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WaterLANDS: A Database of Carbon Stocks, GHG Fluxes and Biodiversity Indicators in Restored European Wetlands

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ABSTRACT

Motivation: Wetland restoration is expected to play an important role in helping Europe achieve its climate and biodiversity targets as stated in the European Green Deal. Restored wetlands sequester atmospheric carbon and provide habitat for a wide range of plant and animal species. To design effective, evidence-based restoration targets and guide future projects, it is critical to understand the impacts of wetland restoration on a diverse range of ecosystem functions. Existing knowledge, however, is scattered across empirical studies assessing restoration outcomes on a limited set of indicators, in specific settings and single locations. This fragmentation limits our ability to assess the effectiveness of wetland restoration across different indicators and contexts. To address this gap, we present a comprehensive dataset on the effects of wetland restoration across Europe. The dataset compiles 2534 entries representing changes in carbon stocks, greenhouse gases (GHG) fluxes, and biodiversity indicators across different wetland types, pre-restoration land use and restoration strategies. The database allows comparisons between restored and both degraded and pristine sites.

Main Types of Variables: The database contains data on carbon stock, GHG fluxes and biodiversity indicators in restored and control wetlands, with standard error, sampling methodology, wetland type, location, climate, restored site area, water table depth, soil characteristics, pre-restoration land use, time since restoration started, and restoration strategy.

Spatial Location and Grain: Europe.

Time Period and Grain: Original data were published between 2000 and 2024. Restoration age ranges from a few months to 139 years.

Major Indicators and Level of Measurement: Carbon stocks, GHG fluxes and biodiversity indicators in restored wetlands and two controls: degraded and pristine sites.

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Software Format: The dataset is available at https://doi.org/10.17026/LS/H5MFEH as a .xlsx file and as a .shp file, with a metadata file.

1 | Introduction

Climate change and biodiversity loss are urgent environmental threats to humanity (IPBES 2019; IPCC 2023) and the restoration of wetland ecosystems could contribute to addressing these threats. Wetland ecosystems are partially water-logged, either seasonally or permanently (Khatik 2022), and include coastal, inland ecosystems like salt marshes, freshwater peatlands, and estuaries. Many of these ecosystems, such as peatlands, have water-logged soils that slow down organic matter decomposition, leading to substantial accumulation of organic carbon (Mitsch et al. 2013; Temmink et al. 2022). Others, such as salt-marshes, exhibit high rates of carbon burial due to water level fluctuations. As a result, wetlands act as persistent carbon sinks, accounting for approximately 20% of the global land CO_2 uptake, though CH_4 emissions and dissolved carbon losses offset some of this sink capacity (Li et al. 2023; Schuster et al. 2024). In addition, wetland ecosystems are significant biodiversity hotspots, hosting a diverse array of species across different taxonomic groups (Minayeva et al. 2008). In Europe, only one-third of historical wetland extent remains today, with even lower figures for specific regions and wetland types (Bertassello et al. 2024; Fluet-Chouinard et al. 2023). This has led to a shift towards the conservation of remaining wetlands and restoration of degraded ones. Under the 2024 EU Nature Restoration Law (Hoek 2024), 20% of all European degraded ecosystems are to be restored by 2030, and at least 90% by 2050, providing potentially significant opportunity to mitigate climate change and biodiversity loss. Over the last decades, the many wetland restoration projects that have been performed have initially focused on restoring hydrodynamics to compensate habitat and biodiversity loss (Craft 2022). Recently, focus has increasingly shifted to the potential of wetland restoration for carbon sequestration (Joosten and Duene 2021).

To assess how wetland restoration can support climate change mitigation and biodiversity conservation requires data on the effects of restoration on:

i. Size of various carbon stocks, including soil organic carbon (SOC) and dissolved organic carbon (DOC).

ii. Greenhouse gases (GHG) fluxes, notably carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

iii. Biodiversity indicators, referring to measures of individuals, species, and taxonomic diversity metrics across various taxonomic groups.

Such data have been gathered through empirical studies and synthesised in meta-analyses on wetland restoration, which have typically focused on specific wetland types, for example, temperate fen peatlands (Kreyling et al. 2021) or coastal ecosystems (O'Connor et al. 2020), and/or on specific indicators such as SOC (Xu et al. 2019). These studies have compared restored wetlands to either pre-restoration conditions or to pristine counterparts, but not both. The latter, however, is crucial to fully determine the completeness of wetland recovery after restoration. Importantly, datasets that underlie meta-analyses are not always available, as only in recent years have journals started requiring authors to make their data openly accessible. Hence, we currently miss a comprehensive, open-access dataset that compiles available empirical data on the effect of European wetland restoration on carbon stocks, GHG fluxes and biodiversity-related indicators. Such data and proper evaluation are critical for policy makers to design effective and realistic restoration targets and strategies, as well as for field practitioners to select evidence-based restoration approaches that achieve desired outcomes.

Here, we present an empirical database on carbon stocks, GHG fluxes and biodiversity indicators in restored wetlands in Europe. The database compiles the results from primary research studies that compare restored to degraded sites and restored to pristine ecosystems. In addition, for each entry we included (i) restoration project data (e.g., restoration strategy and the time elapsed since restoration started), (ii) the condition of the land before restoration (e.g., type and duration of the disturbance), and (iii) the characteristics of the area (e.g., climatic variables, water table depth and soil edaphics). The database can support assessment of the effects of restoration on carbon dynamics and biodiversity across diverse environmental contexts, such as different wetland types and restoration measures. The database also enables analyses of how pre-restoration land uses and restoration practices influence overall or specific ecosystem functions. To show the potential of the database, we present a summary of the data in this study. However, more thorough analyses are needed to address specific questions.

2 | Methods

2.1 | Literature Search

To build our database on carbon stocks, GHG fluxes and biodiversity indicators resulting from wetland restoration, we conducted a systematic literature search using the PICO framework, where P stands for population, I for intervention type, C for comparator and O for output, which is commonly used in meta-studies (Foo et al. 2021). We introduced an additional component, L, for location, to focus on EU member states and other countries within the geographical definition of Europe. For each of the PICO(L) components, we created a single search string and then applied them all in the Web of Science database (WoS), separated by AND, to generate a multi-lined search inquiry (Table 1). We conducted the search across 'all fields' search, which includes title, abstract, author and keywords. The search was performed in January 2024 and retrieved 4169 peer-reviewed research papers. We identified additional sources by extracting the papers synthesised in relevant meta-analyses. To achieve this, we first identified the meta-analyses through WoS using a refined version of the primary search string. This version retains the same P, I, and O components, but excludes the C element, often only mentioned in the full text for meta-analyses, and includes an additional line specifically targeting meta-analyses (the full search string is provided in Table S1).

TABLE 1 | The search string used to extract primary studies. The structure follows the PICO principle, with the location (L) element added to include the geographical scope of Europe. Each line was applied in the Web of Science database separated by an AND.

PICO component	Terms included in the search string
P	peatland$ OR peat$ OR bog$ OR fen$ OR mire$ OR marsh* OR estuar*
I	restor* OR re$vegetat* OR rehabilitat* OR re$generat* OR re$wild* OR recover* OR recuperat* OR reforestat* OR "graz* exclu*" OR re$wet* OR water$logg* OR "secondary vegetation"
C	agricultur* OR cultivat$ OR crop$ OR "rice padd*" OR farm* OR drain* OR pasture$ OR aquaculture OR mine$ OR 'bare land' OR barren OR mining OR logging OR logged OR barren OR degraded OR degradation OR abandon* OR residential OR urban OR dredg* OR dams OR damming OR undrained OR pristine OR polluted
O	diversity OR abundan* OR density OR population$ OR richness OR carbon OR "soil organic matter" OR biomass OR "greenhouse gas* emission$" OR "GHG* sink$" OR "GHG* source$" OR CO_2* OR methane OR CH4 OR "nitrous oxide" OR N_2O OR "global warming potential$" OR "ecosystem service$" OR erosion OR eroded OR "water level$" OR "water depth" OR "water table$" OR runoff$ OR discharge OR flood$ OR "water quality" OR "toxic chemical$" OR "pollutant$" OR "nutrient$ concentration" OR "sediment load"
L	Europe OR Albania OR Andorra OR Austria OR Belarus OR Belgium OR Bosnia OR Herzegovina OR Bulgaria OR Croatia OR Cyprus OR Czech Republic OR Denmark OR Estonia OR Finland OR France OR Germany OR Greece OR Hungary OR Iceland OR Ireland OR Italy OR Kosovo OR Latvia OR Liechtenstein OR Lithuania OR Luxembourg OR Malta OR Moldova OR Monaco OR Montenegro OR Netherlands OR Macedonia OR Norway OR Poland OR Portugal OR Romania OR Serbia OR Slovakia OR Slovenia OR Spain OR Sweden OR Switzerland OR Ukraine OR England OR Scotland OR Wales

We retrieved 233 meta-analyses, whose abstracts were screened to determine whether they included the elements listed in the search string. We selected 8 meta-analyses, which encompass a total of 415 peer-reviewed research papers.

2.2 | Papers Screening

The phases of the data collection process are presented in a PRISMA flowchart (Figure 1). The chart outlines the workflow, starting from the identification of the sources and progressing through screening, eligibility assessment and inclusion. After removing duplicate papers identified through both the search string and meta-analysis sources, an initial screening was performed by a lead reviewer. This reviewer screened the abstract of all sources to determine whether they likely contained the elements specified in the search string, using the "metagear" and "RefManageR" packages in RStudio (version 4.3.2) for abstract visualisation. 1157 papers were selected out of a total of 4491. The selected papers were downloaded and read in full by three independent reviewers. Full-text screening resulted in 130 papers chosen for data extraction based on the following criteria:

i. Studies unambiguously describe a restoration process, defined here as the establishment of natural ecosystems that do not require management in the long term. Commercial plantations, including, for example, paludiculture, were excluded.

ii. Papers report data on at least one control site, which can be either unaltered ecosystems (pristine control) or polluted, managed or abandoned land (degraded control).

iii. Studies focus on one of the following wetland types: peatlands, estuaries and salt marshes, and study sites are located in Europe (see the list of countries in the location L row of Table 1). Peatlands are ecosystems characterised by a layer of decayed organic matter, known as peat, that is at least 30 cm thick (Avetov and Shishkonakova 2019). While some studies simply refer to peatlands, others further categorise them based on hydrology and nutrient content into: bogs, that are low in nutrients and that receive water mostly from precipitation (Bring et al. 2022); fens, fed by more nutrient-rich groundwater (Bring et al. 2022); and mires, a term generally used for peat-forming but also as a synonym of peatland (Bragg 2002). Salt marshes are coastal wetlands periodically flooded by salt water (Cronan 2023), and estuaries are ecosystems characterised by brackish water created by the mix of fresh and salt water where rivers meet the sea (Savage et al. 2012).

iv. Studies report empirical data. Studies reporting only (statistical) model outputs were excluded.

v. Papers specify the methodology used to gather their data.

2.3 | Data Extraction

Reviewers had weekly meetings to discuss and evaluate the data extracted from the papers and, when in doubt, they examined the paper jointly to reach agreement. To assess consistency, all three reviewers independently extracted data from a random subset of 10 papers and compared results. In addition, the lead reviewer performed random checks on data extracted by others to ensure accuracy and uniformity. From each paper that was deemed eligible, we extracted values of carbon stocks, GHG fluxes and biodiversity indicators in restored and control wetlands, with units, sample size, standard error and sampling methodology (the full list of the extracted variables is available in

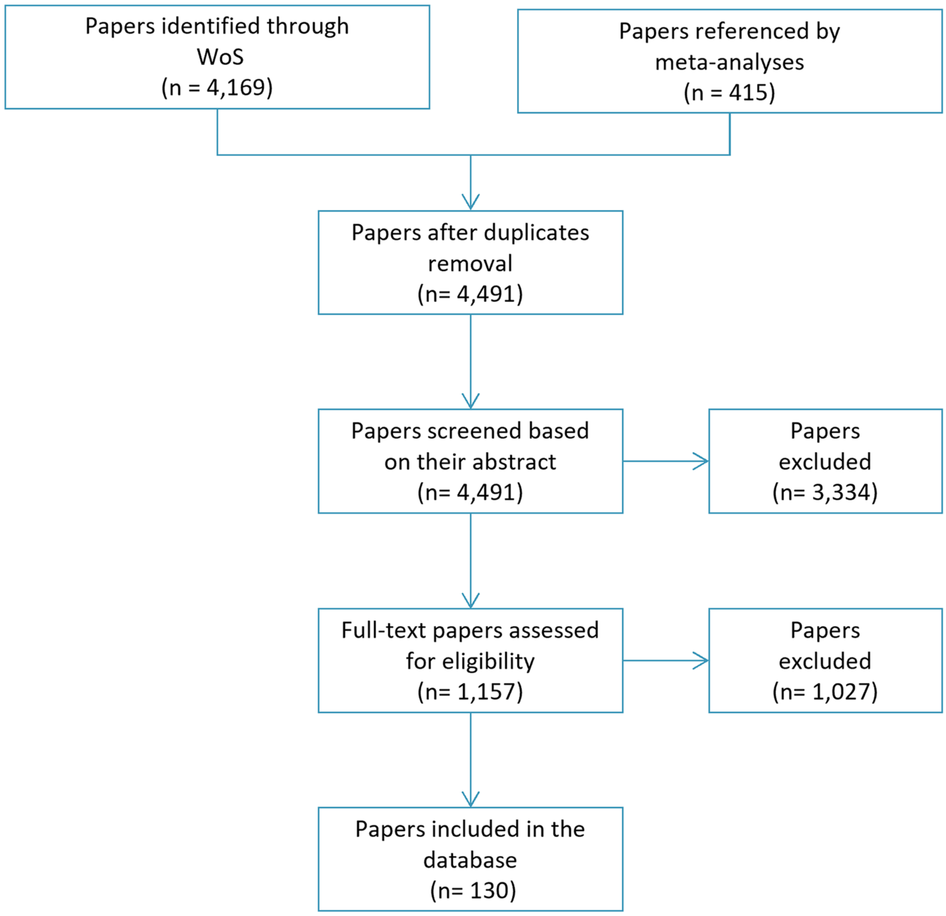

FIGURE 1 | PRISMA flow-chart. The chart shows the identification, screening and selection process of the papers retrieved using the search strings in the Web of Science (WoS) database.

Table S3). The degraded control was either of temporal (i.e., the same area before restoration) or of spatial (i.e., an adjacent site that is not restored) nature, while the pristine control is always spatial. From the original paper, we also collected a wide range of additional data on the sampled ecosystems, such as wetland type, location, climatic conditions, elevation, area of the restored site, pH, bulk density, as well as characteristics of the restoration project, such as the condition of the land before it was restored, time elapsed since restoration started (i.e., restoration age) and restoration methodology. Data were extracted from the text, tables and source data, or when these options were not available, directly from figures using the online tool PlotDigitzer (Version 3.1.5).

2.4 | Data Harmonisation and Integration

Latitude and longitude of the study locations reported in the original papers were converted to decimal degrees. When the coordinates were not reported, they were extracted from Google maps. Based on the coordinates, we used external sources to obtain climatic conditions and elevation only when these variables were not reported in the paper. Average precipitation and temperature were obtained using the WorldClim2.1 dataset, which provides bioclimatic variables at 1 km resolution, based on the averages calculated for the 1970–2000 period (Fick and Hijmans 2017). Elevation data were extracted from the Copernicus GLO-30, a digital surface model with 1 km resolution developed by the European Space Agency (ESA 2024).

In the database, we retained the wetland type definitions provided by the original papers and added a separate column where these were grouped into broader categories. For example, when the original studies referred to peatlands or mires, we classified them into the broader categories of "bog" or "fen" based on information on dominant vegetation, soil nutrient status, or acidity reported in the respective papers. When such information was not available, peatlands and mires were assigned to the general category of "peatland". Similarly, we retained the definitions of the restoration strategies provided in the original papers and also classified them in a separate column into three broad categories: (i) abandonment, that is, the complete cessation of all human activities on the land, which usually leads to spontaneous revegetation; (ii) restoration of the abiotic conditions, that is, efforts that rehabilitate the abiotic processes and components of habitats to trigger spontaneous recovery (Holl 2021), such as the re-establishment of the pre-disturbance hydrological regime (rewetting) or soil amendment through topsoil removal; and (iii) active planting, that is, the direct planting of vegetation in degraded land. When multiple strategies are applied, the classification follows the highest level of human intervention; for example, when active planting follows abiotic restoration, the assigned category is "active planting".

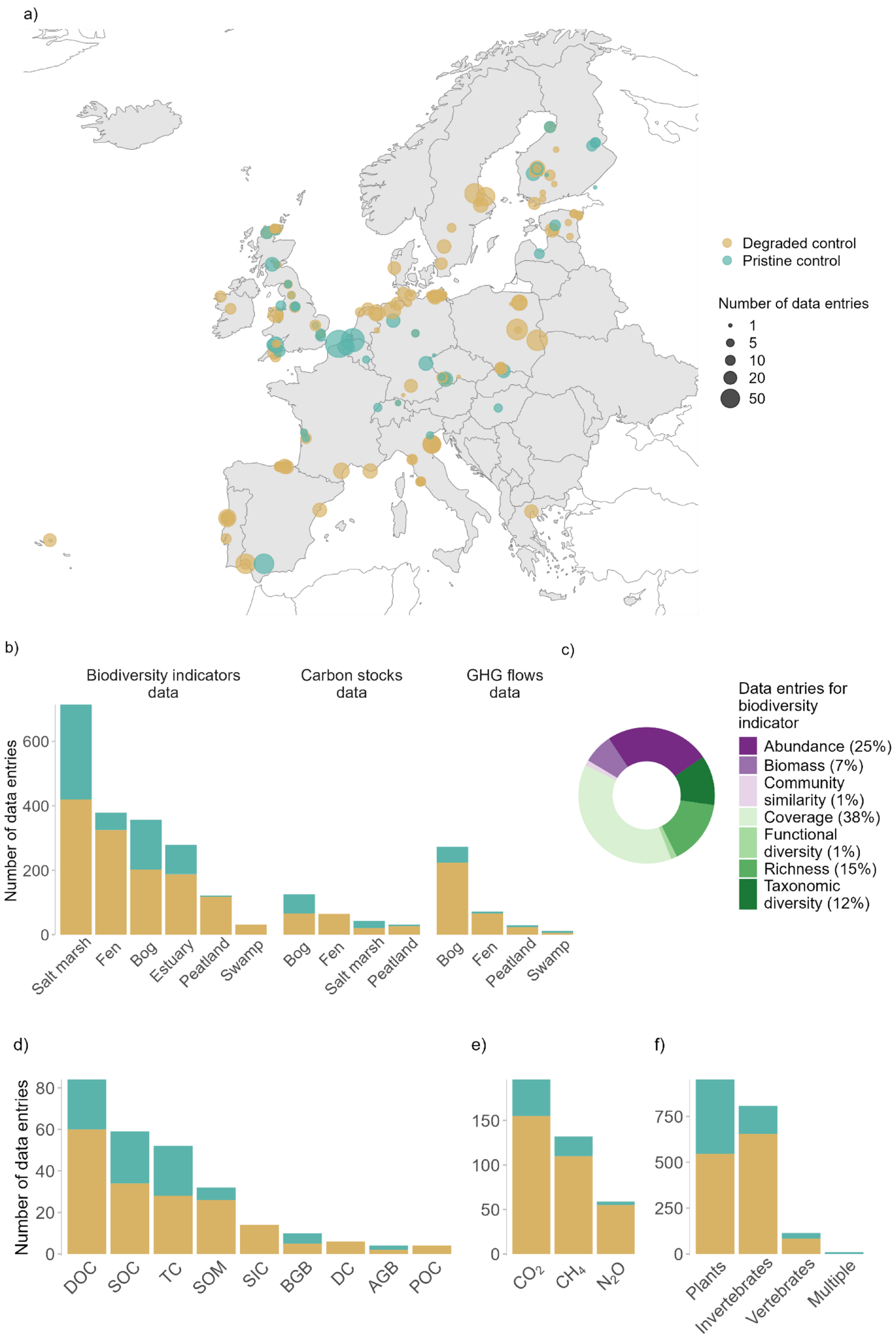

FIGURE 2 | Legend on next page.

FIGURE 2 | Overview of the WaterLANDS database. Panel (a) shows the location of the restoration studies included in this database. Circle colour indicates the type of control reported and circle size indicates the number of data entries per site. Subsequent panels show the number of data entries per wetland type (as broad categories based on the definitions from the original papers) (b), the proportion within the database of the data entries across the biodiversity indicators (shown in different colours) (c), carbon stocks (d) greenhouse gas (e) and each species group (f). The yellow part of each bar indicates data entries with degraded control, and the blue part indicates data entries with pristine control.

For each entry in the database, we calculated the change between restored and control values to describe the proportion of data entries showing increases or decreases. This descriptive comparison serves as an exploratory summary to illustrate the content of the database, rather than to draw conclusions on restoration effects, which requires dedicated statistical analyses. For biodiversity indicators and carbon stocks, we quantified the percentage change between the restored and the control value of each entry. Maximum 0.5% increase or decrease were considered 'no change'. Positive percentages indicate higher biodiversity and larger carbon stocks in restored sites compared to the controls. For dissolved or particulate carbon, such as DOC, however, higher reported concentration could result from lower dilution following restoration, rather than increased carbon supply (Gatis et al. 2023). For GHG fluxes, we quantified the difference between the restored and the control values of each entry, defining 'no change' as a difference smaller than 0.5% of the control. Following the original papers, we grouped GHG fluxes into emissions, uptakes or net fluxes. For emissions, positive changes indicate higher emissions in restored sites and negative changes indicate lower emissions. For uptake, only represented by gross primary production (GPP) in our database, positive changes reflect lower uptake in restored sites and negative changes reflect higher uptake. For net fluxes, positive changes indicate net emissions in restored sites, and negative changes indicate net uptake.

2.5 | Data Access

The wetland restorations database is available via https://doi.org/10.17026/LS/H5MFEH.

We provide one database file containing both pristine and degraded controls, as well as all target variables that is, biodiversity indicators, carbon stocks and GHG fluxes. We also provide a clickable map in a shape file format, showing the database entries in each site location. The database file is supported by a metadata file.

3 | Results

3.1 | WaterLANDS Database Overview

The WaterLANDS database on the effects of wetland restoration on carbon stocks, GHG fluxes, and biodiversity indicators comprises 2534 data entries: each entry includes data for both a restored site and a control site. Of these entries, 70% feature a degraded control and 30% a pristine one. Furthermore, 10% of the entries report measurements of carbon stocks, 15% report GHG fluxes, and 74% report biodiversity. Restoration age is reported for 98% of all data entries and ranges from a few months to 139 years. For carbon stocks and GHG fluxes, the most studied wetland types are bogs, fens, and unspecified peatlands, due to their high carbon accumulation capacity on one hand and potential for high GHG emissions on the other. For changes in biodiversity, salt marshes are the most studied wetland types (Figure 2b). The most analysed carbon stocks are dissolved organic carbon (DOC) and soil organic carbon (SOC) (Figure 2d; see Table 2 for a description of the indicators), while CO_2 and CH_4 are the most studied GHGs (Figure 2e). For biodiversity-related indicators, most entries focused on invertebrates and plants (Figure 2f), with Coverage and Abundance being the most reported indicators (Figure 2c). While many widely used biodiversity indicators are represented in the studies underlying our database, others are missing, such as species occupancy, which describes the presence or absence of species, and phylogenetic diversity, which reflects the evolutionary relationships within an assemblage. These indicators could provide valuable insights in the context of ecosystem restoration, helping to describe species loss resulting from ecosystem degradation and the evolutionary diversity recovered through restoration, respectively.

The relative number of data entries per restoration strategy shows a similar pattern across the different wetland types, with restoration of abiotic conditions being the most studied, followed by abandonment and planting (Figure 3). In our database, restoration of abiotic conditions typically involves rewetting and the reduction of nutrient load, which are often applied in combination but implemented differently across wetland types. We see in the database that in peat-rich wetlands, rewetting usually consists of blocking or filling ditches that were dug to drain water from the peatlands. This is sometimes accompanied by the removal of degraded topsoil and/or residual biomass from previous land uses. In salt marshes, most studies report that rewetting requires removing or modifying built structures, such as embankments or seawalls to restore tidal flooding. Nutrient load reduction, aimed at amending eutrophication, is typically achieved by building or upgrading wastewater treatment plants, diverting nutrient-rich water and improving stream circulation, for example by re-connecting river arms in estuaries. The database shows that land abandonment is less studied than restoration of abiotic conditions, likely because wetland restoration requires the re-establishment of the near-natural hydrology to facilitate revegetation. Furthermore, abandonment often occurs outside the context of restoration projects, so it is rarely monitored over time and, thus, is generally less researched than other strategies and underrepresented in the database. In some cases, restoration entails combining multiple strategies; for example, planting is generally carried out after rewetting or soil amelioration. Details of the restoration strategies used are reported in dedicated columns of the database.

Most studies in our database report draining and peat extraction as the primary pre-restoration disturbances and land uses, respectively, in peat-rich wetlands (Figure 4). The data entries further indicate that drainage is most commonly carried out to enable agricultural use. For other wetland types,

TABLE 2 | Overview of indicators in the WaterLANDS database. Carbon stocks, GHG fluxes, and biodiversity indicators, with description and commonly used units in our database. Biodiversity measures extracted from the papers were grouped according to their main focus, distinguishing whether they describe individuals, species, community composition, trait-based characteristics, etc. (see Table S2 for details). Note that plant biomass is used as a biodiversity indicator in several of the original papers and reported here as such but can also be considered as a carbon stock.

Indicator category	Indicator	Description	Common units
Carbon stocks	Soil organic carbon (SOC)	Carbon in the soil originated from the decomposition of plant and animal matter (Tao et al. 2023)	g/kg
	Soil organic matter (SOM)	Organic matter that accumulates in the soil, mostly from litter fall, decomposed and transformed by soil micro fauna. (Iroshaka Gregory Marcelus Cooray et al. 2025)	g/kg
	Soil inorganic carbon (SIC)	Inorganic carbon in the soil, mainly carbonates, formed through sediment weathering (Sharififar et al. 2023)	mg/L
	Total soil carbon (TC)	All carbon present in the soil, organic and inorganic (Lu et al. 2020)	g/kg
	Particulate organic carbon (POC)	The largest particles of SOC that cannot dissolve in water (Berryman et al. 2020)	mg/L
	Dissolved organic carbon (DOC)	Fraction of organic carbon found in pore water, as well as channels, ditches or streams water (Lu et al. 2020)	mg/L
	Dissolved carbon (DC)	Organic and inorganic carbon found in the water (Lu et al. 2020)	mg/L
	Aboveground biomass (AGB)	The mass of living plant material above the soil, including stems, branches, foliage, stumps and bark	kg/m^2
	Belowground biomass (BGB)	The mass of living roots	kg/m^2
GHG fluxes	Methane (CH_4)	Emitted by methanogens microorganisms during the decomposition of organic matter, and sequestered by methanotrophes (Morant et al. 2020). Reported in the database as net flux mostly	g/m^2 y
	Carbon dioxide (CO_2)	CO_2 fluxes derive from ecosystems respiration and sequestration (Schuster et al. 2024). Reported mostly as ecosystem respiration (Reco), gross primary production (GPP) and net ecosystem exchange (NEE)	g/m^2 y, mg/m^2 h
	Nitrous oxide (N_2O)	Produced mainly by heterotrophic and autotrophic soil bacteria as a byproduct of nitrification and incomplete denitrification (Maslov and Maslova 2022). Reported in the database as net flux mostly	g/m^2 y, mg/m^2 h

(Continues)

TABLE 2 | (Continued)

Indicator category	Indicator	Description	Common units
Biodiversity	Abundance	Number of individuals of a species in an area (He and Gaston 2000)	nr individuals/m^2
	Biomass	Total mass of living material of the specimens collected during an assessment	mg dry weight/m^3, g/m^2
	Coverage	Portion (usually percentage) of the area covered by individuals (Kędzior et al. 2022)	Percentage of measured plot
	Community similarity	Measure of species composition between two similar sites. Higher values indicate more heterogeneous sites (Roden et al. 2018). Mostly repored as Sørensen's and Bray–Curtis's indices	Sørensen's dissimilarity index
	Richness	Number of different species present in an area (Chao 2006)	Number of species
	Functional diversity	Considers trait-based metrics, such as variation between species within a trait space or diversity within a particular trait	Functional dispersion, functional richness
	Taxonomic Diversity	Indices combining species number and evenness. Considers species richness and how evenly the individuals are distributed across the species (Roden et al. 2018)	Shannon's diversity and Pielou's evenness indices

eutrophication and agriculture are the most frequently reported forms of pre-restoration disturbance and land use, respectively, in our database. We see in our database that eutrophication of estuaries and salt marshes is primarily attributed to excessive nutrient inputs from urban and industrial discharges. Agricultural activities in these wetlands are typically established after draining, achieved through the construction of seawalls and embankments.

3.2 | Description of Carbon Stocks Outcomes

When comparing carbon stocks between restored wetlands and pristine controls, the distribution of database entries shows considerable variability (Figure 5). For TC, SOM, and BGB, data entries are mostly classified as "negative", while for SOC, DOC, and AGB, most entries fall into the "positive" category. Comparing restored wetlands to degraded controls (Figure 5), carbon stocks are predominantly classified as "positive". DC entries, however, are split between all categories. Only DOC entries show more "negative" entries after restoration.

3.3 | Description of GHG Fluxes Outcomes

When comparing CO_2 fluxes between restored and pristine wetlands, most NEE data fall into the "Net emission" category. Reco and GPP show slightly more data entries classified as "Negative" indicating both lower respiration and uptake in restored sites (Figure 6a). Compared to pristine sites, CH_4 emissions data entries are classified mostly as "Lower", while Net flux entries are slightly more frequent in the "Net emission" category. For N_2O, Net fluxes data entries mainly occur in the "Net uptake" category (Figure 6b).

When compared to degraded controls (Figure 6a), CO_2 shows most Reco entries in the "Lower" category, while GPP entries are more frequently classified as "Higher". Most NEE entries are categorised as "Net uptake", with fewer "Net emission" entries. For CH_4, most Net fluxes data entries are classified as "Net emission", while data entries for N_2O Net flux are mostly categorised as "Net uptake" (Figure 6b).

3.4 | Description of Biodiversity Indicator Outcomes

Most plant data entries fall into the "negative" category for biodiversity indicators in restored ecosystems, as compared to pristine systems (Figure 7a). When comparing to degraded controls, most data entries are classified as "positive" (Figure 7a).

For invertebrates, the number of data entries is rather similar between "negative" and "positive" categories across biodiversity indicators in restored wetlands compared to both controls

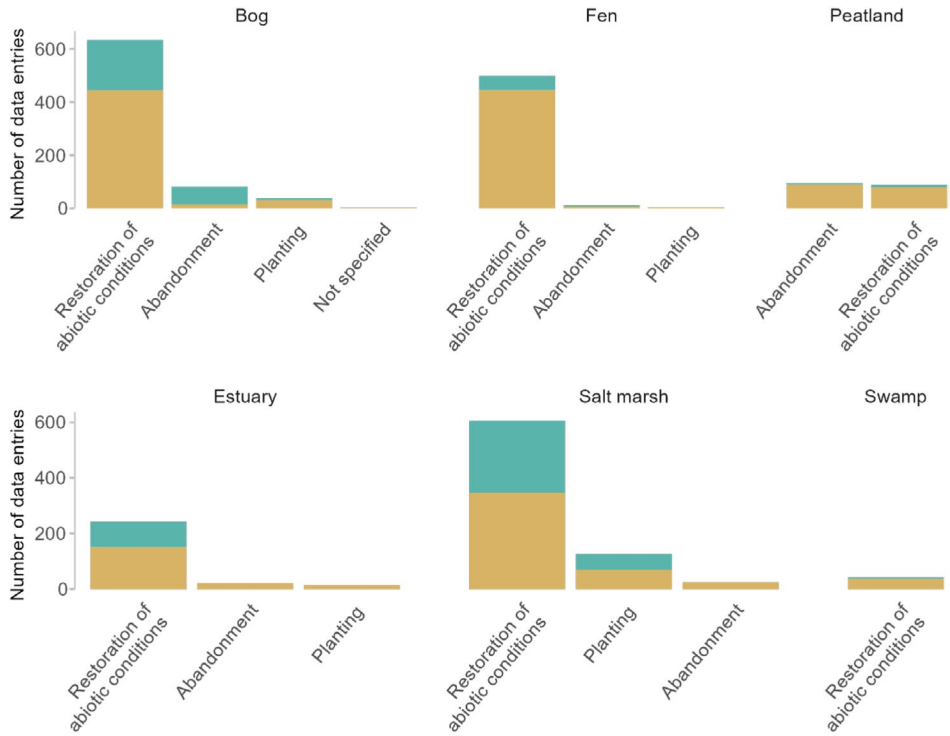

FIGURE 3 | Overview of data entries per restoration strategy. Number of the data entries in the database corresponding to the broad categories of restoration strategies, defined based on the description in the original papers. “Abandonment” is the cessation of all human activities; “restoration of abiotic conditions” involves active removal of disturbances and/or restoration of the abiotic components, for example, rewetting or removing excess nutrients; “planting” consists in actively replanting vegetation. The category “not specified” refers to data that does not specify the restoration strategy applied. The yellow part of each bar indicates data entries with degraded control, and the blue part indicates data entries with pristine control.

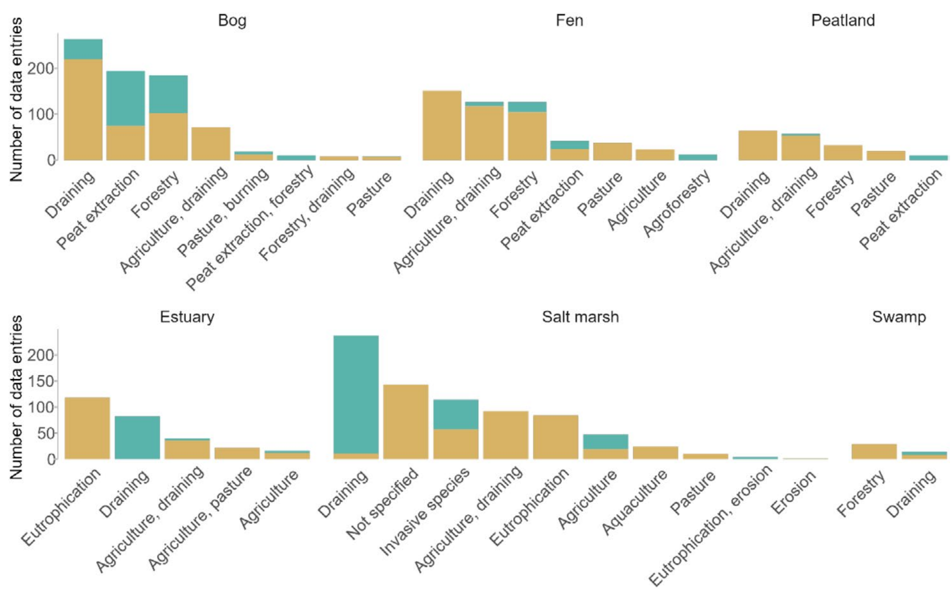

FIGURE 4 | Overview of data entries per pre-restoration land use or disturbance type. Data entries are shown per wetland type, as reported in the original papers. Note that for some sites multiple pre-restoration land uses and/or disturbance types are reported, indicating that the land experienced several uses or disturbances prior restoration. The yellow part of each bar indicates data entries with degraded control, and the blue part indicates data entries with pristine control.

(Figure 7b). Compared to pristine wetlands, abundance and richness show slightly more “positive” data entries, while biomass and coverage entries are comparatively more “negative”. When compared to degraded wetlands, abundance, richness, and taxonomic diversity show slightly higher numbers of “positive” data entries, while biomass shows more “negative” entries.

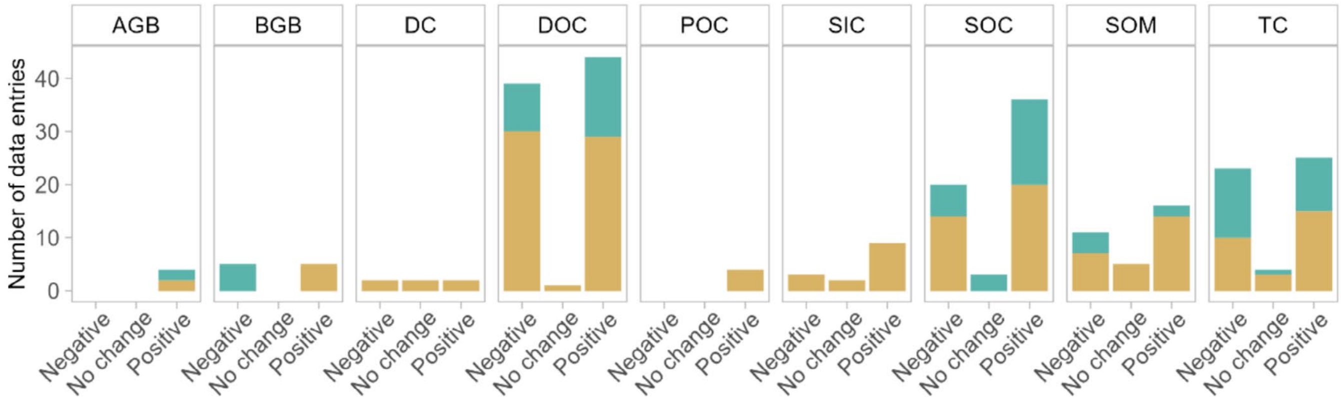

FIGURE 5 | Overview of data entries on carbon stocks. Number of data entries reflecting negative, no change and positive changes between restored and control wetlands across different carbon stocks. Changes were calculated as the percentage of change relative to the control. The yellow part of each bar indicates data entries with degraded control, and the blue part indicates data entries with pristine control. "No change" refers to changes within ±0.5%.

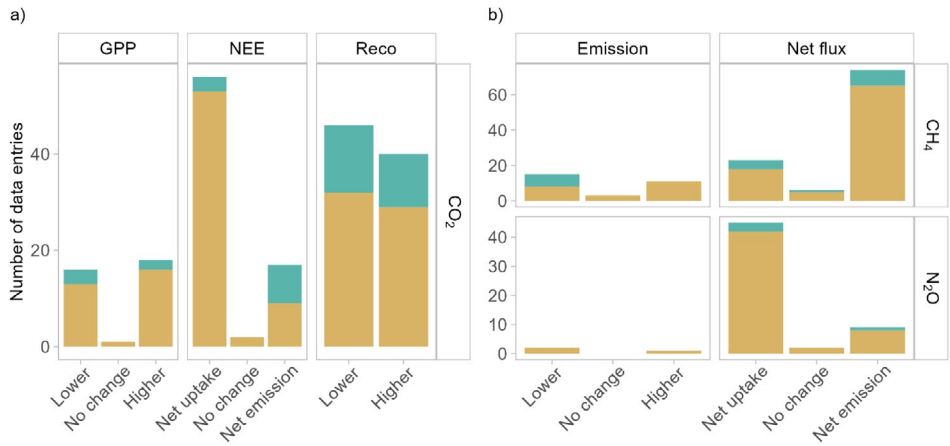

FIGURE 6 | Overview of data entries on greenhouse gas (GHG) fluxes. Number of data entries reflecting change in fluxes calculated between restored and control wetlands for CO_2 (a), CH_4 and N_2O (b). Boxes show different GHG flux types as reported in the original papers. For CO_2, gross primary productivity (GPP) indicates uptake, net ecosystem exchange (NEE) represents the balance between emissions and uptake, and ecosystem respiration (Reco) indicates emissions to the atmosphere. For CH_4 and N_2O, Emission refers to fluxes to the atmosphere, while Net flux represents the balance between emissions and uptake. Changes were calculated as the difference between restored and control sites for each entry and "no change" indicates a difference smaller than 0.5% of the control value. The yellow portions of the bars represent data with degraded control sites, and the blue portions represent data with pristine control sites.

For vertebrates, most data entries fall into the "negative" category for abundance and biomass in restored wetlands as compared to pristine sites (Figure 7c). Compared to degraded sites, most entries for richness and taxonomic diversity are categorised as "positive", while slightly more data entries for abundance are classified as "negative".

4 | Discussion

To the best of our knowledge, we have compiled the most comprehensive database on the effects of wetland restoration in Europe on climate and biodiversity indicators. This database consolidates a broad collection of empirical data on the impact of restoration on carbon stocks, GHGs fluxes and biodiversity indicators and compares restored wetlands to both their degraded and pristine counterparts. It includes data on the ecosystem characteristics, such as wetland type, climate, water table depth, soil features, as well as external factors, such as the pre-restoration disturbance, the restoration strategies applied and the time since restoration started. By bringing together such data, this database provides a valuable resource for assessing the long-term outcomes of wetland restoration in Europe.

While this database represents a step forward in understanding the effects of wetland restoration, users should be aware of some limitations. First, some studies included in our database did not report detailed information on data collection methodologies and sampling errors, which are important to determine data variability and perform advanced statistical analyses. Second, differences in study assumptions can undermine data comparability in future analyses. The definition of spatial pristine controls, for example, differs across studies, due to the limited number of truly pristine sites in Europe (Čížková et al. 2013). Pristine sites are often defined as the best available reference rather than truly undisturbed wetlands; therefore, they may

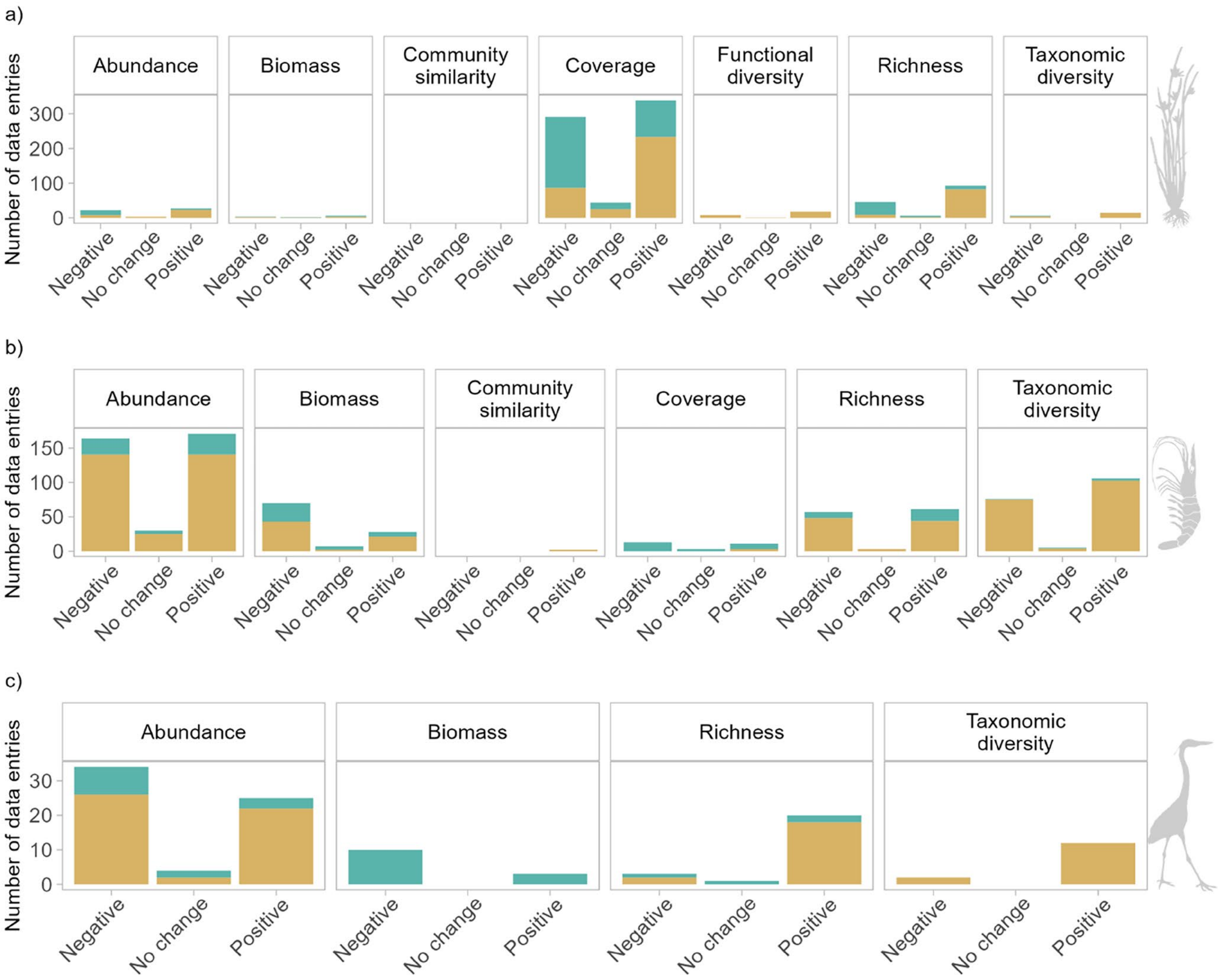

FIGURE 7 | Overview of data entries on biodiversity indicators. Number of data entries reflecting negative, no change and positive percentages of change calculated between restored and control wetlands across different biodiversity indicators for plants (a), invertebrates (b) and vertebrates (c). Changes were calculated as the percentage of change relative to the control. The yellow part of each bar indicates data entries with degraded control, and the blue part indicates data entries with pristine control.

include constructed wetlands, older restored ones, or natural areas that are only slightly disturbed (Dyrcz 2010). Data comparability and cross-study analyses are also complicated when authors use different methods to assess the same indicator. SOC, for example, is measured at different soil depths across studies. More uniform definitions and libraries of protocols would facilitate inter-comparison but may not always fit well within the local context. Third, data precision can vary depending on the measured indicator. Some indicators, such as carbon stocks, are rather stable in space, although they can vary due to differences in vegetation. In contrast, some biodiversity indicators, such as vertebrate and invertebrate abundances, are more susceptible to microhabitat differences, leading to greater fluctuation among measurements in our database.

By compiling a broad collection of empirical data and variables, this database enables the study of restoration outcomes across different wetlands, settings and indicators. It can help deepen our understanding of the key factors shaping restoration success, including the influence of different restoration strategies and pre-restoration land use or disturbances. The inclusion of restoration age data can help study recovery trajectories of different sites, and the comparison between restored and pristine wetlands offers a means to assess the completeness of restoration and identify the conditions that facilitate restored areas to more closely resemble a pristine state. Finally, this database may help restoration practitioners and policymakers to identify effective restoration strategies to achieve successful restoration depending on degradation and ecosystem type. By offering insights into the potential of wetland restoration to sequester atmospheric carbon and rehabilitate the biodiversity of (near)natural wetland types, this database can support policy objectives related to climate change mitigation and species conservation.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The dataset is available at https://doi.org/10.17026/LS/H5MFEH as a .xlsx file and as a .shp file, with a metadata file.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** geb70199-sup-0001-supinfo.docx.