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RESEARCH REPORT

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When things get MESI: The Manipulation Experiments Synthesis Initiative—A coordinated effort to synthesize terrestrial global change experiments

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Abstract

Responses of the terrestrial biosphere to rapidly changing environmental conditions are a major source of uncertainty in climate projections. In an effort to reduce this uncertainty, a wide range of global change experiments have been conducted that mimic future conditions in terrestrial ecosystems, manipulating CO_2, temperature, and nutrient and water availability. Syntheses of results across experiments provide a more general sense of ecosystem responses to global change, and help to discern the influence of background conditions such as climate and vegetation type in determining global change responses. Several independent syntheses of published data have yielded distinct databases for specific objectives. Such parallel, uncoordinated initiatives carry the risk of producing redundant data collection efforts and have led to contrasting outcomes without clarifying the underlying reason for divergence. These problems could be avoided by creating a publicly available, updatable, curated database. Here, we report on a global effort to collect and curate 57,089 treatment responses across 3644 manipulation experiments at 1145 sites, simulating elevated CO_2, warming, nutrient addition, and precipitation changes. In the resulting Manipulation Experiments Synthesis Initiative (MESI) database, effects of experimental global change drivers on carbon and nutrient cycles are included, as well as ancillary data such as background climate, vegetation type, treatment magnitude, duration, and, unique to our database, measured soil properties. Our analysis of the database indicates that most experiments are short term (one or few growing seasons), conducted in the USA, Europe, or China, and that the most abundantly reported variable is aboveground biomass. We provide the most comprehensive multifactor global change database to date, enabling

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the research community to tackle open research questions, vital to global policy-making. The MESI database, freely accessible at doi.org/10.5281/zenodo.7153253, opens new avenues for model evaluation and synthesis-based understanding of how global change affects terrestrial biomes. We welcome contributions to the database on GitHub.

KEYWORDS
climate change, CO_2, drought, manipulation experiment, meta-analysis, nitrogen, precipitation, warming

1 | INTRODUCTION

One of our most important tools to make predictions about the response of terrestrial ecosystems to global change is ecosystem experimentation. Manipulative experiments are especially valuable for acquiring mechanistic insights into, and quantifying the influence of, individual drivers and their interactions in terrestrial ecosystems—which is typically not possible with ecosystem monitoring.

By combining data from many such experiments, meta-analyses can reveal broader scale patterns. Several meta-analyses are based on collecting data from the primary literature, on the initiative of a particular research group or international collaboration, and with a particular set of research questions in mind. Starting data collection anew for each study avoids the possibility of a consistent database creation bias across studies, that is, researcher-specific selection of eligible publications, data interpretation, extraction methods, etc. However, this approach of starting each meta-analysis from scratch is expensive and time-consuming. Moreover, it can lead to contrasting conclusions of different synthesis efforts without being clear about the exact reason behind the divergence (see e.g., Yue et al., 2017 vs. Dieleman et al., 2012).

Meta-analyses of large numbers of experiments can also provide valuable input to validate, improve, and parameterize ecosystem models applicable to the global scale. However, while data from individual smaller sets of global change experiments are indeed increasingly used to test hypotheses embodied by ecosystem models (Zaehle et al., 2014), a wider adoption of model–data syntheses remains hampered by the current lack of comprehensive integration, homogenization, and accessibility of global change experimental data.

We propose that synthesis-related research questions, and the difficulties underlying model–data fusion, would be addressed by using a freely accessible homogenized database (or set of databases) that can be updated with recent experiments or ancillary data (e.g., treatment magnitude, soil properties, climate regime), as necessary. With such an approach, especially when different original constituent databases are combined, fewer experiments are overlooked. This approach will improve the power of analyses, particularly in poorly sampled regions, and for rare combinations of global change drivers. It also facilitates the identification of drivers behind contrasting outcomes and allows researcher (or data extractor) bias to be quantified when analyses explicitly account for different constituent databases.

Here, we present the MESI database, which represents the most comprehensive database of terrestrial ecosystem manipulation experiments to date. This database results from a coordinated intercontinental effort to combine four independently created constituent databases of elevated atmospheric CO_2 (eCO_2), warming, nutrient addition, and precipitation manipulation experiments. The combined, freely accessible and machine-readable database (doi.org/10.5281/zenodo.7153253—Van Sundert et al., 2022) helps bridge the experimental and modeling communities, facilitating the exploitation of the many opportunities such data syntheses have to offer.

2 | DESCRIPTION AND COMPARISON OF THE FOUR CONSTITUENT DATABASES

2.1 | General overview

The Manipulation Experiments Synthesis Initiative (MESI) was constructed as a new database building on four global change databases, previously compiled at the University of Antwerp, Sichuan Agricultural University, Hebei University, and the University of Alberta. All four constituent databases include ecosystem-, species-, and individual-level responses (means, standard deviations, number of replicates; aggregation level specified through a separate column—Table 1) of mostly C and nutrient cycling to single and combined experimental manipulations of CO_2, temperature, and nutrient and water availability, with wide coverage around the globe and across climate zones (Figure 1; Figure S1). Data from 1145 sites were collected from a variety of ecosystem types (e.g., grassland, forest, cropland, shrubland, desert, wetland, tundra) and mainly from field experiments (with natural or planted communities), but, depending on database-specific inclusion and exclusion criteria specified below, also from experiments conducted in greenhouses and growth chambers. Variables include treatment type, treatment magnitude (ppm CO_2, °C of warming, etc.), response name and value, moderators (mean annual temperature and precipitation, age, ecosystem type, experiment type), and other ancillary data such as location coordinates, sampling dates and years (with multiple records for repeated measures), experiment start and end dates, dominant species, fumigation or warming type, and citation (Table 1). A large majority of data were collected from the peer-reviewed literature. A smaller share of data are from unpublished sources (953 of 57,089 records) and were provided by principal investigators at each study site. Data from the literature were extracted from supplementary information and from data files accompanying respective publications, and from figures, tables, and text, with various programs used for figure extraction (specified below per database).

Data from the constituent databases were combined into a single table, in comma-separated values (csv) format, with the specification of the original database for each row. Six additional tables are included within MESI: (i) metadata (explanation of the columns), (ii) description of response variable abbreviations, (iii) methodology of response variable measurements including further comments relevant to data interpretation, (iv) full references, (v) a template for new data contributions, and (vi) additional in situ determined soil data extracted from the original publications (soil texture type and particle size distribution, C:N ratio, organic matter concentration, pH), relevant to water and nutrient availability (Tolk, 2003; Van Sundert et al., 2018), ecosystem function (Vicca et al., 2018), and potentially responses thereof to global change (Cable et al., 2008; Canarini et al., 2017). The database is organized in a "wide" format. That is, observations made under two treatment levels are provided in the same row to facilitate data analysis (e.g., the calculation of response ratios) in a majority of cases. For multifactorial experiments, the value provided for the "control" represents an "absolute" control, where no manipulation is applied. Therefore, responses of the values representing the control treatment are repeated in multiple rows. The long format (with separate rows per treatment including control, but no comparison per row) may be more practical for some applications. R code to translate between wide and long format is provided with the database at doi.org/10.5281/zenodo.7153253 (Van Sundert et al., 2022).

2.2 | The databases within MESI

2.2.1 | University of Antwerp database

With 47,196 observations, the database from the University of Antwerp contains more than 80% of the records in the MESI database. Included are data from 608 sites, originating from 1120 publications collected over the last decade until 2021, using the

TABLE 1 Content description of the combined MESI database

Variable category	Field name	Description
	db	Database name (antwerp, sichuan, hebei, alberta)
	id	Unique identifier per data point
	duplicate_id	As id, but common identifier for data points potentially shared among databases based on identical experiment name “exp” and response variable name “response”
	citation	Reference from which data were extracted
Site characterization	site	Site name (e.g., euroface)
	study	Individual study with one or more manipulation types (e.g., euroface_populusalba)
	exp	Individual experiment with manipulation (e.g., euroface_populusalba_cf)
	lat	Latitude (°, negative for south, positive for north)
	lon	Longitude (°, negative for west, positive for east)
	elevation	m a.s.l.
	mat	Mean annual temperature (°C)
	map	Mean annual precipitation (mm)
	ecosystem_type	For example, grassland, cropland, forest, desert
	vegetation_type	For example, meadow steppe, serpentine grassland, humid tropical forest
	experiment_type	For example, field, greenhouse, outdoor chamber
	community_type	Natural, planted
	dominant_species	Latin genus + species name(s)
	growth_form	Herbaceous, woody
	age	Ecosystem age in years (years since planting or disturbance)
	disturbance_type	Mowing, tilling, defoliation, grazing, fire (e.g., 10,000 = mowing only)
Treatment characterization	treatment	Global change factor(s) manipulated (e.g., c = CO_2, w = warming, cw = CO_2 + warming)
	npk	N, P, and/or K addition (e.g., 100 = N only, 010 = P only, 011 = P and K)
	w_t1	Warming method: soil, air, open top chamber, infrared (e.g., 1000 = soil warming only)
Treatment details	c_c	CO_2 concentration of control treatment (ppm)
	c_t	CO_2 concentration of CO_2 addition treatment (ppm)
	d_t	Targeted precipitation reduction during experimental drought (e.g., 0.6 = 60% reduction)
	d_t2	Precipitation exclusion during drought treatment or per year for continuous treatment (mm)
	n_c	N addition in control treatment (g N/m^2y)
	n_t	N addition in treatment (g N/m^2y)
	p_c	P addition in control treatment (g P/m^2y)
	p_t	P addition in treatment (g P/m^2y)
	k_c	K addition in control treatment (g K/m^2y)
	k_t	K addition in treatment (g K/m^2y)
	i_c	Water addition in control treatment of irrigation experiment (mm/d)
	i_t	Water addition during irrigation treatment of irrigation experiment (mm/d)
	i_t2	Targeted treatment irrigation relative and in addition to control (e.g., 0.6 = +60% addition)
	s_c	Species richness of control treatment
	s_t	Species richness of richness manipulation treatment
	w_t2	Air warming (°C)
	w_t3	Soil warming (°C)
	start_year	Year when experimental treatment began
	duration	Number of years the experiment was running
	treament_duration	Days between start and end of treatment (e.g., drought period)
	fumigation_type	CO_2 addition method (FACE, greenhouse, OTC, SACC, tunnels)

(Continues)

TABLE 1 (Continued)

Variable category	Field name	Description
	start_treatment	Start of treatment (d/m/yyyy or continuous)
	end_treatment	End of treatment (d/m/yyyy or continuous)
Measurement info	response	Response variable (e.g., anpp, bnpp, leaf_n, mineral_soil_cn)
	sampling_year	Year of sampling from start of experiment (1 = in start year, 2 = first year after start)
	sampling_depth	Depth of soil sampling (cm)
	aggregation_level	Representative of plot-level (community) or for species within a community (species)
	x_c	Response value of control treatment
	x_t	Response value of global change treatment
	x_units	Unit of response value
	sd_c	Standard deviation of control response value
	sd_t	Standard deviation of treatment response value
	se_c	Standard error of control response value
	se_t	Standard error of treatment response value
	rep_c	Number of control replicates
	rep_t	Number of treatment replicates
	sampling_date	Date of sampling in d/m/yyyy
	bibliography	Table with full references
	soil	Table with soil properties as ancillary data
	metadata	Table with an explanation of columns
	response variable abbreviations	Table with response variable abbreviations of the main table explained
	methods_comments	Table with methodological information on how response variables were measured per data point, and further comments for data interpretation
	template	Empty table for data contributions, with main table headers

Note: colors represent different database tables.

Web of Science and Google Scholar search engines. Carbon cycle and nutrient cycle responses to global change factors (eCO_2; warming; N, P, and K addition; drought; irrigation; and respective combinations) were collected. C cycle responses include both pools (above- and belowground and total C and biomass, soil C, microbial biomass C, etc.) and fluxes (net primary production, soil respiration, net ecosystem exchange, etc.). Common nutrient cycle-related responses in the database are soil organic and inorganic N, plant tissue nutrient concentrations, and stoichiometric ratios. Extensive background information about the site and the experiments is provided as well, including ecosystem and community type, treatment start date, end date, and intensity, experimental facility, MAT and MAP, dominant species, unit of the response variable, and experiment duration. This database also comes with a separate table containing records of soil properties, measured at 365 experimental studies, providing information on soil texture (USDA classes, and % sand, silt, and clay), soil organic matter and carbon concentrations, soil C:N ratios, and pH. Data presented in figures were extracted with the Engauge Digitizer software (Free Software Foundation, Inc., Boston, MA, USA). Studies using earlier versions of the database, alone or in combination with other data, include Dieleman et al. (2010, 2012), Leuzinger et al. (2011), Terrer et al. (2016, 2019, 2021) and Ogle et al. (2021).

2.2.2 | Sichuan Agricultural University database

Yue et al. (2017) compiled a database of plant community, soil and microbial C pools in response to single and combined experimental eCO_2, warming, N addition, P addition, drought, and irrigation. Data from 518 sites were extracted from 612 peer-reviewed publications found through the Web of Science and Google Scholar search engines in October 2016, resulting in 3478 observations in the MESI database. Ancillary data in the original database were treatment intensity, ecosystem type, experimental facility, MAT, and MAP (extracted from published text or the WorldClim database—http//:www.worldclim.org). For the MESI initiative, additional data were collected on community type (planted vs. natural), dominant species, start and end date within seasons, unit of the response variables, and USDA soil texture classes. Data presented in figures were extracted with the Engauge Digitizer software (Free Software Foundation, Inc., Boston, MA, USA).

2.2.3 | Hebei University database

The Hebei University database presents C stock and flux responses to single and combined eCO2, warming, N and N+P addition,

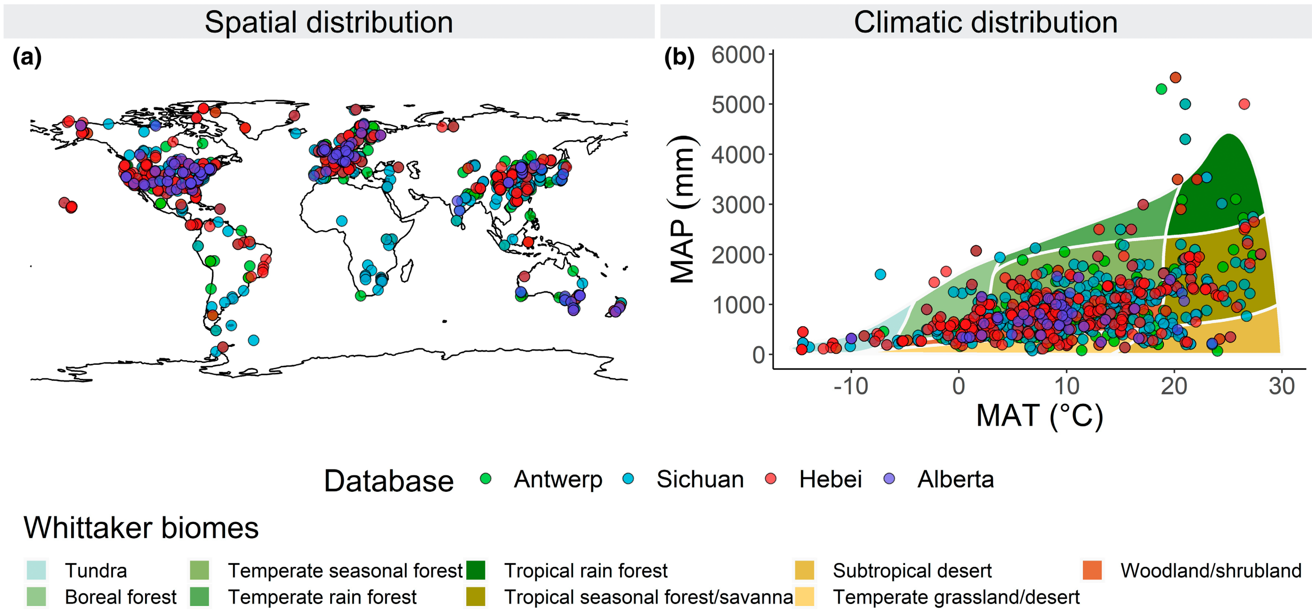

FIGURE 1 Spatial (a) and climatic (b) distribution of global change manipulation experimental sites in databases of the Universities of Antwerp ($n = 608$ sites), Sichuan ($n = 518$ sites), Hebei ($n = 350$ sites), and Alberta ($n = 101$ sites). The Whittaker biome plot (Whittaker, 1970) was created using the R package plotbiomes (Valentin & Levin, 2022). MAP, mean annual precipitation; MAT, mean annual temperature.

drought, and irrigation. Data originate from 445 publications on outdoor experiments at 350 sites and were collected from the Web of Science up to December 13, 2016 for the initial version, plus websites of experimental networks and ecological laboratories (Song et al., 2019, 2020). Cropland and indoor studies were excluded from this database. When available in the publication, MAT and MAP, the experiment duration, elevation, ecosystem type, and treatment intensity were extracted along with response values. Where MAT and MAP were not available, Song et al. (2019) performed a look-up in Climate Model Intercomparison Project phase 5 data (CMIP5—https://esgf-node.llnl.gov/projects/cmip5/). Within the MESI initiative, we added to the database information on sampling dates, community type (natural vs. planted), dominant species, start and end dates of treatments within seasons, and USDA soil texture classes. SigmaScan 5.0 (SYSTAT Software Inc., San Jose, CA, USA) was used to extract means and standard deviations from figures. The database occupies 4895 rows in the MESI database, including both unique and duplicate records overlapping with the other constituent databases.

2.2.4 | University of Alberta database

Ma et al. (2020) created a database on aboveground, belowground, plant organ and total biomass, and C stocks and production in response to multifactor global change. Data were collected from 115 peer-reviewed studies at 101 sites by searching the Web of Science and Google Scholar up to 1 August 2018. The inclusion criteria dictated that only results with mean, standard deviation, and number of replicates were retained, and at least two of the global change factors eCO_2, warming, N addition, drought, irrigation, or species richness were combined per experiment. Originally collected ancillary data were experiment duration (years), treatment intensity, ecosystem type, and unit of the response variable. In our effort to bring together the different databases, we added information on sampling date, community type (natural vs. planted), dominant species, background climate (MAT, MAP), USDA soil texture classes, and start and end date of treatments within seasons (e.g., dates of precipitation exclusion). SigmaScanPro 5.0 (SYSTAT Software Inc., San Jose, CA, USA) was used to extract means and standard errors or deviations from publications and supplemental figures. The database contributes 1520 records to our MESI database.

2.3 | Comparison of the databases

A common feature among the original four databases is the worldwide coverage of experimental C cycle responses to global change in a variety of terrestrial ecosystem types (grassland, forest, etc.) (Figure 1; Figure S1). The main contrasts are in the type of C cycle variables collected, the collection of nutrient cycle responses, and the availability of ancillary soil data. While the Sichuan and Alberta databases focused on C pools only, both pools and fluxes were collected for the Antwerp and Hebei databases. Only the database from the University of Antwerp has nutrient cycle responses and information on various soil properties beyond soil texture. Some differences also occur in the type of global change factors included: only the Alberta database explicitly includes species richness as a manipulated factor (although lines with specified but always equal richness for control and treatment do occur in the Antwerp and

Hebei databases), and only the Antwerp database contains data from full-factorial experiments of N, P, and K addition.

Complementarity among the databases exists not only in terms of the variables collected but also in coverage of data from different sites (Figures 1 and 2; Figure S1). Comparing all experimental sites of all databases, irrespective of the manipulation or response variables, limited overlap exists among the four databases: 73%, or 841 of 1145 sites are unique to one database (Figure 2a). Complementarity among the four constituent databases is also evident when looking at aboveground biomass—the most common variable across the databases: 75%, or 386 of 518 sites are unique to one database (Figure 2b). This complementarity in sites emphasizes the value of our data integration effort and the potential for more powerful analyses using the combined dataset, emerging here from our MESI project.

3 | DISCUSSION

3.1 | Applications and examples

Earlier meta-analyses based on individual databases adopted specific scopes. For example, several studies have examined responses to simultaneous manipulation of multiple factors (Dieleman et al., 2012; Leuzinger et al., 2011; Ma et al., 2020), the role of moderators such as treatment duration and magnitude (Leuzinger et al., 2011; Ma et al., 2020), types of mycorrhizal symbionts present in investigated plots (Ainsworth et al., 2002; Terrer et al., 2016, 2021), and the influence of soil N and P on above- and belowground C cycle to (primarily) CO_2 (de Graaff et al., 2006; van Groenigen et al., 2006; Terrer et al., 2019, Table 2). Notably, contrasting results were sometimes reported among studies using different constituent databases. For example, Dieleman et al. (2012) suggested, based on an earlier version of the University of Antwerp database, that antagonistic interactions between global change factors (e.g., CO_2 and warming) would be common, while Yue et al. (2017) found mostly additive effects in the Sichuan database. Such contrasting results should be explored further to unravel the cause of the discrepancy, for example, the choice of global change drivers and response variables considered, the number and spatial spread of data points, or data interpretation and extraction methods while using the same primary literature.

Our comparison of the four global change databases points to their complementarity with respect to experimental sites covered (Figure 2). While the original databases can be used separately, combining the databases can reduce the uncertainty of ecosystem responses in understudied regions, where even a few additional data points represent a substantial increase in the available information given the scarcity of multifactor global change studies in some regions. Also, combining data from highly sampled regions can prove useful in tackling more detailed unresolved questions. For example, a broader combined dataset could allow researchers to test the role of background gradients in determining global change responses or identify whether researcher bias could have led to differences among databases. In this regard, we recommend analyses on the combined database, provided that the different origins of the four databases are taken into account. That is, data duplicates can be transparently handled, for example, in a sensitivity analysis, thanks to the information provided in the MESI database, that is, a column identifying 6938 potential duplicates that were

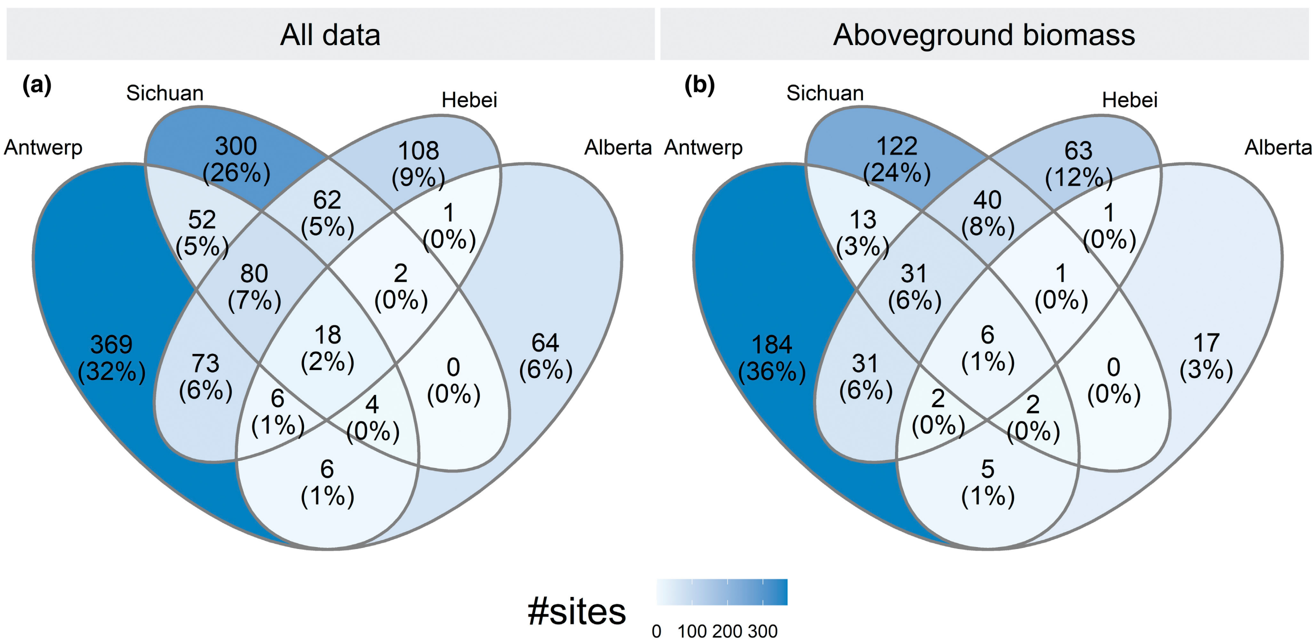

FIGURE 2 Site overlap among the global change constituent databases. Panel a was based on all variables and treatments in the databases, panel b was based on all treatments but aboveground biomass only. Diagrams were made using the ggVenndiagram R package (Gao et al., 2021).

TABLE 2 Examples of past and potential research topics applicable to single and combined global change databases, and options for expansions

MESI constituent database	Example research topics
Antwerp, Sichuan, Hebei, Alberta: analyses on single and combined databases	• Single and multifactor global change effects on C cycling[a, b, c, d] • Moderating role of background climate gradients, ecosystem type, treatment duration, and magnitude[a,e] • Model–data synthesis
Antwerp	• Role of soil and nutrients in global change responses[f, g, h] • Global change effects on leaf, plant, and soil stoichiometry • Comparison of global change responses among spatial scales (e.g., leaf vs. ecosystem[e])
Alberta	• Influence of species richness alone on C cycling, and in combination with global change factors[a]
Expansions (in combination with other databases)	• Role of biodiversity, incl. species composition, in determining responses to global change[i] • Comparison against data from global change experimental networks • Comparison of terrestrial versus aquatic versus marine global change responses

[a]Ma et al. (2020).
[b]Dieleman et al. (2012).
[c]Song et al. (2019).
[d]Yue et al. (2017).
[e]Leuzinger et al. (2011).
[f]Terrer et al. (2016).
[g]Terrer et al. (2019).
[h]Terrer et al. (2021).
[i]CORRE database: https://corredata.weebly.com/publications.html.

flagged based on identical experiment name and response variables, and by using information such as dates of experiment and sampling, and units (Table 1).

Some studies have compared ecosystem model outputs against data from one or a few global change experiments (Paschalis et al., 2020; Wu et al., 2018; Zaehle et al., 2014). However, a lack of data integration and homogenization has thus far been an obstacle to true multi-experiment synthesis in combination with modeling. That is, comparing treatment effects on multiple response variables across many experiments to test hypotheses brought forward by models, comparing the performance of alternative model structures, reduce uncertainties, and parameterize based on the synthesis results (Keenan et al., 2011; LeBauer et al., 2013). Questions arising from models can further inform relevant new variables to measure in situ (Medlyn et al., 2015), and based on uncertainty quantifications, on what variables should be sampled more intensively, and on what locations or in which types of ecosystems (Dietze et al., 2013). In order to enable such model–data synthesis, clear, quantitative information is required on the database side on treatments and their magnitudes, ancillary and response variables, and distinction among individual experiments and studies. Ideally, data from many related response variables are collected and reported in this way, such that hypotheses can be tested on, for example, why a model performs (apparently) well for one variable (e.g., NPP), but not for another (e.g., N uptake—Zaehle et al., 2014). MESI opens doors for data–model synthesis by providing such carefully homogenized, accessible, and integrated data.

Many large-scale studies have considered the role of background climate (especially MAT and MAP) in influencing global change responses. These studies often found a significant role in climate; for example, site aridity interacting with eCO_2 (Lu et al., 2016; also see De Kauwe et al., 2021). However, if such background gradients covary with other background variables that are not considered, it may lead to incomplete or erroneous conclusions. One frequently neglected factor is nutrient availability or soil properties in general (Vicca et al., 2018). Soil properties influence nutrient availability (Du et al., 2020; Van Sundert et al., 2018; Van Sundert, Radujković, et al., 2020), such that part of the variation related to climate may actually be attributed to a gradient in nutrient availability (Vicca et al., 2012).

In order to facilitate the incorporation of soil and nutrient information in future database analyses, we collected new in situ measured data on various soil properties as part of the MESI effort. Soil texture data were collected for all constituent databases. The soil C:N ratio is available both as a response variable and as background soil information for many of the experiments. In addition, multiple soil properties such as organic matter (SOM) concentration and pH were provided with the University of Antwerp database. While it is well established that such soil properties and nutrient availability play a key role in the structure and functioning of ecosystems (Cleveland et al., 2011; Van Sundert, Radujković, et al., 2020; Vicca et al., 2012; Vitousek & Howarth, 1991), these are often ignored in meta-analyses, except for some studies on the role of nutrient availability gradients in response to eCO_2 (Terrer et al., 2019). The soil data we collected should thus enable the disentangling of the role of soil properties and nutrients in determining ecosystem responses to not only eCO_2 but also warming, nutrient addition, and precipitation manipulation. Analyses spanning gradients in nutrient availability can then be compared to those from experiments manipulating nutrients in combination with other global change factors.

The standardized structure of the MESI database facilitates the addition of new records and moderators as new or supplementary data become available. Coupling to databases of other initiatives is also possible based on the experiment identifiers. Biodiversity, for instance, is not included as a global change factor in our set of constituent databases (except for some data on species richness), while aspects of biodiversity, such as plant community and functional group composition, and species richness and evenness, are important determinants of productivity, the overall functioning of ecosystems (Hooper et al., 2005), and responses to climate extremes (Kreyling et al., 2017; Van Sundert, Arfin Khan, et al., 2021) and to gradual global change (Komatsu et al., 2019). Databases such as the Community Responses to Resource Experiments (CORRE—https://corredata.weebly.com/publications.html) database could be used to further unravel the role of biodiversity in large-scale ecosystem responses to global change. Additional leaf-level measurements, as well as more ecophysiological and hydraulic variables, are further possibilities for database extension.

The Alberta, Antwerp, Hebei, and Sichuan databases contain mean treatment responses with standard deviations to manipulated global changes at 1145 sites and 3644 experiments extracted from the scientific literature. This includes data from individual initiatives of site principal investigators, as well as published data from coordinated global change networks (Fraser et al., 2013) such as the Nutrient Network (NutNet—Borer et al., 2017) and DroughtNet (Knapp et al., 2017). However, more plot-level data exist for these networks that are not publicly available. Compared to our approach, such data from standardized networks are easier to compare across sites within the network and, therefore, easier to interpret. In NutNet, for instance, standardized quantities of N, P, K, and micronutrients are added annually at all sites of the network (Borer et al., 2017). In DroughtNet, severe one in 100-year chronic drought is imposed by passively intercepting a site-specific percentage of precipitation (Knapp et al., 2017; Yahdjian & Sala, 2002). While such standardization facilitates cross-site comparisons of responses to a common driver in a common framework, data from coordinated distributed experiments alone do not cover the full range of available data from diverse global change experiments (e.g., acute droughts in different seasons). Where overlap exists in research questions addressable with both network and literature databases such as ours, results of both types of databases can be compared. Research questions that cannot be answered with network databases can be tackled with a unified database such as the one presented here.

3.2 | Remaining gaps in data coverage

MESI represents the most complete database of global change experiments to date in terms of studies, factorial combinations, ancillary data, and response variables covered. Plotting the data across spatial, climatic, and temporal dimensions provides insights into existing gaps in experimental coverage, and can help in deciding on future experimental locations, designs, and sampling strategies.

3.2.1 | Spatial, climatic, and biome coverage

As reported in earlier studies (Martin et al., 2012), a substantial share of experimental sites are concentrated in temperate grasslands (n = 306) and forests (n = 150) of North America (n = 158), Europe (n = 137), and East Asia (n = 128) (Figure 1; Figure S1), with sparser representation of the remaining geographical space. Particularly understudied are tropical rainforests, especially in the (African) paleotropics (n = 4), which potentially function differently than neotropical forests (Hubau et al., 2020). When distinguishing among global change manipulation types (Figure 3; Figure S2), the low number of studies in the tropics becomes even more apparent for warming, eCO_2, and, to a lesser degree, precipitation manipulation experiments. A substantial share of experiments in the tropics has focused on nutrient limitation, with particular emphasis on the role of P versus N (n = 20). In this regard, we note that, given the importance of, and uncertainty around, the tropical carbon sink and its responses to eCO_2 and climate change (Crezee et al., 2022; Harris et al., 2021; Okello et al., 2022), more global change experiments are being set up or have recently started, such as AmazonFACE that will investigate eCO_2 effects on a mature Amazonian rainforest (Fleischer et al., 2019). Also, specifically for croplands, only a few global change experiments are found in tropical regions (Figure S3), despite the particularly important socio-economic role of the primary sector here, and the vulnerability of food security to climate change (Lobell et al., 2008). Tropical ecosystems are thus vastly understudied, whether natural, seminatural, or agricultural.

Warming experiments have been prioritized in the colder regions, that is, boreal and tundra biomes (n = 64), as opposed to eCO_2 (n = 14) and precipitation manipulation experiments (n = 31). This prioritization logically follows from the observed and projected faster-than-global warming at high latitudes and elevations (Wang et al., 2016), and the often carbon-rich soils in these ecosystems may be susceptible to loss of carbon in a fast-warming climate, providing a potential positive feedback loop to the climate system (Cao & Woodward, 1998). In contrast to temperature, precipitation is considered non-limiting to biomass production in the colder regions (Bergh et al., 1999—but see Nilsson, 1997), and most of these regions are becoming wetter (Box et al., 2019). Consequentially, fewer irrigation and drought studies have been performed here. However, recent extreme events (e.g., the 2018 European drought that impacted parts of Scandinavia—Buras et al., 2020) and publications suggest that at least in the southern fractions of the boreal biome, severe seasonal droughts may become more common because of changing circulation patterns (Mann et al., 2017), indicating relevance for experimental and other studies with focus on water availability also in boreal ecosystems.

3.2.2 | Coverage of experiment duration

Two hundred and fifteen of 693 studies with specified treatment duration in MESI are 1-year experiments, or longer term experiments from which only first-year data were reported and collected

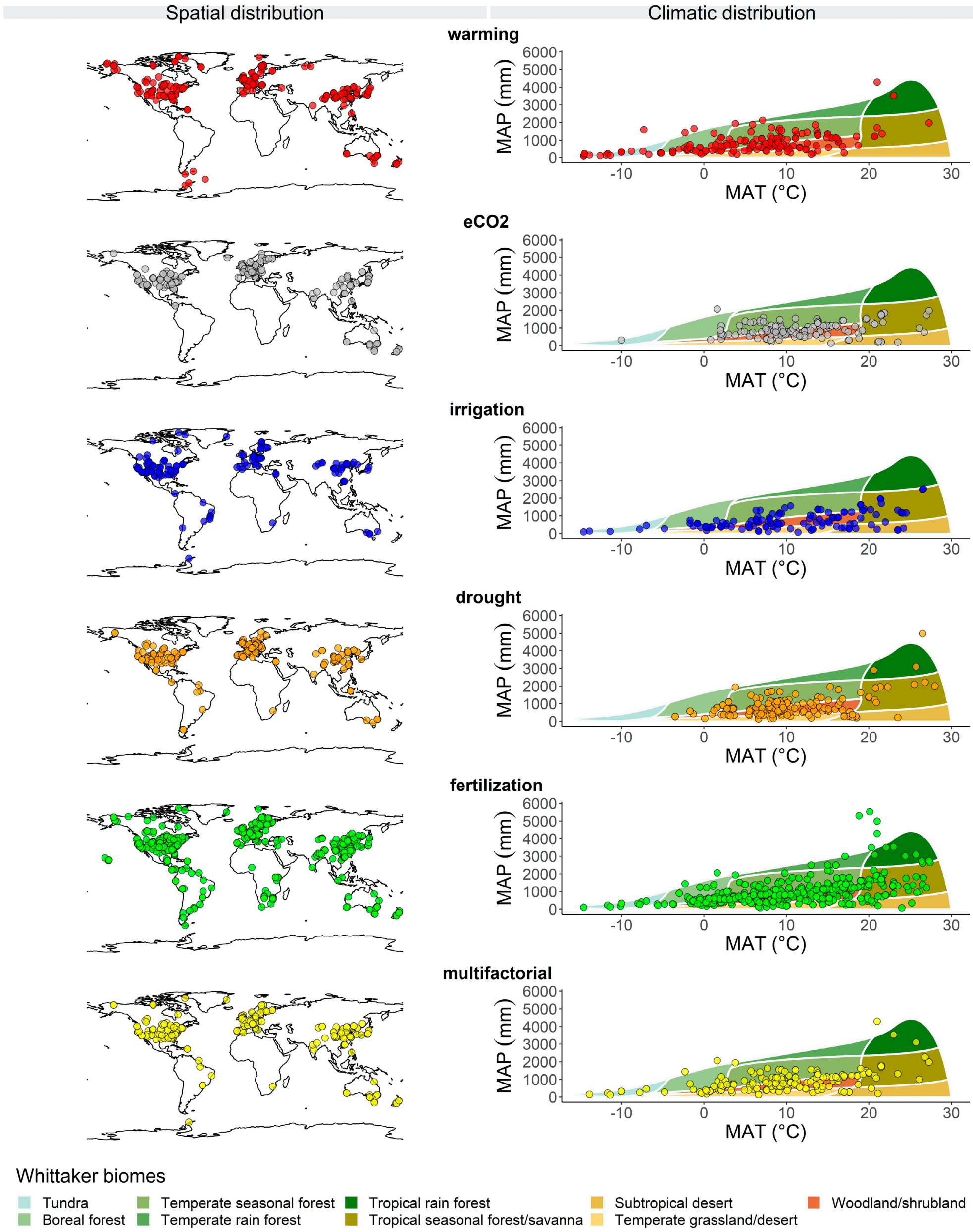

FIGURE 3 Spatial and climatic distribution of 1145 global change manipulation experimental sites per manipulation type. Whittaker biome plots (Whittaker, 1970) were created using R package plotbiomes (Valentin & Levin, 2022). MAP, mean annual precipitation; MAT, mean annual temperature.

(Figure 4a). While valuable, such short-term reports on global change impacts are prone to unstable initial responses (e.g., only initial soil carbon loss under warming—Verbrigghe et al., 2022), and effects may exhibit a multi-year lag because of gradual shifts in plant community composition (Langley & Megonigal, 2010), plant–soil feedbacks (Van Sundert, Linder, et al., 2021), etc. With increasing experiment duration, the share of single-factor experiments—especially fertilization studies—increases in MESI. The few longer term multifactorial experiments in the database exemplify the relevance of concurrent manipulation of global change drivers over longer timescales. For instance, some $eCO_2 \times N$ experiments in forests (Norby et al., 2010) and grasslands (Reich & Hobbie, 2013) exhibited a weakening of the CO_2 fertilization effect on NPP over time under ambient but not under elevated soil fertility. We recommend the further establishment of longer term, bi- or multifactorial experiments that identify concurrent versus lagged, and direct versus indirect effects of global change on terrestrial ecosystems.

3.2.3 | Coverage of multifactorial treatment combinations

Albeit generally of shorter duration, multifactorial experiments are quite common in the MESI database (30% with two or more factors

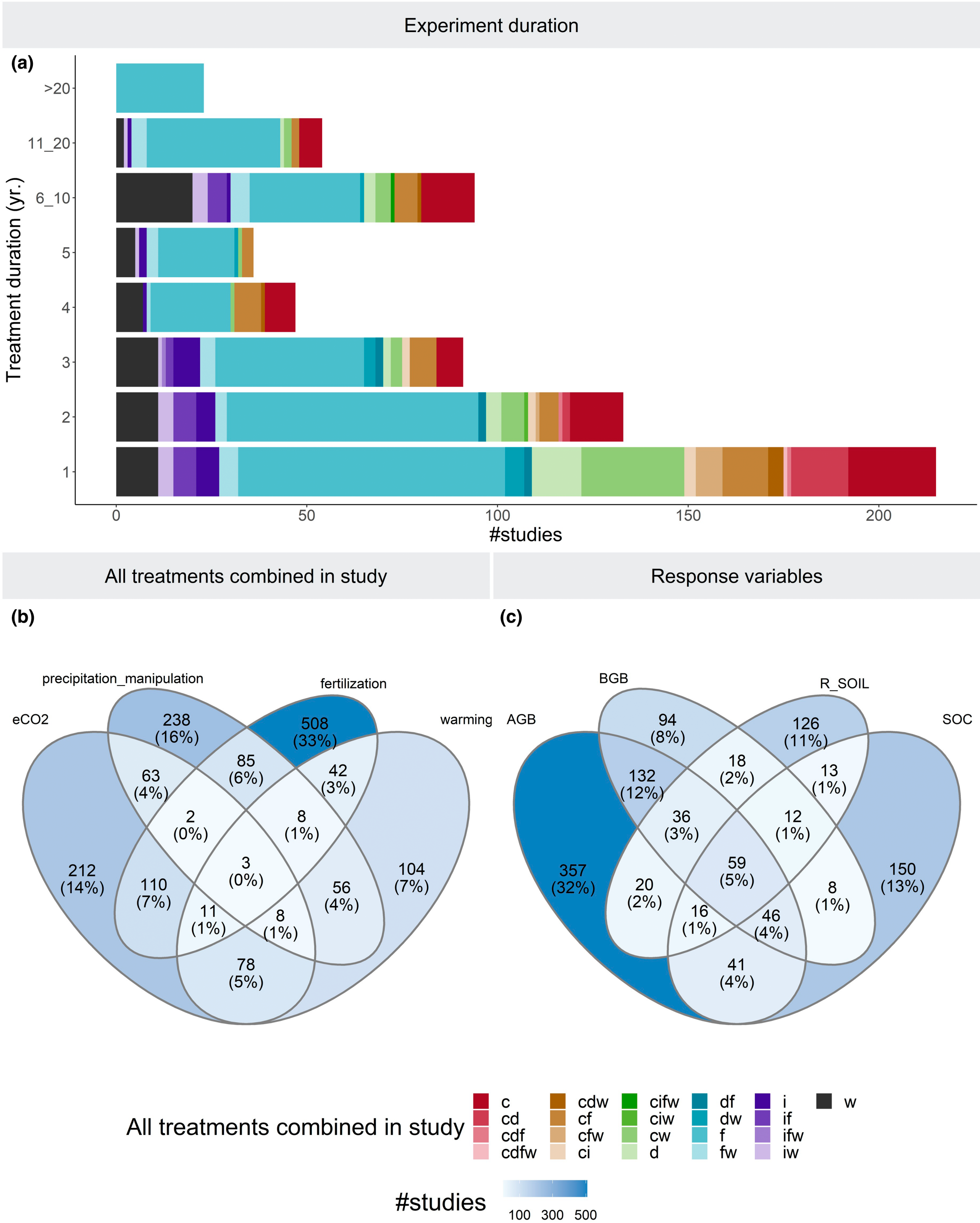

FIGURE 4 Distribution of experiment duration ($n = 693$), factors investigated ($n = 1528$), and some commonly measured responses ($n = 1128$) across studies in MESI. For display purposes, precipitation manipulation in panel b refers to both irrigation and drought experiments. AGB, aboveground biomass; BGB, belowground biomass; c, eCO_2; d, drought; f, fertilization; i, irrigation; R_SOIL, soil respiration; SOC, soil organic carbon concentration; w, warming.

manipulated—Figure 4b). In these 466 multifactorial studies, croplands are relatively overrepresented with a share of 33% (154 studies), as opposed to single-factor experiments where 907 of 1062 studies occurred in (semi-)natural grasslands, forests, or shrublands. The underrepresentation of non-cropland multifactor studies is illustrated by the eCO_2 × drought experiments in the database: Of 37 studies manipulating at least the CO_2 level and reducing precipitation, only 13 were in grassland, shrubland, or forest. Such eCO_2 × drought experiments in grasslands and forests are relevant for constraining models: despite long-known effects of eCO_2 on stomatal closure, much uncertainty still remains on under what circumstances (e.g., duration, atmospheric water demand) eCO_2 mitigates drought stress (De Kauwe et al., 2021). Such gaps identified by modeling, on key moderators influencing organism and ecosystem function, should more often inform the design of (multifactorial) experiments (e.g., bifactorial, longer term and with regression-design treatment levels—see also Collins et al., 2022) as well as what variables to monitor (e.g., vapor pressure deficit, leaf area).

3.2.4 | Coverage of (coupled) response variables

MESI describes a total of 262 response variables, of which 111 are related to carbon and 140 to nutrient cycling. The most commonly reported responses are above- and belowground biomass (AGB and BGB), soil respiration (R_SOIL), and soil organic carbon concentration (SOC) (Figures 4c and 5). These variables have regularly been measured together to test hypotheses on plant carbon allocation (AGB vs. BGB—Verlinden et al., 2018) and the ecosystem carbon balance (AGB + BGB vs SOC, R_SOIL—Terrer et al., 2021). MESI facilitates syntheses of such carbon allocation and balance studies to further disentangle context dependence of these coupled responses, for example, on how background gradients such as in climate and nutrient availability modify the relationships. While many studies present both AGB and BGB, more common reporting on both soil (SOC) and whole-plant (AGB + BGB) carbon or dry mass at the same experiment would be useful to this end.

In general, no striking differences among studies manipulating different factors appear in terms of their reporting of commonly collected carbon pool, carbon flux, and nitrogen pool responses (Figure 5; Figure S4). One notable exception is a relative overrepresentation of R_SOIL and an underrepresentation of SOC data at precipitation manipulation experiments: 40% of studies that report R_SOIL manipulated the availability of water, alone or in combination with other factors, whereas for SOC, this was only 19%. The most probable explanation for the preference of reporting soil-related flux rather than pool data is in the design of drought and irrigation experiments: Many manipulate water availability only for a number of weeks within growing seasons, in contrast to usually “continuous” nutrient addition, eCO_2, and warming experiments. Because of the shorter duration of these events, chances of (at least short term and first year) significant changes in SOC are lower here than for the other manipulation types. Fluxes, on the other hand, often respond strongly during and shortly after imposed shifts in water availability (Van Sundert, Brune, et al., 2020). We recommend that experimentalists clearly report on sampling dates (before, during, or after experiment, average over manipulation period, or growing season). In specified columns of our MESI database, we provide sampling dates and show the start and end of manipulation periods within the growing season (Table 1), such that immediate, lagged, and seasonally

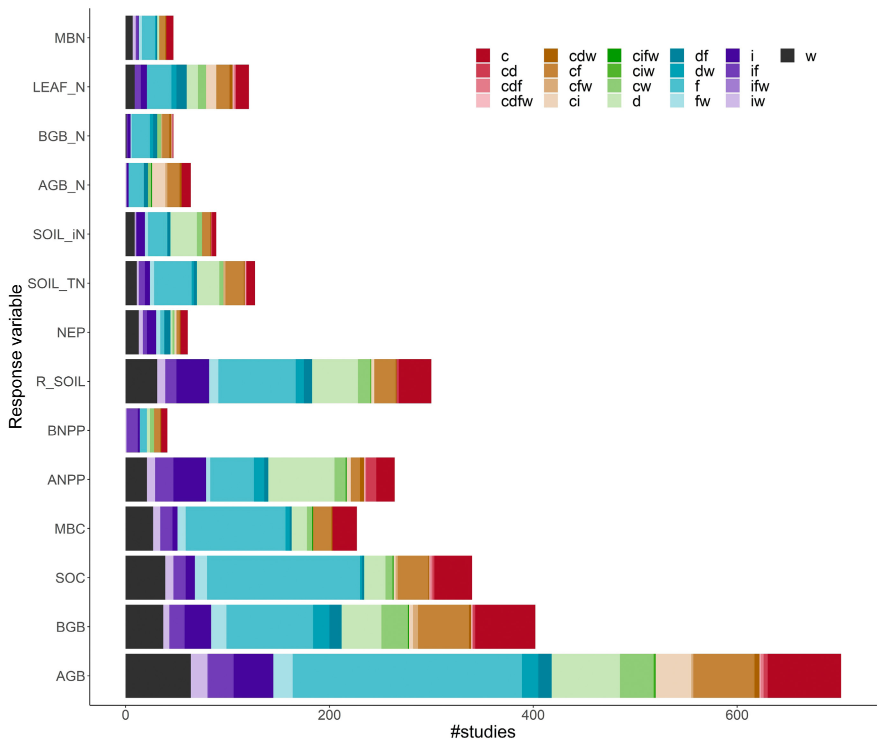

FIGURE 5 Availability of some commonly measured C cycle pool, flux, and N pool responses across 1536 unique studies in MESI, stratified by factors that were manipulated. AGB, aboveground biomass; AGB_N, aboveground plant N concentration; ANPP, aboveground net primary production; BGB, belowground biomass; BGB_N, belowground plant N concentration; BNPP, belowground net primary production; c, eCO_2; d, drought; f, fertilization; i, irrigation; LEAF_N, mass-based leaf N concentration; MBC, microbial biomass C; MBN, microbial biomass N; NEP, net ecosystem production; R_SOIL, soil respiration; SOC, soil organic C concentration; SOIL_TN, soil total N concentration; SOIL_iN, soil inorganic N (N-NH_4^+ and N-NO_3^-); w, warming.

averaged responses can be distinguished in analyses. Furthermore, a thorough assessment of the effect of precipitation changes on SOC would require more SOC data, from a greater diversity of experiments. This would make it more straightforward to verify if precipitation change impacts on SOC (if any) found in experiments are less pronounced than under naturally occurring deviations, analogous to what Kröel-Dulay et al. (2022) recently found for AGB.

3.3 | MESI as a dynamic database—Data management, use, and citation

Within the MESI initiative (Figure 6), we follow the FAIR (Findable, Accessible, Interoperable, Reusable) and TRUST (Transparency, Responsibility, User focus, Sustainability, Technology) principles for data stewardship and repositories (Kim et al., 2022; Lin et al., 2020; Wilkinson et al., 2016). We host the MESI database on GitHub (github.com/MESI-organization/mesi-db), from where versions are managed, tagged, and released to Zenodo (Van Sundert et al., 2022—doi.org/10.5281/zenodo.7153253), under open access license CC-BY-4, meaning that the database can be freely used and edited, provided that the present study and the database at Zenodo are properly cited. We invite the research community to suggest updates to MESI through pull requests and the issue tracker on GitHub, or by simply emailing the lead authors of the database and present study. Contributions from the community may include additional data and experiments; the combination of MESI with other databases of similar form and scope; or the highlighting of issues, gap filling, and suggestions for improvements. Substantial contributions to the current version (v1.0.2) are acknowledged with co-authorship on the next citable Zenodo data release. Researchers intending to use the database for their own meta-analyses are particularly encouraged to suggest improvements to the MESI database, as questions emerge during the process of preparing a study, and new data may be collected. For reuse, it is relatively straightforward to perform basic meta-analyses, but we strongly advise researchers to carefully consider the exact meaning of the data, including particularities of individual experiments, the meaning and interpretation of variables, etc. Therefore, we encourage involving MESI team members in future studies to advise data use, processing, and interpretation.

4 | CONCLUSIONS

Our Manipulation Experiments Synthesis Initiative (MESI) addresses a key gap in global change research by providing a platform to store all past and future global change manipulation experimental results. This facilitates the synthesis of global response patterns in an unprecedented way, allowing updatable, dynamic information extraction using standardized protocols. We invite research teams around the globe concerned with meta-analyses of global change experiments to add their data to the MESI database on GitHub (github.com/MESI-organization/mesi-db; doi.org/10.5281/zenodo.7153253—Van Sundert et al., 2022). We also propose that funding agencies consider the importance of supporting initiatives such as ours over long periods (decades) to ensure the continued curation of such overarching databases.

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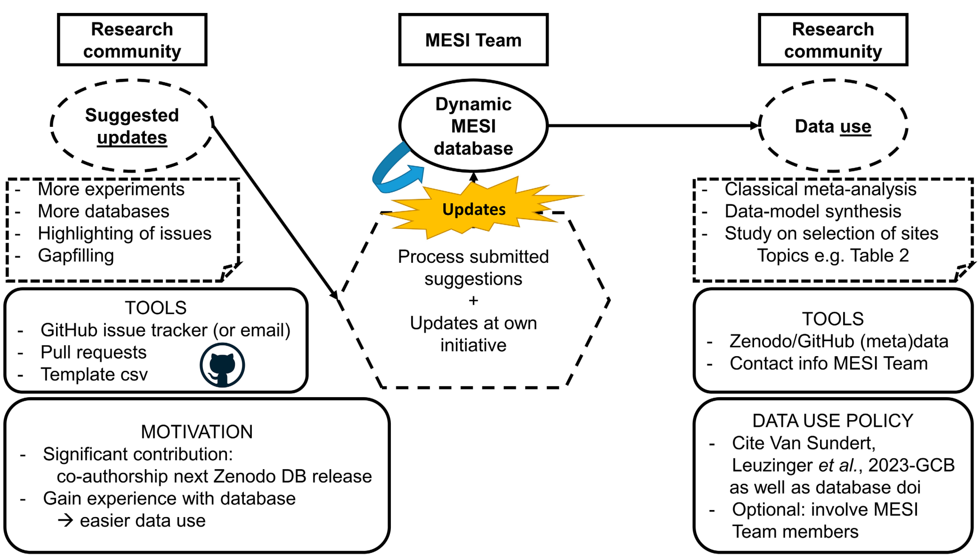

FIGURE 6 Protocol for MESI data maintenance, use, and citation, including a non-exhaustive list of suggestions for updates and data uses.

DP190102025). JS is supported by the National Natural Science Foundation of China (32101346). SQW is supported by the National Natural Science Foundation of China (31830012) and Hebei Natural Science Foundation (C2022201042). BDS was funded by the Swiss National Science Foundation grant PCEFP2_181115. We wish to thank the following contributors to data collection: Jonas Torfs, Dries Vrijens, Oberon Geunens, Adrita Ballal, Thomas D'heer, Amélie De La Rocha, Gert-Jan Goeminne, Jaime Escobar, Robin Halffman, Lena Kuperus, Pieter Luys, and Quinten Versmissen. Several of our institutions sit on indigenous peoples' lands. These include but are not limited to MIT, Stanford University, and Northern Arizona University. MIT acknowledges Indigenous Peoples as the traditional stewards of the land, and the enduring relationship that exists between them and their traditional territories. The land on which MIT sits is the traditional unceded territory of the Wampanoag Nation. We acknowledge the painful history of genocide and forced occupation of their territory, and we honor and respect the many diverse indigenous people connected to this land on which we gather from time immemorial. Stanford sits on the ancestral land of the Muwekma Ohlone Tribe. This land was and continues to be of great importance to the Ohlone people. Consistent with Stanford's values of community and inclusion, the university has a responsibility to acknowledge, honor, and make visible its relationship to Native peoples. Northern Arizona University sits at the base of the San Francisco Peaks, on homelands sacred to Native Americans throughout the region. We honor their past, present, and future generations, who have lived here for millennia and will forever call this place home.

CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

The updatable MESI database of global change experiments is open access available at doi.org/10.5281/zenodo.7153253. The main table of experimental effects and ancillary experiment information, as well as the bibliography, soil property and metadata were uploaded in csv format. We also provide an R script for conversion of the main table from wide to long format. We encourage researchers focusing on ecological synthesis, modeling and/or experiments to use and contribute to the MESI database. All display items and statistics presented in the manuscript were based on database version v1.0.1 that was released at the time of manuscript submission.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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