han, Fang, Guo, & Zhang, 2005)
54	Floridian Leaf Traits Database	Jeannine Cavender-Bares	(Cavender-Bares, Keen, & Miles, 2006)
55	Jasper Ridge Californian Woody Plants Database	Will Cornwell	16
56	Wetland Dunes Database	Peter van Bodegom	75
57	Categorical Plant Traits Database	Ian Wright	unpublished
59	Frost Hardiness Database	Anja Rammig	unpublished
60	KEW African Plant Traits Database	Don Kirkup	(Kirkup, Malcolm, Christian, & Paton, 2005)
61	Global Wood Density Database	Amy Zanne	(Chave et al., 2009)
62	Global Vessel Anatomy Database	Amy Zanne	(Zanne et al., 2010)
63	Fonseca/Wright New South Wales Database	Ian Wright	(Fonseca, Overton, Collins, & Westoby, 2000)
64	Neotropic Plant Traits Database	Ian Wright	(Wright et al., 2006)
65	Overton/Wright New Zealand Database	Ian Wright	unpublished
66	Midwestern and Southern US Herbaceous Species Trait Database	Evan Weiher	unpublished
67	Leaf Physiology Database	Jens Kattge	(Kattge, Knorr, Raddatz, & Wirth, 2009)
68	The Functional Ecology of Trees (FET) Database - Jena	Christian Wirth	(Wirth & Lichstein, 2009)
70	Cedar Creek Savanna SLA, C, N Database	Peter Reich	(Willis et al., 2009)
71	BIOPOP: Functional Traits for Nature Conservation	Peter Poschlod	(Poschlod et al., 2003)
72	Sheffield & Spain Woody Database	Johannes Cornelissen	(Castro-Díez, Puyravaud, Cornelissen, & Villar-Salvador, 1998)
73	Tundra Plant Traits Database	F Stuart Chapin III	unpublished
74	Costa Rica Rainforest Trees Database	Bryan Finegan	unpublished
75	ECOQUA South American Plant Traits Database	Valerio Pillar	(Müller, Overbeck, Pfadenhauer, & Pillar, 2006)
76	European Mountain Meadows Plant Traits Database	Michael Bahn	118
77	FAPESP Brazil Rainforest Database	Enio Sosinski	unpublished
78	Global Wood Anatomy Database 1	Steven Jansen	unpublished
79	BIOME-BGC Parameterization Database	Michael White	(White, Thornton, Running, & Nemani, 2000)
80	French Massif Central Grassland Trait Database	Frédérique Louault	(Louault, Pillar, Aufrère, Garnier, & Soussana, 2005)
81	Global Leaf Element Composition Database	Steven Jansen	(Watanabe et al., 2007)
82	Global Wood Anatomy Database 2	Steven Jansen	unpublished
84	Causasus Plant Traits Database	Nadejda Soudzilovskaia	unpublished
86	Sheffield-Iran-Spain Database	Sandra Díaz	(Díaz et al., 2004a)
87	Global Leaf Robustness and Physiology Database	Ülo Niinemets	(Niinemets, 2001)
88	The Netherlands Plant Traits Database	Jenny Ordonez	(Ordoñez et al., 2010)
89	ArtDeco Database	Will Cornwell	(Cornwell et al., 2008)
90	Ukraine Wetlands Plant Traits Database	Peter van Bodegom	unpublished
91	Catalonian Mediterranean Forest Trait Database	Josep Peñuelas	(Ogaya & Peñuelas, 2003)
92	PLANTSdata USDA	Walton Green	30
93	Ponderosa Pine Forest Database	Daniel Laughlin	(Laughlin, Leppert, Moore, & Sieg, 2009)
94	Global A, N, P, SLA Database	Peter Reich	(Reich et al., 2009)
95	The Tansley Review LMA Database	Hendrik Poorter	(Poorter, Niinemets, Poorter, Wright, & Villar, 2009)
96	Global Respiration Database	Peter Reich	(Reich et al., 2008)
97	Plant Physiology Database	Owen Atkin	(Campbell et al., 2007)
98	New South Wales Plant Traits Database	Michelle Leishman	unpublished
99	Tropical Traits from West Java Database	Satomi Shiodera	(Shiodera, Rahajoe, & Kohyama, 2008)
100	Plant Traits in Pollution Gradients Database	Madhur Anand	unpublished
101	Photosynthesis Traits Database	Dennis Baldocchi	(Xu & Baldocchi, 2003)
102	Photosynthesis and Leaf Characteristics Database	Benjamin Blonder	unpublished
104	Categorical Plant Traits Database	Olivier Flores	unpublished
105	Traits from Subarctic Plant Species Database	Gregoire Freschet	(Freschet, Cornelissen, van Logtestijn, & Aerts,

			2010)
106	Climbing Plants Trait Database	Rachael Gallagher	(Gallagher, Leishman, & Moles, 2011)
108	The DIRECT Plant Trait Database	Peter Manning	(Fry, Power, & Manning, 2013)
109	Leaf Chemical Defense Database	Tara Massad	unpublished
110	Categorical Plant Traits Database	Hendrik Poorter	unpublished
111	Leaf and Whole-Plant Traits Database	Lawren Sack	(Nakahashi, Frole, & Sack, 2005)
112	Panama Plant Traits Database	S. Joseph Wright	(Wright et al., 2010)
113	Panama Leaf Traits Database	Julie Messier	(Messier, McGill, & Lechowicz, 2010)
114	Hawaiian Leaf Traits Database	Josep Peñuelas	(Penuelas et al., 2009)
115	Herbaceous Traits from the Öland Island Database	Thomas Hickler	135
116	The Netherlands Plant Height Database	Wim Ozinga	unpublished
117	Categorical Plant Traits Database	Peter van Bodegom	unpublished
119	Seed Information Database (SID) Seed Mass 2010	Udayangani Liu	447
120	Tropical Respiration Database	Jeffrey Chambers	(Chambers et al., 2004)
121	Fern Spore Mass Database	Johannes Cornelissen	unpublished
122	Plant Habit Database	Cyrille Violle	unpublished
123	VirtualForests Trait Database	Alvaro G. Gutierrez	(Gutiérrez & Huth, 2012)
124	Leaf Biomechanics Database	Yusuke Onoda	(Onoda et al., 2011)
125	Quercus Leaf C&N Database	Benjamin Yguel	(Yguel et al., 2011)
129	The Americas N&P database	Brian Enquist	(Kerkhoff, Fagan, Elser, & Enquist, 2006)
130	Global 15N Database	Joseph Craine	(Craine et al., 2009)
131	Catalonian Mediterranean Shrubland Trait Database	Josep Peñuelas	unpublished
133	New York Old Field Plant Traits Database	Andrew Siefert	(Siefert, 2011)
150	French Weeds Trait Database	Bernard Amiaud	unpublished
151	Aluminium Tolerance Dataset	Mehdi Abedi	(Abedi, Bartelheimer, & Poschlod, 2012)
152	Functional Traits of Graminoids in Semi-Arid Steppes Database	Peter Adler	(Adler, Milchunas, Lauenroth, Sala, & Burke, 2004)
154	Leaf Photosynthesis and Nitrogen at Oak Ridge Dataset	Dennis Baldocchi	(Wilson, Baldocchi, & Hanson, 2000)
156	Plant Traits of Canadian Forests	Benjamin Bond-Lamberty	(Bond-Lamberty, Wang, Gower, & Norman, 2002)
157	Litter N Content of Canadian Forests	Benjamin Bond-Lamberty	(Bond-Lamberty, Gower, Wang, Cyr, & Veldhuis, 2006)
158	Plant Traits from Circeo National Park, Italy	Sabina Burrascano	(Burrascano et al., 2015)
159	Traits of US Desert Woody Plant Species	Bradley Butterfield	(Butterfield & Briggs, 2010)
160	SLA and LDMC for Canadian Wetland Species	Chaeho Byun	(Byun, de Blois, & Brisson, 2012)
161	Leaf Traits in Central Apennines Beech Forests	Giandiego Campetella	(Campetella et al., 2011)
162	Mycorrhizal Intensity Database Across the Former Soviet Union	Nadejda Soudzilovskaia	(Akhmetzhanova et al., 2012)
163	Plant Traits for Grassland Species (Konza Prairie, Kansas, USA)	Joseph Craine	(Craine et al., 2011)
164	Italian Alps Plant Traits Database	Matteo Dainese	(Bragazza, 2009)
165	Leaf Traits From Madagascar	Kerry Brown	(Brown et al., 2013)
166	Traits of Hemiparastic Plants	Andreas Demey	(Demey et al., 2013)
167	Leaf N-Retention Database	Franciska de Vries	(de Vries & Bardgett, 2016)
168	Traits for Herbaceous Species from Andorra	Clara Pladevall	unpublished
169	Traits for Submerged Species (Aquatic Macrophytes)	Matthew Dunkle	unpublished
170	Plant Functional Traits of Arid Steppes in Eastern Morocco (ECWP-Morocco)	Cedric Frenette-Dussault	(Frenette-Dussault, Shipley, Léger, Meziane, & Hingrat, 2011)
171	Seed Characteristics of Ericaceae	Jaime Fagundez	239
172	Leaf Characteristics of Pinus Sylvestris and Picea Abies	Katrin Fleischer	unpublished
173	eHaloph - Halophytes Database (2013)	Tim Flowers	(Flowers, Galal, & Bromham, 2010)
174	Ecological Flora of the British Isles	Henry Ford	(A. H. Fitter & Peat, 1994)
175	BASECO: a floristic and ecological database of Mediterranean French flora	Sophie Gachet	(Gachet, Véla, & Tatoni, 2005)
176	Climbing plants trait dataset	Rachael Gallagher	(Gallagher & Leishman, 2012)
177	Litter Traits Dataset	Pablo García-Palacios	(García-Palacios, Maestre, Kattge, & Wall, 2013)
178	PLANTATT - Attributes of British and Irish Plants	Biological Records Centre (BRC)	238

179	Leaf Gross Morphometrics Within one Species in Relation to Latitude, Altitude and Time	Greg Guerin	(Guerin, Wen, & Lowe, 2012)
180	Leaf Ash Content in China's Terrestrial Plants	Wenxuan Han	307
181	Leaf Nitrogen and Phosphorus for China's Terrestrial Plants	Wenxuan Han	311
182	Eleven Mineral Elements in Plant Leaves Across China	Wenxuan Han	unpublished
183	Komati Leaf Trait Data	Wesley Hattingh	unpublished
184	Cold Tolerance, Seed Size and Height of North American Forest Tree Species	Bradford Hawkins	unpublished
185	cDNA Content of Carex	Andrew Hipp	251
186	Growth and Herbivory of Juvenil Trees	Hervé Jactel	unpublished
187	Xylem Functional Traits (XFT) Database: Nature Subset	Steven Jansen	(Choat et al., 2012)
188	Orchid Trait Dataset	Yael Kisel	(Kisel et al., 2012)
189	Mycorrhiza Database	Ian Dickie	(Koele, Dickie, Oleksyn, Richardson, & Reich, 2012)
190	Yasuni Ecuador Leaves	Nathan Kraft	(Kraft, Valencia, & Ackerly, 2008)
191	Baccara - Plant Traits of European Forests	Koen Kramer	unpublished
192	Meadow Plant Traits: Biomass Allocation, Rooting depth	Vojtech Lanta	unpublished
193	Plant Traits for Pinus and Juniperus Forests in Arizona	Daniel Laughlin	(Laughlin, Fulé, Huffman, Crouse, & Laliberté, 2011)
194	Leaf Traits From the LBA SECA Rain Exclusion Experiment	Jens Kattge	555
195	Leaf Herbivores, Fibres and Secondary Compounds For European Grassland Species	Jessy Loranger	(Loranger et al., 2012)
196	Rainfor Leaf Shape, Driptip, Compoundness and Size Database	Ana Malhado	(Malhado et al., 2012)
197	Plant Hydraulic Traits	Stefano Manzoni	(Manzoni, Vico, Porporato, & Katul, 2013)
198	Global Leaf-Sapwood Area Ratios	Maurizio Mencuccini	267
199	Whole Plant Hydraulic Conductance	Maurizio Mencuccini	(Mencuccini, 2003)
200	Altitudinal Vicariants Spain	Ruben Milla	(Milla & Reich, 2011)
201	Phalaris Arundinacea Genotypes	Jane Molofsky	(Lavergne & Molofsky, 2007)
202	Traits from the Wildfire Project	Marco Moretti	265
203	Plant Traits from Romania	Kinga Öllerer	223
204	Impatiens Glandulifera Dataset	Anna Pahl	(Pahl, Kollmann, Mayer, & Haider, 2013)
205	Leaf Allometry Dataset	Charles Price	(Price & Enquist, 2007)
206	Maxfield Meadow, Rocky Mountain Biological Laboratory - LMA	Quentin Read	unpublished
207	Herbaceous Plants Traits From Southern Germany	Christine Roemermann	unpublished
208	Response of Tree Growth to Light and Size, Barro Colorado Island, Panama	Nadja Rueger	(Rüger, Berger, Hubbell, Vieilledent, & Condit, 2011)
209	Leaf Area, Dry Mass and SLA Dataset	Brandon Schamp	unpublished
211	BIOTREE Trait Shade Experiment	Michael Scherer-Lorenzen	(Scherer-Lorenzen, Schulze, Don, Schumacher, & Weller, 2007)
212	Herbs Water Relations on Soil Moisture Gradients	Serge Sheremetev	(Sheremetiev & Chebotareva, 2018)
213	Day and Night Gas Exchange of Deciduous Tree Seedlings in Response to Experimental Warming and Preci	Nick Smith	unpublished
214	Maximum Height of Chinese Tree Species (From Silva Sinica)	Nathan Swenson	312
215	Plant Functional Traits From the Province of Almeria (Spain)	Alexia Totte	unpublished
216	Traits for Common Grasses and Herbs in Spain	Fernando Valladares	unpublished
217	Canopy Traits for Temperate Tree Species Under High N-Deposition	Kris Verheyen	197
218	Plant Traits, Virginia, USA	Betsy von Holle	(Von Holle & Simberloff, 2004)
219	Seed Mass from Literature	Zhonglei Wang	unpublished
220	Leaf Traits in Italian Central Apennines Beech Forests	Giandiego Campetella	(Campetella et al., 2011)

221	Leaf Economic Traits Across Varying Environmental Conditions	Justin Wright	(Wright & Sutton-Grier, 2012)
223	San Lorenzo Epiphyte Leaf Traits Database	Gerhard Zotz	(Petter et al., 2015)
224	LBA-ECO CD-02 C and N Isotopes in Leaves and Atmospheric CO2, Amazonas, Brazil	Alessandro de Araujo	230
225	Diameter at Breast Height and Life Form of Amazonian Flora	Erika Berenguer	unpublished
226	Leaf Structure, Venation and Economic Spectrum	Benjamin Blonder	(Blonder, Violle, Bentley, & Enquist, 2010)
227	Leaf Structure and Economics Spectrum	Bruno E. L. Cerabolini	(Pierce, Ceriani, De Andreis, Luzzaro, & Cerabolini, 2007)
228	Flora d'Italia Functional Traits Hoard (FIFTH)	Bruno E. L. Cerabolini	(Cerabolini et al., 2010)
229	Hydrophytes Traits Database	Bruno E. L. Cerabolini	(Simon Pierce, Brusa, Sartori, & Cerabolini, 2012)
230	Panama Tree Traits	Dylan Craven	(Craven et al., 2007)
231	TROBIT West Africa	Tomas Domingues	(Tomas Ferreira Domingues et al., 2010)
232	LBA ECO CD02: Tapajos Leaf Water Potential	Tomas Domingues	255
234	Leaf Traits Mount Hutt, New Zealand	Gregoire Freschet	(Kichenin, Wardle, Peltzer, Morse, & Freschet, 2013)
236	Chinese Traits	Sandy Harrison	(Prentice et al., 2010)
237	Harze Trait Intravar: SLA, LDMC and Plant Height for Calcareous Grassland Species in South Belgium	Mélanie Harzé	unpublished
238	Fire Related Traits in Proteaceae and Pinaceae	Tianhua He	unpublished
239	LABDENDRO Brazilian Subtropical Forest Traits Database	Pedro Higuchi	unpublished
240	Nutrient Resorption Efficiency Database	Robert Jackson	304
241	Xylem Functional Traits (XFT) Database	Steven Jansen	216
242	Ellenberg Indicator Values	Gerhard Boenisch	236
243	CLO-PLA : a Database of Clonal Growth in Plants	Jitka Klimesova	(Klimešová & de Bello, 2009)
244	Global Wood Anatomy Database 1	Frederic Lens	343
245	Ecotron Species Composition and Global Change Experiment	Peter Manning	(Manning et al., 2006)
247	Traits of Halohytic Species in North-West-Germany	Vanessa Minden	(Vanessa Minden & Kleyer, 2011)
248	Photosynthesis Type Database	Hendrik Poorter	(Kapralov, Smith, & Filatov, 2012)
249	California Coastal Grassland Database	Brody Sandel	(Sandel, Corbin, & Krupa, 2011)
250	FYNBASE - Database of Plant Traits From the South African Fynbos Biome	Frank Schurr	(Schurr et al., 2007)
251	The Xylem/Phloem Database	Fritz Schweingruber	292
252	Leaf Structure and Chemistry	Bill Shipley	(Auger & Shipley, 2012)
253	Allometric Coefficients of Aboveground Tree Biomass	Carlos Sierra	(Zapata-Cuartas, Sierra, & Alleman, 2012)
255	LBA ECO Tapajos: Leaf Characteristics and Photosynthesis	Tomas Domingues	(Domingues, Martinelli, & Ehleringer, 2007)
256	Niwot Alpine Plant Traits	Marko Spasojevic	(Spasojevic & Suding, 2012)
258	Global Wood Decomposition Database (version 1.1)	James Weedon	(Weedon et al., 2009)
259	Angiosperm Shoot Ionomes Dataset	Philip White	277
262	LBA-ECO CD-09 Soil and Vegetation Characteristics, Tapajos National Forest, Brazil	Mathew Williams	308
263	Costa Rican Tropical Dry Forest Trees	Jennifer Powers	(Powers & Tiffin, 2010)
264	Functional Traits Of Bulgarian Grasslands	Kiril Vassilev	(Vassilev, Pedashenko, Nikolov, Apostolova, & Dengler, 2011)
265	Saskatchewan Plant Trait Database	Eric Lamb	(Guy, Mischkolz, & Lamb, 2013)
266	Hawaiian Lobeliad	Rebecca Montgomery	(Givnish, Montgomery, & Goldstein, 2004)
267	Functional Traits for Restoration Ecology in the Colombian Amazon	Andres Gonzalez-Melo	unpublished
268	Seed Longevity of European Early Successional Species	Harald Albrecht	unpublished
269	The Bridge Database	Chris Baraloto	(Baraloto, Timothy Paine, et al., 2010)
270	Plant Traits of Acidic Grasslands in Central Spain	Begoña Peco	(Peco, de Pablos, Traba, & Levassor, 2005)
271	Traits of Species of Bajo Calima Region, Buenaventura Colombia	Fernando Fernández-Méndez	(Bocanegra, Fernández, & Galvis, 2015)
272	Plant Coastal Dune Traits (France, Aquitaine)	Estelle Forey	unpublished
273	Plant Trait Database in East and South-East Asia	Fumito Koike	(Koike, 2001)

274	Crown Architecture Database	Felipe Lenti	unpublished
275	Plant Traits From Spanish Mediteranean shrublands	Nicholas Gross	unpublished
276	Global Checked Taxonomy	Amy Zanne	324
277	UV-B Radiation Sensitivity of Hieracium Pilosella	Michael Beckmann	(Beckmann, Hock, Bruelheide, & Erfmeier, 2012)
278	Photosynthetic Capacity Dataset	Patrick Meir	(Meir et al., 2002)
279	Global Leaf Phenology Database	Ian Wright	(Zanne et al., 2014)
280	Global Woodiness Database	William Cornwell	(Zanne et al., 2014)
281	Minimum Freezing Exposure Database	Daniel McGlinn	(Zanne et al., 2014)
283	Response of Tree Mortality to Light, Size and Past Growth, Barro Colorado Island, Panama	Nadja Rüger	(Rüger, Huth, Hubbell, & Condit, 2011)
284	Response of Tree Recruitment to Light, Barro Colorado Island, Panama	Nadja Rüger	(Rüger, Huth, Hubbell, & Condit, 2009)
285	Functional traits explaining variation in plant life history strategies	Peter Adler	(Adler et al., 2013)
286	Global Respiration Database	Owen Atkin	(Atkin et al., 2015)
287	Biomass allocation of Carex obnupta and Carex stipata	Nate Hough-Snee	(Hough-Snee, Nackley, Kim, & Ewing, 2015)
288	CTFS Luquillo Forest Dynamics Plot	Nathan Swenson	(Swenson, Anglada-Cordero, & Barone, 2010)
289	Cabo de Gata-Níjar Natural Park	Angel de Frutos	(de Frutos, Navarro, Pueyo, & Alados, 2015)
290	Traits of halophytic species	Vanessa Minden	(Minden & Kleyer, 2015)
291	MARGINS - leaf traits database	Daniel Hornstein	unpublished
292	TOPIC (Traits of Plants in Canada)	Isabelle Aubin	724
293	Jasper Ridge leaf chemistry data	Kyla Dahlin	(Dahlin, Asner, & Field, 2013)
294	Siberian shrub allometry	Logan Berner	(Berner et al., 2015)
295	Leaf functional traits in the Hawaiian silversword alliance	Benjamin Blonder	(Blonder, Baldwin, Enquist, & Robichaux, 2015)
296	Northern mixed-grass prairie species traits - Wyoming, USA	Dana Blumenthal	unpublished
297	Traits of Polygonum viviparum L.	Florian Boucher	(Boucher, Thuiller, Arnoldi, Albert, & Lavergne, 2013)
298	Plant traits from Greby, Oeland, Sweden	Hans Henrik Bruun	(Baastrup-Spohr, Sand-Jensen, Nicolajsen, & Bruun, 2015)
299	Traits related to riparian plant invasion in South East Australia	Jane Catford	(Catford, Morris, Vesk, Gippel, & Downes, 2014)
300	Leaf traits from the Loess Plateau region of northern Shaanxi in China	Yongfu Chai	unpublished
301	Specific leaf area responses to environmental gradients through space and time	John Dwyer	(Dwyer, Hobbs, & Mayfield, 2014)
302	Traits from Semi-Arid Mediterranean Ecosystems	Daniel Flynn	(de Frutos et al., 2015)
303	Traits from Cabo de Gata-Níjar Natural Park	Angel de Frutos	unpublished
304	Leaf traits from North West Italy	Giovanni Gligora	unpublished
305	Araucaria Forest Database	Pedro Higuchi	(Higuchi et al., 2012)
306	Plant traits from Costa Rica	Karen Holl	unpublished
307	Hokkaido leaf traits	Akira Mori	(Mori et al., 2015)
308	Plant traits from Andorra	Benjamin Komac	(Komac, Pladevall, Domènech, & Fanlo, 2014)
309	Plant traits of grassland species	Kim La Pierre	(La Pierre & Smith, 2014)
310	French Alps Trait Data	Sandra Lavorel	(Lavorel et al., 2010)
311	Structural and biochemical leaf traits of boreal tree species in Finland	Petr Lukes	(Lukeš, Stenberg, Rautiainen, Mõttus, & Vanhatalo, 2013)
312	Traits of temperate rainforest tree seedlings from New Zealand	Chris Lusk	(Lusk, Kaneko, Grierson, & Clearwater, 2013)
313	Wood carbon content database	Adam Martin	422
314	Shoot dry mass of annual grassland species	Zia Mehrabi	unpublished
315	Leaf traits for Picea glauca and Pinus sylvestris on University of Calgary (Canada) campus	Sean Michaletz	(Michaletz & Johnson, 2006)
316	Element contents of plant organs of halohytic species, NW-Germany	Vanessa Minden	(Minden & Kleyer, 2014)
317	Traits of Hypochaeris radicata under shade and drought conditions	Rachel Mitchell	unpublished
318	Leaf traits related to mesophyll conductance in wild relatives of tomato (Solanum lycopersicon)	Christopher Muir	(Muir, Hangarter, Moyle, & Davis, 2013)

319	Plant Traits from Fynbos Forests in the Cape Region	Renske Onstein	(Onstein, Carter, Xing, & Linder, 2014)
320	Grassland Plant Trait Database	Meelis Pärtel	444
321	Leaf angles	Jan Pisek	(Pisek, Sonnentag, Richardson, & Mõttus, 2013)
322	Shoot N/P stoichiometry of Inner Mongolia grassland species	Qiang Yu	(Yu et al., 2011)
323	Rocky Mountain Biological Laboratory WSR/gradient plant traits	Quentin Read	unpublished
324	BiodiERsA-PEATBOG campaign: plant CNP	Bjorn Robroek	unpublished
325	Rollinson DBH	Emily Rollinson	unpublished
326	Leaf nutrient concentrations	Victor Rolo Romero	(Rolo, López-Díaz, & Moreno, 2012)
327	Eastern US Old Field Plant Traits Database	Andrew Siefert	(Siefert, Fridley, & Ritchie, 2014)
328	Root Traits of Grassland Species	Stuart William Smith	(Smith, Woodin, Pakeman, Johnson, & van der Wal, 2014)
329	Plant traits from alpine plants on Mt. Malaya Khatipara	Nadejda Soudzilovskaia	(Soudzilovskaia et al., 2013)
330	Traits of Ukraine native and invasive plant species	Peter van Bodegom	unpublished
331	Traits of savannah trees in the Hluhluwe-iMfolozi Game reserve, South Africa	Fons van der Plas	(Van der Plas, Howison, Reinders, Fokkema, & Olff, 2012)
332	Photosynthetic parameters, respiration and leaf traits of a Peruvian tropical montane cloud forest	Marjan van de Weg	(van de Weg, Meir, Grace, & Ramos, 2011)
333	LMA, leaf tissue density and N&P content along the Amazon-Andes gradient in Peru	Marjan van de Weg	(van de Weg, Meir, Grace, & Atkin, 2009)
334	A Global Data Set of Leaf Photosynthetic Rates, Leaf N and P, and Specific Leaf Area	Anthony Walker	436
335	Plant traits from Wisconsin, USA	Evan Weiher	unpublished
336	Ecophsiological traits of Pinus halepensis Miller	Tamir Klein	437
337	Tree Anatomy China	Jingming Zheng	(Zheng & Martínez-Cabrera, 2013)
338	Leaf Traits and Seed Mass of Cover Crops	Hélène Tribouillois	(Tribouillois et al., 2015)
339	FRED - Fine Root Ecology Database	Colleen Iversen	(Iversen et al., 2017)
340	Global leaf size dataset	Ian Wright	(Wright et al., 2017)
341	eHALOPH - Halophytes Database (2015)	Tim Flowers	539
342	Photosynthesis Traits Worldwide	Vincent Maire	(Maire et al., 2015)
343	Sphagnum tissue CNP	Bjorn Robroek	unpublished
344	LosTuxtlas_functionaltraits	Cristina Martinez-Garza	(Martínez-Garza, Bongers, & Poorter, 2013)
345	CIRAD Selmet Tree LNC Sahel	Simon Taugourdeau	unpublished
346	Leaf traits of Dipterocarpus alatus Roxb. ex. G. Don	Anh Tuan Dang-Le	(Dang-Le, Edelin, & Le-Cong, 2013)
347	Traits of 59 grassland species	Alexandra Weigelt	(Schroeder-Georgi et al., 2015)
348	Leaf traits data (SLA) for 56 woody species at the Smithsonian Conservation Biology Institute-Forest	Erika B. Gonzalez-Akre	450
349	Mediterranean psammophytes	Daniela Ciccarelli	(Ciccarelli, 2015)
350	Trait Data for African Plants - a Photo Guide	Marco Schmidt	(Dressler, Schmidt, & Zizka, 2014)
351	Miombo tree species - SLA, leaf and seed size	Colleen Seymour	(Joseph, Seymour, Cumming, Cumming, & Mahlangu, 2014)
352	Miombo tree species - leaf nutrients	Colleen Seymour	(Seymour et al., 2014)
353	Old fields of Eastern US (Siefert Data)	Luka Negoita	(Siefert et al., 2014)
354	Cedar Creek prairie plants (leaf, seed, dispersule, height, plant, root)	Jane Catford	(Catford et al., 2019)
355	Knautia arvensis; Mid-Norway	Knut Hovstad	470
356	Aboveground morphological traits of grassland species	Marina Semchenko	(Abakumova, Zobel, Lepik, & Semchenko, 2016)
357	Functional traits of woody species in the Brazilian semi-arid region	Guilherme Mazzochini	unpublished
358	Leaf Respiration Acclimation in Panama	Martijn Slot	(Slot, Rey-Sánchez, Winter, & Kitajima, 2014)
359	Plant traits of Arabidopsis thaliana	Benjamin Blonder	(Blonder, Vasseur, et al., 2015)
360	Fossil Leaf Traits	Benjamin Blonder	(Blonder, Royer, Johnson, Miller, & Enquist, 2014)
361	Angiosperm leaf venation networks	Benjamin Blonder	(Blonder & Enquist, 2014)
362	Leaf economics spectrum and venation networks in Populus tremuloides	Benjamin Blonder	(Blonder, Violle, & Enquist, 2013)
364	Plant species high elevation dataset	Christien Steyn	(Steyn, Greve, Robertson, Kalwij, & le Roux, 2016)
365	Tree of sex: a database of sexual systems	Sarah Otto	478

366	Plant Traits from LTER Matsch (Mazia), Italy	Veronika Fontana	unpublished
367	Tree species functional traits from Dinghushan Biosphere Reserve, southern China	Pengcheng He	(Li et al., 2015)
368	Wood traits of trees and lianas from the Brazilian Atlantic Forest	Arildo Dias	unpublished
369	Traits and ecological strategies of 66 subtropical tree species in the Brazilian Atlantic Forest	Alexandre Souza	(Forgiarini, Souza, Longhi, & Oliveira, 2014)
370	Trait Data from Niwot Ridge LTER (2016)	Adam Chmurzynski	unpublished
371	Olive Lawn Orchid Trait Database (OLO)	Bruno E. L. Cerabolini	(Simon Pierce, Vagge, Brusa, & Cerabolini, 2014)
372	Malga San Simone Trait Database (MSS)	Bruno E. L. Cerabolini	(Cerabolini, Pierce, Luzzaro, & Ossola, 2009)
373	Leaf vein density of Fagus sylvatica L. and Quercus faginea Lam.	Raquel Benavides	unpublished
374	Traits of fertile (spore bearing) leaves of rainforest ferns from El Verde Field, Puerto Rico	Joanne Sharpe	502
375	Traits of sterile (non-spore bearing) leaves of rainforest ferns from El Verde Field, Puerto Rico	Joanne Sharpe	503
376	Biomass allocation in beech and spruce seedlings	Christian Ammer	(Schall, Lödige, Beck, & Ammer, 2012)
377	Functional Traits of Trees in Golfo Dulce, Costa Rica	Eduardo Chacon	(Chacón-Madrigal, Wanek, Hietz, & Dullinger, 2018)
378	Traits of the Hungarian flora	Anikó Csecserits	(Lhotsky, Csecserits, Kovács, & Botta-Dukát, 2016)
379	Stomatal conductance photosynthesis, soil water content & survival along a water stress experiment	Michaël Belluau	(Belluau & Shipley, 2017)
380	Plant growth form dataset for the New World	Kristine Engemann	(Engemann et al., 2016)
381	Leaf traits from Baltic Island species	Markus Bernhardt-Römermann	519
382	Species able to reproduce after fire in a Brazilian Savanna	Aelton Giroldo	542
383	Species and trait shifts in Apennine grasslands	Eleonora Giarrizzo	(Giarrizzo et al., 2016)
384	Panama wood anatomy	Peter Hietz	(Hietz, Rosner, Hietz-Seifert, & Wright, 2016)
385	Photosynthesis Temperature Response Panama	Martijn Slot	(Slot & Winter, 2017)
386	Rehabilitating Coastal Dune Forest	Victor Rolo Romero	(Victor Rolo, Olivier, & van Aarde, 2016)
387	LEVA-UFPE plant trait database	Bruno Pinho	unpublished
388	Leaf traits (and a few seed weights) collected from plants in the Macquarie Marshes, Australia	Samantha Dawson	(Dawson et al., 2017)
389	Leaf element composition of ferns and lycophytes	Steven Jansen	(Schmitt et al., 2017)
390	Rhododendron leaf and root economics traits	Juliana Medeiros	(Medeiros, Burns, Nicholson, Rogers, & Valverde-Barrantes, 2017)
391	Dataset for Rosell 2016 New Phytologist	Julieta Rosell	(Rosell, 2016)
392	Dataset for Rosell et al. 2017 New Phytologist	Julieta Rosell	(Rosell, Olson, Anfodillo, & Martínez-Méndez, 2017)
393	LABDENDRO Brazilian Subtropical Forest Traits Database [Dataset II]	Ana Carolina Silva	(Souza et al., 2017)
394	Great Basin sagebrush seedlings-greenhouse experiment	Courtney Collins	unpublished
395	Senckenberg leaf venation data of West African Plants	Julio Schneider	unpublished
396	Rehabilitating Coastal dune forest	Victor Rolo Romero	(Victor Rolo et al., 2016)
397	Fine root traits of 141 Central European grassland species	Joana Bergmann	(Bergmann, Ryo, Prati, Hempel, & Rillig, 2017)
398	Yangambi (DR Congo) tropical forest tree traits	Elizabeth Kearsley	(Kearsley et al., 2016)
399	Ozark - woody plants - Tyson	Marko Spasojevic	(Spasojevic, Turner, & Myers, 2016)
400	Leaf Mass Area, Leaf Carbon and Nitrogen Content, Barrow, Alaska	Alistair Rogers	(Rogers, Serbin, Ely, Sloan, & Wullschleger, 2017)
401	Arctic Leaf Photosynthetic Parameters Vcmax and Jmax Estimated from CO2 Response Curves	Alistair Rogers	(Rogers et al., 2017)
402	Arctic Photosynthetic parameter Vcmax Estimated Using the 1-Point Method	Alistair Rogers	(Rogers et al., 2017)
403	Iranian Plant Trait Dataset	Mehdi Abedi	unpublished
404	Leaf nutrients and SLA for old field shrubs and small trees from northeastern Connecticut, USA	Nicole Kinlock	unpublished
405	JACARE A-Ci leaf trait data base 2017	Owen Atkin	(Bahar et al., 2016)

406	Whole plant traits and leaf traits of four grassland species in Central Apennines (Italy)	Giandiego Campetella	(Wellstein et al., 2013)
407	Leaf nutrient concentration_Scalon et al. 2017	Marina Scalon	(Scalon, Haridasan, & Franco, 2017)
408	Alaska Peatland Experiment PFT values	Mara McPartland	605
409	Seed trait data from Neuschulz et al. 2016 Sci REp.	Eike Lena Neuschulz	(Neuschulz, Mueller, Schleuning, & Böhning-Gaese, 2016)
410	Onoda 2017 leaf dataset	Yusuke Onoda	(Onoda et al., 2017)
411	Fall Velocity from Baltic Island species	Markus Bernhardt-Römermann	607
412	The Global Leaf Traits	Serge Sheremetev	unpublished
413	Zanne et al. Global wood density database.	Lopez-Gonzalez	89
414	eHALOPH - Halophytes Database (2018)	Tim Flowers	608
415	Ozark glade grassland plants	Jesse Miller	(Miller, Ives, Harrison, & Damschen, 2017)
416	Garmisch-Partenkirchen elevational gradients	Solveig Franziska Bucher	(Bucher et al., 2016)
417	Leaf angles Raabe et al 2015	Jan Pisek	(Raabe, Pisek, Sonnentag, & Annuk, 2015)
418	Ozark Tree leaf traits	Marko Spasojevic	(Spasojevic et al., 2016)
419	Sherbrooke	Yuanzhi Li	628
420	Chinese savanna trees - aboveground trait data	Coline Boonman	unpublished
421	LECA - Traits of the European Alpine Flora	Louise Boulangeat	630
422	Hawaii native and non indigenous species. Traits and environment	Zdravko Baruch	(Baruch & Goldstein, 1999)
423	Leaf economic traits in wheat and maize	Adam Martin	(Martin, Hale, et al., 2018)
424	LCE: Leaf carbon exchange dataset for tropical, temperate, and boreal species of North and Central A	Nick Smith	(Smith & Dukes, 2017)
425	Linking hard and soft traits	Michaël Belluau	(Belluau & Shipley, 2018)
426	Ti Tree	Rachael Nolan	(Nolan et al., 2017)
427	Coffea arabica var. Caturra - leaf traits	Serra Willow Buchanan	(Buchanan, Isaac, Van den Meersche, & Martin, 2018)
428	Trait and biomass data 2014 and 2015 of the BE_LOW project	Helge Bruelheide	(Herz et al., 2017)
429	TraitDunes	Alicia T.R. Acosta	unpublished
430	A Global Dataset of Leaf Delta13C Data	Will Cornwell	(Cornwell et al., 2018)
431	BAAD: a biomass and allometry database for woody plants	Daniel Falster	(Falster et al., 2015)
432	Global Dataset of Maximum Rooting Depth	Ying Fan Reinfelder	(Fan, Miguez-Macho, Jobbágy, Jackson, & Otero-Casal, 2017)
433	Wood carbon database	Adam Martin	(Martin, Doraisami, & Thomas, 2018)
434	Seed mass and nutrient concentration in Grevillea and Hakea species	Tianhua He	unpublished
435	Functional Resilience of Temperate Forests Dataset	Mario Liebergesell	(Liebergesell et al., 2016)
436	Global Leaf Gas Exchange Database (I)	Yan-Shih Lin	(Lin et al., 2015)
437	Global Leaf Gas Exchange Database (II)	Belinda Medlyn	(Knauer et al., 2017)
438	Crop Trait Database	Adam Martin	(Martin, Hale, et al., 2018)
439	Functional Traits of Trees	C. E. Timothy Paine	400
440	P50R - A global P50 & Resprouting Database	Juli Pausas	(Pausas et al., 2015)
441	BBB - A global Belowground Bud Bank database	Juli Pausas	(Pausas, Lamont, Paula, Appezzato-da-Glória, & Fidelis, 2018)
442	Plant Trait Dataset for Tree-Like Growth Forms	Arthur Vinicius Rodrigues	(Rodrigues et al., 2018)
443	The China Plant Trait Database	Han Wang	(Wang et al., 2017)
444	Symbiotic N2-Fixation Database	Gijsbert Werner	(Werner, Cornwell, Sprent, Kattge, & Kiers, 2014)
445	Mycorrhizal Association Database	Gijsbert Werner	(Werner et al., 2018)
446	Ring-width dataset of dead and living trees	Maxime Cailleret	663
447	Herbaceous plants of Rouge National Urban Park	Marc Cadotte	unpublished
448	Cadotte 2017 Ecology Letters: herbaceous traits measured in the filed	Marc Cadotte	(Cadotte, 2017)
449	KIT herbaceous functional gradient (median)	Teja Kattenborn	(Kattenborn, Fassnacht, & Schmidtlein, 2018)
450	BryForTrait – a life-history trait database of forest bryophytes	Markus Bernhardt-Römermann	(Bernhardt-Römermann, Poschlod, & Hentschel, 2018)
451	NodDB - a global database of plants with root-symbiotic nitrogen fixation	Leho Tedersoo	(Tedersoo et al., 2018)
453	European North Russia	Alexander Novakovskiy	700
454	Leaf traits from ECOSHRUB Dovrefjell Norway	Mia Vedel Sørensen	unpublished

456	Trait-responses of Impatiens species to light and nutrients	Vanessa Minden	(Minden & Gorschlüter, 2016)
457	Antibiotics-effects on plant traits	Vanessa Minden	(Minden, Deloy, Volkert, Leonhardt, & Pufal, 2017)
458	Antibiotics-effects on plant elements	Vanessa Minden	(Minden, Schnetger, Pufal, & Leonhardt, 2018)
459	Yasuni Ecuador Leaf Drought Tolerance and Mechanical Toughness	Ian McFadden	(McFadden et al., 2019)
460	TRY Categorical Traits Dataset (update 2018)	Angela Guenther	unpublished
461	Western Pamirs	Kim André Vanselow	(Vanselow, Samimi, & Breckle, 2016)
462	RBGKew Palm leaf traits	Thaise Emilio	unpublished
463	Leaf Chlorophyll and carotenoids Database	Leonid Ivanov	unpublished
464	Leaf traits of selected trees and lianas_vivek	Vivek Pandi	unpublished
465	Yasuni Ecuador Leaf ITV	Ian McFadden	(Fortunel, McFadden, Valencia, & Kraft, 2019)
466	Leaf and stem traits of Eremanthus erythropappus	Mateus Silva	(Silva, Teodoro, Bragion, & van den Berg, 2019)
467	Data on chlorophylls and carotenoids in plants and lichens at the European Northeast of Russia	Olga Dymova	(Golovko, Dymova, Yatsco, & Tabalenkova, 2010)
468	Tundra Trait Team	Anne Bjorkman	727
469	ACi-TGlob_V1.0: A Global dataset of photosynthetic CO2 response curves of terrestrial plants	Dushan Kumarathunge	(Kumarathunge et al., 2019)
470	Neotropical woody plants functional trait database	Bruno Pinho	unpublished
471	Species Growth Forms (Angiosperms)-Update 9	Serge Sheremetev	761
472	Traits data for plant species from Western Australia	Tianhua He	unpublished
473	Functional trait data Colombian dry Forest trees	Evert Thomas	762
474	BROT 2.0	Juli Pausas	(Tavşanoğlu & Pausas, 2018)
475	Woody plant traits from southeast Queensland, Australia	James McCarthy	(McCarthy)
476	Leaf traits and litter properties in Dinghu mountain, Guangdong province, China	Enqing Hou	(Hou, Chen, McGroddy, & Wen, 2012)
477	Fazlioglu et al. 2018_raw data	Fatih Fazlioglu	767
478	Fazlioglu, 2011, MSc Thesis	Fatih Fazlioglu	768
479	Functional trait data Colombian dry Forest trees	Evert Thomas	762
480	Fazlioglu, 2008	Fatih Fazlioglu	769
481	Fazlioglu et al. 2016	Fatih Fazlioglu	(Fazlioglu, Al-Namazi, & Bonser, 2016)
482	Fazlioglu et al. 2017	Fatih Fazlioglu	(Fazlioglu, Wan, & Bonser, 2016)
483	A Geological Age of an Angiosperm Genera and Families	Serge Sheremetev	761
484	Lariz Occidentalis branch section specific leaf area and dry mass	Andrew Nelson	(Williams & Nelson, 2018)
485	Catimbau National Park, Brazil	Julia Sfair	(Sfair, de Bello, de França, Baldauf, & Tabarelli, 2018)
486	Brassica tournefortii	Daniel Winkler	774
487	Sasa kurilensis	Daniel Winkler	(Winkler, Amagai, Huxman, Kaneko, & Kudo, 2016)
488	IR_DowlatAbad	Mohammad Bagher Erfanian	unpublished
489	Pladias: Ellenberg-type indicator values for the Czech flora	Milan Chytry	(Chytrý, Tichý, Dřevojan, Sádlo, & Zelený, 2018)
490	Fazlioglu et al. 2016-Data-synthesis	Fatih Fazlioglu	(Fazlioglu & Bonser, 2016)
491	Leaf inclination angle	Francesco Chianucci	(Chianucci et al., 2018)
492	Torres-Ruiz	Jose M. Torres-Ruiz	(Torres-Ruiz et al., 2017)
493	Weiqi-Sardans-Penuelas-China-plants	Josep Peñuelas	780
494	Poblet Ecophysiogology	Víctor Resco de Dios	(Nolan, Hedo, Arteaga, Sugai, & Resco de Dios, 2018)
495	Live fuel moisture data at a pine forest	Víctor Resco de Dios	782
496	Garraf-Penuelas	Josep Peñuelas	(Peñuelas et al., 2017)
497	Prades-Penuelas	Josep Peñuelas	(Peñuelas et al., 2018)
498	Fruit type, fruit dimension and flowering time	Si-Chong Chen	(Chen, Cornwell, Zhang, & Moles, 2016)
499	Growth form data for 3581 Australian species	Si-Chong Chen	(S.-C. Chen et al., 2016)
500	Pladias: Life forms and heights of the Czech flora	Jiøí Danihelka	787
501	Leaf traits of beech forest understory species	Stefano Chelli	unpublished
502	Yangambi arboretum	Marijn Bauters	(Bauters et al., 2015)

503	Leaf and whole plant traits of Val Cervara old growth beech forest (Central Apennine, Italy)	Roberto Canullo	unpublished
504	Djolu	Marijn Bauters	(Bauters et al., 2019)
505	Nyungwe_Rwanda	Marijn Bauters	(Bauters et al., 2017)
506	Functional traits of Cistus species leaf cohorts	Giacomo Puglielli	(Puglielli & Varone, 2018)
507	Freschet et al. 2018	Gregoire Freschet	(Freschet, Violle, Bourget, Scherer-Lorenzen, & Fort, 2018)
508	ladias: leaf traits in the Czech flora	Zdenka Lososová	793
509	Leaf functional traits for tropical saplings from Jianfengling, Hainan Island, China	J. Aaron Hogan	(Hogan, Valverde-Barrantes, Ding, Xu, & Baraloto, 2019)
510	Freschet et al. 2015 - VU greenhouse	Gregoire Freschet	(Freschet, Swart, & Cornelissen, 2015)
511	Freschet et al. 2015 - Mount Hutt	Gregoire Freschet	(Freschet, Kichenin, & Wardle, 2015)
512	chromosomes.senckenberg.de	Thomas Gregor	(Paule et al., 2016)
513	Traits of urban trees of Ibague, Colombia	Fernando Fernández-Méndez	(Núñez-Florez, Pérez-Gómez, & Fernández-Méndez, 2019)
514	Macquarie_xylem_leaf_site_hydraulic	Sean Gleason	unpublished
515	A-Ci curves	Lahcen Benomar	(Benomar et al., 2017)
516	Pladias: Flowering time of the Czech flora	Zdenik Kaplan	800
517	Mt Baldy whole plant traits	Benjamin Blonder	(Blonder et al., 2018)
518	Plant traits along NPK gradients	Vanessa Minden	(Minden & Olde Venterink, 2019)
519	SwissNationalPark_Engadine	Christian Rossi	803
520	Pinnacle Reserve, ACT	Andrew OReilly-Nugent	804
521	Heterotheca brandegei traits	Daniel Winkler	805
522	Ecophysiology of Selaginella and fern species in a Costa Rica wet tropical forest floor	Courtney Campany	(Campany, Martin, & Watkins, 2018)
523	SLA and height data of exotic plant species in highland forest of Java and Bali	Decky Indrawan Junaedi	unpublished
524	AlpinePlants_Austria	Robert R. Junker	807
525	Arboretum Grosspoessna 2014 leaf chemical and photosynthesis traits	Benjamin Dechant	(Dechant, Cuntz, Vohland, Schulz, & Doktor, 2017)
526	KIT herbaceous functional gradient (weekly measurements)	Teja Kattenborn	(Kattenborn & Schmidtlein, 2019)
527	CNP seed stoichiometry	Tereza Mašková	unpublished
528	Hawaii Floral traits	Jonas Kuppler	(Kuppler et al., 2017)
529	Diurnal and nocturnal gas exchange Quercus spp.	Elena Granda	813
530	Seasonal gas exchange photoperiod Quercus spp.	Elena Granda	814
531	ParacouITV	Sylvain Schmitt	815
532	UppangalaTraits	Sylvain Schmitt	816
533	Atlantic forest and Mexican forests	Bruno Pinho	(Pinho et al., 2017)
534	Silva el al. 2019	Vasco Silva	(V. Silva et al., 2019)
535	Tree mortality	Izabela ALEIXO	(Aleixo et al., 2019)
536	NZ_kettehole	Daniel Laughlin	(Purcell, Lee, Tanentzap, & Laughlin, 2018)
537	Hokkaido plant traits 2	Akira Mori	unpublished
538	NZ_trees	Daniel Laughlin	(Jager, Richardson, Bellingham, Clearwater, & Laughlin, 2015)
539	Thermo-Mediterranean species along Greece	Chrysanthi Michelaki	(Michelaki et al., 2019)
540	PalmTraits_1.0	W. Daniel Kissling	unpublished
541	Rede Amazônia Sustentável	Joseph Hawes	824
542	Smilax auriculata nonstructural carbohydrates under-ground	Milton Diaz	unpublished
543	Functional traits related to flammability	Carolina Santacruz	825
544	MediterraneanRoadcutTraitData	Valerie Raevel	(Raevel, Violle, & Munoz, 2012)
545	Dataset on reproductive traits of Scandinavian alpine plants	Hans Henrik Bruun	(Bruun, 2019)
546	Tene_Traits	Bruno Herault	828
547	Traits of Alpine species in GLORIA regions Hochschwab, Schrankogel, Majella and Lefka Ori	Klaus Steinbauer	unpublished
548	Leaf economic traits in soy	Adam Martin	(Hayes et al., 2018)
549	Soy root traits	Adam Martin	(Martin et al., 2019)
550	Leaf economic traits in coffee	Adam Martin	(Martin et al., 2016)
551	coffee traits	Marney Isaac	(Isaac et al., 2017)

552	Plants of the Experimental forest of the Botanical Garden Institute FEB RAS (Vladivostok, Russia)	Kirill Korznikov	unpublished
553	Herbaceous leaf traits database from Mediterranean serpentine and non-serpentine soils	George Adamidis	(Adamidis, Kazakou, Fyllas, & Dimitrakopoulos, 2014)
554	Leaf functional traits from Sino-US Dimension project (Chinese collaborators)	Yunpeng Zhao	unpublished
555	Teshio grassland plant traits	Akira Mori	unpublished
556	Utanai forest tree traits	Akira Mori	unpublished
557	Kuujjuarapik-Whapmagoostui	Akira Mori	unpublished
558	Sonnier&Boughton_ABS	gregory sonnier	unpublished
559	Haean_South_Korea_Traits	Ali Hamada	(Ali, Reineking, & Münkemüller, 2016)
560	FruitTraits_Ecuador_NeuschulzSchleuningBoeGae	Eike Lena Neuschulz	(Quitián et al., 2018)
561	Nutrient Network leaf trait dataset	Jennifer Firn	(Firn et al., 2019)
562	1000Seedweight	Mark van Kleunen	(Chrobock, Kempel, Fischer, & van Kleunen, 2011)
563	Germination	Mark van Kleunen	(Chrobock et al., 2011)
564	Competition	Mark van Kleunen	(Kempel, Chrobock, Fischer, Rohr, & van Kleunen, 2013)
565	Seed Information Database, Royal Botanic Gardens, Kew	Udayangani Liu	841
566	Mediterranean Forests in Transition (MEDIT) dataset	Nikolaos Fyllas	(Nikolaos M. Fyllas et al., 2017)
567	LABDENDRO Brazilian Subtropical Forest Traits Database [Dataset IV]	Pedro Higuchi	unpublished
568	LABDENDRO Brazilian Subtropical Forest Traits Database [Dataset III]	Ana Carolina Silva	(Soboleski et al., 2017)
569	SW Michigan restored prairies	Chad Zirbel	(Zirbel, Bassett, Grman, & Brudvig, 2017)
570	CLE_restored_prairie_greenhouse_traits	Chad Zirbel	unpublished
571	New Zealand Bark Thickness	Sarah Richardson	(Richardson et al., 2015)
572	New Zealand Nothofagus leaf and stem traits	Sarah Richardson	(Richardson et al., 2013)
573	New Zealand Alpine Granite Leaf Nutrient Concentrations	Sarah Richardson	(Richardson et al., 2012)
574	Traits of 48 native and alien Asteraceae in Germany (common-garden experiment)	Christine Sheppard	unpublished
575	Myricaria germanica	Sitzia Tommaso	(Sitzia, Michielon, Iacopino, & Kotze, 2016)
576	Bauerle Vcmax and Jmax data	William Bauerle	(Bauerle et al., 2012)
577	Marion Island Fine Scale	Tanya Strydom	unpublished
578	Moravcova-Pysek Reproductive traits of neophyte in the Czech Republic	Petr Pysek	850
579	Effect of drought on pine needle traits	Hervé Jactel	851
580	alpyr	Estela Illa	unpublished
581	Charidemi Database	Ruben Tarifa	unpublished
582	Guisane2080	Cécile Albert	(Cécile Hélène Albert et al., 2010)
583	Ecophy	Cécile Albert	(Cécile H. Albert et al., 2011)
584	Traits of Woody Plants in Hluhluwe-iMfolozi Park	Simon D. Schowanek	854
585	Arable weed trait data set	Jana Bürger	unpublished
586	Cedrus atlantica traits	Alain Hambuckers	unpublished
587	Raja Ampat tree dataset	Julian Schrader	unpublished
588	Leaf trait records of rare and endangered plant species in the Pannonian flora	Anna Vojtko	856
589	JenaExperimentTraits	Christiane Roscher	(Gubsch et al., 2010)
590	Leaf Traits of Aquatic Plants	Dina Ronzhina	(Ronzhina & P'Yankov, 2001)
591	Mediterranean mixed forest	Antonio Jesus Perea	unpublished
592	Mont_Mégantic_Individual_Traits_2016-2017	Julie Messier	866
593	branch_anatomy	Bernhard Schuldt	(Schuldt, Leuschner, Brock, & Horna, 2013)
594	Traits_Arum_pictum_Farris_UNISS	Emmanuele Farris	unpublished
595	UFPR Atlantic Forest Tree Traits	Marcos Carlucci	unpublished
596	Zieminska1	Kasia Zieminska	unpublished
597	shade (for TRY)_mvk	Mark van Kleunen	(Feng & van Kleunen, 2014)

598	Soft traits of the Northern Swan Coastal Plain and Geraldton Sandplain kwongan vegetation, Western A	James Tsakalos	unpublished
599	Trait data Pibiri - Masha van der Sande	Masha van der Sande	(van der Sande et al., 2017)
600	Bay of Biscay dunes	Juan Antonio Campos	(Torca, Campos, & Herrera, 2019)
601	IanWrightNTsavannaTraits	Ian Wright	878
602	Chajul secondary forest species	Madelon Lohbeck	(Lohbeck et al., 2012)
603	Plant traits of granite outcrops' vegetation of Southwestern Australia	Gianluigi Ottaviani	880
604	Absorptive root morphological traits of boreal and hemioboreal alder and birch forests	Ivika Ostonen	(Ostonen, Tedersoo, Suvi, & Lõhmus, 2009)
605	Terrestrial Mediterranean Orchids Functional Traits	Michele Lussu	888
606	Colt Park Mesocosms	Benjamin Jackson	(De Long et al., 2019)
607	Sardinia_elevation gradient	Michela Marignani	(Campetella et al., 2019)
608	Traits of understory plants of western Canadian forest	Tanvir Ahmed Shovon	893
609	SERC-PREMIS Leaf Trait Dataset	Lillie Haddock	unpublished
610	Ash Free Dry Mass of Ceratophyllum submersum	Ivana Svitkova	unpublished
611	Temperate tree species in New Jersey USA	Anping Chen	(A. Chen, Lichstein, Osnas, & Pacala, 2014)
612	CONCERNING SOME ECOPHYSIOLOGICAL PARAMETERS OF TREE LEAVES IN FOREST-STEPPE PLANTINGS.Tree and shrub	Nikolai Yankov	unpublished
613	Inner bark and wood NSC concentrations,density, height, phenology, bark photosynthesis, bark thickne	Julieta Rosell	unpublished
614	Ausplot_traits	ning dong	(Dong et al., 2017)
615	Yarramundi species trait data	Sally Power	unpublished
616	Div_Resource Pot Experiment	Alrun Siebenkäs	unpublished
617	Forbs and grasses in North East Belgium	Elisa Van Cleemput	(Van Cleemput, Roberts, Honnay, & Somers, 2019)
618	Montane_grassland_FT	Stephni van der Merwe	898
619	sub-Antarctic_tundra_FT	Stephni van der Merwe	898
620	leaf and flower pressure volume curve data	Adam Roddy	(Roddy, Jiang, Cao, Simonin, & Brodersen, 2018)
621	TRY_Metasequoia glyptostroboides_Shanghai_China	Ji Zheng	(Ji Zheng et al., 2018)
622	Daintree Rainforest Functional Traits Data	Deborah Apgaua	(Apgaua et al., 2015)
623	Fagus sylvatica Paggeo Greece	Aristotelis C. Papageorgiou	unpublished
624	CPCRW Carbon Dynamics Along Permafrost Gradient: Specific Leaf Area of Alder and Spruce	Carolyn Anderson	904
625	Tng et al 2013 Traits	David Tng	(Tng, Jordan, & Bowman, 2013)
626	BolivianBofedalTraitData	Valerie Raevel	(Raevel, Anthelme, Meneses, & Munoz, 2018)
627	functional traits native and invasive species in tropical dry forest	Maribel Vasquez	907
628	Peel Forest New Zealand Sycamore dataset	Mason Heberling	(Heberling & Mason, 2018)
629	Traits of Plants in Canada (TOPIC)	Isabelle Aubin	909
630	Watkins, Sjoman and Hitchmough CSR ordination of trees	Harry Watkins	unpublished
631	inus_traits_Beloiu_Beierkuhnlein_06_2019	Carl Beierkuhnlein	unpublished
632	Atractocarpus from new Caledonia	David Bruy	(Bruy et al., 2018)
633	Bark Wood traits New Phytol 2014 & Oecologia 2015	Julieta Rosell	(Rosell, Gleason, Méndez-Alonzo, Chang, & Westoby, 2013)
634	Trillium Trail Forest Wildflower Carbon Gain Phenology	Mason Heberling	(Heberling, Cassidy, Fridley, & Kalisz, 2018)
635	Olson PNAS 2018	Mark E. Olson	(M. E. Olson, Soriano, et al., 2018)
636	La Selva FT Data	Vanessa Boukili	(Boukili & Chazdon, 2017)
637	Rosell_Olson_Self_Non self_VD_scaling	Mark E. Olson	(Rosell & Olson, 2014)
638	Olson et al AnnBot 2018 Corners Rules	Mark E. Olson	(Olson, Rosell, Zamora Muñoz, & Castorena, 2018)
639	Mt Baldy seed traits	Courtenay Ray	unpublished
640	Olson et al EcoLett Vessel diameter scaling	Mark E. Olson	(Olson et al., 2014)
641	ParanaTrees2015	Federico Brumnich	(Brumnich, Marchetti, & Pereira, 2019)
642	USA-China Biodiversity (USA samples)	Jeremy Lichstein	unpublished

643	Lapalala grass trait data 2019	Arend de Beer	937
644	Delpierre_QuercusPetraea_Photosynthesis_Seasonal_ClimateChambers	Nicolas Delpierre	(Verdier et al., 2014)
645	Barbeau Leaf Minerals, Quercus petraea, Carpinus betulus	Nicolas Delpierre	(Delpierre, Berveiller, Granda, & Dufrêne, 2015)
646	AM fungi and plant growth	Daijun Liu	940
647	Observation of Ginkgo tree morphological difference	Daijun Liu	unpublished
648	LEVEG-UFRGS	Sandra Müller	unpublished
649	Alpine tundra plants - effects of climate warming on some traits of species inhabiting mid-latitude	Michele Carbognani	unpublished
650	SLA data La Palma 2019 (MIREN project)	Anke Jentsch	941
651	SLA data La Palma 2019 (SLA project)	Anke Jentsch	942
652	SLA data La Palma 2019 (SLA project)	Anke Jentsch	942
653	RASGOS FUNCIONALES ESPECIES ARBOREAS CUENCA AMAZONICA	JAIME VILLACIS	unpublished
654	Plant height of Mediterranean herb layer communities, Sardinia, Italy	Erika Bazzato	943
655	Functional Flowering Plant Traits	Jane Morrison	unpublished
656	Decomposition experiment with standard substrate. Funcional traits (SLA, LDMC and SSD) associated to	Ricardo Oliveira	(Oliveira, Marques, & Marques, 2019)
657	López-García et al. Denmark	Alvaro Lopez-Garcia	945
658	Functional Traits of Tropical Dry Forest (Colombia) Fundación Natura and Enel-Emgesa	Mary Berdugo	946
659	Sjöman-Hirons Leaf Turgor Loss with Osmotic Potential at Full Turgor	Andrew Hirons	(Sjöman, Hirons, & Bassuk, 2015)
660	Bahalkeh 2019	khadijeh bahalkeh	unpublished
661	Mediterranean Forests in Transition MEDIT dataset	Nikolaos Fyllas	(Nikolaos M. Fyllas et al., 2017)
662	Thom 2019	Dominik Thom	unpublished
663	Plant three traits (SLA,LA, Height) of 14 plots in Easten Tibetan subalpine meadow	Xine Li	950
664	Khalil Prairie Plant Traits	David Gibson	951
665	Species patch metrics	Sitzia Tommaso	(Sitzia, Dainese, Krüsi, & McCollin, 2017)
666	Iranian Marl database	Khadijeh Bahalkeh	unpublished
667	Intraspecific variation leaf traits temperate rainforest	Chris Lusk	(Lusk, 2019)
668	Traits of urban species from Ibagué Colombia	Fernando Fernández-Méndez	(Núñez-Florez et al., 2019)
669	Leaf Economics Traits of Woody Species in Dinghushan Biosphere Reserve, Southern China	Pengcheng He	(He et al., 2019)
670	Fabio Carvalho lowland fen peatland	Fabio da Silva	(Carvalho et al., 2019)
671	Morton Arboretum Experimental Prairie traitset 1, 2019	Andrew Hipp	(Hipp et al., 2018)
672	DISEQU-ALP	Sabine Rumpf	637
673	Wagenführ Woodatlas	Steven Jansen	967
674	Staples et al Australian Reforestation Tree Database	Timothy Staples	(Staples, Dwyer, England, & Mayfield, 2019)

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Author contribution

Jens Kattge, Gerhard Bönisch, Sandra Díaz, Sandra Lavorel, Ian C. Prentice, Paul Leadley, and Christian Wirth developed the concept and draft manuscript. Susanne Tautenhahn and Gijsbert Werner contributed analyses and plots for Figure 10, 11 and 12. The other authors contributed plant trait data and/or supported data curation and analysis. All authors contributed to writing.

Conflict of interest

All authors declare no conflict of interest.

Supporting Information

- TRY data curation workflow (TRY database version 5, extended version)
- Figure 10 based on the full phylogeny dataset
- Figure 10 based on full phylogeny dataset, including species names at tips.

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