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Perspective

More Than Dirt: Soil Health Needs to Be Emphasized in Stream and Floodplain Restorations

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Abstract: Soil health is not explicitly included in current stream and floodplain restorations. This may be one of the many reasons that stream restorations are not achieving their full restoration and ecological benefits. The lack of design and implementation procedures for providing healthy soils and the absence of specific soil metrics for evaluation are some of the reasons for the non-inclusion of soil health in floodplain restorations. Here, we have brought together a team of researchers and practitioners to provide a blueprint for the inclusion of soil health in floodplain restorations, with a specific emphasis on approaches that may be easily accessible for practitioners. We describe the challenges posed by current restoration procedures for physical, chemical, and biological soil conditions. The top ten soil metrics that could be easily measured and could be leveraged by practitioners to assess floodplain soil conditions before and after restorations were identified and selected. The best design and construction practices for improving soil health on floodplains are presented. We also recommend that the current crediting approaches and regulatory mechanisms for stream restorations be updated to incentivize soil health. The inclusion of soil health will help us attain the ecological services and functional uplift goals that are being targeted by environmental agencies and the restoration community.

Keywords: soil health; floodplain restoration; soil chemistry; microbial ecology; nutrients

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1. Introduction

Stream and floodplain restoration has become a growing billion-dollar environmental industry in the United States and globally [1–4]. The intent of these restorations is to mitigate the degraded status of streams and floodplains, improve water quality and ecological conditions, and return them to a more natural state [5–7]. In the Chesapeake Bay watershed alone, at least USD 400 million has been spent on stream restoration projects since 1990 [8]. Similarly, the Chesapeake and Atlantic Coastal Bays Trust Fund has funded over 200 stream restoration projects, and in the 2019–2020 fiscal year they allocated almost USD 20 million for stream restoration projects [9]. During 2015–2020, both the number of permits and the length of stream restoration increased, with a tripling of the average restoration length from 233 to 670 m [9]. The cost of stream restoration is also significant, at USD 1600–4000 per meter of restored stream length [10]. However, despite gaining popularity and acceptance, many challenges remain, particularly regarding long-term effectiveness, sustainability, and the resiliency of these practices [1,10–12]. Here, we discuss one of the key challenges and knowledge gaps—the importance and lack of consideration of soil health in stream and floodplain restorations. We focused primarily on the Mid-Atlantic US and Chesapeake Bay region as a case study based on our previous work and experience, but our conceptual framework for including soil health has implications for other regions. We brought together a team of stream and floodplain restoration researchers and practitioners to highlight that the current focus on the stream channel form alone, at the expense of floodplain soil health, may preclude restorations from achieving their full ecological potential and may also be undercutting their long-term effectiveness, sustainability, and resiliency.

In the Mid-Atlantic US, the primary motivation of stream restorations is to mitigate sediment and nutrient nonpoint pollution and improve the ecological conditions of stream and river corridors [11,13,14]. Stream and floodplain restoration projects include the reconfiguration of the stream channels; legacy sediment removal (LSR) and floodplain reconnection; and riparian tree planting or revegetation [15–17]. Many of the streams targeted for restoration are highly impaired in terms of water quality and listed on their state's total maximum daily load (TMDL) [18]. Thus, sediment and nutrient improvements and gains from restoration efforts are being leveraged as credits to meet water quality regulatory targets under state and county TMDLs in the Chesapeake Bay watershed [18]. In many cases, the water quality and "functional uplift" or ecological uplift credits play a key role in determining the design of stream restoration and its implementation at a particular site. Functional uplift refers to the potential for the restoration to enhance broader ecological services such as the provision of riparian and aquatic insects and other aquatic biota [19].

For decades, the Natural Channel Design (NCD; [20]) has been the most widely used and popular approach for guiding stream and floodplain restorations, especially in the Chesapeake Bay watershed [16]. This approach has focused on fluvial geomorphic concepts for creating a single-threaded, defined, and stabilized channel set within a hydrologically connected but separated floodplain. The channel design includes the creation of meander bends, pools, and riffles. It also includes changes in the longitudinal stream gradient by raising or lowering the stream bed through logs and cross vanes. Root wads and coarse substrate are also added for bank stability. Collectively, these modifications are designed to decrease stream flow velocities; enhance surface water infiltration; decrease bank erosion and sediment loads; enhance nitrogen (N) removal via denitrification; and foster aquatic habitat [7,11,21].

In addition to the NCD, other approaches such as legacy sediment removal (LSR) and regenerative storm conveyance (RSC) are increasingly being implemented [22,23]. The stream–floodplain connection for all restoration approaches is accomplished by grading the banks so that overbank flooding occurs with storms of a specific return period (1–2 years) [16]. This hydrologic reconnection is assumed to increase the hydrologic residence times of stream and ground water traveling through floodplains, and provide ample opportunities for denitrification, N retention, and transformation on the restored floodplains and fringing wetlands [24]. In addition, there can also be sediment deposition of particulate N and phosphorus (P), which helps to retain nutrients [25–28]. Each of the restoration techniques is applied to achieve channel stability and ecological goals by quantifying aquatic habitat features, the reduction in erosion, and nutrient removal in the stream. However, beyond the addition of some organic matter, very little additional attention is paid to managing and measuring the effects of restoration on the floodplain soil profile [29].

Floodplain soil health, in particular, is given very little consideration in stream restoration projects, especially those following the NCD approach. As defined here, soil health refers to physical, chemical, and biological soil attributes that enhance soil ecosystem functions and services such as infiltration, water retention, reduced surface runoff, erosion control, and nutrient cycling and sequestration [30]. There are multiple reasons for the lack of consideration for soil health in floodplain restoration design: a lack of information about potential "desirable" ecological or soil health endpoints or reference conditions; the unavailability of design and construction protocols or "best practices" for soil health; the absence of specific soil health metrics to evaluate the change in soil conditions pre and post restoration; and a lack of regulatory incentives or credits for enhancing soil health.

We propose that the lack of consideration for soil health in stream restorations is a significant missed opportunity to leverage floodplain hydrologic and biogeochemical processes to meet ecosystem services and objectives. Healthy floodplains provide valuable nutrient removal services such as denitrification [11,31,32] and nutrient retention through sediment trapping [26–28], and they also support broader riparian and ecological health [33]. While stream restoration designers may implicitly include floodplain nutrient removal services due to hydrologic reconnection (e.g., the use of the specific denitrification rates in design protocols; [16]) the non-inclusion of soil health may be undercutting the full potential of such floodplain ecosystem services. Healthy soils rich in organic carbon (C) and microbial communities could potentially sustain higher denitrification rates than those currently assumed for design protocols. Not surprisingly, then, this could be one of the many reasons why stream restorations could be falling short in meeting their pollution and ecological uplift goals [15,19,34].

If we truly want our restorations to succeed and the motivating "Field of Dreams" paradigm—"if you build it, they will come" [35]—driving the restorations to come true, greater attention needs to be paid to enhancing soil health and ecology in stream and floodplain restorations. A similar sentiment in support of soil ecology in restorations was previously voiced by [36,37], and more recently by [38]. Farrell [38] also called for increased collaborations between restoration researchers and practitioners to develop specific protocols that could enhance the inclusion of soil health and ecology in restoration practice.

Below, we discuss the key soil health challenges that current stream restoration design and implementation approaches pose, and propose how these could be reversed. We discuss this from the perspectives of both stream and floodplain restoration researchers and practitioners. We also identify specific soil indices that can be used to characterize soil health, and recommend methods or best practices that can be adopted for improving soil health on restored floodplains. Ecosystem services that healthy floodplain soils provide are also highlighted.

2. Current Restoration Approaches and Challenges for Floodplain Soil Health

The focus on stream channel form in restorations has resulted in a number of challenges for the physical, chemical, and biological components of floodplain soil health (Figure 1). We elaborate on some of the challenges below. We recognize that soil health challenges differ with the types of restoration approaches used (i.e., NCD versus RSC versus LSR), but highlight the common problems reported.

2.1. Challenges for Physical Soil Conditions in Floodplain Restorations

The challenges for physical soil conditions include suboptimal floodplain soil thickness, compacted floodplain soils with low soil porosities and high bulk densities, poor soil aggregation, reduced hydraulic conductivities, low infiltration, and high surface runoff rates (Figure 1; [15,29,39,40]).

Under the NCD criteria, the floodplain soil thickness is typically determined by the depth needed for floodplain hydrologic reconnection. This reconnection is assumed to occur when the streamflow spills over and overtops the floodplains for storms corresponding to specific magnitude and return periods (e.g., 1–2 years; [16]). The floodplain depth can be found by grading the banks (including legacy sediment removal) and/or raising the stream bed. In many instances, however, streams are highly incised with steep banks [12]. The regrading of such banks can result in the exposure of previously buried, highly compacted, coarse-grained and nutrient-poor soils (occasionally containing gravel) at the base of the streambanks. The construction process does not typically control for the compaction of subgrade soils. The removal of trees/forests along the restored floodplains can also contribute to a loss of porous, organic-matter-rich, top soils [17]. While limited "topsoil" or "soil conditioners" or organic matter dressing is provided on the restored floodplain surfaces, the thickness of these layers is constrained by the allowable floodplain design thickness. The end result is suboptimal floodplain thickness with compacted soils with coarse/poor texture.

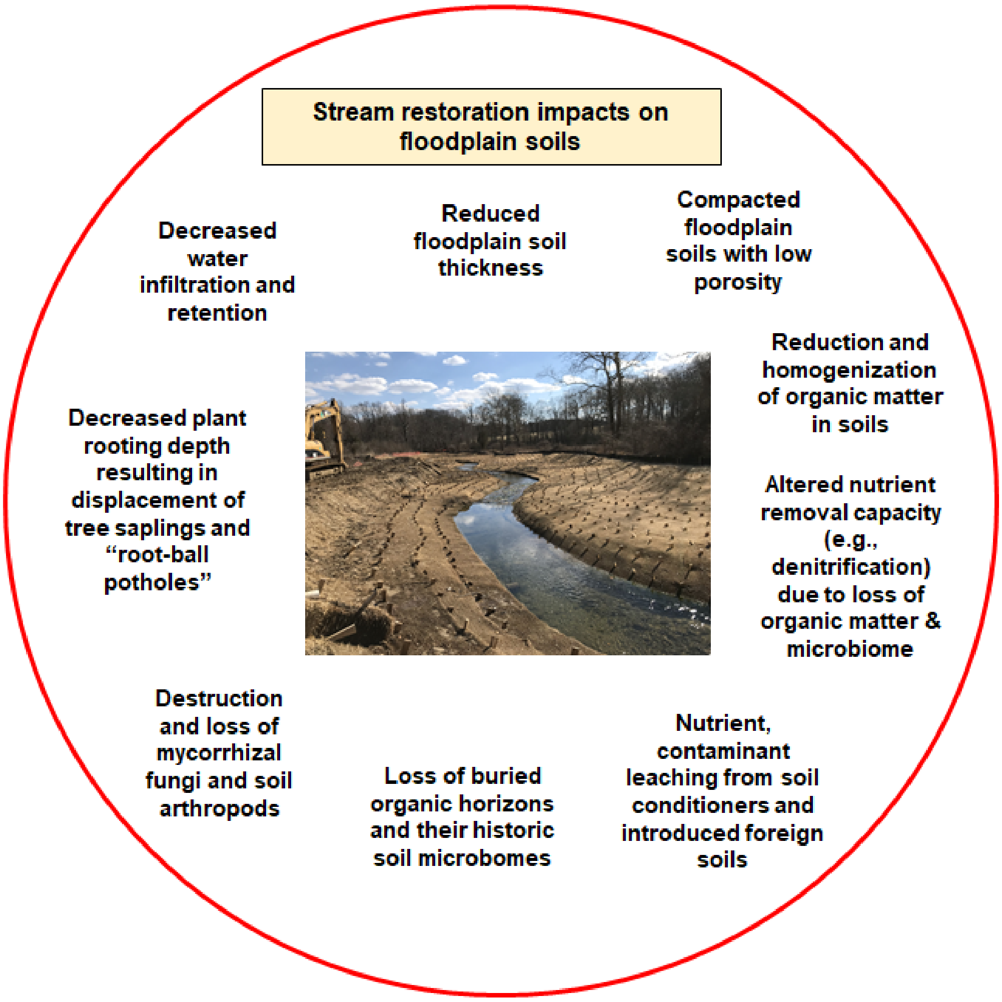

Figure 1. Potential impacts of stream restoration practices on floodplain soils. Lack of consideration for floodplain soil health results in loss of ecosystem services. The photo shows a stream in Cecil County, Maryland immediately after restoration (based on NCD).

In addition to the constraints enforced by site conditions and design features, much of the floodplain regrading and legacy sediment removal is accomplished through the use of heavy excavators and earth moving equipment, with the floodplain surface serving as the primary "work area" and the travel route [39,40]. This results in the further compaction of floodplain soils that were already compacted and of poor quality. This soil compaction decreases the soil porosity, increases bulk density, and subsequently reduces runoff infiltration and increases surface runoff. Laub [39] found that bulk density was 19% and 11% higher in the top 10–20 and 20–30 cm of restored soil layers. Newly restored floodplains with shallow depths and compacted soils result in poor water retention, decreased hydraulic conductivity, and the inability of floodplains to absorb overbank flows, and are especially vulnerable to intense storms that generate large surface runoff that results in bank erosion, including the stripping of the newly installed erosion fabric in some instances (e.g., Figure 2). The erosion of such soils is also expedited by the poor soil aggregation of compacted and organic-poor soils.

Figure 2. Floodplain erosion and fabric tear (arrow) and "potholes" (encircled) created by uprooted plant saplings following a large storm on a recently restored site. Toppled wire meshes used for planted saplings can also be seen in the background on the opposite floodplain. The photo is facing downstream, and the direction of the overbank flows is indicated by the toppled grass in the downstream direction.

2.2. Chemical Components of Soil Health

Poor physical conditions of the soil can have direct negative consequences for chemical/nutrient soil processes and functions (Figure 1). In addition to direct impacts through compaction, restoration practices result in a decrease in the amount of soil organic matter and its reduced spatial variability on floodplains [15,39,40]. Laub [39] found a 16% and 49% decrease in soil organic matter and root biomass, respectively, for surficial (10–20 cm) soils following restoration. Unghire [40] not only reported a significant decrease in soil organic matter from a mean of 9.6% pre-restoration to 6.9% three years post-restoration, but also found that the restoration resulted in a spatial homogenization of soil organic matter across the floodplain surface and a loss of "hot spots" or pockets of elevated organic matter concentrations. Spatial variability in soil organic matter is important for soil nutrient functions, with locations of elevated organic matter typically serving as hot spots for biogeochemical processes such as denitrification [41]. The loss of spatial variability in soil organic matter was attributed to the mixing and redistribution of soils on the restored floodplains as well as the oxidation of organic matter during the mixing and overturning of the soils [40]. This oxidation of the organic matter can also release inorganic nutrients (e.g., N and P) and other carbon-bound contaminants and enhance their leaching to stream waters, particularly in the initial period (1–5 years) following restoration [42].

In addition to the surficial loss of organic matter, the regrading of floodplains could result in the removal and loss of buried, relict organic soil horizons [12]. In the Mid-Atlantic US, many of the precolonial marsh and wetland organic soil horizons were buried by legacy sediments as a result of widespread agricultural erosion and sedimentation in the 17th–19th centuries [43–49]. The removal or retention of these relict organic horizons during floodplain restorations depends on their depth vis à vis the new floodplain surface and the restoration approach used (NCD or LSR). Where the stream has incised considerably and the new NCD designed floodplain surface is below the relict horizon, these layers are typically not incorporated in the restored floodplain [12]. In contrast to NCD, LSR restoration approaches will typically retain such relict horizons [23,50]. A loss of native soil horizons is not beneficial for the new nutrient regime of the restored floodplains.

Even where such relict hydric horizons are retained and leveraged into the restored floodplains, soil nutrient cycling services may take time to recover. Clague [51] found that the denitrification rates were lower for buried subsoils than the surficial A horizon.

Similarly, Mattern [12] reported very low denitrification rates for buried organic horizons despite the presence of associated microbes. Some of the reasons could be that the buried C is more recalcitrant than that for the surficial soil, or that the metabolic capacity of the buried microbial community is lower than the surficial soils [51,52]. While the organic C and N content of these relict organic layers may be lower than the surficial organic horizons, they likely still represent a valuable reservoir of native soil microbiome and seeds [50,53] that could potentially play an important role in enhancing nutrient cycling and biodiversity.

Where the excavated stream bank material is not enough and/or of appropriate quality, commercially available organic material and soils, soil amendments, or soils from offsite locations are imported and used for grading and topdressing the floodplain surfaces. Typically, none of these foreign materials and soils are tested for nutrients or contaminants before use. The use of these foreign soils, especially if they contain construction material and/or nutrient-rich amendments (e.g., compost or manure), could increase the pH and leaching of nutrients and other contaminants from the newly restored floodplain surfaces [15,22,42,54]. We also need to recognize that the hydrologic, redox and biogeochemical conditions of the newly restored floodplains are likely very different from pre-restoration bank conditions, and would likely have a different effect (from pre-restoration conditions) on the release and leaching of soils whether they come from an external source or are sourced from the original streambank itself. In addition, the removal of mature trees and vegetation during the construction process can disrupt soils and significantly enhance C and nutrient mineralization and transport to groundwater and streams during the early phases of stream and floodplain restoration [17].

An emerging issue, especially in urban landscapes, which could affect floodplain restorations, is the salinization of urban streams and rivers from road salts, the weathering of impervious surfaces, sewage, and other sources [55–57]. This salinization could reduce the effectiveness of riparian zones and floodplain restoration BMPs in retaining nutrients, metals, and other contaminants [57,58]. For example, Na^+ in road salts has been shown to displace ammonium-N ions from soil sorption surfaces, depress nitrification and denitrification processes, and enhance N mineralization [59–62]. In addition, soil aggregation and the quality of organic matter can be altered from salinization due to the dispersive and cation bridging effects of Na^+ [61]. Thus, restored floodplain soils that are in greater contact with salty stream waters could potentially switch from a sink to a source of nutrients and contaminants.

2.3. Biological Soil Health and Diversity

Compared to physical and chemical soil conditions, biological health and biodiversity in soils have received even less attention in stream and floodplain restorations [38,63]. Much of the biological focus with regard to riparian plants and biodiversity in stream restorations to date has primarily been on native versus invasive/exotic plant species and the evolution of plant diversity post restoration [15]. These studies yield mixed results, with some indicating increasing invasive and exotic plant encroachment on newly restored floodplains and others reporting no significant change [15]. Though a variety of factors such as post-restoration planting, local climate and hydrology, and watershed-wide land use are likely come into play, floodplain soil health is likely an important contributor to vegetation survival and succession on restored riparian/floodplain sites. The compacted and disturbed soils could, however, provide a favorable environment for the establishment and proliferation of pioneer non-native and invasive plants [15]. In addition, a shallow floodplain soil thickness with compacted soils limits root growth [64] and do not provide a robust substrate for plants and trees to anchor into and survive the erosive forces of large storms. Toppled and displaced tree saplings and plants, along with “root-ball potholes”, are a common sight in such conditions (e.g., Figure 2). This sight is especially common when the floodplains are subjected to large rainfall and storm events immediately after restoration. Indeed, climate change is likely going to increase the frequency and intensity of such storms, with the possibility of increased incidences of such erosive events [65].

Floodplain construction practices probably have the greatest impacts on surface and subsurface soil microbiomes and their functions. Low porosity and high bulk density soils will provide a poor environment for microbes involved in nutrient cycling and removal [37,66], which can be further aggravated by a lack of organic matter in the soils [67]. Buried soils, including the relict hydric soils (Figure 3), have typically been reported to have lower metabolic microbial activity compared to organic horizons at the surface [52]. Thus, when these buried streambank soils are exposed at the floodplain surface, a new soil microbiome regime is likely established. This change could be even more dramatic and likely detrimental for nutrient processing, if foreign soils with a completely different microbiome community are introduced at the site.

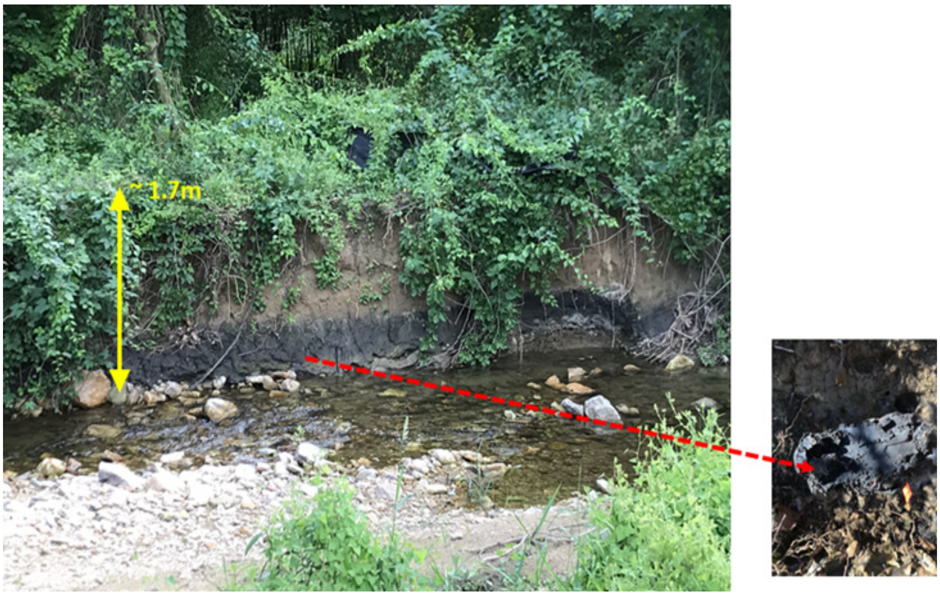

Figure 3. Buried organic horizon along Gramies Run in Cecil County, Maryland, that was carbon-dated to 950 ± 30 BP [12]. These precolonial organic horizons buried under light-colored legacy sediments are especially common in the Mid-Atlantic United States. Currently, there are no specific guidelines on how these historic hydric soils should be preserved and retained in stream and floodplain restorations, and this void typically results in a loss of these horizons during restorations.

Some studies suggest that microbial processes such as denitrification may be virtually nonexistent for long buried soils since the microbial communities responsible are either dead or in hibernation [68,69]. Others, however, have reported that denitrification does occur, but the process rates may initially be very slow and significant recovery could take 1–2 years or more [70,71]. Beyond denitrification, we also know very little about the response of other microbial N processes such as mineralization and nitrification when buried soils are exposed on the floodplains. Surprisingly, our understanding of how buried, relict, hydric soils respond to floodplain restoration and how microbes "wake up" [72] following deep hibernation is extremely poor and limited and needs more attention.

Excavation of the stream banks, overturning and mixing of surficial soils, and regrading of the floodplains also substantially alters, if not destroys, the valuable network of mycorrhizal fungi in the soils. Mycorrhizal fungi produce glomalin, the glycoprotein that has been shown to help with soil aggregation and stability [73]. While bacteria contribute to the formation of micro-aggregates, fungi are the builders of macro-aggregates. Mycorrhizal fungi are also the heavy movers and miners of the subterranean surface [74]. They mine nutrients such as N and P from distal locations on soils and rock surfaces, and transport or move them to the plants in exchange for sugars [75]. Beyond supplying nutrients, healthy mycorrhizal populations also enhance the capacity and resiliency of plants to fight off infections and survive environmental stresses such as those associated with droughts [76].

In the absence of such a support network, it is difficult for newly planted shrubs and tree saplings, particularly native species, to survive on restored floodplain surfaces or in alien/foreign floodplain soils [76].

3. Recommendations for Improving Floodplain Soil Health

The lack of consideration and implementation of soil health in contemporary stream and floodplain restorations is likely a consequence of multiple factors, including (a) an absence of information on specific soil metrics or indices that can be used to monitor the physical, chemical, and biological health of soils and their evolution over time; (b) the unavailability of specific construction and design protocols for providing and maintaining healthy soils on floodplains; (c) the absence of "reference soil conditions" or desired soil health endpoints for restoration and realistic timeframes over which they can be accomplished; and (d) a lack of credits or regulatory benefits that restoration agencies can receive for considering soil health. These knowledge gaps and methods to incentivize soil health need to be addressed to allow for the greater inclusion of healthy soils in floodplain restoration practice. Below, we provide our recommendations for indices evaluating soil health during the stream and floodplain restoration process.

3.1. Soil Indices/Metrics to Characterize Physical, Chemical, and Biological Soil Health

In the absence of specific metrics or indices to characterize soil physical, chemical, and biological health, it is very difficult to assess soil conditions pre- and post-restoration and if and how they evolve with time. Fortunately, this lack of information on soil health metrics has been acknowledged by many researchers and there are increasing efforts to identify and develop robust and reliable soil health metrics. New initiatives have been launched in the agricultural science community to identify soil health parameters for cropland soils [77], with similar efforts, past and present, in the restoration community [63,78–80]. These studies provide valuable initial guidance for the selection of such metrics for floodplain restorations. Important criteria that should be considered in selecting soil quality metrics for floodplain restorations are: (a) indices should be able to characterize and quantify the key functions or ecosystem services that the floodplains are providing (e.g., water retention, N removal, etc.); (b) they should be sensitive to various restoration and management treatments and should have low variability; (c) indices should be easy to implement and interpret by practitioners; (d) they should be easily analyzed and be cost effective; and (e) metrics should be applicable to crediting protocols or regulatory requirements to provide incentives for implementation. The last three criteria are particularly critical if we are to encourage practitioners to routinely implement these metrics as a part of their restoration projects. Furthermore, Lozano-Baez [63] also recommended that these assessments should not just be limited to surficial soils (<20 cm), but should extend to the full soil profile being disturbed and restored.

An initial shortlist of potential soil health indices that could be considered for floodplain restorations is provided in Table 1, along with the motivations for use and the analytical methods and citations. This list is derived from some of the recommendations provided by [77] for agricultural soils, but modified for natural floodplains, and is in no measure complete or exhaustive. It may be preferable to start with a smaller set of metrics and standard methods that practitioners can easily adopt (e.g., the "top 10" list of metrics highlighted in Table 1), and subsequently expand the metrics as the technology and availability of the methods improves and becomes more cost effective. Some suggestions for more "advanced" metrics are also included. Establishing links between easily measured soil metrics with complex and beneficial soil biome functions will allow for economical monitoring to determine effectiveness. If these functions can be associated with established environmental regulations or with a crediting protocol, there will be an incentive for practitioners to implement these soil conditions in future stream designs.

Table 1. Potential list of top 10 indices (in bold) or metrics that could be used to assess the physical, chemical, and biological health of soils on restored floodplains (modified from [77] for floodplains). Indices indicated with an asterisk are advanced tests that could be implemented if these are accessible and cost effective for the practitioners.

Soil Metric	Motivation/Used For	Method/Citation
	Physical soil properties	
Bulk density	Compaction	[81]
Penetration test	Compaction	Using a penetrometer; [82]
Porosity	Compaction, water retention, nutrient conditions, microbial habitat	Derived from bulk density measurements; [83]
Texture	Basic soil metric used for numerous other soil properties	[84]
Aggregate stability	Potential for erosion resistance	[85]
In situ infiltration rate	Water retention; potential for surface runoff and erosion	[86]
	Chemical soil properties	
pH and organic matter	Basic chemical condition	[87]; loss on ignition
Electric conductivity	Presence of ions and metals, salinization	Hand-held electric conductivity sensor—e.g., Hanna Soil Test meter.
Total C and N	C and N sequestration	[88]
Nitrate-N and ammonium-N by KCl extraction	Inorganic N removal and retention in soils	[89]
* Mehlich-3 extraction for select cations and metals	Phosphorus and metal content and removal	[90]
	Biological soil properties	
Phospholipid fatty acids (PLFAs)	Broader test for active microbial biomass; fungi to bacteria ratio	[91]
* Genomics—16S rRNA	More specific microbial composition	[92]
Fine root biomass	Potential for plant growth and recovery	[93]

3.2. A Top 10 List of Soil Metrics (See Table 1)

Soil bulk density: bulk density is a standard and routine soil metric that has been used widely and can be easily adopted for assessing the compaction of floodplains using heavy equipment (Table 1). Hale [79] recommended bulk density as a promising metric which had low variability and direct relevance to restoration effects on soils. Soil bulk density can also be used to compute the total soil porosity, which is a valuable soil physical characteristic which affects a suite of soil chemical and biological functions [81]. More recently, commercially available soil penetrometers (e.g., Gemplers Spot-On digital compaction meter) have also become available that could provide a quick estimate of soil compaction and bulk density [82].

Soil Texture: Similar to bulk density, soil texture (% sand, silt and clay contents) is a basic soil physical property that has important implications for numerous other soil processes and functions. Soil removal or the introduction of foreign soils to floodplains could directly alter the soil texture and associated soil properties.

Soil Aggregate Stability: Soil aggregate stability would likely decrease considerably following restoration because of the disturbance and overturning of floodplain soils, but could increase/improve with time with an increase in soil organic matter and biological communities [83]. Both bulk density and aggregate stability would be expected to be fairly sensitive to restoration disturbance and treatments. A direct measure of water retention and surface runoff production for restored floodplain soils could be gained from an in situ water infiltration test. This infiltration rate is a function of bulk density and aggregate stability and will directly address one of the key functions of floodplain restorations.

Soil pH and organic matter (SOM): Soil pH and SOM are key first-order chemical properties that influence a host of other soil properties as well as functions and processes. These metrics are expected to change considerably following restoration [40]. It is likely that SOM values may be spatially uniform immediately following restoration, but could vary spatially with time—a desirable result. Assessing such changes would require a spatially distributed sampling pattern across the restored floodplain with multiple sampling locations.

Soil electric conductivity: Soil electric conductivity is a good proxy for the concentrations of various ions in floodplain soils and a good indicator of salinization effects on floodplains. This metric could be used to assess how floodplain soils evolve following restoration, and could be easily assessed via hand-held conductivity meters such as a Hanna Soil test meter (Table 1). Other, more advanced soil metrics could include the cation exchange capacity or the sodium adsorption ratio to assess the effects of sodium on other cations [83].

Soil C and N contents: The total C and N contents of soils were the other two promising metrics recommended by [79] for their functional relevance and low variability. The determination of these metrics will directly address the C and N sequestration and removal (via denitrification for N) functions of restored floodplains. Similarly, soil nitrate-N and ammonium-N are also key measures for N removal in floodplain soils. These can be highly variable, both spatially and temporally [79], and thus may require a greater extent of sampling (sample numbers).

Soil ions/metals: Additional insights into key nutrients (e.g., P) and ions/metals (e.g., sodium and iron) could be provided by Mehlich-3 extractable tests [94,95]; however, the cost and labor associated with these tests could be a factor in their use by practitioners.

Soil N processes: While there are potential denitrification enzyme assays [96] for the characterization of soil denitrification rates, they are not easily available (primarily conducted by researchers) and are labor intensive and expensive, and thus may not be practical for practitioners to deploy on a routine basis.

Soil microbial characterization: In comparison with soil physical and chemical analysis, biological and, particularly, microbial characterizations for soils would be more expensive and labor-intensive but could provide important integrated insights into soil ecological recovery post restoration. Given that the microbial components may be responsible for 90% of the soil ecosystem functions [97], they could be more sensitive compared to the physical and chemical characteristics [63,98].

Soil microbial/PLFA test: One of the quickest and most inexpensive ways to assess total active microbial biomass would be through soil phospholipid fatty acid analyses (PLFA) [99]. PLFA methods may not provide the level of phylogenetic microbial resolution that genomic methods (e.g., rRNA) do, but they may be more sensitive in determining the changes in microbial biomass as a result of restoration treatments [100]. Importantly, PLFA methods characterize the metabolically active part of the microbial community [101], which may be very useful in determining how buried, relict organic soils with inactive microbial communities evolve when subjected to labile C input [52]. A similar change/input of labile C would be expected when buried organic soils are exposed to the surface of restored floodplains.

The PLFA analysis also provides the fungi/bacteria ratio, which may be a valuable metric for assessing the recovery of fungi and bacteria post restoration [80]. PLFA analysis is also typically provided by commercial environmental analytical labs, which may make it more accessible and attractive for restoration practitioners. Where a greater level of microbial community resolution is required, genomic 16S rRNA techniques could be assessed, but these would require a greater level of knowledge and expertise for the interpretation of the results.

Fine Root Biomass: Beyond microbes, other larger scale and higher-level biological assessments could involve determining the fine root biomass in floodplain soils. Fine root biomass (Table 1) would likely be a relatively easy test for practitioners to implement, with some guidance. While microbial responses would likely be apparent within weeks to months post restoration, the higher-level fine root responses may require months to years to yield significant change but may be a strong, integrated indicator of improving soil health for plant growth. Other higher-level metrics such as soil insects or earthworm populations could also provide a similar integrated response, but would require additional guidance and expertise for their interpretation (which may not be an issue for restoration companies with biologists and ecologists).

3.3. Best Practices for Healthy Soils on Restored Floodplains

Best practices will have to be developed by the restoration community to allow for the provision of healthy soils on restored floodplains. These could include design, construction, and regulatory approaches that incentivize soil health. Here, we briefly describe some best practices that can be easily adopted.

The provision of appropriate floodplain soil thicknesses and the avoidance of soil compaction during construction are likely the most important practices that practitioners can immediately and most easily implement. For restoration designs following the NCD approach, floodplain soil thickness could be reached by raising the stream bed to the level that allows for the designed overbank flooding and floodplain reconnection. A depth of 40–50 cm or more of uncompacted, organic rich soil would likely be needed to provide an adequate substrate for plant roots and growth and a healthy microbial environment. Floodplain soil compaction could be avoided by using the stream channel as the “work area” during restoration. This would likely increase the level of compaction for the stream bed and its hyporheic environment, but given the typically gravelly and coarser texture of this substratum it could be the lesser of the two evils.

The provision of topsoil that is organic-rich and microbially active is another key challenge for floodplain restorations. An evaluation of studies using organic amendments including topsoil and “allochthonous organic matter” (e.g., compost and manure) by [54] indicated that topsoil, overall, was more favorable for the restoration sites. Another study [102] in a marsh community indicated that topsoil favored the growth of the desired plant species over the more undesirable ones. One option, as recommended by [38], would be to excavate and save the native, pre-restoration topsoil from the restoration site and reuse it on the newly created floodplain surface. Such an approach would be ideal if the topsoil was not contaminated with chemicals and/or exotic species and their microbiome and seeds were intact. While spreading this topsoil on the new floodplain surface, care should be taken to avoid a homogenous distribution of organic matter spatially and with soil depth. Pockets or locations of elevated concentrations of organic matter or C may be preferred so as to create hot spots of biogeochemical activity [40] on the floodplain. If commercial soil conditioners or offsite organic soils are imported, they should be tested for nutrients or contaminants that could leach following their application to the restored floodplain surface. Where floodplain soil compaction is unavoidable or where the subsurface soil layer (following legacy sediment excavation) is compacted, contractors could implement spike, core, or plug aeration methods similar to those used by turf or lawn professionals [103] to increase soil porosity.

If buried, relict, organic soil horizons are exposed to the surface of the restored floodplain, care should be taken (using the erosion fabric as protection) to avoid their erosion and loss/removal with erosive flows associated with intense storm events. In addition, as indicated earlier, the microbial community of such buried soils could be inactive or dormant. Buried organic horizons at the Gramies Run restoration [12] indicated an active

PLFA-derived microbial biomass of only 15 nmol/g and a fungi/bacteria ratio of zero compared to values of 117 nmol/g and 0.59, respectively, for the surficial soil of a contemporary wetland located less than 100 m away. This suggests that the microbial communities in the buried organic soil profile would likely not be able to participate in floodplain biogeochemical (e.g., denitrification) and plant support processes right away, and could take some time for recovery. One potential option to enhance the soil microbiome of the relict soils in such cases would be to inoculate the soil with the native soil microbiome from adjoining wetlands or "reference" sites in the vicinity—like the adjacent wetland complex at Gramies Run. It is expected that such inoculation could stimulate the recovery of bacteria and fungi and associated biogeochemical processes and other microbial services in the relict soils [37]. Such approaches have been tried elsewhere, and have yielded both positive [76] as well as negative [104] outcomes. The recovery of relict, historic soil microbiomes would also be valuable in terms of enhancing floodplain microbiome diversity and contribute to the "rewilding" of the landscape [105]. Following the "Old Friends" hypothesis (that humans/mammals have coevolved with an array of organisms that help to train and regulate our immune systems), the diversification of soil microbiomes, particularly in urban and ecologically degraded green spaces, can provide important biodiversity gains that could extend to providing human health benefits [105,106].

Changes in the soil microbiome also raise other key challenges that are faced by the restoration community—i.e., what are the desired soil health end points or targets for floodplain restorations, and what is the time frame over which restored floodplains can be expected to recover to meet the endpoints? Desired soil health endpoints can likely be set using some of the soil indices and metrics (identified in the previous section) for reference or using undisturbed sites in the vicinity of the restoration location. For example, the PLFA value of 117 nmol/g for the undisturbed wetland soils can be considered a target endpoint for surficial microbial biomass for the restored floodplain at Gramies Run. Similar comparisons against reference sites could be established for other soil indices listed in Table 1, and would enable a more useful evaluation of restoration sites [107]. However, identifying the time frame over which these targets could be achieved is much more challenging.

Very little research exists that has evaluated how floodplain soil characteristics evolve over time post-restoration, and if and when they attain the desired conditions reported for reference or undisturbed sites. The studies that exist, including those for wetland restorations, suggest that soil health recovery post-restoration could be slow and take many years to reach the desirable conditions [80]. More research and information, however, is needed on this issue to provide robust and reliable guidance for restoration practitioners. One approach would be to conduct a thorough assessment of soil health indices (e.g., in Table 1) for selected reference sites and restored floodplain soils spanning a range of time periods (e.g., 0 to 30 years) since restoration. If the assessment has a sufficient spatial and temporal sampling resolution, it could help to identify which soil metrics are most sensitive to change, how and at what rate they evolve with time, and whether the restored site soil health metrics approach the reference or target values.

Finally, one of the best ways to ensure that good soil health practices are implemented for floodplain restorations is to incentivize their inclusion through restoration credits or similar regulatory mechanisms. For example, in the Chesapeake Bay region, water quality managers, municipalities/counties, and restoration designers receive pollution reduction credits for implementing stream restorations that mitigate sediment and nutrient (N and P) pollution. This is accomplished through specific design protocols (#s 1–5) developed by an Urban Stormwater Workgroup made up of regulators, restoration practitioners and researchers [16]. The current Chesapeake Bay protocols are, however, focused primarily on the hydraulics and hydrology of the stream–floodplain connection and do not explicitly consider soil health attributes for nutrient reduction. We propose that these protocols could be revised, or preferably a new protocol (e.g., #6) could be developed that explicitly accounts for soil health through the inclusion of the best practices and soil metrics described above. For example, environmental credits could be provided for implementing a specific soil depth on floodplains; achieving a healthy soil bulk density or organic matter content for restored soils; leveraging buried historic soil horizons in the restoration; and having a vigorous microbial biomass (determined by PLFA, Table 1) post restoration. By including soil health, restoration practitioners and environmental agencies will not only enhance sediment and nutrient reductions, but achieve broader habitat and ecosystem services (see Figure 4) and thus receive additional credits for the attainment of such services.

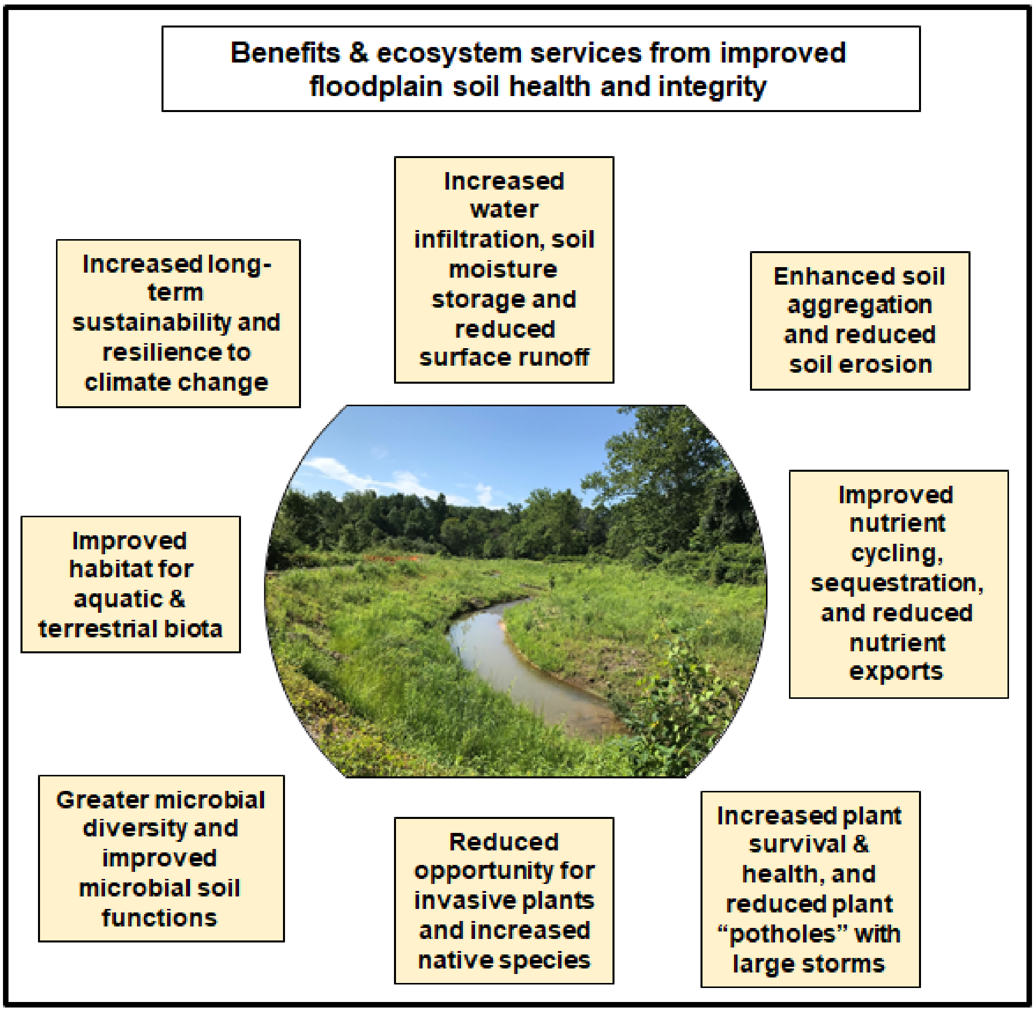

Figure 4. Ecosystem benefits and services expected from improved floodplain soil health and management.

4. Conclusions

Due to the lack of specific design and construction guidelines, soil metrics for evaluation, and regulatory incentives, soil health is not currently included or addressed in stream and floodplain restorations. Given the critical role of soils in facilitating a variety of ecosystem services, the widespread implementation of stream restorations, and the large amounts of money being invested in these restorations, the non-inclusion of soil health is a missed opportunity. Here, we present a blueprint of how we can enhance floodplain restorations through best practices for soil health and the use of specific soil metrics to design and evaluate soil health over time. The implementation of these guidelines will help to truly attain the ecological and functional uplift that is elusive in current restoration approaches.

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