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LETTER

Soil health metrics for assessment of floodplain restorations

Joseph George Galella[1], **Md Moklesur Rahman**[1], **Eric Moore**[1], **Marc Peipoch**[2], **Jinjun Kan**[2], **Alexis M Yaculak**[3], **Matthew Sena**[4], **Bisesh Joshi**[3], **Sujay S Kaushal**[5] **and Shreeram Inamdar**[1,*]

1 Department of Plant and Soil Sciences, University of Delaware, Townsend Hall, Newark, DE 19716, United States of America
2 Stroud Water Research Center, 970 Spencer Rd, Avondale, PA 19311, United States of America
3 Water Science & Policy Graduate Program, University of Delaware, Newark, DE 19716, United States of America
4 Plant and Soil Science Graduate Program, University of Delaware, Newark, DE 19716, United States of America
5 Department of Geology & Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD 20740, United States of America
* Author to whom any correspondence should be addressed.

E-mail: inamdar@udel.edu

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Supplementary material for this article is available online

Abstract

While healthy soils are critical for stream and floodplain restoration, little guidance is available to restoration practitioners on which soil metrics to measure and when to expect the signs of recovery post-restoration. Here, we address this important knowledge gap through a study of 37 soil metrics for 11 restored floodplains and two reference sites across a chronosequence of 0–22 years. Soil metrics differed in their sensitivity and response to restoration and followed different rates of change including fast (0–2 years), moderate (2–10 years), and slow (>10 years). Physicochemical metrics dominated the first two trajectories, whereas biological metrics, while sensitive, fell into the last trajectory. Soil recovery rates for restored sites differed considerably for reference sites highlighting the need to better define reference conditions. Availability of consistent and sensitive soil health metrics will allow restoration practitioners to better assess restoration recovery and receive regulatory credits for meeting restoration targets.

1. Introduction

Soil health defines the collective state of multiple physical, chemical, and biological soil attributes that contribute to valuable ecosystem functions and services (Lehmann *et al* 2020, Inamdar *et al* 2023). For floodplains and riparian zones, such ecosystem functions/services include water infiltration and retention, erosion control, nutrient cycling, and plant growth (Palmer *et al* 2014, Noe *et al* 2024). Stream and floodplain restoration projects that include streambank grading and sediment removal for stream–floodplain reconnection can have substantial detrimental effects on soil health attributes (Unghire *et al* 2011, Laub *et al* 2013, McMillan and Noe 2017, Inamdar *et al* 2023). Restoration assessments, however, rarely monitor and address impacts on soil health because there is a lack of consistent information on: (a) how and which soil properties are affected; (b) the expected timing of changes in soil parameters after restoration; and (c) the 'desirable' soil health endpoints or reference conditions which restorations should achieve (Muñoz-Rojas *et al* 2016, Wood and Blankinship 2022, Inamdar *et al* 2023). We addressed these key knowledge gaps in this study.

Stream restoration can alter floodplain soil characteristics resulting in suboptimal soil thickness, low soil porosities and elevated bulk densities, compromised soil aggregation, diminished hydraulic conductivities, reduced water infiltration, and subsequently elevated overland flow (Gift *et al* 2010, Unghire *et al* 2011, Laub *et al* 2013, Beauchamp *et al* 2015, Inamdar *et al* 2023). Most of the floodplain resurfacing and sediment removal is accomplished via heavy machinery which results in significant compaction of floodplain soils, slowing soil recovery, and impeding root growth (Kimble *et al* 2000, Ballantine *et al* 2012, Brown and Norris 2018). Because of this,

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Laub *et al* (2013) found that soil bulk density was 19% and 11% higher in the top 10–20 and 20–30 cm restored soil layers, respectively.

In addition to direct impacts on soil physical conditions, restoration practices typically decrease the amount of soil organic matter in floodplain soils, as well as its natural spatial heterogeneity (Unghire *et al* 2011, Laub *et al* 2013, Beauchamp *et al* 2015, Brown and Norris 2018). Brown and Norris (2018) found that post restoration, soil organic matter decreased relative to unrestored sites, taking approximately a decade to recover to initial levels. Laub *et al* (2013) reported a 16% decrease in soil organic matter for surficial (10–20 cm) floodplain soils following restoration. Unghire *et al* (2011) not only reported a significant decrease in soil organic matter (9.6% to 6.9%) but also noted spatial homogenization of soil organic matter across the floodplain surface. This homogenization undermines the 'hot spots' of biogeochemical processes such as denitrification and mineralization (Vidon *et al* 2010) which are important for floodplain functions.

Compared to physical and chemical soil conditions, floodplain construction practices likely have the greater impacts on soil microbiomes (Farrell *et al* 2020). Construction-induced low porosity soils degrade soil microbial habitat vital for nutrient cycling and removal (Dong *et al* 2023). Reduced organic matter can exacerbate the impact on microbial communities, perhaps for a decade or more post restoration (Mackay *et al* 2016, Brown and Norris 2018). Excavation of floodplains and overturning and mixing of soils also substantially alters, if not destroys, the valuable network of mycorrhizal fungi in the soils. Mycorrhizal fungi help with nutrient mobilization and also enhance the capacity and resiliency of plants to fight off infections and overcome environmental stresses (Allen *et al* 2003). In the absence of such a supportive underground network, it is difficult for newly planted shrubs and tree saplings, particularly native species, to survive on restored floodplain surfaces (Grman *et al* 2020).

Thus, healthy soils with favorable physical, chemical, and biological attributes are essential for successful floodplain restoration but specific protocols for monitoring and evaluating soil health are unavailable. Many recent studies have called for increased guidance on selecting soil metrics for stream restoration assessment indicating that they need to be sensitive to change, provide clear directional change, be linked to ecosystem functions, and be cost-effective, easy to implement, and understood by restoration practitioners (Doran and Zeiss 2000, Morrow *et al* 2016, Wade *et al* 2022, Wood and Blankinship 2022). We respond to this call by addressing the following key questions:

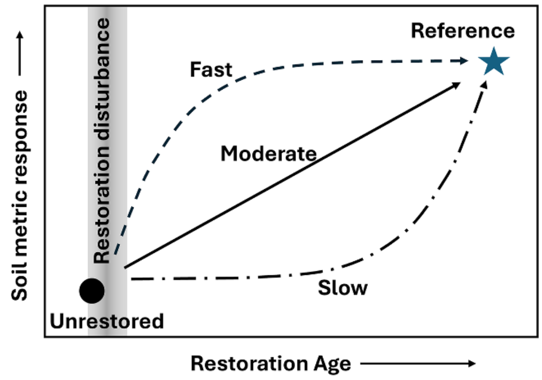

Figure 1. Conceptual model of how soil metrics are expected to evolve with time since restoration. We hypothesized that these trajectories included fast (0–2 years), moderate (2–10 years), and slow (>10 years) post restoration and initial disturbance. Shaded region indicates post restoration disturbance and initial uncertainty and variability in soil metrics.

- How do soil health parameters change following restoration, and which metrics are sensitive and show consistent change?
- How do the restored soil health metrics compare against those for 'reference' floodplains and what does this indicate about the choice of reference conditions?

We investigated these questions for a chronosequence of 11 mid-Atlantic restoration sites spanning a post-restoration period of 0–22 years. Two relatively undisturbed floodplain wetland sites were also included to characterize reference benchmark or 'desirable' soil health conditions. Sampling was performed for a suite of physical, chemical, and biological soil attributes that are linked to valuable floodplain ecosystem services. We predicted that most soil health parameters will initially be negatively affected by floodplain restoration (shaded region in figure 1) but will improve and follow different trajectories towards reference conditions including fast (0–2 years), moderate (2–10 years), and slow (>10 years) (figure 1). We expected that certain soil chemical attributes would recover early followed by physical and biological parameters. Identifying these metrics and temporal trajectories will contribute to effective soil health in restorations, quantify soil recovery, and allow practitioners to seek regulatory incentives or credits towards enhancing soil health.

2. Methods

2.1. Study sites

Soil samples were collected from a total of 13 sites (11 restored and two reference) across the Mid-Atlantic Piedmont Region of the United States (US)

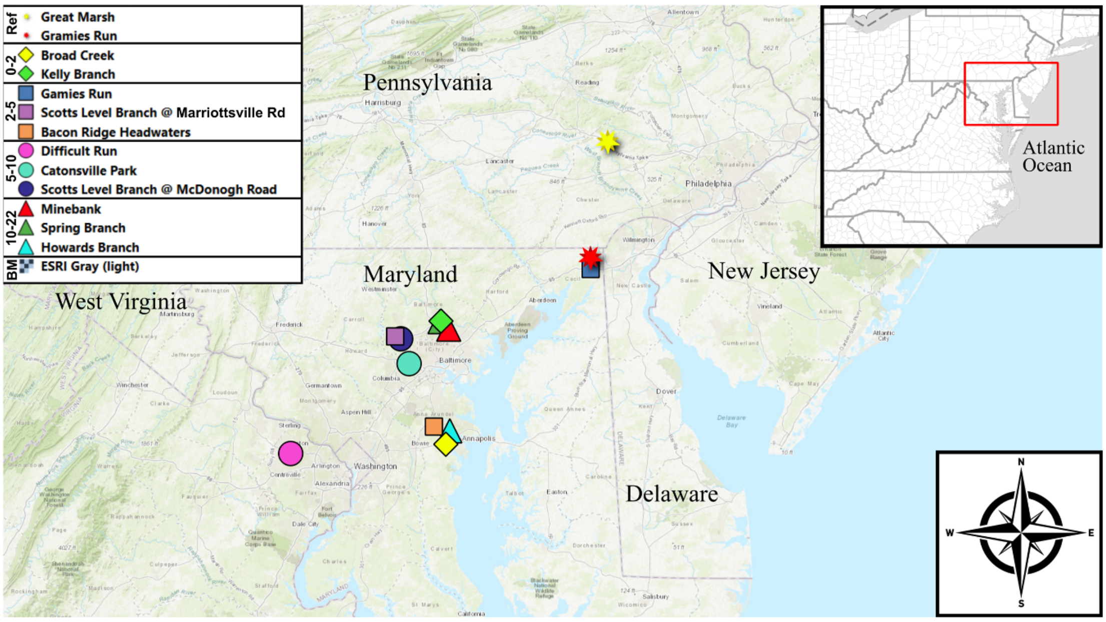

Figure 2. Locations of the 13 sampling sites (11 floodplain restorations + two reference sites) selected for this study in Maryland, Virginia, and Pennsylvania (United States). All sites are within the Mid-Atlantic region (inset). Great marsh and Gramies run are reference wetlands, and the remainder of the sites are restored floodplains. The shapes of the symbols represent reference sites and different restoration time frames for restoration sites (indicated in the legend at the top left).

(Galella *et al* 2025). Reference sites included Gramies Run (GR) forested/shrub wetland in Maryland (MD), and Great Marsh (GM) freshwater emergent wetland in Pennsylvania (PA), (figure 2 and table S1).

Restored sites were grouped into a chronosequence of four categories: 0–2, 2–5, 5–10, and 10–22 years post restoration. The first category (0–2 years) includes two sites whereas all other categories have three replicate sites (table S1). Floodplain restorations primarily followed the Natural Channel Design approach coupled with elements of floodplain reconnection and regenerative stormwater conveyance (Wood and Schueler 2020). The GR forested/shrub wetland reference site was a relatively undisturbed wetland site within immediate proximity of the GR restoration (Mattern *et al* 2020). In contrast, the GM (freshwater emergent marsh) location is one of the few minimally disturbed Holocene wetlands relatively unaffected by anthropogenic landuse activities with organic rich soils 1–1.6 m thick and over 10 000 years old (Merritts and Rahnis 2022, Peck *et al* 2024). We selected the GM site as an upper or 'ideal' endmember and expected that restored floodplains could take significant time to achieve these soil conditions.

2.2. Field sampling

Soil samples were collected using a clean trowel from within the top 20 cm of mineral soil in 1 l zip-loc bags. At each floodplain restoration site, ten soil samples were collected which included six (1, 2, and 3 m from the stream from each bank) from the restored reach and four (1 and 3 m from the stream and each bank) from the upstream unrestored section. At reference wetland sites, four to six samples were collected at random for each site. Samples for soil bulk density were collected using a metal cylinder with known dimensions (2 cm inner diameter and 3.2 cm length) and care was taken to obtain exact, uncompressed soil volume by hammering the cylinder vertically through the surficial mineral profile.

2.3. Sample analysis

Soil bulk density samples were dried in a lab oven at 65 °C for 48 h. Soil bulk density was calculated as the oven-dried mass divided by the known soil cylinder volume. Soil porosity was calculated using standard equation (Porosity = 1-[Bulk density/Particle density]) with a particle density of 2.65 g cm^{-3} (Weil and Brady 2017). Gravimetric Water Content (GWC) was the ratio of water mass (wet soil minus dry soil) by the dry soil mass of each sample. Volumetric water content (VWC) was computed as the product of GWC and soil bulk density divided by the water density (assumed 1 g ml^{-1}).

Particle size analysis was performed using standard hydrometer methods (Gee and Bauder 1986). Sieves of >0.25 mm and <0.25 mm and >0.053 mm were used to collect soil macroaggregates and microaggregates, respectively. Soil organic matter (SOM) was determined via loss on ignition in a 400 °C furnace. Soil organic carbon (SOC) and total nitrogen

(TN) were determined via combustion using an Elementar TC/TN analyzer. A Lachat instrument was used to determine 2 M KCl extracted nitrate-N (NO_3^-) and ammonium-N (NH_4^+) concentrations. Soil organic nitrogen (SON) was determined by subtraction of NO_3^- and NH_4^+ from soil TN. Soil elemental concentrations were determined through Melich-3 extraction (Sims *et al* 2002) and analyzed via Inductively Coupled Plasma Optical Emission Spectrometer.

Microbial metrics were determined via phospholipid fatty acid (PLFA) analysis measured following Frostegård *et al* (2011). The full list of all physical, chemical, and biological soil metrics is provided in table S2.

2.4. Statistical methods

Principal Component Analysis (PCA) was performed to determine differences between unrestored, restored (various age categories), and reference sites, and the soil parameters that explained variation along the first two principal components. To investigate the change in soil parameter values between unrestored and restored age categories, we computed percent change as:

$$Percent\,Change = ((Restored - Unrestored) * 100 \div (Unrestored)).$$

To assess if soil parameter changes shifted towards reference site conditions post-restoration, we computed the Achieved Restoration (AR) index (Marchand *et al* 2021) for each age category as:

$$Achieved\,Restoration = 100 * (Restored - Unrestored \div (\text{Reference} - \text{Unrestored})).$$

Following Marchand *et al* (2021), AR values between 0–100 indicate successful ecological restoration, while values <0 indicate failed restoration, and values >100 indicate that restored sites have exceeded expected reference values. In some data, soil metrics were higher in unrestored and restored soils than in reference soils, yielding erroneous AR results; these data are marked with a yellow star. AR values were computed separately for GR and GM reference sites due to substantial differences in reference soil metrics.

Changes between restored and unrestored reaches and across age categories were assessed using box plots and the percent change metric. The AR index was used to assess temporal evolution and recovery of soil metrics towards reference benchmark values. Time (in years) to reach reference benchmark values was estimated by linear extrapolation between restored floodplain values and reference values.

3. Results

3.1. Distinct clustering of unrestored, restored, and reference sites and key soil parameters that explain the variation

PCA revealed distinct separation among the unrestored and restored age categories, and reference sites (figure 3(a)). Principal component (PC) 1 explained 58.9% of total variation, while PC2 explained 15.4% of total variation. Organic matter, organic carbon, VWC, sand, and bulk density loaded the strongest along PC1, while undifferentiated PLFA and soil pH loaded heavily on PC2 (figure 3(b)). Unrestored sites across all age categories grouped together (red oval in figure 3(a)). In contrast, restored sites differed by age categories with an elongation along PC1 (2–5 and 5–10 age categories) and PC2 (0–2 age category). The oldest age category (10–22 years) displayed the greatest elongation along PC1 (figure 3(a)). Eigenvectors and Eigenvalues for PCA are reported in figure S1.

3.2. Changes in soil parameters between restored and unrestored floodplains and recovery with age category

Box plots (figures 4 and 5) and percent change metric (figure 6) revealed key changes in soil metrics between unrestored and restored reaches with a recovery over time. Variability in soil parameters was found to be higher in restored soils compared to unrestored soils. Interquartile ranges increased with time since restoration for GWC, NH_4^+, organic matter, sodium and total nitrogen at restored sites (figure 4). In comparison to physicochemical metrics, PLFA metrics (figure 5) were more negatively affected by restoration in the initial age categories, with a slower recovery in later age categories.

Percent change (figure 6) indicated that all metrics other than bulk density, GWC, and NH_4^+ decreased immediately (red bars and negative values) after restoration (particularly 0–2 year age category), signifying substantial post-restoration disturbance. On average, during the 0–2 year age category, soil parameters decreased by 21% whereas PLFA metrics decreasing by 38.5% compared to the unrestored reaches. Uplift (positive percent change) during the 2–5, year age category was more pronounced with all metrics other than bulk density and NO_3^- increasing. Percent change continued to trend positively during the 5–10 year age category with some PLFA metrics decreasing in value (total living microbial biomass, total bacteria, gram positive and actinomycetes). Similar to the 2–5 year age category, all soil metrics increased during the 10–22 year age category except bulk density and NO_3^-. Soil metrics including GWC, VWC, SOM, SOC, NH_4^+ and total nitrogen had consistent positive % change from 2 years

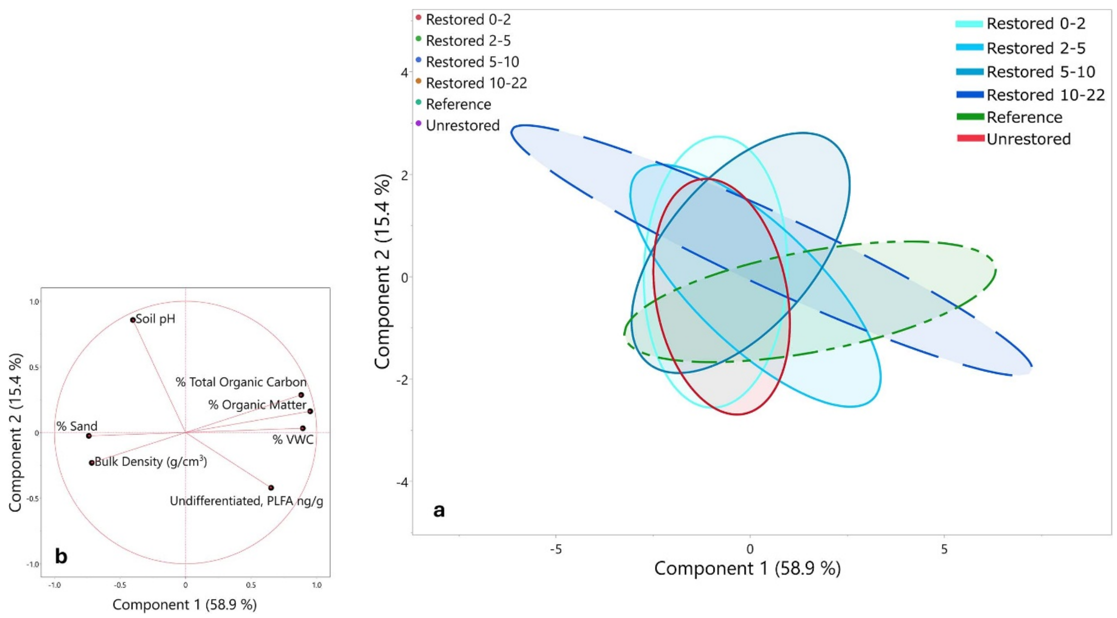

Figure 3. (a) PCA principal components 1 and 2 (with 95% confidence intervals) grouped by reference sites, unrestored sites, and restored sites by age category; and (b) PCA loading plot.

post-restoration onwards. Conversely, bulk density and NO_3^- exhibited decreasing % change after 2 years post-restoration.

Soil metrics in restored soils that did not show consistent change compared to unrestored reaches include particle size (sand, silt, and clay) as well as aggregates (micro and macro) (figure S2). Sand, silt and clay did not change noticeably after restoration and did not show consistent change as sites aged. Microaggregates and macroaggregates also did not change consistently over time with microaggregates increasing initially, but then diminishing in concentration as sites aged (5–10 year age category). Mehlich-3 extractable elements generally did not vary with age, but sodium (Na) increased over time (figure 4). Zinc concentrations initially decreased immediately after restoration (0–2 years) but then markedly increased in all age categories. The sharpest increase in zinc occurred during the 5–10 year age category where concentrations increased by over 400% (figure S2).

3.3. Comparison of restored soil metrics against reference values and time needed to reach reference conditions

GR and Great Marsh reference sites were significantly different from one another for all values other than NH_4^+, NO_3^-, sodium, and arbuscular mycorrhizal fungi ($p < 0.05$). Except these three parameters, physicochemical and PLFA metrics for Great Marsh exceeded and were more variable than those measured for GR (figures 4 and 5) to the extent that maximum concentrations for actinomycetes, total living microbial biomass, saprophytic fungi, and total fungi at GR were lower than the minimum values recorded at Great Marsh.

AR results indicate that post-restoration, NH_4^+, NO_3^-, and GWC were the only metrics to shift towards reference conditions immediately after restoration during the 0–2 year age category, with all other soil health parameters decreasing or displaying an undesirable increase (bulk density) (figure S3). Based on this AR response and the temporal patterns (figures 4 and 5), NH_4^+, NO_3^-, and GWC were classified into the fast category (table 1). VWC, bulk density, total nitrogen and organic matter appeared to be more affected by restoration-based disturbance and did not begin to trend towards reference conditions until the 2–5 year age category. Thus, these metrics were grouped under the moderate (2–10) change category in table 1. PLFA values did not indicate consistent uplift towards reference conditions until 10–20 years after restoration, and fungal communities took the longest to reach recovery (figures S3 and 5). Thus, PLFA metrics were assigned to the slow (>10) recovery category (table 1).

Time (in years) required for restored soil metrics to reach reference benchmark conditions (separately for GR and Great Marsh) is presented in figure 7. Soil conditions at GR reference wetland were the most achievable, with bulk density, GWC, VWC, actinomycetes, saprophytic fungi and total fungi abundance, meeting, or exceeding reference conditions immediately after restoration (figure 7). The remainder of the soil health metrics met reference conditions at GR

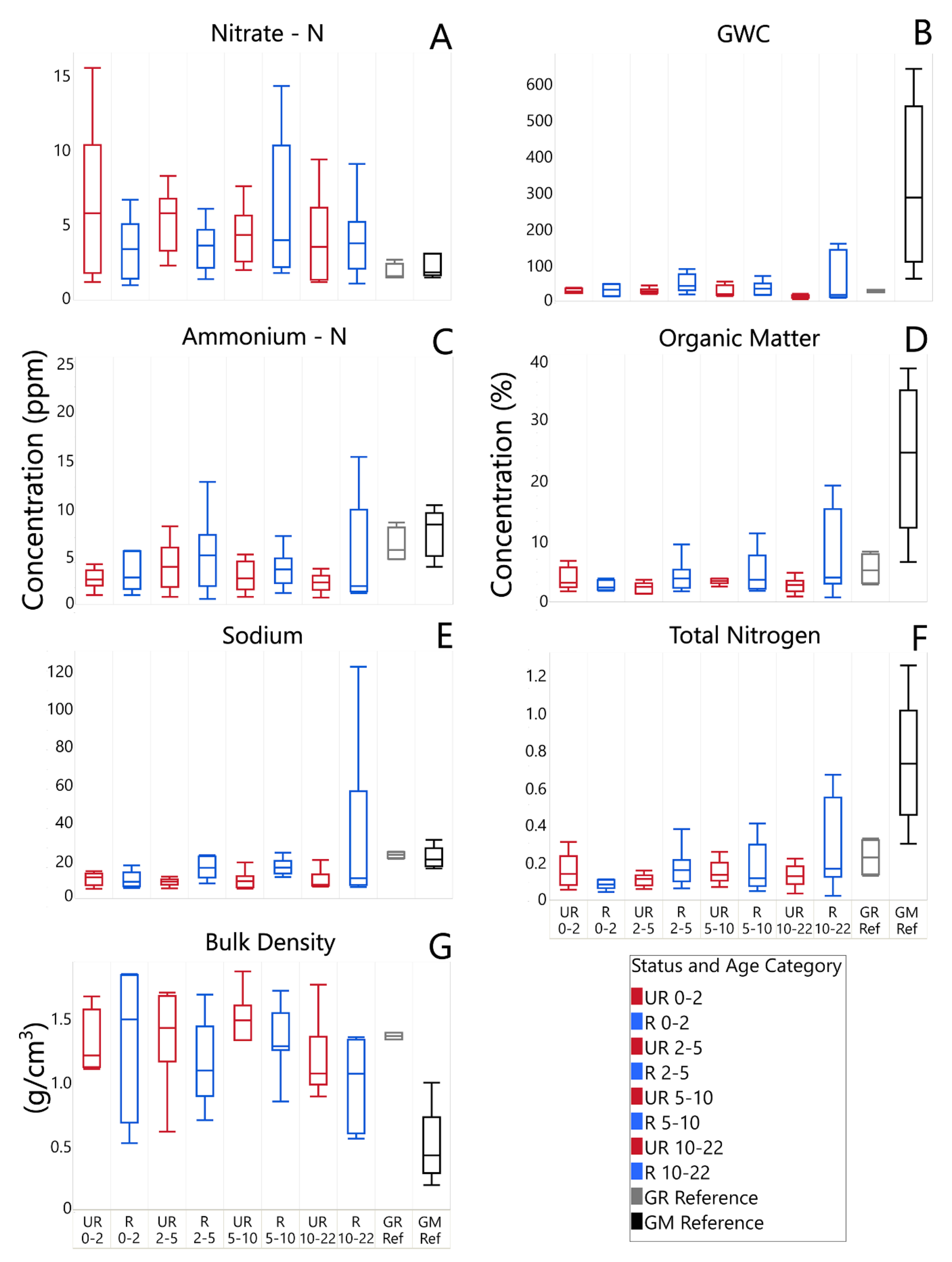

Figure 4. Box and whisker plots of selected soil health parameters that show consistent recovery towards reference conditions over time since restoration-based disturbance. Unrestored sites (UR, red), restored sites (R, blue), Gramies Run (GR) wetland (grey) and Great Marsh (GM, black) show upper and lower quartile ranges with median values shown at the center.

in less than 25 years, except for arbuscular mycorrhizal fungi abundance and NO_3^- (54 and 90 years, respectively, figure 7). When compared with Great Marsh, most of the soil metrics took 50 years or longer to achieve reference conditions, with GWC, VWC, saprophytic fungi and total fungi taking over a century (top right) to make a full recovery (figure 7).

4. Discussion

4.1. How do soil health parameters change following restoration, and which metrics are sensitive and show consistent change?

Virtually all physical, chemical, and microbial (PLFA) metrics were initially impacted by stream and floodplain restoration, but the extent of impact and the

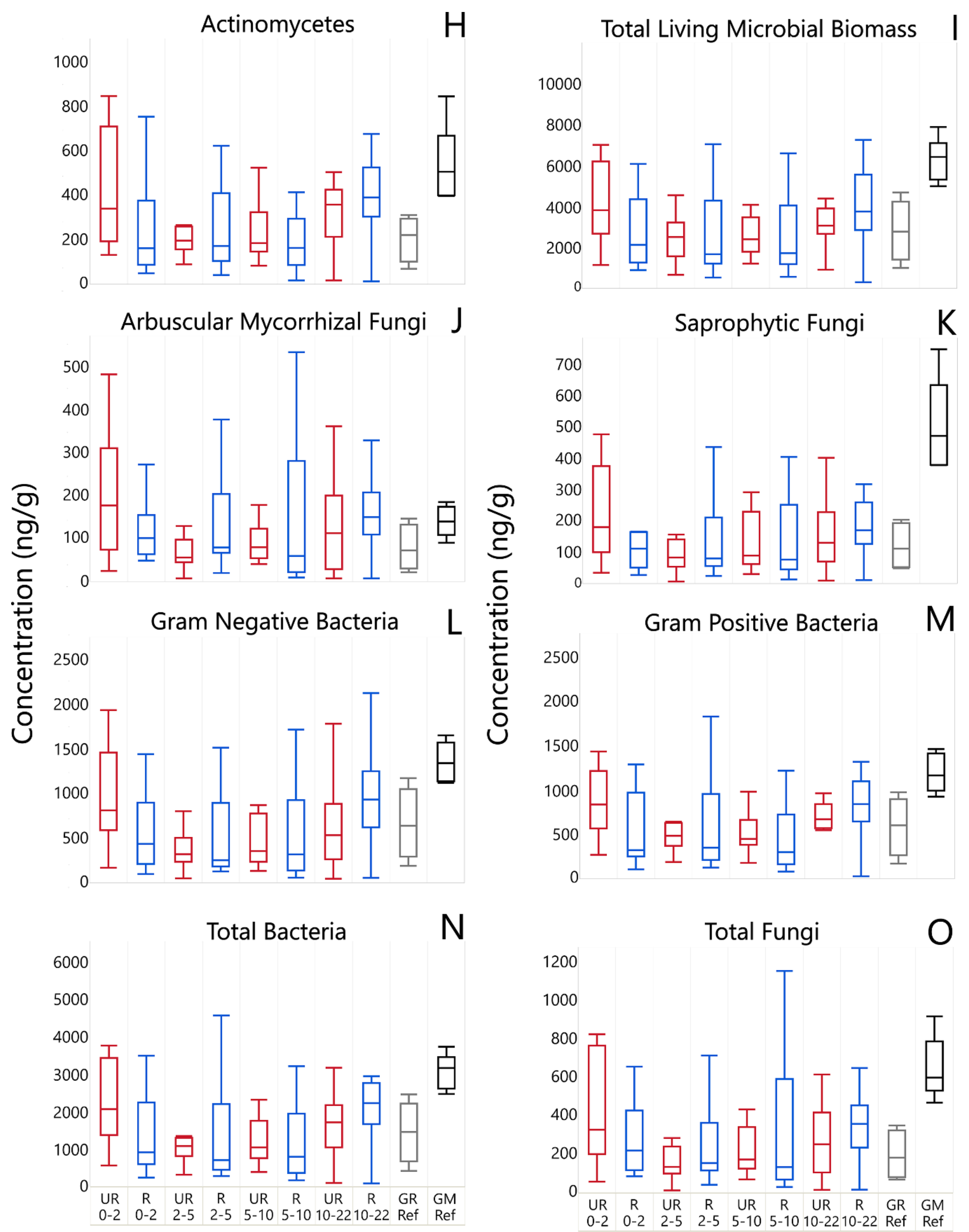

Figure 5. Box and whisker plots of selected soil health parameters that show consistent recovery towards reference conditions over time since restoration-based disturbance. Unrestored sites (UR, red), restored sites (R, blue) Gramies Run (GR) wetland (grey) and Great Marsh (GM, black) show upper and lower quartile ranges with median values shown at the center.

trajectories/rates of recovery post disturbance varied substantially across the soil metrics. These results reveal that soil health parameters differ in their level of sensitivity and resilience. The initial degradation of floodplain soil health depends on the restoration practice adopted, but could include tree removal, soil excavation, sediment removal, and regarding of the banks (Wood *et al* 2022). Regrading could also involve addition of foreign substrates and soil conditioners that could introduce non-native soils and materials. Much of this is accomplished using heavy machinery which results in soil compaction with potentially cascading detrimental effects for soil biogeochemical and microbial properties (Laub *et al* 2013, Inamdar *et al* 2023).

In this study, water content was the fastest metric to recover post-restoration, with GWC (%) improving immediately within the first two years. This is likely related to reconnection of the floodplain (Noe *et al* 2019, McMahon *et al* 2021). Other studies

Soil Health Metric	% Change 0-2	% Change 2-5	% Change 5-10	% Change 10-22	% Change Overall
Bulk Density (g/cm^3)	3.06	-11.70	-8.70	-16.23	-9.86
GWC (%)	10.15	64.62	31.93	360.68	87.49
VWC (%)	-4.18	32.75	20.22	170.78	39.75
Organic Matter (%)	-16.62	81.73	34.16	182.58	69.65
NO_3^- - N (ppm)	-47.28	-26.23	41.32	-0.28	-9.96
Na (ppm)	-2.79	115.11	88.24	227.05	117.28
Organic Carbon (%)	-25.63	92.03	70.80	121.94	74.30
NH_4^+ - N (ppm)	66.89	28.92	29.00	156.87	62.13
Total Nitrogen (%)	-35.88	64.50	18.66	120.89	44.51
Total Living Microbial Biomass PLFA (ng/g)	-36.17	19.89	-14.91	35.25	2.67
Total Bacteria PLFA (ng/g)	-41.86	34.83	-12.10	33.33	4.03
Gram Pos Others PLFA (ng/g)	-38.81	18.09	-24.68	30.53	-1.50
Actinomycetes PLFA (ng/g)	-41.16	21.20	-24.37	22.34	-3.87
Gram Neg Others PLFA (ng/g)	-44.81	68.65	7.36	41.42	13.77
Total Fungi PLFA (ng/g)	-34.13	86.48	10.56	13.18	10.80
Arbuscular Mycorrhizal Fungi PLFA (ng/g)	-35.02	99.55	35.66	0.03	12.96
Saprophytic Fungi PLFA (ng/g)	-33.36	76.98	-6.54	26.38	9.00

Figure 6. Percent change of soil metrics for the four age categories and averaged over the entire study period. Blue bars indicate an increase (improvement, other than bulk density and NO_3^-) and red bars indicate a decrease (degradation, other than bulk density and NO_3^-) in the soil metric. Measured decreases in bulk density and NO_3^- are considered as environmental uplift or improvement.

Table 1. Classification of soil metrics into rate of recovery categories. Fast recovery began immediately after construction was completed in the 0–2 year age category, moderate recovery began during the 2–10 year age category and slow recovery took >10 years to maintain recovery above unrestored values.

Fast recovery (0–2 years)	Moderate recovery (2–10)	Slow recovery (>10)
Gravimetric water content	Volumetric water content	Total living microbial biomass
NO_3^-—N	Bulk density	Total bacteria
NH_4^+—N	Total nitrogen	Gram positive bacteria
	Organic matter	Actinomycetes
		Gram negative bacteria
		Total fungi
		Arbuscular mycorrhizal fungi
		Saprophytic fungi

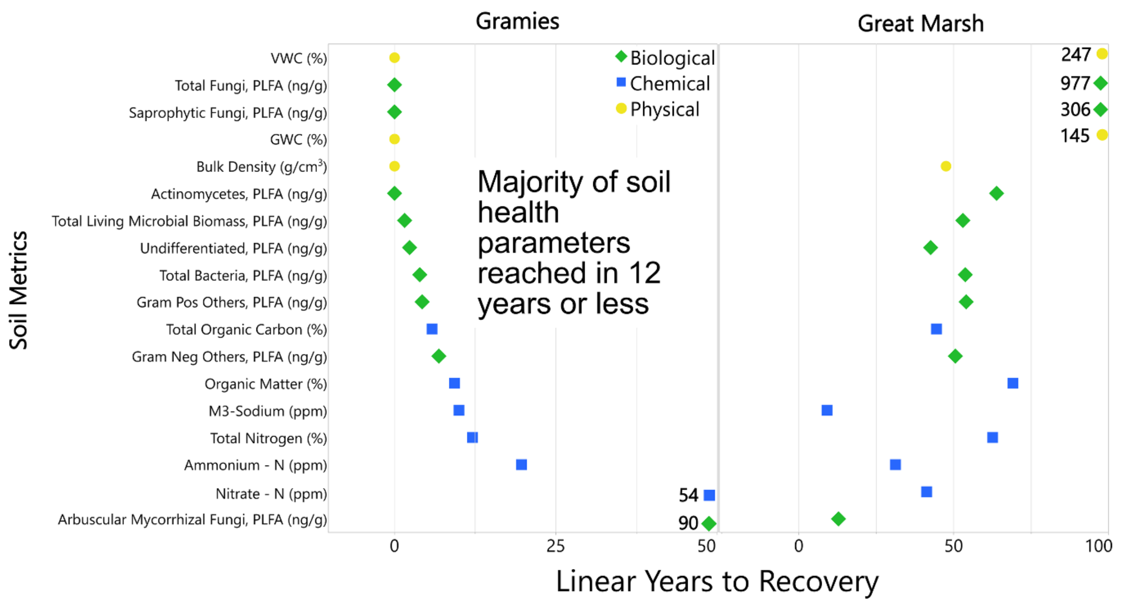

Figure 7. Linear years to recovery for selected soil health metrics when compared against Gramies run and great marsh reference wetlands. Biological, chemical, and physical characteristics are shown by green, blue, and yellow points, respectively. Parameter values that exceed the *x* axis scale are listed with the specific years to recovery (bottom of Gramies panel and top right for great marsh panel).

of restored wetlands and urban stream restorations showed near immediate recovery of GWC as well, increasing within one year of restorations being completed (Brown and Norris 2018, Napora et al 2023). Other fast responding metrics at our sites included soil NH_4^+ and NO_3^- which likely responded to the improved hydrologic reconnection of the floodplain with drying and wetting cycles that accelerated mineralization, nitrification, and denitrification (McMillan and Noe 2017, McMahon et al 2021, Inamdar et al 2023). If restoration practitioners only have a brief (0–2 years) monitoring period post-restoration to assess floodplain soil biogeochemical recovery, GWC, NH_4^+, and NO_3^- are the soil metrics that should be targeted along with water quality indices (Galella et al 2025).

Soil variables that recovered over the 2–5 year period in our study included organic matter, total nitrogen and bulk density and were classified under the moderate category. This recovery rate is similar to those reported by others (Unghire et al 2011, Laub et al 2013, Brown and Norris 2018, Napora et al 2023). Brown and Norris (2018) reported that soil organic matter took a decade to recover to pre-restoration levels. Similar to our findings, organic matter and total nitrogen were found to co-vary for wetland creation projects in PA (Bishel-Machung et al 1996). Napora et al (2023) studied 18 floodplain restoration sites in northern Virginia, US (in the mid-Atlantic region) and found that both total carbon and nitrogen gradually increased through their 1–5 and 6–10 year age categories. They attributed the gains to the gradual recovery of floodplain vegetation (particularly woody) and the retention and incorporation of organic biomass into the soils. While the total amounts of organic matter and nitrogen may register valuable gains over this time frame (5–10 years), the spatial heterogeneity or 'patchiness' of these variables in restored floodplain may still not be achieved (Unghire et al 2011). Given that stream and floodplain projects in the eastern US have a five-year post-restoration monitoring requirement (Wood et al 2020) to demonstrate effectiveness, we recommend that soil health metrics in our fast and moderate categories would be helpful in making this assessment.

PLFA microbial metrics were sensitive to restoration changes but showed the slowest recovery (> 10 years). Compared to physicochemical parameters, PLFA soil microbial assessments have been limited and have yielded mixed results. Mackay et al (2016) studying pasture reforestation of riparian zones in Victoria, Australia, found that PLFA-derived soil microbial metrics remained low for up to 14 years post restoration, but rebounded at the 23 year-old restoration sites. They also found that PLFA microbial metrics were positively correlated with organic carbon and soil moisture, both of which co-varied in the 10–22 year age category in our dataset as well. In comparison, work of Muñoz-Rojas et al (2016) showed that PLFA metrics were sensitive to microbial change four years following restoration and highlighted the differences in restoration treatments; but the restored soil values were still considerably below their reference sites. One potential explanation for the delay in soil microbial recovery could be the lag associated with establishment of mature vegetation and its many benefits, including organic carbon and extensive root and mycorrhizal networks. Early vegetationon disturbed floodplains is typically annuals, herbaceous, and invasive species. These observations, taken together, suggest that PLFA derived soil microbial metrics are valuable indicators of restoration and may help discriminate between restoration practices, but may not change much over the short term. The benefit of PLFA metrics, however, is that they are relatively inexpensive (compared to molecular DNA and RNA methods) and are now being routinely performed by many commercial soil laboratories (easy availability for practitioners) and may not require too much technical expertise for interpretations. Thus, we recommend inclusion of some PLFA metrics, if not all, for floodplain soil health assessments over the short (<5 years) as well as long-term (>5 years). This will also assuage concerns about the lack of meaningful biological assessments in the restoration community and will help link floodplain health to stream biological uplift (Hilderbrand et al 2023).

4.2. How do the restored soil health metrics compare against 'reference' conditions and what does this indicate about the choice of references?

Comparison of soil health metrics from restored sites against the reference benchmark sites revealed significant differences, and these differences were particularly large for the Great Marsh site. At the start of the restoration, nearly all the soil metrics were well below the reference values, with some trending further away from the reference values. As the restoration aged, soil health indices improved and trended towards reference values following different recovery trajectories. The difference between reference sites was so substantial, that for GWC, actinomycetes, total living microbial biomass, saprophytic fungi, and total fungi, the datasets had no overlap. When compared with GR, nearly all but three of the selected soil metrics attained the reference values in 12 years' time. When compared with Great Marsh, many soil health indices required 50 years or more with total fungi taking nearly a millennium to reach reference conditions. Large differences between restored and reference soils as well as long lag times for recovery have also been noted by other studies (Muñoz-Rojas et al 2016, Brown and Norris 2018, Napora et al 2023). Brown and Norris (2018) noted different lag times for various metrics for their wetland restoration site in western New York, US, with GWC (%) recovering after an estimated 37 years, bulk density in ∼27 years, and soil organic matter (%) in ∼74 years.

We had expected that the GR forested/shrub floodplain wetland reference site would likely represent the more realistic and attainable reference conditions, while the Great Marsh site (a freshwater emergent marsh) would represent the upper-end or 'ideal' goal. Our time to recovery values for soil health indices confirmed this assessment and also underscored the challenge and importance of the choice of reference conditions for restoration. Ideally, reference sites should be representative of the historic and contemporary conditions of the restoration sites geographically, ecologically, and with similar biological assemblages and soil morphology (Whittier *et al* 2007). While we did not have the historic details for all the restoration sites, it is very likely that many of the restoration sites were historically (prior to anthropogenic alteration) floodplain wetlands, similar to the GR reference site. In that sense, the GR floodplain wetland was a better reference choice for our restorations than the Great Marsh site. Thus, historic conditions along with the wetland type needs to be considered while selecting a reference site for restoration. In addition, while we were limited to only two sites because of permissions to access sites and funding, a greater number of sites would better capture the spatial and temporal variability of soil parameters and allow for more rigorous assessments of recovery rates. The choice of reference sites should also account for the goals of restoration and the expected time frames for recovery of soil parameters. For stream and floodplain restorations that are typically driven by pollution mitigation and water quality improvement goals, regulatory time frames are typically 20 years or less. Restorations or soil metrics that require longer recovery periods (>25 years) may require more attention to demonstrate improvement within the time frame of assessment. The choice of appropriate references may become especially critical if future restoration credits and/or payments are linked to the achieved restoration of soil health metrics. Thus, these observations emphasize the need for additional research on how we identify and define reference sites and the potential time frames for recovery of soil health metrics.

5. Conclusions and recommendations

Assessment of 37 soil PLFA metrics across a chronosequence of 0–22 years of 11 restored sites and two reference floodplain sites revealed that soil health metrics differed significantly in their sensitivity and resilience and followed different recovery trajectories post restoration. Differences in recovery rates—fast, moderate, and slow allowed us to identify and prioritize soil metrics for post monitoring floodplain assessment. Thus, this study advances scientific understanding of floodplain soil health and importantly, provides valuable guidance for practitioners and the restoration community. Adoption of these recommendations will help formalize inclusion of soil health metrics in floodplain restoration monitoring protocols. This study also highlighted the need to better define reference benchmark sites for restoration. For broader applicability, future soil health studies need to be conducted across a variety of physiographic and eco regions, climate regimes, and across more diverse floodplain and wetland restoration practices.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://zenodo.org/records/15467191.

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Conflict of interest

Authors declare no conflicts of interest.

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