Carbon stock recovery and greenhouse gas shifts following wetland restoration: a global meta-analysis

Antonio Camacho[1,*,†,+], Daniel Morant[1,+], Benjamin Misteli[2,+], Maria Adamo[3], Giancarlo Bachi[4], Martynas Bučas[5], Miguel Cabrera-Brufau[6], Rafael Carballeira[1,7], Lamara Cavalcante[8], Giovanni Checcucci[4], João Pedro Coelho[8], Charlotte Doebke[2,9], Valentin Dinu[10], Anis Guelmami[11], Relu Giuca[10], Ana I. Lillebø[8], Camille Minaudo[6,12], Jorge Juan Montes-Pérez[6,13], Biel Obrador[6], Bruna R.F. Oliveira[8], Jolita Petkuvienė[5], Antonio Picazo[1], Marinka E.B. van Puijenbroek[14], Michael Ronse[11], Carlos Rochera[1], Ana I. Sousa[8], Daniel von Schiller[6,13], Claudia Tropea[4,15], Diana Vaičiūtė[5], Katrin Attermeyer[2,9,*,†],

[+] These authors contributed equally: Antonio Camacho, Daniel Morant, Benjamin Misteli

[†] These authors jointly supervised this work: Antonio Camacho, Katrin Attermeyer

* **Corresponding Authors:**

Antonio Camacho (antonio.camacho@uv.es); Katrin Attermeyer (katrin.attermeyer@wcl.ac.at)

Affiliations:

1. Cavanilles Institute of Biodiversity and Evolutionary Biology, University of Valencia, C/ Catedrático José Beltrán Martinez 2, E-46980 Paterna, Spain
2. WasserCluster Lunz - Biological Station, Dr. Carl Kupelwieser-Prom. 5, 3293 Lunz am See, Austria
3. National Research Council of Italy (CNR), Institute of Atmospheric Pollution Research (IIA), c/o Interateneo Physics Department, Via Amendola 173, 70126 Bari, Italy
4. Istituto di Biofisica, CNR Pisa, Via Giuseppe Moruzzi 1, 56124 Pisa, Italy
5. Marine Research Institute, Klaipėda University, Universiteto Ave. 17, 92294 Klaipėda, Lithuania
6. Departament de Biologia Evolutiva, Ecologia i Ciències Ambientals, Universitat de Barcelona (UB), Diagonal 643, 08028 Barcelona, Spain
7. Departamento de Ciencias Farmacéuticas y de la Salud, Facultad de Farmacia, Universidad San Pablo-CEU, CEU Universities. Urbanización Montepríncipe, 28660 Boadilla del Monte, Spain
8. CESAM, Centre for Environmental and Marine Studies, Department of Biology and Department of Environment and Planning, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal
9. Department of Functional and Evolutionary Ecology, Unit Limnology, University of Vienna, Djerassiplatz 1, 1030 Vienna, Austria
10. University of Bucharest, Spl. Independentei 91-95, 050095 Bucharest, Romania
11. Tour du Valat, Research Institute for the Conservation of Mediterranean Wetlands, 13200 Arles, France
12. Institut de Recerca de la Biodiversitat (IRBio), Universitat de Barcelona (UB), Diagonal 643, 08028 Barcelona, Spain
13. Institut de Recerca de l'Aigua (IdRA), Universitat de Barcelona (UB), Montalegre 6, 08001 Barcelona, Spain
14. Wageningen Marine Research, Wageningen University, Ankerpark 27, 1781 AG Den Helder, Netherlands
15. University of Pisa, Lungarno Antonio Pacinotti 43, 56126 Pisa, Italy

Abstract

Wetland restoration is widely promoted as a complementary nature-based climate solution, but its net carbon and GHG effects across wetland types and interventions remain poorly quantified at the global scale. We address this gap with a global meta-analysis spanning all major wetland types and restoration strategies. We conducted a global meta-analysis of 617 restored-altered pairs from 149 studies on five continents to assess how restoration influences major carbon stocks and greenhouse gas (GHG) fluxes relative to altered wetlands. Overall, across all wetland types studied, restoration significantly increased aboveground biomass, belowground biomass and soil carbon. Restored wetlands also exhibited significantly lower CO_2 fluxes, consistent with increased primary production and reduced aerobic decomposition following hydrological and vegetation recovery, but also higher CH_4 emissions particularly in peatlands where rewetting enhances anaerobic conditions. By contrast, neither N_2O flux (though close to) nor, particularly dissolved organic carbon concentration showed statistically significant overall changes. These global patterns were robust to sensitivity and leave-one-out analyses but varied strongly among wetland types and restoration approaches. Restored mangroves and peatlands more clearly exhibited significant biomass and soil carbon gains, whereas restored freshwater wetlands and peatlands significantly displayed strong belowground biomass and and decreases in both CO_2 fluxes, though the later showed significant CH_4 flux increases. Other wetland types displayed more variable responses to restoration, if any. Hydrological restoration (mainly rewetting) produced the strongest improvements in aboveground biomass, soil carbon and N_2O flux reductions, though it significantly increased CH_4 flux. Vegetation recovery was significantly effective action increasing above- and belowground biomass, soil carbon, and decreasing CO_2 fluxes. Data were dominated by studies from Asia, Europe and North America, by far made in the Northern hemisphere, highlighting major geographical gaps in Southern areas. Overall, our synthesis shows that wetland restoration reliably regenerates carbon stocks and reduces CO_2 emissions, supporting its inclusion in climate mitigation portfolios and nature-based solution frameworks. Short-term CH_4 emission increases and ecosystem-specific responses highlight the need for long-term monitoring, context-dependent restoration design and improved global coverage to optimise carbon benefits and inform on climate's friendly restoration policies and actions.

Keywords: Wetland restoration; Carbon sequestration; Greenhouse gas fluxes; Soil carbon; Methane emissions; Nature-based solutions; Climate change mitigation; Global meta-analysis

Introduction

Wetlands, defined by their waterlogged soils, hydrophytic vegetation, and distinct biogeochemical conditions, are among the most carbon-dense ecosystems on Earth (Mitra et al., 2005; Adhikari et al., 2009; Canadell & Monteiro 2021). These ecosystems play a key role in the global carbon cycle through their capacity to accumulate organic matter, regulate greenhouse gas (GHG) fluxes and stabilise hydrological regimes (Mitsch et al., 2013, IPCC, 2023). Despite covering a relatively small proportion of the planet's surface, wetlands store disproportionately large amounts of carbon in vegetation and soils, particularly in long-term reservoirs such as peat (Blodau, 2002). These systems also influence the atmospheric balance of CO_2, CH_4 and N_2O, making them critical components of climate-change mitigation and global biogeochemical dynamics (Mitsch et al., 2013; Rosentreter et al., 2021). However, decades of drainage, land-use change, pollution and hydrological modification have resulted in the widespread degradation of wetlands worldwide, impairing their capacity to store carbon and exacerbating GHG emissions (Beaulieu et al., 2019; Tan et al., 2020; Bonaglia et al., 2025). This has generated increasing interest in wetland restoration as a Nature-based Solution (NbS) to support both biodiversity recovery and climate mitigation goals (Chausson et al., 2020; Bertolini & da Mosto, 2021).

Different wetland types contribute in distinct ways to the global carbon cycle, shaped by their vegetation characteristics, hydrological regimes and soil properties, as well as by its conservation status (Morant et al, 2020a, 2020b; Camacho-Santamans et al., 2024). Peatlands represent the largest terrestrial organic carbon reservoir, accumulating carbon over millennia given the slow anaerobic decomposition of mosses and other peat-forming vegetation (Vasander et al., 2003). Mangroves sequester large quantities of carbon as both above- and belowground biomass and trap organic-rich sediments in their dense root systems (Alongi et al., 2012). These ecosystems are recognised as "blue carbon" hotspots with some of the highest carbon accumulation rates globally (Alongi, 2020). Saltmarshes and seagrass meadows also contribute to blue carbon stocks, capturing fine sediments and storing carbon in deep, mineral-rich soils with relatively low CH_4 emissions due to salinity constraints on methanogenesis (Morant et al., 2020a). Freshwater marshes and floodplain wetlands, by contrast, support high plant productivity and rapid carbon turnover in soils, but their saturated conditions can promote CH_4 emissions, making their role in the carbon cycle highly dynamic (Rosentreter et al., 2021). Shallow lakes and lacustrine wetlands contribute to carbon cycling mainly via organic sediment accumulation and linkages between aquatic and terrestrial habitats (Kenney et al., 2010), though their responses to disturbance and restoration remain understudied. These functional differences underline the need to evaluate carbon responses to restoration across a wide diversity of wetland types, because the balance between carbon sequestration and GHG emissions is likely to vary among them.

Given the key role of wetlands in natural carbon storage and GHG regulation, their degradation has major implications for climate change (Tan et al., 2020). Over the past century, wetlands have experienced widespread degradation driven by land conversion, drainage, hydrological alterations and other anthropogenic pressures (van Asselen et al., 2013; McCauley et al., 2015; Newton et al., 2020, Fluet-Chouinard, et al., 2023). For instance, when drained or disturbed, peatlands shift from long-term carbon sinks to major CO_2 sources due to the oxidation of peat (Waddington & McNeil, 2002), whereas degradation of inland saline lakes and climate shifts may strongly enhance CH_4 emissions (Camacho et al., 2017; Morant et al, 2020b; 2024). In response, wetland restoration has emerged as a key strategy to recover ecosystem functions, enhance biodiversity, and reinforce climate-related benefits (Zedler, 2000; Erwin, 2009; Griscom et al., 2017). Restored wetlands are expected to exhibit improved vegetation structure, enhanced primary productivity, and greater carbon accumulation in soils and biomass (Ferreira et al., 2015; Azman et al., 2021; Mander et al., 2024). However, restoration may also influence anaerobic microbial processes that affect GHG emissions (Günther et al., 2020; Taillardat et al., 2020; Rosentreter et al., 2021; Schuster et al., 2024). In particular, the re-establishment of saturated conditions and organic matter inputs can lead to short-term increases in CH_4 emissions (Kustina et al., 2025), while the responses of CO_2, N_2O and dissolved organic carbon (DOC) may remain highly variable across systems (Wickland et al., 2007; Armstrong et al., 2012; Morse et al., 2013; Kluber et al., 2014). This complexity reflects the strong role of hydrological regimes (Rochera et al., 2025), vegetation traits (Ge et al., 2024), nutrient availability (Moran et al., 2024) and management practices in shaping biogeochemical dynamics.

Although numerous case studies have examined carbon pools and fluxes in restored wetlands (Hemes et al., 2018; Xu et al., 2019a; He et al., 2024; Schuster et al., 2024; Kustina et al., 2025), evidence remains fragmented, localized and often methodologically inconsistent. Such heterogeneity limits the ability to draw generalizable conclusions about whether restoration consistently enhances carbon storage, how it alters different GHG fluxes which wetland types respond most strongly, and which type of restoration actions are more effective for C-storage and GHG concentrations abatement. Furthermore, the growing policy emphasis on ecological restoration further underscores the need for robust, quantitative evidence. The European Union Nature Restoration Regulation (European Union, 2024), adopted as part of the EU Green Deal, mandates the restoration of degraded ecosystems, including a specific focus on wetlands, to enhance biodiversity, strengthen resilience and contribute to climate change mitigation. Similarly, global climate frameworks such as the Paris Agreement, the UN Decade on Ecosystem Restoration and the expansion of NbS within national climate commitments, identify wetland restoration as a cornerstone strategy for achieving net-zero emissions and enhancing natural carbon sinks (Seddon et al., 2020; 2021), though the need to a full decarbonisation of economy cannot be forgotten. Despite the policy momentum, the research focus was mostly on single wetland types or individual carbon components, which prevents direct comparison of restoration outcomes across ecosystems, carbon pools and gases. In particular, it remains unclear (i) how strongly restoration modifies carbon stocks and GHG fluxes relative to degraded conditions, (ii) whether these effects differ consistently among major wetland types and (iii) how they depend on restoration strategies. Understanding these large-scale patterns is especially important given the functional and biogeochemical contrasts among wetland types, which may lead to divergent responses in biomass accumulation, soil carbon recovery and GHG fluxes.

To address these gaps, we conducted a global meta-analysis of key carbon indicators, including above- and belowground biomass, soil carbon, DOC and the major GHG fluxes (CO_2, CH_4 and N_2O), comparing restored and altered wetlands (drained, converted or otherwise degraded wetlands) across a wide range of wetland types and restoration strategies. With the integration of heterogeneous empirical evidence by assessing the direction and significance of restoration effects, this work aims to (i) quantify the overall effect of restoration on key carbon pools and GHG-fluxes, (ii) evaluate how they vary with restoration strategies, and (iii) assess how these effects differ among major wetland types. Based on existing knowledge, we hypothesise that restored wetlands will show increased carbon accumulation in biomass and soils, reduced CO_2 emissions due to enhanced primary productivity, and potentially elevated CH_4 emissions linked to the recovery of anaerobic conditions. This synthesis provides a comprehensive assessment of carbon outcomes following wetland restoration and offers a foundation for improving the role of wetland management in climate mitigation initiatives.

Methods

Literature search

The evidence base for this meta-analysis was assembled following the PRISMA 2020 guidelines (see Page et al., 2021). We searched for peer reviewed studies that report original field data on the effects of wetland restoration on carbon storage and GHG pathways. Target variables were soil (including sediment) organic carbon, aboveground and belowground biomass, DOC, and GHG fluxes of CO_2, CH_4 and N_2O.

Searches were run in the Web of Science Core Collection and Scopus in January 2024 and updated on October 7th, 2024, to include newly published work. In both databases we used a structured search string that combined three groups of terms:

1. Carbon and GHG related terms: carbon stock*, carbon sequestration, carbon storage, carbon flux*, GHG, organic matter*, greenhouse*, CO_2, CH_4, N_2O, DOC, TOC, DOM, recalcitrant carbon, soluble organic matter, soluble organic carbon, methane, nitrous oxide, carbon dioxide, aboveground biomass, belowground biomass;

2. Ecosystem terms capturing wetlands: wetland*, lagoon*, estuar*, delta*, mangrove*, peatland*, seagrass, "sea grass", fen*, bog*, swamp*, marsh, floodplain*;

3. Terms related to restoration and management: restoration*, rehabilitation*, revitali*ation, renaturali*ation, management*.

The searches were restricted to publications in English language and including only research articles and data papers using the database filters on language and document type. The exact database specific syntax is provided in the ***Supplementary Methods***. Records from the two databases were merged and duplicates removed in R (R 4.3.2; R Core Team, 2023) using the package *dplyr* (Wickham et al., 2020). After duplicate removal, 13,913 unique records remained.

Eligibility and data extraction

The collected studies were screened for eligibility against predefined inclusion and exclusion criteria (***Supplementary Table S1***). Studies were eligible when they all into the following criteria:

- the study system is a wetland, including both coastal (mangroves, saltmarshes, seagrass meadows, brackish wetlands) and inland systems (peatlands, freshwater marshes, floodplain and riverine wetlands);
- the work was based on field measurements rather than laboratory or mesocosms experiments;
- the design included an explicit comparison between altered (degraded or impacted) and restored conditions, using Before After (BA), Control Impact (CI), Before After Control Impact (BACI) or analogous paired designs;
- the study reported enough information to calculate effect sizes for at least one target variable (means, some measure of dispersion and sample size for both altered and restored sites).

Studies that only compared restored sites with undisturbed reference wetlands, as well as purely modelling studies, reviews and meta-analyses, non-wetland ecosystems and cases where neither variance nor sample size could be obtained or derived, were removed.

All records were screened in two stages against the inclusion and exclusion criteria. In the first stage, titles and abstracts were checked. Records were split among co-authors for reviewing, and each record was independently assessed by two reviewers. If both agreed that a study did not fulfil the inclusion criteria, it was excluded at this step; any disagreement or uncertainty led to retention for full text assessment. In the second stage, full texts were read by a different reviewer than in the first stage, again using the same inclusion and exclusion rules. For studies that still qualified, the same co-author extracted the relevant quantitative data as well as descriptive information about the study, the site history and the restoration context. Every extracted dataset was verified by a second contributor, who checked for consistency with the original publication and requested corrections wherever needed. When key statistics were missing, the corresponding authors of the original paper were contacted for clarification if the study had been published within the last 5 years. Older papers for which essential information could not be reconstructed, and papers lacking statistics for which we did not receive feedback from the corresponding author within three months were excluded. Number of studies per stage are included in ***Supplementary Figure 1***.

For all 149 eligible publications the data were organised in a structured spreadsheet at the level of pairwise comparisons. A "comparison" was defined as one altered versus one restored site (or experimental unit) for a single parameter. For each comparison we recorded:

- study level metadata (region, wetland type, restoration and alteration type, time since restoration);
- the response variable, its units, mean, dispersion and number of replicates for both altered and restored sites;
- relevant methodological notes (sampling approach, analytical methods, instruments, flux calculation method).

When a study reported several measurements that were not clearly independent (e.g., sediment cores from the same restored marsh or multiple sampling dates), we followed the original authors' aggregation or, when necessary, calculated a single mean and dispersion per site and parameter following standard formulas. The final dataset thus contained one value per parameter, per altered site and per restored site. The database was extended with 55 additional comparisons generated as part of the RESTORE4Cs project (Cabrera-Brufau et al., 2025). Based on the coordinates of the wetlands reported, each comparison was assigned to a Köppen Geiger climate class using the global maps of Beck et al. (2018). To simplify interpretation, the temperate classes Cfa, Cwa and Csa were merged into a broader "subtropical" category, while retaining the other climate zones as defined in the original classification.

Descriptive summaries and mapping

We mapped all study locations using the reported latitude and longitude of each site and coloured points by wetland type to highlight where different ecosystem types have been studied. In addition, we summarized geographic coverage with bar plots showing the number of comparisons per region (continent level) and per biogeographical realm. World coastlines and political boundaries were obtained from Natural Earth via the *rnaturalearth* package (South, 2017) and handled as simple features with *sf* (Pebesma, 2018). All maps and other figures (bar plots for wetland type, climate zone, region and biogeographic realm, as well as forest plots and moderator plots) were produced with *ggplot2* (Wickham, 2016).

Effect size calculations

All analyses and calculations for this study were conducted in R (R 4.3.2; R Core Team, 2023). For each altered versus restored comparison, we calculated the standardized mean difference (SMD, Hedges' g; Hedges, 1981) using the *metafor* package (Viechtbauer, 2010). SMD captures the significance and direction of the difference in mean response between restored and altered sites. Positive SMD values indicate that the restored site has a higher mean value than the corresponding altered site, whereas negative values indicate lower values after restoration.

A few studies reported exact zeros in means or standard deviations, which would cause problems when computing standardized effect sizes or coefficients of variation. To keep these comparisons in the dataset, we applied two simple rules. First, when a mean or standard deviation was reported as exactly zero, we added a small positive constant (10^{-6}). Second, when the reported standard deviation was extremely small relative to the mean, we imposed a lower bound equal to 5% of the absolute mean. These steps prevent infinite or unrealistically large coefficients of variation and excessively large weights, while leaving the substantive results unchanged (Sweeting et al., 2004; Ren et al., 2021; Nakagawa et al., 2022).

Meta-analytic models

The meta-analytic models were fitted with "rma.mv" from the *metafor* package, using restricted maximum likelihood (REML). The random effects structure accounted for non-independence of comparisons within publications and within experiments through a nested random-intercept term of the form: "~ 1 | study / substudy"; where "study" refers to the publication and "substudy" indexes distinct experimental units within a study (e.g., different restoration sites, distinct restoration actions or experimental blocks that share a common design). This structure prevents studies that contribute many related comparisons from being overweighed while allowing for between-study and within-study heterogeneity.

Intercept-only multilevel models (without moderators) provided pooled estimates of the mean effect of restoration on each parameter. For each parameter, we fitted a separate model and reported the pooled SMD with its 95% confidence interval. For each model, we calculated standard heterogeneity statistics: the test of residual heterogeneity (Q), its degrees of freedom and p-value, the proportion of total variability attributable to between-comparison heterogeneity (I^2, computed from Q) and the total between-comparison variance (sum of the estimated variance components, tau^2).

To examine which factors modulate restoration outcomes, we fitted multilevel meta-regressions separately for each response parameter using the same random-effects structure as the intercept-only models (random intercepts for study and substudy). For each parameter, we included a common set of ecological and management moderators (***Supplementary Table S2)***: alteration type (hydrology, morphology, hydromorphology, land-use change, vegetation or habitat loss, water-quality or pollution, natural disturbance), wetland type (peatland, freshwater wetland, seagrass, saltmarsh, mangrove, brackish wetland), and restoration type (hydrological, morphological, hydromorphological, soil-focused, vegetation-focused, passive restoration), together with mean annual temperature, temperature seasonal variation, annual precipitation, precipitation seasonal variation, and the time since restoration. Continuous moderators were z-standardised before fitting and one level of each factor was treated as the reference level.

Because not all studies reported the full set of covariates, these models were fitted on the subset of comparisons with complete metadata (k = 99 for soil carbon, 27 for aboveground biomass, 25 for belowground biomass, 59 for CO_2, 44 for CH_4, 21 for N_2O and 17 for DOC). For each parameter, we report the omnibus test for moderators (QM, df, p) from *metafor* and interpret individual coefficients based on their Wald z-statistics and 95% confidence intervals.

For an in-depth analysis and visualization, we fitted separate random effects models within each wetland type and restoration type whenever more than one comparison was available and plotted the resulting pooled SMDs and confidence intervals alongside the individual comparisons. When only a single comparison existed for a given parameter/category combination, we showed the raw effect size without a pooled estimate.

Small study effects, publication bias and robustness

We evaluated potential small study effects and publication bias using standard diagnostics implemented in *metafor*. Funnel plots were constructed for each parameter from the multilevel intercept-only models to visualize the relationship between effect size and its precision. Because Egger-type regression tests are defined for single-level random effects models, we additionally refitted each parameter using “rma” with a single random effect and used these uni-level models for formal small-study diagnostics.

For parameters with at least 10 comparisons, we applied Egger’s regression test (“regtest”, with the standard error as predictor) to examine funnel plot asymmetry. In parallel, we computed Kendall’s rank correlation (“cor.test” with method = 'kendall' in the *stats* package) between the effect sizes and their standard errors as a non-parametric check for the same pattern. For parameters where the pooled effect from the intercept-only model was statistically significant, we also calculated Rosenthal's fail-safe N (fsn) to gauge how many hypothetical unpublished studies showing a null effect would be required to attenuate the overall effect to non-significance.

To assess robustness to individual studies, we carried out leave-one-out analyses based on uni-level random effects models. For each parameter, we successively omitted each comparison, refitted the model and recorded the resulting pooled SMD and its confidence interval. We then counted how often omitting a single comparison changed the sign or statistical significance of the pooled effect. Finally, we computed influence diagnostics with *metafor*'s "influence" function and flagged comparisons as influential when they triggered any of the built-in influence criteria. At the parameter level, we summarized the number and percentage of comparisons classified as influential. These diagnostics are reported in the some of the ***Supplementary materials*** and used to qualify the interpretation of any apparently strong or highly significant effects.

Results

Distribution of wetlands included in the meta-analysis

A. Restoration projects by wetland type
50°N
0°
50°S
120°W
60°W
0°
60°E
120°E
Wetland type
Floodplain and riverine
Peatland
Freshwater wetland
Seagrass
Saltmarsh
Mangrove
Brackish wetland
B. Region
Number of comparisons
200
150
100
50
0
Asia
Europe
North America
Oceania
South America
Africa
C. Realm
300
200
100
0
Palearctic
Nearctic
Indo-Malay
Australasian
Neotropical
Afrotropical

327

328

Figure 1. Global distribution of wetlands included in the meta-analysis (A). Points are color-coded by wetland type. The barplots illustrate geographic coverage across continents (B) and major biogeographic realms (C). Data represent 617 paired comparisons extracted from 149 studies.

A total of 617 paired comparisons were extracted from 149 studies spanning six continents and all major biogeographic realms (***Figure 1***; ***Supplementary Figure S1***). Most data originated by far from the Northern Hemisphere (all but a dozen), with Asia (n = 211) and Europe (n = 202), followed by North America (n = 165). Wetland types were dominated by peatlands (n = 182), mangroves (n = 134) and freshwater wetlands (n = 118), with fewer cases for saltmarshes (n = 68), floodplain/riverine wetlands (n = 57), seagrass beds (n = 42), and brackish systems (n = 28). Climate zones were primarily subtropical (n = 209) and temperate (n = 163), with tropical (n = 93), cold (n = 121), and arid (n = 29) regions less represented (***Supplementary Figure 2***).

Global effects on carbon indicators

Across all wetland types and restoration strategies, SMD indicated significant positive effects of restoration on biomass and soil carbon accumulations, all of them displaying statistically significant increases, while contrasting responses were found among GHG fluxes (***Figure 2***; ***Supplementary Table S3***). Aboveground biomass showed the largest effect size (SMD = 2.52; 95% CI: 1.17–3.87; k = 73), followed by belowground biomass (SMD = 1.94; 95% CI: 0.95–2.92; k = 53). Soil carbon increased significantly (SMD = 0.62; 95% CI: 0.23–0.99; k = 207). CO_2 flux decrease was statistically significant (SMD = –0.43; 95% CI: –0.84 to –0.01; k = 111), indicating reduced emissions after restoration. Thus, the responses of all the above parameters demonstrate a link of wetland restoration to their contribution to climate change mitigations by increasing the C-sink and GHG-abatement. In contrast, CH_4 flux increased (SMD = 0.44; 95% CI: 0.14–0.74; k = 95), displaying an opposite pattern. N_2O, flux showed instead a trend though non statistically significant towards reduction (SMD = –0.23; 95% CI: –0.49 to 0.03; k = 50). Dissolved organic carbon (DOC) concentration exhibited no significant change neither any visible trend (SMD = 0.03; 95% CI: –0.31 to 0.36; k = 28). Taken together, these patterns indicate that restoration strongly rebuilds biomass and soil carbon, reduces CO_2 and (potentially) N_2O fluxes, but leaves DOC largely unchanged, while introducing a moderate increase in CH_4 emissions.

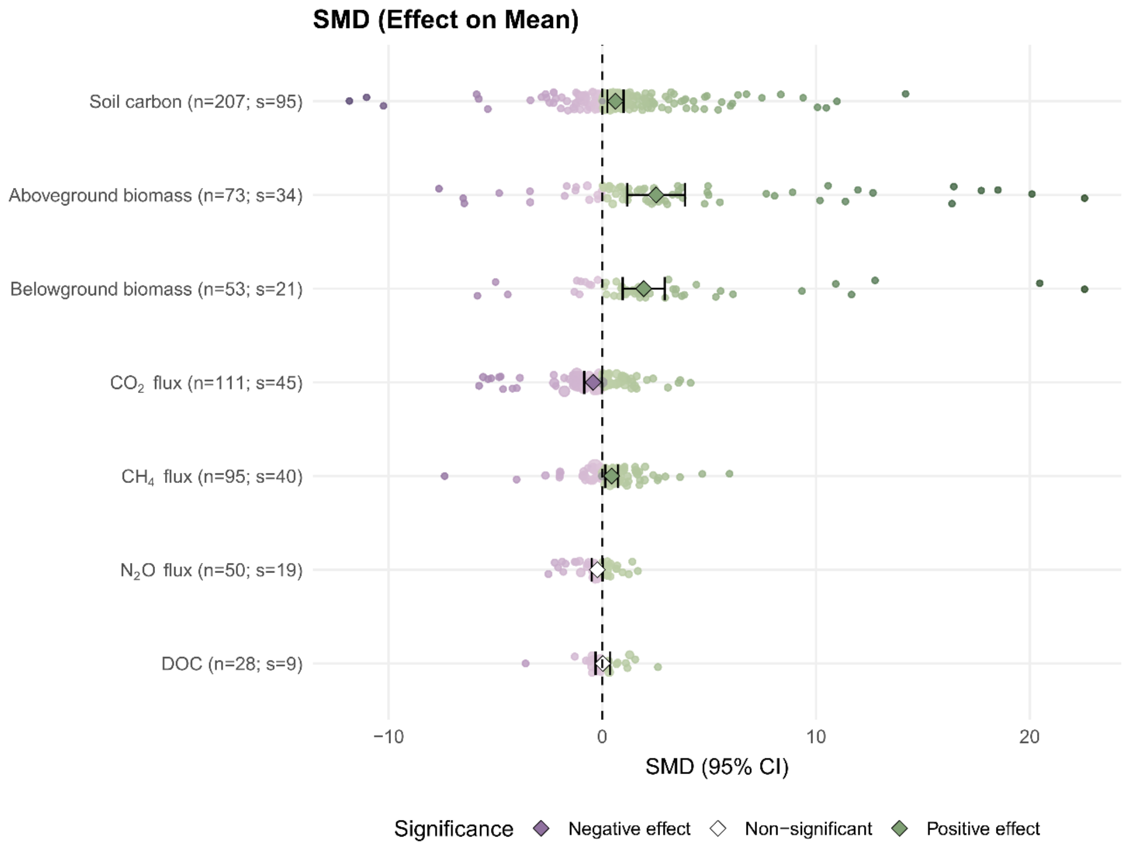

Figure 2. Global standardized mean differences (SMD) for carbon indicators comparing restored to altered wetlands. Indicators include soil carbon, aboveground biomass, belowground biomass, CO_2 flux, CH_4 flux, N_2O flux, and dissolved organic carbon (DOC). The number of used comparisons are indicated as "n" and the number of studies as "s". Error bars denote 95% confidence intervals. Positive values indicate higher values in restored wetlands; negative values indicate reductions after restoration.

Heterogeneity and sensitivity

Heterogeneity was high for all indicators ($I^2 > 79\%$; ***Supplementary Table S4***), with the greatest variability observed for CO_2 flux ($I^2 = 97.3\%$) and aboveground biomass ($I^2 = 93.3\%$). Publication bias was detected for soil carbon and both biomass indicators (Egger's test $p < 0.001$), while heterogeneity tests for GHG fluxes were generally non-significant, except for a weak asymmetry signal in CO_2 based on Kendall's tau (***Supplementary Figure S3; Supplementary Table S5***).

Leave-one-out analyses confirmed robustness of pooled estimates, with no significance flips across 617 iterations (***Supplementary Table S6***). Sensitivity analyses indicated no influential cases (prop_influential = 0% for all indicators; ***Supplementary Table S7***), this is, there were no cases with strongest weighting in the results of the meta-analyses than others. The range of pooled estimates under leave-one-out scenarios was narrow (ΔSMD ≤ 0.22 for aboveground biomass; ≤ 0.16 for belowground biomass; ≤ 0.08 for DOC; ≤ 0.05 for soil carbon; and ≤ 0.05 for the three GHG fluxes included), confirming stability of global trends. In other words, although individual studies span a wide range of contexts and effect sizes, the direction and significance of the overall restoration effects are remarkably stable.

Moderators analysis

The full moderator set did not improve fit for above- and belowground biomass or CH_4 flux. For these parameters, the omnibus test for moderators was clearly non-significant (aboveground biomass: Q_M = 4.4, df = 13, $p = 0.99$; belowground biomass: Q_M = 3.0, df = 12, $p = 1.00$; CH_4 flux: Q_M = 16.1, df = 16, $p = 0.44$; ***Supplementary Table S8***), indicating that the multivariable models did not explain a substantial share of between-comparison variability beyond the overall mean.

By contrast, for CO_2 flux, the full model explained significant heterogeneity (Q_M = 56.7, df = 17, $p < 0.001$; ***Supplementary Table S8***). Among individual predictors, warmer climates were associated with stronger CO_2 flux reductions after restoration: the coefficient for standardised temperature was negative (β = –3.67, 95% CI: –6.46 to –0.88, $p = 0.01$), meaning that, per one standard deviation increase in temperature, the restored–altered contrast in CO_2 flux became more strongly negative. For soil carbon, the omnibus moderator test was only marginal (Q_M = 31.6, df = 21, $p = 0.07$; ***Supplementary Table S8***), but two climate variables showed consistent positive effects: both mean annual temperature (β = 1.63, 95% CI: 0.54–2.73, $p = 0.003$) and temperature seasonality (β = 1.43, 95% CI: 0.44–2.43, $p = 0.005$) were associated with larger soil carbon gains in restored relative to altered wetlands. In other words, within this dataset, restored sites in warmer and more temperature-seasonal climates tended to show stronger soil carbon recovery.

For N_2O flux and DOC, the moderator blocks were also statistically significant (N_2O: Q_M = 51.3, df = 9, $p < 0.001$; DOC: Q_M = 30.0, df = 8, $p < 0.001$; ***Supplementary Table S8***), but individual coefficients were generally estimated with wide confidence intervals. The only N_2O term reaching conventional significance was the time since restoration variable (β = 0.60, 95% CI: 0.00–1.20, $p = 0.05$), suggesting that N_2O responses to restoration change along the restoration-time gradient.; however, the direction and magnitude of that pattern remain uncertain given the small sample size ($k = 21$). For DOC, the intercept of the multivariable model was positive (β = 3.09, 95% CI: 0.34–5.85, $p = 0.03$), but no single moderator stood out as a clear driver; the significant omnibus test therefore reflects the combined, diffuse contribution of the full set of covariates rather than a strong effect of any one factor.

Drop-one model comparisons based on AIC supported the idea that restoration time is an important cross-cutting predictor. Removing the time since restoration variable produced by far the largest increase in AIC for all parameters (ΔAIC = 29–437 across indicators), whereas dropping other moderators led to much smaller changes. This pattern indicates that, even when individual coefficients are imprecise, the restoration-time gradient captures a substantial part of the residual heterogeneity in the multivariable models. Overall, climate variables and time since restoration were the most consistent predictors of CO_2 and soil carbon responses, whereas variation in biomass and CH_4 was less systematically explained at the global scale.

Effect sizes varied substantially across restoration strategies (***Figure 3***) and wetland types (***Figure 4)***. For the restoration type (***Figure 3***), vegetation-based and hydrological restoration were the most influential as significantly changing four parameters each. Vegetation-based restoration significantly increased both aboveground and belowground biomass, as well as soil carbon, whereas it significantly decreased CO_2 fluxes. Hydrological restoration (most generally rewetting) generated the largest positive effects on aboveground biomass and also increased significantly soil carbon. Hydrological interventions also produced the most pronounced changes in GHG dynamics, characterised by significant reductions in N_2O flux (negative SMD) and elevated CH_4 flux (positive SMD) in hydrologically restored sites relative to altered sites (***Table 1***). Instead, both passive restoration and morphological restoration significantly increased both aboveground and belowground biomass but had no significant effects on the other parameters. Actions on soils, much less represented in the meta-analysis, only showed significant increases of soil carbon, whereas the single study that covered water quality improvements displayed significant decreases in both parameters tested thereby, namely aboveground biomass and, mostly, of CO_2 fluxes. Full statistical support for moderator differences is provided in ***Supplementary Tables S8*** and ***S9***.

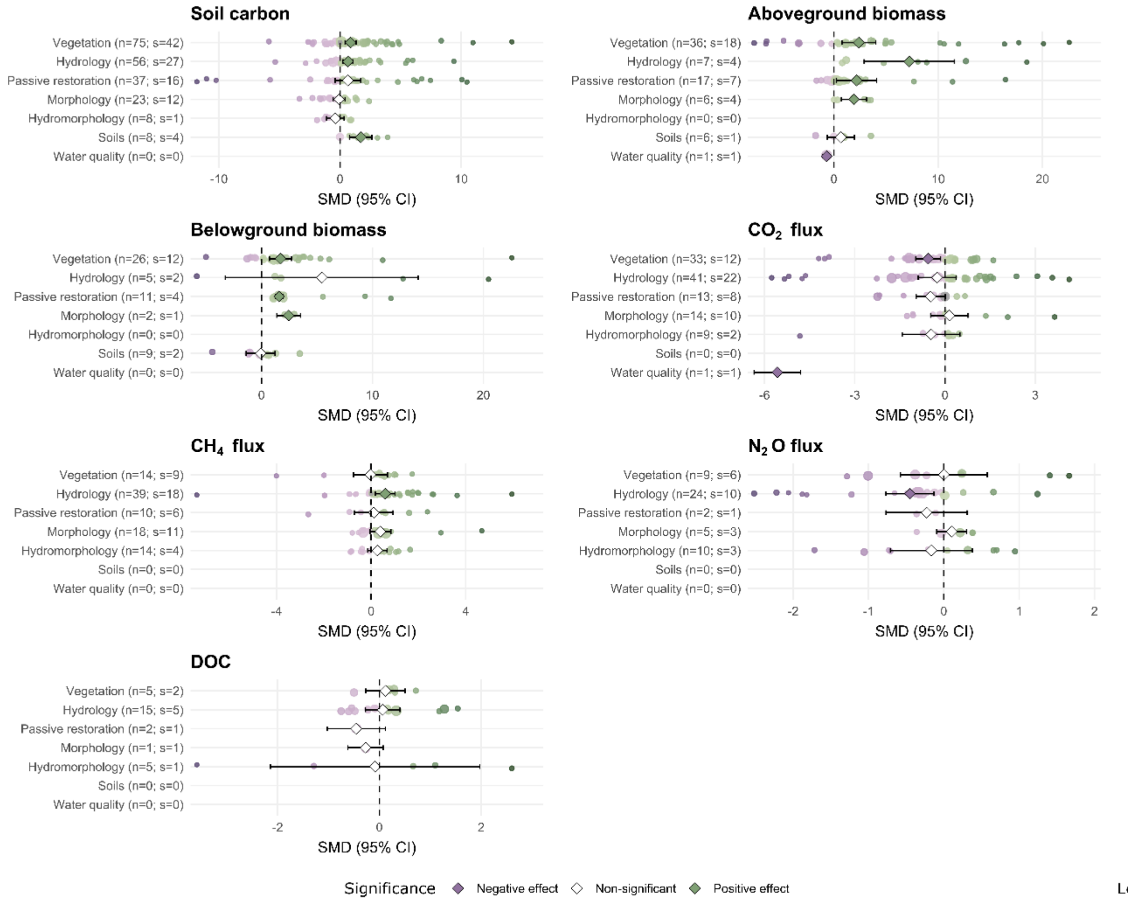

***Figure 3*. Subgroup analysis of restoration strategies. Forest plots show SMD for each indicator grouped by restoration type: hydrological interventions (rewetting), vegetation-based restoration, passive restoration, morphological modifications, and soil amendments. Error bars represent 95% confidence intervals.**

***Table 1.* Overall trends by the different types of restoration actions for the parameters studied in the meta-analysis. Green arrows mean cooling capacity created by the restoration-linked changes, either by increasing carbon storage or by GHG abatement, whereas red arrows mean warming capacity appearing associated to restoration, either by decreasing carbon storage capacity or by increasing GHG fluxes towards the atmosphere.**

TYPE OF RESTORATION	Aboveground biomass	Belowground biomass	Soil C	DOC	CO_2	CH_4	N_2O
Vegetation	↑	↑	↑		↓		
Hydrology	↑		↑			↑	↓
Passive	↑	↑					
Morphology	↑	↑					
Hydro-morphology							
Soils			↑				
Water quality	↓				↓		

A moderator analysis performed by wetland type revealed substantial variation in restoration outcomes among ecosystems (***Figure 4***). Peatland restoration achieved statistically significant increases in above and belowground biomass and soil carbon, also promoting significant CO_2 flux reductions, though CH_4 fluxes significantly increased reflecting strong anaerobic conditions after rewetting. Mangroves also exhibited substantial increases in above- and belowground biomass, as well as in soil carbon, though no significant responses were found for GHG fluxes. Freshwater wetlands showed significant improvements in aboveground biomass and significant decreases of CO_2 fluxes. For the rest of the wetland types, generally much less represented in the dataset, seagrasses only displayed significant increases of CH_4 fluxes whereas both saltmarshes and floodplain and riverine wetlands only increased significantly belowground biomass, and brackish wetlands only increased significantly soil carbon (***Table 2***).

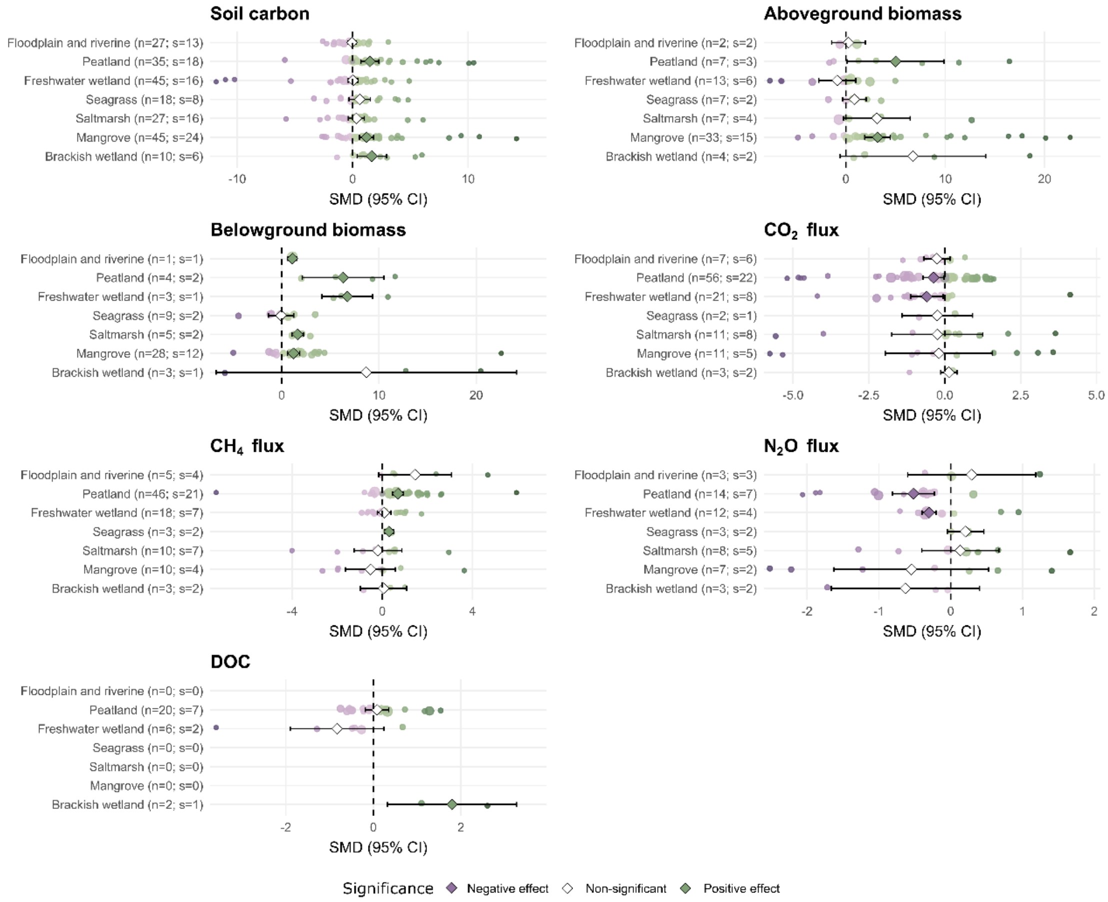

***Figure 4*. Subgroup analysis by wetland type. Forest plots display SMD for carbon indicators across peatlands, mangroves, saltmarshes, freshwater wetlands, seagrass beds, brackish wetlands, and floodplain/riverine systems. Positive values indicate increases in restored sites relative to controls; negative values indicate decreases.**

***Table 2*. Overall trends of the effects of restoration over different types of wetlands for the parameters studied in the meta-analysis. Green arrows mean cooling capacity created by the restoration-linked changes, either by increasing carbon storage or by GHG abatement, whereas red arrows mean warming capacity appearing associated to restoration by increasing GHG fluxes towards the atmosphere.**

WETLAND TYPE	Aboveground biomass	Belowground biomass	Soil C	DOC	CO_2	CH_4	N_2O
Floodplain & Riverine		↑					
Peatlands	↑	↑	↑		↓	↑	
Freshwater wetlands		↑			↓		
Seagrasses						↑	
Saltmarshes		↑					
Mangroves	↑	↑	↑				
Brackish wetlands			↑				

Discussion

Our global meta-analysis shows that wetland restoration consistently rebuilds carbon stocks, especially soil carbon and above- and belowground biomass, and alters GHG fluxes in predictable ways. Carbon pools respond strongly and robustly, indicating that restoration reactivates key processes that drive long-term carbon accumulation. CO_2 emissions decline soon after restoration, whereas CH_4 emissions typically rise in the short-term, with emerging evidence that these increases weaken as ecosystems mature (Kayranli et al., 2010; Mitsch et al., 2013; He et al., 2024;).

Restoration enhances carbon stocks through improved hydrology and morphology, vegetation recovery and passive processes

The consistent increases in above- and belowground biomass in restored wetlands, especially in mangroves, reflect the re-establishment of hydrological regimes and vegetation communities that support high primary productivity (Callaway et al., 2003; Kayranli et al., 2010; Azman et al., 2021; He et al., 2024). All actions related to the restoration of the vegetation cover resulted in statistically significant increases of the biomass and soil carbon variables, as vegetation is the main component incorporating the biomass as plant components and soil carbon as producing the organic matter, highly recalcitrant, that is accumulated in wetland soils. Active vegetation restoration can further accelerate canopy development in some systems (Callaway et al., 2003; Ferreira et al., 2015). Hydrological restoration, mostly rewetting, relieves the water physiological stress, facilitates colonisation by native wetland plant species and enhances nutrient cycling, which overall drives rapid biomass accumulation (Waddington et al., 2010; Geurts et al., 2020). Passive restoration, where natural hydrological and ecological processes are allowed to recover after removal or reduction of disturbances, together with morphological restoration, were also particularly effective for increasing biomass and soil carbon. When barriers for plant colonization are removed, natural regeneration rebuilds plant cover and diversity (De Steven et al., 2010), and re-establishes soil feedback, successional dynamics and soil carbon inputs (An et al., 2021).

Soil carbon gains are closely tied to the return of saturated conditions, which suppresses (the faster) aerobic decomposition and promotes the accumulation of particulate and dissolved carbon, with permanently flooded wetlands often storing the largest soil carbon stocks (Yin et al., 2019). In peatlands, raising water tables slows peat oxidation and enables peat-forming vegetation to expand (Vasander et al., 2003), whereas in mangroves, hydrological rehabilitation enhances sediment trapping and dense root growth (Twilley & Rivera-Monroy, 2005). These processes explain the strong and consistent recovery of biomass accumulation and soil carbon across restored sites, even though some studies suggest that restored wetlands may not fully reach the carbon levels of intact reference sites (Xu et al., 2019a).

Even if some publication bias was detected for soil carbon and both biomass indicators, there was no overall differential weighting of any of the data sources. Further, leave-one-out analyses narrow scenarios confirmed the robustness of pooled estimates. These confirm that the patterns demonstrated in the meta-analysis concerning biomass and soil carbon accumulation are consistent and represent stable global trends in the direction and significance of the overall restoration effects on these parameters.

Divergent GHG dynamics: immediate reductions in CO_2 but short-term increases in CH_4

The clear biomass and carbon stock improvements contrast with the more modest GHG flux responses achieving statistically significant significance. Though, both the fact that heterogeneity tests for GHG fluxes were generally non-significant, as well as the narrow range of the estimates under leave-one-out scenarios, support the strength of the meta-analysis results for GHG fluxes and show that the obtained patterns are robust.

CO_2 emissions drop as linked to restoration (Figure 2), which is consistent with most studies stating that CO_2 fluxes decreased almost immediately after restoration (e.g. Darusman et al., 2023; Schuster et al., 2024). This is driven by reductions in aerobic decomposition (Crase et al., 2013; Valach et al., 2021) and, principally, by increased plant CO_2 uptake (Waddington et al., 2010), where the meta-analysis clearly identified the direct vegetation restoration as the main actions achieving statistically significant CO_2. flux reductions.

In contrast, CH_4 emissions increased significantly in restored wetlands, reflecting the re-establishment of anoxic conditions that stimulate methanogenesis (Urbanová et al., 2011; Hemes et al., 2018). Rewetting increases soil saturation and organic substrate availability, creating favourable conditions for CH_4 production (Rosentreter et al., 2021; Darusman et al., 2023; Cui et al., 2024). According to our meta-analysis, this short-term CH_4 pulse is consistent across wetland types and restoration strategies. However, long-term datasets suggest that CH_4 emissions may decline as vegetation communities stabilise, root oxygenation increases and microbial processes tend to adapt to new equilibrium conditions (Mitsch et al., 2013; Delwiche et al., 2025). Restored wetlands require several decades to develop carbon sequestration capacities comparable to those of natural systems (Kayranli et al., 2010), which may result in the maintenance of a certain warming potential of the restored wetlands in the short-term (in some cases, decades), though overall restoring wetlands are is crucial for long-term cooling ability (Taillardat et al., 2020). In fact, CH_4 emissions in wetlands can peak initially but tend to stabilize after ~10 years (He et al., 2024). In peatlands, for instance, restoration via rewetting is effective despite initial CH_4 spikes (Günther et al., 2020; Kustina et al., 2025), thus considering the rewetting a viable approach for long-term carbon sequestration (Mander et al., 2024). However, it must be recognized that the support for our interpretation does not come from the meta-analysis itself, but instead uses specific results from particular studies, as our CH_4 moderator analysis was not able to find significant effect of time-since restoration with our dataset, The limited duration of most post-restoration studies prevents firm conclusions referring the role of aging, highlighting the need for long-term monitoring to better characterise CH_4 trajectories as wetlands mature after restoration. This is not trivial, since various studies (Mistch et al., 2013; Neubauer et al., 2014; Schuster et al, 2024) show controversies about the time frame after which the effects of restoration can transform an altered wetland from a source of heating to a cooling capacity

N_2O and DOC responses were not statistically significant overall, implying that these indicators are more strongly governed by local nutrient availability, soil chemistry and hydrological variability than by restoration status alone, though also size effects and other aspects can explain the results as both parameters behave very differently. For N_2O, the number of related studies provided less than half of pairwise comparison than for CO_2 and CH_4, respectively. Given that nearly significant reductions of N_2O fluxes were shown in the meta-analysis, the trend relating restoration to N_2O, reductions could be considered as a likely possibility, which could be associated to the induced changes in the biogeochemistry and complexity of nitrogen cycling pathways, which depend on the balance between nitrification and denitrification, and the availability of inorganic nitrogen substrates (White and Reddy, 2009). Many restored wetlands experience rapid changes in oxygen availability and water table height, but N_2O production is often constrained by low nitrate concentrations, reducing conditions that favour complete denitrification to N_2 rather than N_2O (Kluber et al., 2014; Kasak et al. 2021). However, the context dependency of nitrogen dynamics, driven by factors such as legacy nutrient loads, external inputs from agriculture, or tidal flushing in coastal wetlands, can party override the influence of the restoration, affecting in a different way the soil microbial communities and processes (Morse et al., 2013; Kluber et al., 2014), thus masking a possible significant improvement by reducing N_2O fluxes as a consequence of restoration (Bianchi et al., 2021).

Contrarily, no trend could be observed on the DOC responses to restoration, which likely reflects the interplay between hydrology, vegetation type, organic matter quality and bacterial community activity (Evans et al., 2005; Mladenov et al., 2005; Armstrong et al., 2012; Strack et al., 2015), not only in the wetland itself but also in its catchment. DOC dynamics may reflect transient flushing of dissolved organics, with longer-term patterns depending on plant community composition, redox oscillations and soil sorption capacity (Wickland et al., 2007). The net effect across systems is therefore highly variable, so it is not surprising the lack of consistent global trend in DOC change following restoration.

Restoration strategies affect carbon stocks and GHGs differently

The meta-analysis results highlight the differentiated roles of restoration strategies for carbon outcomes (***Figure 3*** and ***Table 1***). Vegetation-based restoration demonstrated the most effective mitigation effects, as being effective in increasing carbon capture either directly as biomass or as increasing carbon storage in wetland's soils but also reducing CO_2 fluxes. This demonstrates that the recolonization by natural vegetation, mainly helophytes, should be a main target for ecological restoration with a climatic perspective as recovering the role of wetlands s carbon sinks (Morant et la., 2020, 2024; Camacho-Santamans et al., 2024) reflecting their capacity to restore organic matter inputs, rhizosphere processes and successional vegetation dynamics that drive long-term carbon accumulation (Callaway et al., 2003; Suir et al., 2019). Both morphological and passive restoration also increased biomass accumulation, mainly by increasing vegetation, mainly by favouring ecological scenarios that allow plant primary production processes to increase (e.g. higher habitat availability for macrophytes by increasing the rooting surface o by reducing turbidity and thus the shading effect). Similarly, for similar reasons, hydrological restoration, mostly rewetting, also favours increases in aboveground biomass and soil carbon accumulation, though after rewetting of dried lands (e.g. land reclamation from agricultural uses), these restored wetlands can trigger short-term CH_4 emission spikes (Darusman et al., 2023; Kustina et al. 2025). Remarkably, N_2O fluxes are also reduced after rewetting, which was previously reported by Kasak et al (2021) for rewetted agricultural lands, Though certainly difficult to be attributed to specific reasons because of the complexity of the nitrogen cycle, given that most hydrological restorations collected in the papers are associated to rewetting of old agricultural lands, this can be related to the decrease of nitrate availability when crop fertilization stops, then nitrates remaining in soils could be quickly removed by runoff and the limited nitrate availability for denitrification in the restored wetland could be one of the causes of the N_2O fluxes reduction pattern shown by the meta-analysis after hydrological restoration. Overall, these distinct effects show that restoring vegetation is crucial for long-term carbon storage, while hydrological recovery mainly shapes GHG fluxes.

Wetland types vary in their contribution to carbon outcomes

Different wetland types contributed differently to carbon responses (***Figure 4*** and ***Table 2***). Mangroves and peatlands, the most studied wetland types (Schuster et al., 2024), dominated the dataset and showed some of the strongest positive responses in carbon stocks. Restored mangroves exhibit substantial increases in above- and belowground biomass, attributable to rapid tree growth and dense root networks (Alongi, 2012), but also contribute decisively to soil carbon storage by favouring sedimentation as acting as sediment traps. Peatlands showed pronounced soil carbon increases when restored, due to halted peat oxidation and resumed peat accumulation following rewetting (Günther et al., 2020), though they also achieve significant CO_2 fluxes reduction as reactivating peat accumulation, though partially counteracted by the above mentioned CH_4 increases linked to rewetting inducing lower redox conditions and thus favouring methanogenesis given their waterlogged soils, high organic content and the relative potential of its methanogenic microbial communities (Torres-Alvarado et al., 2005; Liu et al., 2011; Rosentreter et al., 2021), especially in wetland types where high sulphate concentrations does not impede methanogenesis activation, (Koebsch et al., 2019, Lin,et al., 2024; Morant et al, 2024, Miralles-Lorenzo et al, 2025). But even in sulphate-rich environments, such as seagrass beds, methanogenesis is possible provided that methylotrophic archaea are responsible for this activity (Schorn et al., 2022), which would explain the CH_4 increases in these ecosystems after restoration as significantly demonstrated in our meta-analysis (***Table 2***),

On the other hand, freshwater wetlands, floodplains, and saltmarshes, when restored, were found to significantly increase belowground biomass, but the former also demonstrated significant capacity to reduce CO_2 fluxes. Brackish wetlands and s seagrass beds were underrepresented, which limits generalisation for these systems.

Geographic and ecosystem biases constrain global inference

The geographical distribution of available studies is strongly biased towards the Northern hemisphere, North America, Europe and Asia, accounted for most of the studied cases, with limited representation from South America, Africa and Oceania, despite their wetlands' importance (Xu et al., 2019b). On global scale this imbalance is critical because underrepresented regions contain vast carbon-rich wetlands, such as Amazonian floodplains, Andean peatlands and the Congo Basin, that may exhibit different restoration trajectories and carbon dynamics. Without expanding research in the Global South, global restoration policies risk overlooking major carbon reservoirs and misestimating restoration benefits. Improving monitoring capacity and data collection in these regions is therefore essential for accurate global carbon assessments.

Management Implications and Policy Relevance

The global patterns identified here have direct implications for restoration planning and climate policy. Consistent increases in soil carbon and above- and belowground biomass across restored wetlands affirm restoration as an effective nature-based climate solution for carbon storage, supporting its inclusion in frameworks such as the UN Decade on Ecosystem Restoration, and the newly adopted EU Nature Restoration Regulation (European Commission, 2024) which specifically mandates the recovery of degraded wetlands to enhance biodiversity and strengthen climate mitigation. However, some authors claimed that wetland restoration would not fit the time frames of the climate agreements, such as the Paris Agreement (Schuster et al., 2024), thus highlighting the preference of wetlands conservation on a good health status over wetland restoration (Morant et al., 2020b). In fact, the "so-called" recovery-debt (Moreno-Mateos et al., 2017) linked to functional and structural losses of restored ecosystems (Moreno-Mateos et al.,

2012) may seriously compromise the climatic gains of wetland restoration. Actually, the climatic effects of restoration are very much dependent on the effects of specific restoration actions on specific types of wetlands (Meli et al., 2014; Morant et al., 2020b; Camacho-Santamans et al., 2024, Jones et al., 2024). This is mediated by the biogeochemical changes induced by each specific restoration action and their interactions, which further can be not only wetland-type specific (Reddy et al., 2022), but also context specific. For instance, short term increases in CH_4 emissions could be interpreted in the context of long-term net carbon benefits: although CH_4 would rise initially, restoration may rapidly reduce CO_2 emissions and enhance carbon storage, yielding strong climate gains over time (Taillardat et al., 2020; Mander et al., 2024; Delwiche et al., 2025). In this example, the selection of restoration strategies and their *ad hoc* design can help minimising CH_4 pulses by avoiding abrupt oversaturation and promoting vegetation assemblages that moderate anaerobic conditions. Policymakers and wetland managers and restoration practitioners should therefore avoid uniform prescriptions and instead tailor restoration approaches to site specific carbon and GHG goals and local biophysical constraints.

Climate change is expected to profoundly alter carbon dynamics in wetland ecosystems, potentially undermining their role as long term carbon sinks (Wang et al., 2018). These findings highlight the vulnerability of peat-rich systems to climatic variability and underscore the need for conservation and restoration strategies and policies that integrate climate projections. Therefore, as demonstrated by this meta-analysis proactive management should prioritise adaptive measures, such as hydrological stabilisation and vegetation recovery, while considering regional climate trajectories to safeguard the sink function of wetlands in the coming decades.

Ecosystem specific responses should also guide decision making. Mangroves offer particularly high returns in vegetation biomass, peatlands provide substantial soil carbon benefits and reductions in CO_2 emissions, whereas some wetland types require targeted strategies for managing CH_4 fluxes. Funding mechanisms and national climate plans should align investments with these strengths, prioritising restoration where carbon gains are highest and tailoring GHG fluxes, particularly CH_4 management where risks are greatest.

Finally, addressing geographic research gaps is essential for equitable and effective global climate mitigation. Expanding conservation and restoration sciences and monitoring in South America, Africa and Oceania will improve carbon accounting, strengthen restoration outcomes and ensure that the world's most carbon rich wetlands contribute fully to global climate targets, also providing economic credits allowing the Global South countries to maintain these world-benefits under an ecological transition with justice

Management and Policy Recommendations

Our findings support several evidence-based recommendations for practitioners, policymakers and restoration planners:

1. Conserve before needing to restore. The targets of restoration are recovering the natural behaviour of the restored ecosystem. By avoiding wetland alteration, the natural role of wetlands as carbon sinks and (for most wetland types) also GHG mitigation ecosystem can be maintained.

2. Prioritise hydrological restoration where climate mitigation is a key objective. Rewetting produces the clearest and most consistent gains in soil carbon and reduces CO_2 emissions across wetland types.

3. Promote vegetation recovery to maximise biomass carbon stocks, especially in peatlands, mangroves, saltmarshes and freshwater marshes. Passive recovery can be effective, but active habitat recovery and planting may accelerate carbon accumulation in high-productivity ecosystems.

4. Account for short-term CH_4 increases following rewetting, especially in peatlands and freshwater wetlands, where salinity restrictions would not control the increase in CH_4 fluxes. Monitoring frameworks and carbon crediting schemes should incorporate temporal dynamics rather than relying solely on snapshot measurements.

5. Design restoration strategies to match ecosystem-specific responses. Mangroves and saltmarshes are high-priority systems for biomass-based mitigation, whereas peatlands and floodplain wetlands offer substantial soil carbon gains but require careful CH_4 management and monitoring.

6. Implement integrated Nature-based Solutions that combine restoration with hydrological reconnection, sediment management and vegetation rehabilitation, aligning with the EU Nature Restoration Regulation, the UN Decade on Ecosystem Restoration, and worldwide and national climate strategies.

7. Expand long-term monitoring in understudied regions, particularly tropical and subtropical wetlands outside Asia, to address gaps in global carbon budgets and enhance the effectiveness of restoration investments.

Overall, wetland restoration emerges as a potentially effective approach, though just complementary to the decarbonisation of the economy, climate mitigation tool, with strong potential to regenerate carbon stocks, reduce CO_2 emissions and support biodiversity recovery. To fully realise these benefits, restoration must be implemented at scale, tailored to ecosystem-specific carbon dynamics and embedded within national and international policy frameworks.

Our synthesis provides a quantitative foundation for optimising wetland restoration as a complementary climate solution and for guiding future research toward the most critical ecological and geographic gaps.

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Author Contributions

AC, KA, BM, DM, conceived the study. BM, DM, AC, coordinated data compilation and screening. All authors extracted and curated the data. AC, BM, DM, designed the statistical framework. BM, DM, AC, performed the meta-analyses and moderator analyses. AC, BM, DM, interpreted the results. AC, DM, BM, drafted the manuscript. AC wrote the final version of the manuscript. All authors contributed to manuscript revision and approved the final version.

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Supplementary material

Supplementary Methods:

WOS:

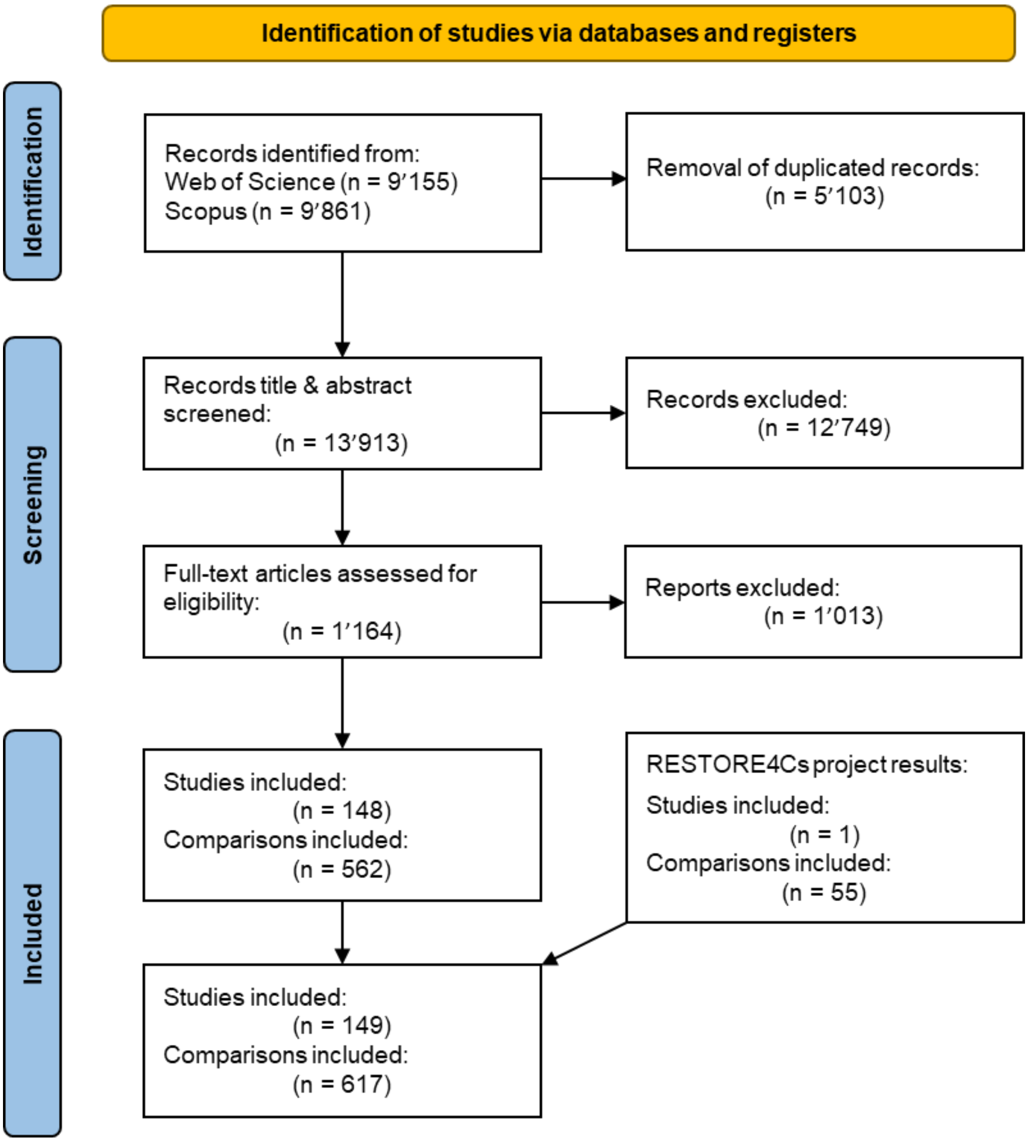
TS=(("carbon stock*" OR "carbon sequestration*" OR "carbon storage" OR "carbon flux*" OR GHG* OR "organic matter*" OR greenhouse* OR CO2 OR CH4 OR N2O OR DOC OR TOC OR DOM OR "recalcitrant carbon" OR "soluble organic matter" OR "soluble organic carbon" OR methane OR "nitrous oxide" OR "carbon dioxide" OR "aboveground biomass" OR "belowground biomass") AND (wetland* OR lagoon* OR estuar* OR delta* OR mangrove* OR peatland* OR seagrass OR "sea grass" OR fen* OR bog* OR swamp* OR *marsh* OR floodplain*) AND (restoration* OR rehabilitation* OR revitali*ation* OR renaturali*ation* OR management*)) AND LA=(English) AND DT=(Article OR Data Paper)

SCOPUS:

TITLE-ABS-KEY (("carbon stock*" OR "carbon sequestration*" OR "carbon storage" OR "carbon flux*" OR GHG* OR "organic matter*" OR greenhouse* OR CO2 OR CH4 OR N2O OR DOC OR TOC OR DOM OR "recalcitrant carbon" OR "soluble organic matter" OR "soluble organic carbon" OR methane OR "nitrous oxide" OR "carbon dioxide" OR "aboveground biomass" OR "belowground biomass") AND (wetland* OR lagoon* OR estuar* OR delta* OR mangrove* OR peatland* OR seagrass OR "sea grass" OR fen* OR bog* OR swamp* OR *marsh* OR floodplain*) AND (restoration* OR rehabilitation* OR revitali*ation* OR renaturali*ation* OR management*)) AND LANGUAGE (english)

Supplementary Table S1. Criteria for inclusion and exclusion during the review process.

Criteria	Include	Exclude
Source	Web of Science Core Collection and Scopus	Other data sources
Publication type	Research articles or data papers reporting original field measurements	Reviews, meta-analyses, modeling-only studies, extrapolations without field data, laboratory or mesocosm studies
Language	English	All other languages
Ecosystem	Sites historically classified as wetlands	Terrestrial ecosystems, other types of freshwater systems, marine ecosystems
Geography	Studies conducted across the globe	-
Restoration action	Any active or passive restoration or management action that aims to recover coastal wetland structure or function	Monitoring of only natural or only impacted sites with no restored control sites
Variables	Quantified carbon pools (soil or sediment, aboveground or belowground biomass), DOC or GHG fluxes (CO_2, CH_4, N_2O)	Studies that do not report any of these variables
Design	Direct comparisons of altered (degraded, impacted) versus restored sites; BA (Before-After), CI (Control-Impact), or BACI (Before-After-Control-Impact) comparisons	Studies reporting only restored versus natural reference comparisons, or restored sites only
Data provision	Means, SDs, and sample sizes for each group, or convertible statistics allowing SD derivation (SE, CI, IQR, range)	Statistics insufficient to derive SD or unclear sample sizes even after author contact (for studies published in the past 5 years)

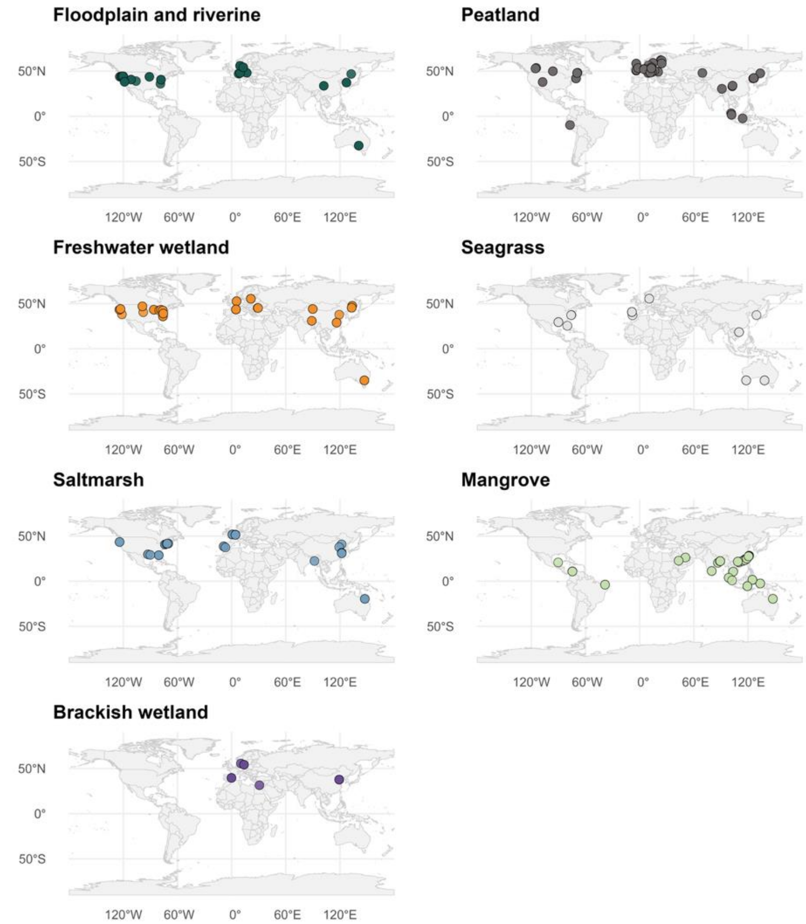


Supplementary Figure S1. Number of studies included in each stage during the review process.

Supplementary Table S2. Definitions of moderator classes used for grouping studies in the meta-analysis

Moderator Category	Class	Definition
Alteration Type	**Hydrology**	Alterations involving changes to water level, hydroperiod, surface–groundwater connectivity, tidal regime, drainage, or flooding patterns.
	Hydromorphology	Combined hydrological and morphological disturbances, such as channelization, bank stabilization, or modifications affecting both flow regime and geomorphic structure.
	Land-use Change	Conversion of wetlands to agricultural, urban, industrial or other terrestrial uses, including grazing, cropping, infrastructure development or forestry.
	Morphology	Physical reconfiguration of wetland shape or structure, such as excavation, infilling, dredging, shoreline modification, or changes to microtopography.
	Vegetation or Habitat Loss	Removal, degradation or fragmentation of native wetland vegetation, through harvesting, overgrazing, invasive species encroachment, or other processes reducing plant biomass or cover.
	Water-quality or Pollution	Chemical degradation through nutrient enrichment, eutrophication, salinisation, heavy metals, organic pollutants or acidification.
	Natural Disturbance	Alteration resulting from naturally occurring events such as storms, wildfires, droughts or floods.
Wetland Type	**Peatland**	Terrestrial wetland ecosystems in which waterlogged conditions prevent plant material from fully decomposing.
	Floodplains and riverine wetlands	Flat areas of land next to a river or stream permanently or temporary flooded.
	Freshwater Wetland	Non-peat freshwater systems such as marshes, swamps and ponds.
	Seagrass	Submerged marine angiosperm meadows occupying shallow coastal areas.
	Saltmarsh	Intertidal coastal wetlands dominated by halophytic vegetation and subject to tidal flooding.
	Mangrove	Intertidal forested wetlands in tropical and subtropical coasts dominated by mangrove tree species.

	Brackish Wetland	Wetlands influenced by mixed freshwater and saline conditions, including estuarine and lagoonal systems.
Restoration Type	**Hydrological Restoration**	Actions focused to restore natural water flow patterns, water levels, and hydroperiods within wetland ecosystems.
	Morphological Restoration	Actions targeting geomorphic structure, including channel reconfiguration, topographic re-construction, shoreline reshaping or creation of microtopographic features.
	Soil-focused Restoration	Measures focused on soil properties or processes, such as re-establishing sediment inputs, changing soil organic matter, stabilising substrates or reducing erosion.
	Vegetation-focused Restoration	Direct interventions involving planting, seeding, translocation or protection of native vegetation to accelerate recovery of above- and belowground biomass and habitat structure.
	Passive restoration	Process that eliminates the factors of degradation and disturbance and permits the natural regeneration of the ecosystem.



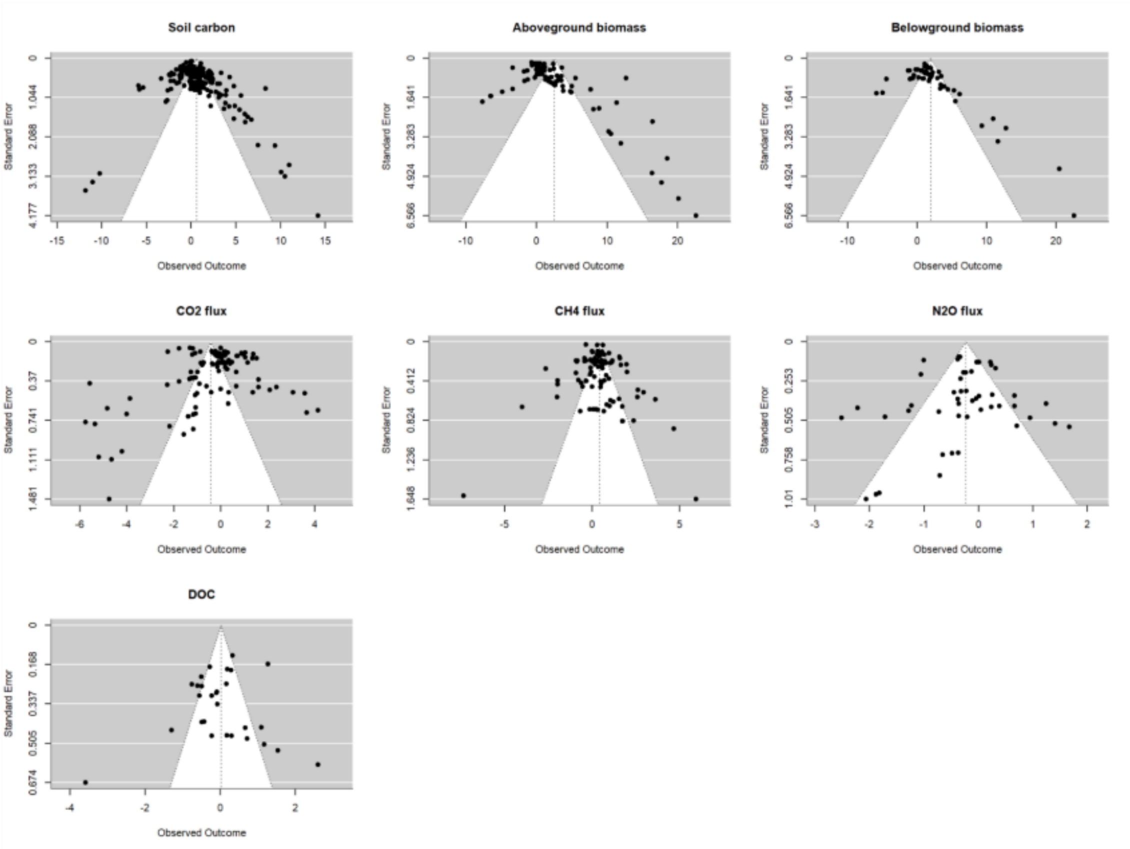
Supplementary Figure S2. Distribution of restoration projects by wetland type

Supplementary Table S3. Pooled effect sizes (standardized mean differences, SMD) for carbon indicators comparing restored and unrestored wetlands. Values include point estimates, 95% confidence intervals, significance category, and number of comparisons and studies contributing to each estimate.

Parameter	Estimate	Lover CI	Upper CI	Significance	Nr. Comparisons	Nr. Studies
Soil carbon	0.615119621	0.234490317	0.995748925	Positive effect	207	95
Aboveground biomass	2.518918974	1.166814623	3.871023326	Positive effect	73	34
Belowground biomass	1.938163518	0.952974364	2.923352672	Positive effect	53	21
CO2 flux	-0.427299424	-0.841017922	-0.013580926	Negative effect	111	45
CH4 flux	0.439658673	0.141630129	0.737687218	Positive effect	95	40
N2O flux	-0.229069545	-0.490360119	0.032221028	Non-significant	50	19
DOC	0.027659372	-0.309282062	0.364600805	Non-significant	28	9

Supplementary Table S4. Heterogeneity statistics for meta-analyses of carbon indicators. Reported metrics include Q statistic, degrees of freedom, p-value, I^2 (percentage of total variability due to heterogeneity), and τ^2 (between-study variance).

Parameter	k	Q	df_Q	p_Q	I^2_Q	τ^2_total
Soil carbon	207	1930.65	206	1.85E-277	89.3	3.6217
Aboveground biomass	73	1070.39	72	1.20E-177	93.3	17.79
Belowground biomass	53	352.53	52	3.01E-46	85.2	6.4046
CO_2 flux	111	4108.56	110	0	97.3	2.8538
CH_4 flux	95	1494.81	94	7.52E-251	93.7	1.1224
N_2O flux	50	243.09	49	1.57E-27	79.8	0.4433
DOC	28	178.78	27	2.52E-24	84.9	0.6477



Supplementary Figure S3. Funnel plots for publication bias assessment across all indicators.

Supplementary Table S5. Publication bias assessment for each indicator. Egger's regression test and Kendall's tau rank correlation are reported with corresponding p-values.

Parameter	k	Egger_Z	Egger_p	Kendall_tau	Kendall_p
Soil carbon	207	4.049	7.28E-05	0.274	4.68E-09
Aboveground biomass	73	4.071	1.20E-04	0.452	1.53E-08
Belowground biomass	53	2.315	0.024644	0.361	1.33E-04
CO2 flux	111	0.911	0.364319	-0.19	0.00309
CH4 flux	95	1.045	0.298928	0.095	0.172812
N2O flux	50	0.127	0.899318	-0.116	0.234876
DOC	28	-0.781	0.441625	0.138	0.316765

Supplementary Table S6. Leave-one-out sensitivity analysis for pooled effect sizes. For each indicator, the table shows the full-model effect estimate with 95% CI, range of estimates under leave-one-out scenarios, maximum absolute change in SMD, and number of significance flips.

Parameter	k_effects	Full effect (95% CI)	Range LOO est.	Max |ΔSMD|	Sig. flips
Soil carbon	207	0.63 [0.37, 0.88]	0.58 - 0.65	0.05	0
Aboveground biomass	73	2.46 [1.46, 3.46]	2.24 - 2.55	0.22	0
Belowground biomass	53	1.67 [0.92, 2.43]	1.52 - 1.74	0.16	0
CO2 flux	111	-0.39 [-0.69, -0.09]	-0.42 - -0.33	0.05	0
CH4 flux	95	0.36 [0.13, 0.60]	0.33 - 0.40	0.03	0
N2O flux	50	-0.24 [-0.45, -0.03]	-0.27 - -0.20	0.04	0
DOC	28	0.03 [-0.30, 0.37]	-0.04 - 0.11	0.08	0

Supplementary Table S7. Influence diagnostics for meta-analyses of carbon indicators. The table reports the number and proportion of influential cases identified for each indicator.

Parameter	k_effects	n_influential	prop_influential
Soil carbon	207	0	0.00%
Aboveground biomass	73	0	0.00%
Belowground biomass	53	0	0.00%
CO_2 flux	111	0	0.00%
CH_4 flux	95	0	0.00%
N_2O flux	50	0	0.00%
DOC	28	0	0.00%

Supplementary Table S8. Fit statistics for multivariable meta-regression models of restoration effects on carbon indicators. *Summary of full multilevel meta-regression models fitted separately for each response variable (soil carbon, aboveground biomass, belowground biomass, dissolved organic carbon, and* CO_2*,* CH_4 *and* N_2O *fluxes). For each parameter, the table reports the number of comparisons included (k), the omnibus test for moderators (QM, degrees of freedom and p-value), measures of residual heterogeneity (total* τ^2*) and overall model fit (AIC and BIC). Significant QM values indicate that effect sizes vary systematically along at least one of the moderators.*

parameter	k	AIC	BIC	tau2_total	QM	QM_df	QM_p
Soil carbon	105	362.5622	420.6144	2.984231	31.56513	21	0.064753
Aboveground biomass	28	109.0777	119.3027	75.55709	4.39554	13	0.98621
Belowground biomass	26	108.6303	117.1046	23.99945	3.045648	12	0.995213
CO2 flux	59	443.7996	478.0711	4.061636	56.73534	17	3.60E-06
CH4 flux	44	143.4998	168.1207	1.780619	16.14293	16	0.443031
N2O flux	21	33.65455	38.42929	0.040141	51.28654	9	6.17E-08
DOC	17	27.60671	28.48057	0.063485	30.03669	8	2.08E-04

Supplementary Table S9. Regression coefficients for full multivariable meta-regression models. *Estimated fixed effects from the full multilevel meta-regression models for each response variable. The table lists the intercept and all moderator terms (alteration type, wetland type, restoration type/category, sampling and restoration years, and climatic variables), together with their estimates (β), standard errors, Wald z-values, 95% confidence intervals and p-values. Continuous moderators were z-standardised prior to modelling, so coefficients represent the change in standardized mean difference (SMD) associated with a one standard deviation change in the predictor. Positive coefficients indicate larger values in restored compared to altered wetlands along that gradient; negative coefficients indicate smaller restored–altered differences.*

term	estimate	se	zval	pval	ci.lb	ci.ub
Soil carbon						
intercept	-0.89085	1.529534	-0.58243	0.560274	-3.88868	2.106979
Alteration type: Hydrology	1.590559	1.592605	0.998715	0.317933	-1.53089	4.712006
Alteration type: Hydromorphology	1.430628	1.830522	0.781541	0.434484	-2.15713	5.018386
Alteration type: Land use change	2.260088	1.472632	1.534727	0.124851	-0.62622	5.146393
Alteration type: Morphology	2.206393	1.838534	1.200083	0.230107	-1.39707	5.809855
Alteration type: Vegetation/habitat loss	1.914139	1.62475	1.178113	0.238752	-1.27031	5.098591
Alteration type: Water quality/pollution	2.622893	1.69931	1.543505	0.122708	-0.70769	5.953479
Wetland type: Peatland	1.722315	1.073261	1.60475	0.108549	-0.38124	3.825867
Wetland type: Freshwater wetland	-0.16156	1.28472	-0.12576	0.899924	-2.67957	2.356442
Wetland type: Seagrass	0.520746	1.314861	0.396046	0.692071	-2.05633	3.097827
Wetland type: Saltmarsh	-0.84809	1.251197	-0.67782	0.497886	-3.30039	1.604215
Wetland type: Mangrove	-1.25008	1.306007	-0.95717	0.338479	-3.8098	1.309649
Wetland type: Brackish wetland	0.461961	1.909605	0.241914	0.808846	-3.2808	4.204718
Restoration type: Morphology	-1.01048	1.017063	-0.99353	0.320453	-3.00389	0.982926
Restoration type: Passive restoration	0.50658	1.112898	0.45519	0.648972	-1.67466	2.68782
Restoration type: Soils	-0.94808	1.567216	-0.60495	0.545214	-4.01977	2.123603
Restoration type: Vegetation	-0.55756	0.6385	-0.87324	0.382533	-1.809	0.693874
Temperature	1.633681	0.557375	2.931025	0.003378	0.541245	2.726116
Temperature seasonality	1.434123	0.507371	2.826575	0.004705	0.439693	2.428552
Precipitation	0.013217	0.241126	0.054815	0.956285	-0.45938	0.485816
Precipitation seasonality	0.285491	0.349326	0.817261	0.413779	-0.39918	0.970158
Time since restoration	0.211918	0.142127	1.491046	0.135949	-0.06665	0.490481
Aboveground biomass						
intercept	-152.85	140.187	-1.09033	0.275567	-427.612	121.9112
Alteration type: Hydrology	-192.583	195.6343	-0.9844	0.324917	-576.019	190.8529
Alteration type: Land use change	9.49456	13.23703	0.717273	0.473206	-16.4495	35.43865
Alteration type: Vegetation/habitat loss	15.84706	27.49035	0.576459	0.564305	-38.033	69.72716

Alteration type: Water quality/pollution	21.49658	13.23729	1.623941	0.104388	-4.44803	47.4412
Wetland type: Peatland	-353.773	348.2545	-1.01585	0.309703	-1036.34	328.7934
Wetland type: Seagrass	359.0109	329.8658	1.088355	0.276439	-287.514	1005.536
Wetland type: Saltmarsh	566.5262	540.6693	1.047824	0.29472	-493.166	1626.219
Wetland type: Mangrove	214.8835	196.1159	1.095697	0.273212	-169.497	599.2635
Temperature	-130.797	131.7795	-0.99255	0.320932	-389.08	127.4859
Temperature seasonality	59.90325	57.2369	1.046585	0.295291	-52.279	172.0855
Precipitation	-29.2548	20.76247	-1.40902	0.158828	-69.9485	11.4389
Precipitation seasonality	129.2651	125.3828	1.030963	0.302558	-116.481	375.0109
Time since restoration	0.162408	0.777043	0.209008	0.834442	-1.36057	1.685384
Belowground biomass						
intercept	56.04572	71.62783	0.782457	0.433946	-84.3422	196.4337
Alteration type: Hydrology	-40.4241	74.25791	-0.54437	0.586184	-185.967	105.1187
Alteration type: Land use change	-8.47452	12.457	-0.6803	0.496313	-32.8898	15.94075
Alteration type: Vegetation/habitat loss	-2.68254	13.02805	-0.20591	0.836865	-28.217	22.85196
Alteration type: Water quality/pollution	34.49373	40.05471	0.861165	0.389147	-44.012	112.9995
Wetland type: Peatland	4.917093	12.80639	0.383956	0.701011	-20.183	30.01715
Wetland type: Seagrass	-63.8298	78.11072	-0.81717	0.413831	-216.924	89.2644
Wetland type: Saltmarsh	-7.32939	11.79357	-0.62147	0.534288	-30.4444	15.78558
Wetland type: Mangrove	-62.3729	81.69822	-0.76345	0.445192	-222.498	97.75267
Temperature	19.97926	36.82915	0.542485	0.587484	-52.2046	92.16308
Temperature seasonality	14.59312	33.0207	0.441938	0.658534	-50.1263	79.31251
Precipitation	13.64304	14.69982	0.928109	0.353351	-15.1681	42.45415
Time since restoration	0.131361	1.313505	0.100008	0.920338	-2.44306	2.705783
CO2 flux						
intercept	0.420679	2.142805	0.196322	0.844358	-3.77914	4.6205
Alteration type: Hydromorphology	0.667678	2.119489	0.315018	0.752748	-3.48644	4.8218
Alteration type: Land use change	1.240837	1.851078	0.670332	0.502646	-2.38721	4.868884
Alteration type: Morphology	0.813639	2.935922	0.277132	0.781679	-4.94066	6.567941
Alteration type: Natural disasters	-3.01672	2.764841	-1.0911	0.275229	-8.43571	2.40227

Alteration type: Water quality/pollution	5.707711	4.673849	1.221202	0.22201	-3.45286	14.86829
Wetland type: Peatland	-3.14267	2.500159	-1.25699	0.208757	-8.0429	1.757548
Wetland type: Freshwater wetland	0.190459	2.638498	0.072185	0.942455	-4.9809	5.361821
Wetland type: Saltmarsh	1.438293	3.306173	0.435033	0.663539	-5.04169	7.918272
Wetland type: Mangrove	2.171613	4.765393	0.455705	0.648602	-7.16839	11.51161
Restoration type: Morphology	-3.15182	2.097892	-1.50237	0.133	-7.26361	0.959973
Restoration type: Passive restoration	1.674649	2.509805	0.667243	0.504617	-3.24448	6.593776
Restoration type: Vegetation	0.80585	0.816793	0.986603	0.323837	-0.79503	2.406734
Temperature	-3.66963	1.422503	-2.5797	0.009889	-6.45768	-0.88158
Temperature seasonality	-0.97287	0.824332	-1.18019	0.237924	-2.58853	0.642792
Precipitation	1.381217	1.290901	1.069963	0.284636	-1.1489	3.911338
Precipitation seasonality	-1.23974	0.674438	-1.83819	0.066034	-2.56162	0.082129
Time since restoration	0.471232	0.318076	1.481508	0.138471	-0.15219	1.09465
CH4 flux						
intercept	4.27503	2.253992	1.896649	0.057874	-0.14271	8.692773
Alteration type: Hydromorphology	0.697404	1.165494	0.598376	0.549589	-1.58692	2.98173
Alteration type: Land use change	0.470002	1.015326	0.462908	0.643431	-1.52	2.460004
Alteration type: Morphology	-4.06889	2.384161	-1.70663	0.08789	-8.74176	0.603984
Alteration type: Water quality/pollution	-2.10085	2.893813	-0.72598	0.467852	-7.77261	3.570922
Wetland type: Peatland	-3.82887	2.021129	-1.89442	0.058169	-7.79021	0.132469
Wetland type: Freshwater wetland	-3.89003	2.19434	-1.77276	0.076269	-8.19086	0.410795
Wetland type: Saltmarsh	-0.97025	2.405812	-0.40329	0.686733	-5.68555	3.745059
Wetland type: Mangrove	-3.9102	2.457168	-1.59135	0.111532	-8.72616	0.905757
Restoration type: Hydromorphology	-0.50152	0.954083	-0.52566	0.599125	-2.37149	1.368445
Restoration type: Morphology	-0.74717	1.01681	-0.73482	0.462449	-2.74008	1.245738
Restoration type: Vegetation	-0.588	0.82037	-0.71674	0.473532	-2.19589	1.019901
Temperature	-0.47904	0.847599	-0.56517	0.57196	-2.1403	1.182228
Temperature seasonality	-0.76585	0.486596	-1.57389	0.115513	-1.71956	0.187862
Precipitation	-0.47282	0.774619	-0.6104	0.5416	-1.99105	1.045401

Precipitation seasonality	-0.28551	0.300321	-0.95067	0.341772	-0.87412	0.303112
Time since restoration	0.028597	0.311937	0.091676	0.926956	-0.58279	0.639983
N2O flux						
intercept	-40.179	47.05962	-0.85379	0.393222	-132.414	52.05618
Alteration type: Hydromorphology	-44.4253	50.96977	-0.8716	0.383427	-144.324	55.47366
Wetland type: Peatland	49.38638	58.8077	0.839794	0.401024	-65.8746	164.6473
Wetland type: Freshwater wetland	79.06523	93.50783	0.845547	0.397806	-104.207	262.3372
Wetland type: Mangrove	48.37076	59.07896	0.818748	0.41293	-67.4219	164.1634
Restoration type: Vegetation	18.23793	20.06755	0.908827	0.363442	-21.0938	57.56961
Temperature	-49.3458	57.25985	-0.86179	0.388805	-161.573	62.88147
Temperature seasonality	-44.489	52.97749	-0.83977	0.401037	-148.323	59.34501
Precipitation	-2.22722	4.267234	-0.52194	0.601715	-10.5908	6.136403
Time since restoration	0.59756	0.304824	1.960342	0.049956	1.15E-04	1.195004
DOC						
intercept	3.092653	1.405383	2.200577	0.027766	0.338153	5.847154
Alteration type: Hydromorphology	-12.1958	11.07424	-1.10127	0.270778	-33.9009	9.50935
Alteration type: Land use change	44.5532	52.29589	0.851945	0.394245	-57.9449	147.0513
Restoration type: Vegetation	-21.9018	23.01498	-0.95163	0.341284	-67.0103	23.20676
Temperature	-29.1864	32.12721	-0.90846	0.363634	-92.1546	33.78179
Temperature seasonality	-13.9061	15.18062	-0.91604	0.359644	-43.6596	15.84736
Precipitation	2.967315	2.943476	1.008099	0.313407	-2.80179	8.736422
Precipitation seasonality	0.2251	0.77051	0.292145	0.770176	-1.28507	1.735272
Time since restoration	-0.26159	0.186014	-1.40631	0.159633	-0.62617	0.102988

Supplementary Table S10. Single-term deletion (drop-one) model comparison for multivariable meta-regressions. *Results of the single-term deletion analysis used to assess the relative importance of individual moderators in the multivariable meta-regression models. For each response variable and each moderator (or moderator block, in the case of categorical factors), the table reports the change in Akaike information criterion (ΔAIC), change in Bayesian information criterion (ΔBIC) and change in total* τ^2 *when that term is removed from the full model. Positive ΔAIC/ΔBIC values indicate a worsening of model fit when the moderator is dropped, with larger increases highlighting moderators that contribute more strongly to explaining between-comparison heterogeneity.*

term	AIC	BIC	tau2_red	dAIC	dBIC	d_tau2
Soil carbon						
Alteration type	374.730	419.525	2.729	12.167	-1.089	-0.256
Wetland type	378.244	423.039	2.882	15.682	2.425	-0.103
Restoration type	369.592	418.910	2.685	7.030	-1.704	-0.300
Temperature	371.789	427.698	3.509	9.227	7.084	0.525
Temp. seasonality	371.683	427.591	3.453	9.120	6.977	0.469
Precipitation	363.296	419.205	2.920	0.734	-1.410	-0.064
Pre. seasonality	364.350	420.259	2.850	1.788	-0.355	-0.134
Time since restoration	799.730	879.554	2.920	437.167	458.939	-0.064
Aboveground biomass						
Alteration type	125.326	136.158	65.014	16.248	16.855	-10.544
Wetland type	113.135	123.756	51.666	4.057	4.453	-23.891
Restoration type	109.078	119.303	75.557	0.000	0.000	0.000
Temperature	112.902	123.522	48.563	3.824	4.220	-26.994
Temp. seasonality	112.771	123.392	45.363	3.693	4.089	-30.194
Precipitation	113.591	124.212	40.550	4.513	4.909	-35.007
Pre. seasonality	112.801	123.422	46.244	3.723	4.119	-29.313
Time since restoration	327.999	374.363	24.564	218.922	255.061	-50.993
Belowground biomass						
Alteration type	114.863	124.068	15.279	6.233	6.963	-8.720
Wetland type	112.003	120.950	16.813	3.373	3.845	-7.187
Restoration type	108.630	117.105	23.999	0.000	0.000	0.000
Temperature	108.630	117.105	23.999	0.000	0.000	0.000
Temp. seasonality	108.630	117.105	24.000	0.000	0.000	0.000
Precipitation	108.630	117.105	24.000	0.000	0.000	0.000
Pre. seasonality	108.630	117.105	23.999	0.000	0.000	0.000
Time since restoration	227.637	258.744	19.364	119.007	141.640	-4.635
CO2 flux						
Alteration type	456.348	483.778	3.636	12.548	5.707	-0.425
Wetland type	452.827	481.733	3.717	9.027	3.662	-0.345
Restoration type	452.268	482.599	4.287	8.469	4.528	0.226

Temperature	450.882	483.897	6.458	7.082	5.826	2.396
Temp. seasonality	446.955	479.971	4.258	3.156	1.900	0.196
Precipitation	446.521	479.537	3.874	2.721	1.465	-0.188
Pre. seasonality	448.571	481.587	5.017	4.772	3.516	0.955
Time since restoration	624.257	683.439	4.364	180.457	205.368	0.303
CH4 flux						
Alteration type	152.007	173.517	2.011	8.508	5.397	0.231
Wetland type	150.630	172.140	1.956	7.130	4.019	0.175
Restoration type	145.758	168.177	1.574	2.258	0.056	-0.206
Temperature	144.322	168.302	1.681	0.822	0.181	-0.100
Temp. seasonality	146.257	170.237	1.973	2.757	2.116	0.192
Precipitation	144.406	168.385	1.670	0.906	0.265	-0.111
Pre. seasonality	144.972	168.952	1.663	1.472	0.831	-0.117
Time since restoration	337.709	388.399	1.085	194.210	220.278	-0.696
N2O flux						
Alteration type	33.655	38.429	0.040	0.000	0.000	0.000
Wetland type	31.925	37.259	0.037	-1.730	-1.171	-0.003
Restoration type	33.655	38.429	0.040	0.000	0.000	0.000
Temperature	33.655	38.429	0.040	0.000	0.000	0.000
Temp. seasonality	33.655	38.429	0.040	0.000	0.000	0.000
Precipitation	33.655	38.429	0.040	0.000	0.000	0.000
Pre. seasonality	33.655	38.429	0.040	0.000	0.000	0.000
Time since restoration	99.576	128.256	1.079	65.921	89.826	1.039
DOC						
Alteration type	26.697	28.669	0.068	-0.910	0.188	0.004
Wetland type	27.607	28.481	0.063	0.000	0.000	0.000
Restoration type	26.395	28.367	0.063	-1.212	-0.114	0.000
Temperature	26.313	28.285	0.062	-1.294	-0.196	-0.001
Temp. seasonality	26.327	28.299	0.062	-1.280	-0.181	-0.001
Precipitation	26.503	28.475	0.065	-1.104	-0.005	0.002
Pre. seasonality	25.530	27.502	0.052	-2.077	-0.978	-0.012
Time since restoration	56.756	67.573	3061.445	29.150	39.092	3061.382

1193