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Spatial Variability of Sediment Nutrient Storage Across Restored and Undisturbed Wetland Habitats

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Abstract: The sediments in wetlands are reservoirs of carbon, nitrogen, and phosphorus, although their concentrations vary significantly depending on the particular habitat, making it difficult to assess the success of a restoration project based on reference data from undisturbed wetlands. This paper investigates how the nutrient storage in wetland sediments varies depending on the particular habitat and how these differences are related to the data on nutrient storage in undisturbed wetlands. The concentration of total carbon, total nitrogen, and total phosphorus in surface sediments was calculated for each particular habitat separately within three sequential cell treatment wetlands, two restored floodplain wetlands and adjacent croplands, and was evaluated using a systematic literature review of twelve scientific articles published from 2014 until 2022. Carbon stocks ranged from 27.5 to 46.5 g kg^{-1} and nitrogen from 2.60 to 3.90 g kg^{-1}, with the richest ecosystems storing up to 69 % and 50 % more carbon and nitrogen, respectively, than croplands. Phosphorus stocks had a different distribution, varying from 499 to 831 mg kg^{-1}, with the values being lower in three out of five studied wetlands, so that there was almost no correlation between phosphorus stocks and those of carbon and nitrogen (correlation coefficient between carbon and nitrogen $r = 0.99$; correlation coefficient between carbon and phosphorus $r = 0.24$). Literature review suggests that restored wetlands tend to be behind their natural analogues with regard to carbon and nitrogen for about one to two decades. Thus, monitoring programmes have to sample habitats separately and assess nutrient stocks independently.

Keywords: Sediment Nutrients; Spatial Variability; Wetland Restoration; Reference Wetlands; Carbon; Nitrogen; Phosphorus.

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I. Introduction

Wetland sediments are known to be one of the best natural sinks for carbon, nitrogen and phosphorus. Nutrient retention occurs through sedimentation of minerals and organic matter, burial of plant litter and roots, biotransformation and sorption on mineral surfaces, which, in turn, are responsible for the functioning of wetlands in improving water quality, sequestering carbon and providing habitats. Due to extensive draining and cultivation of wetlands, considerable effort has been put into their restoration, and the amount of nutrients retained in restored sediments has become one of the indicators of success.

It is still unclear whether restored sediments will be as efficient in terms of nutrient retention as natural undisturbed wetlands. A recent study of a hydrologically restored riparian wetland demonstrated that total carbon, total nitrogen and phosphorus were less in all restored sites compared to a reference site (Koontz et al., 2014). Organic carbon and nutrients pools in restored depressional wetlands in the Glaciated Interior Plains of the USA five to ten years after restoration have been found smaller compared to those in natural depressional wetlands, while restored riparian buffers have achieved the state of natural buffers already in four years (Marton et al., 2014). Restoration, therefore, is influenced by hydrogeomorphic setting, land use prior to restoration and time since the restoration, and using the mean value as a proxy for the entire restored area will obscure many of these dependencies.

The mean value obscures spatial variability. A comparison between a restored and a natural floodplain demonstrated greater variability in denitrification in the former one and absence of the spatial variability observed in the latter, due, in part, to different land use prior to restoration (Orr et al., 2014). Spatial variability is important for at least three reasons. First, ignoring it may result in misestimation of nutrient pools and classification of restoration success. Second, habitats within one wetland may show as much

difference as different wetlands. Third, carbon, nitrogen and phosphorus do not have to vary together, so accumulation of carbon does not imply retention of phosphorus.

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II. Literature Review

Recovery of Sediment Nutrient Stores After Restoration

Synthesis of studies conducted in the entire U.S. found that carbon and nitrogen contents in restored and created wetlands were still 52% and 50% lower than in natural wetlands, respectively, 11 to 20 years post-restoration. The rate of recovery was higher in restored compared to created wetlands, and the two primary abiotic controls were mean annual temperature and soil texture (Yu et al., 2017). As can be seen from the long recovery time period, comparisons between restored and undisturbed habitats should consider not only the hydrogeomorphic environment but also the age of the site in question, and the restored site could have higher contents than the pre-habitat, yet be far behind the undisturbed one.

This synthesis also showed that there was a positive relationship between the recovery of carbon and nitrogen, consistent with the idea that nitrogen limitation would be relieved as the buildup of organic matter proceeds (Yu et al., 2017). Phosphorus is quite different in many cases, since it is primarily bound by mineral sorption rather than by organic matter, and published analyses of phosphorus recovery have consequently been less consistent. It is for this reason, among others, that it is appropriate to separately analyze the recovery of each of the three nutrients in the present study.

Recovery is also influenced by the comparator used. The reference wetland is an indication of where restoration is headed, while the cropland baseline indicates where restoration begins from, and each answers a different question. As a result, studies that use only one comparator can provide biased indications of progress. Concentrations determined on a per unit mass basis of sediment are also not necessarily equivalent to areal stocks due to variations in bulk density as a result of restoration activities.

Spatial Heterogeneity within Restored and Rewetted Systems

Small-scale studies reveal the great heterogeneity of sediments in rewetted systems. For example, in the case of a rewetted degraded peatland, plant-available nutrients had coefficients of variation ranging from 15 to 117 %. However, for the vast majority of both total and oxalate extractable element concentrations, variation did not exceed 15 %, and strong spatial correlation on small scales was found for most chemical and biochemical parameters (Negassa et al., 2019). The difference between labile and total fractions is important for sampling, since total nutrient pools are relatively stable over short distances.

Sampling scale greatly affects what is seen. If a property has spatial autocorrelation within just a few meters, it requires more samples than a smoothly varying property, and a sampling grid too coarse compared to the spatial autocorrelation range will fail to capture it. This implies that the density and placement of

sampling sites should be determined individually for each nutrient faction and not applied to all variables, and results from small plots should not be extended to the whole wetland without verification using larger scales.

Patterns do not only occur in temperate zones. In an artificially constructed wetland in India, soil organic carbon ranged from 0.079% to 2.94%, while principal component analysis distinguished nitrogen and phosphorus as the limiting nutrients, organic carbon and its ratios, and potassium as separate components; high values of carbon underlined the possibility of carbon sequestration by the wetland (Saluja & Garg, 2016). All these findings demonstrate that the wetland soils have spatial structures, that the structures differ among nutrient groups, and that the scale at which they appear depends on the variable examined.

Hydrology, Inputs and Nutrient Gradients

The influence of hydrology and the placement of a habitat concerning nutrient inputs through water plays a key role in regulating nutrient distributions. The increase in hydroperiod in Everglades restoration wetlands by 87 days was accompanied by a maximum and greatest variability in phosphorus in several compartments at locations one kilometer away from the water-carrying canal, indicating legacy phosphorus from upstream sources, which decreased with increasing distance downstream of the canal (Sarker et al., 2020). Thus, restoring hydroperiod in the wetland can lead not only to change in nutrient concentration but also to its redistribution.

Specifically, phosphorus storage is strongly dependent on location. Phosphorus bound with iron and aluminium was found to decrease in the following order: rhizosphere, near-rhizosphere and non-rhizosphere substrates as well as from inflow to outflow sections, whereas total phosphorus distribution varied depending on constructed wetland type and hydraulic loading (Yu et al., 2015). These results suggest that phosphorus storage in two habitats located in the same restored wetland can differ from each other despite similar carbon and nitrogen concentrations.

Habitat-Resolved Data from Agricultural Landscapes

There is a lack of habitat-specific sediment data, including restored habitats and cropland baseline. Among the few such datasets available are those in Illinois where three sequential-cell treatment wetlands constructed in order to decrease nitrogen content in tile drainage along with two restored floodplain wetlands and associated agricultural land were sampled; soils of the upper 0 to 7.5 cm of the surface were examined for their carbon, nitrogen, and phosphorus content (VanZomeren et al., 2020). It was noted that there was a change in phosphorus storage capacity with the direction of water flow in wetlands which varied depending on the type of treatment wetland, ranging from sink to possible source of phosphorus, while the farm fields were the biggest source of it (VanZomeren et al., 2020).

Three gaps that appear in the literature include the following: firstly, restoration success in terms of restoration with respect to an undisturbed benchmark has largely been assessed based on averages rather than differences between various habitats in the restored area. Secondly, carbon, nitrogen, and phosphorus are often considered together in the literature despite the different mechanisms of control for each. Lastly, very few databases consider both restored habitats and disturbed baseline habitats, and thus, it becomes difficult to isolate the effect of restoration from land use.

III. Materials and Methods

Study Design and Data Source

The research involved the analysis of an existing body of habitat-resolved data on nutrient levels in sediments, along with an extensive literature review; no additional samples were collected for this study. The data set (Section 2.4) includes six different habitats within an agricultural landscape, namely three sequentially-connected treatment wetlands built in 2005 for intercepting nutrients from tile drainage (T-E, T-G, and T-W), two restored floodplain wetlands receiving drainage and overbank flooding (F1 and F2),

and actively cultivated croplands near these wetlands as a disturbed baseline (Crop). For conciseness, the five wetland habitats are collectively referred to as restored habitats, despite being constructed rather than restored in the true sense of the word.

Surface sediments (0 to 7.5 cm) were sampled in triplicates in each habitat along transects, yielding 44 sampling sites and two depth intervals (88 samples) altogether. Total carbon and total nitrogen concentrations were measured using elemental combustion and total phosphorus concentration through ashing and digestion. The depth intervals were pooled since no difference between depths was found. In this study, the habitat mean and standard error of each variable were utilized as reported. Since there is no undisturbed reference wetland in the dataset, the benchmark values of undisturbed wetlands were adopted from literature studies.

Derived Indicators and Analysis

Total carbon (TC) and total nitrogen (TN) are in units of g kg^{-1} while total phosphorus (TP) is in mg kg^{-1}. Mass per unit mass of sediment is the index used to describe storage and areal stocks were not calculated since the bulk density values obtained are not appropriate to convert into areal stocks. Four indices were created from the means of the habitat. Carbon to nitrogen ratio (TC:TN) was determined as TC/TN while nitrogen to phosphorus ratio (TN:TP) as TN in mg kg^{-1}/TP, both are mass ratios. Percentage difference of each restored habitat from the cropland control was determined as (habitat-cropland)/cropland * 100. Relative standard error was calculated as standard error/mean in percentage to show within-habitat precision. Pearson correlation coefficient was calculated between the six means of each habitat for TC, TN and TP and is presented descriptively because n=6.

Cropland was selected as the baseline for comparison since it is the previous land use of the area prior to restoration and it was collected using the same method used for collecting samples from the wetland habitat. The percentage difference from the baseline refers to the extent of enrichment compared to the cultivated land rather than the recovery from an undisturbed wetland. The mass ratio was favored over the molar ratio since it allows the conversion of the concentration data into the indicator values without making any assumptions. Since only the means and standard error of the habitat means are available, no statistical comparisons between the habitats were made.

Literature Review Procedure

In order to situate the above values within the context, 12 peer-reviewed articles published between 2014 and 2022 have been considered. Articles which provided information on sediment and soil carbon, nitrogen or phosphorus content of restored, created, rewetted or reference wetlands in a comparative or spatial study design were selected. Findings from these articles are utilized in Sections 1, 2 and 5 to establish the objectives, identify research gaps and explain results.

IV. Results

Differences in Nutrient Storage Among Habitats

There was considerable variation in sediment nutrient storage among the habitats (Table 1 and figure 1). The value for TC varied from 27.5 g kg^{-1} in cropland to 46.5 g kg^{-1} in restored floodplain F1 by a factor of 1.7 while TN varied from 2.60 g kg^{-1} in cropland to 3.90 g kg^{-1} in treatment wetland T-E by a factor of 1.5. On the other hand, TP values varied from 499.3 mg kg^{-1} in T-W to 830.7 mg kg^{-1} in F2 by a factor of 1.7. However, the habitats with maximum/minimum TP (F2 and T-W) did not have maximum/minimum C and N (F1 and T-E, cropland).

Table 1: Sediment Nutrients and Stoichiometric Ratios Across Habitats

Habitat	Class	TC (g kg⁻¹)	TN (g kg⁻¹)	TP (mg kg⁻¹)	TC:TN	TN:TP
T-E	Treatment wetland	46.4 ± 5.73	3.90 ± 0.41	804.7 ± 33.5	11.9	4.85
T-G	Treatment wetland	39.2 ± 4.02	3.54 ± 0.34	504.1 ± 37.5	11.1	7.02
T-W	Treatment wetland	29.3 ± 3.60	2.77 ± 0.30	499.3 ± 26.3	10.6	5.55
F1	Restored floodplain	46.5 ± 3.01	3.88 ± 0.25	648.6 ± 29.7	12.0	5.98
F2	Restored floodplain	35.0 ± 2.02	3.19 ± 0.16	830.7 ± 29.7	11.0	3.84
Crop	Cropland baseline	27.5 ± 3.31	2.60 ± 0.29	702.0 ± 41.1	10.6	3.70

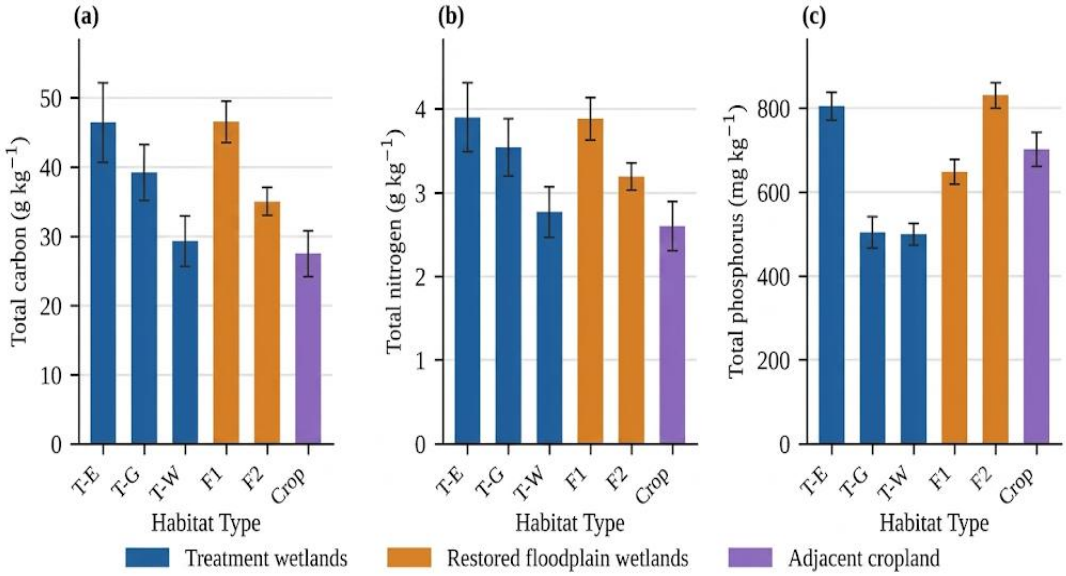


Figure 1: Mean (± Standard Error) (a) Total Carbon, (b) Total Nitrogen and (c) Total Phosphorus in Surface Sediments of Three Treatment Wetlands (T-E, T-G, T-W), Two Restored Floodplain Wetlands (F1, F2) and Adjacent Cropland (Crop)

Variability within the habitat types was just as high as variability between the habitats. Between the treatment wetlands, T-E contained 58 % more TC and 61 % more TP than T-W. Between the restored floodplain wetlands, F1 contained 33 % more TC than F2, while F2 contained 28 % more TP than F1, and therefore the rank order of the two floodplain wetlands differed between carbon and phosphorus. The relative standard error of the habitat means was 5.8 to 12.3 % for TC, 5.0 to 11.2 % for TN and 3.6 to 7.4 % for TP, showing that the habitat differences in TC and TN and the maximum differences in TP are larger than the within-habitat sampling error.

Storage Relative to the Cropland Baseline

In all five habitats that had been restored, there was an increase in both TC and TN above the cropland value (Figure 2). TC increased by 6.5 to 69.1 % and TN by 6.5 to 50.0 %. This is the highest for T-E and F1 and lowest for T-W. In terms of TP, the results were inconsistent. TP in T-E increased by 14.6 % and in F2 by 18.3 %. However, it decreased in T-G by 28.2 %, in T-W by 28.9 %, and in F1 by 7.6 %. This means that three of the five restored habitats contained less phosphorus than the cropland habitat.

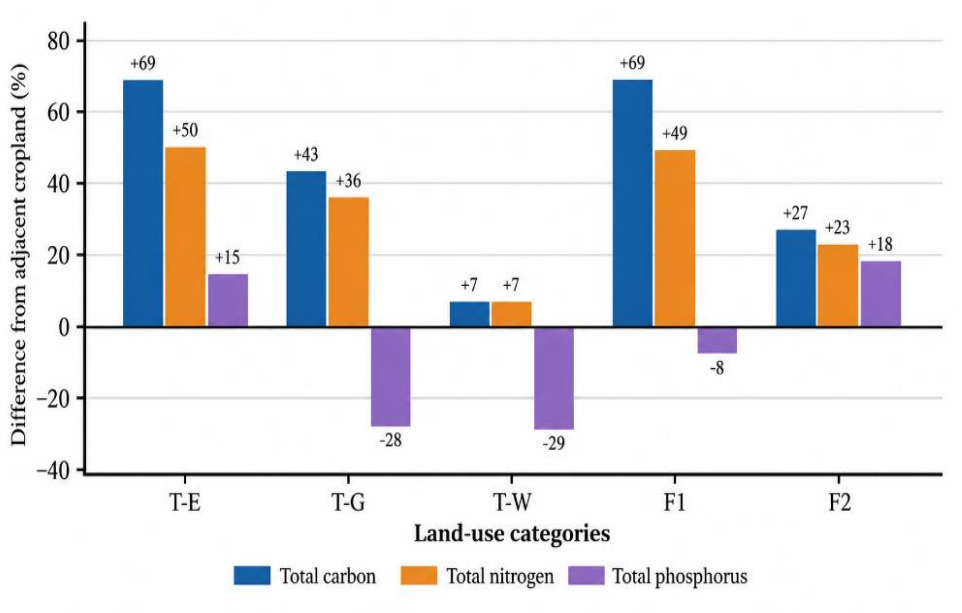


Figure 2: Percentage Difference in Total Carbon, Total Nitrogen and Total Phosphorus of Each Restored Habitat Relative to Adjacent Cropland. Positive Values Indicate Higher Storage than Cropland; Labels Give the Rounded Percentage

Coupling Among Nutrients

The coupling between carbon and nitrogen was very high (r = 0.99) across the six habitats means, while the coupling between phosphorus and carbon (r = 0.24) and phosphorus and nitrogen (r = 0.20) were weak. TC:TN was confined in a small range from 10.6 in T-W and cropland to 12.0 in F1, but TN:TP differed by 1.9 folds, varying from 3.70 in cropland to 7.02 in T-G. Thus, the stoichiometry of the restored habitats diverged from that of cropland primarily by changing the phosphorus stoichiometry relative to nitrogen and not by changing carbon stoichiometry relative to nitrogen. The two habitats which TN:TP was close to that of cropland (3.70) were F2 (3.84) and T-E (4.85), the two habitats which contained more phosphorus than cropland, while the three habitats with lower phosphorus than cropland had TN:TP of 5.55 to 7.02.

V. Discussion

From the analyzed data, it is clear that there indeed was an increase in nutrients due to the restoration of the habitats, but the increase was inconsistent. All the restored habitats contained higher amounts of carbon and nitrogen than the cropland, varying from 7% to 69% for carbon, but the increase was dependent on the habitat, while there was no such increase in the case of phosphorus. Thus, this confirms the theory stated in Section 2 that a site-level mean cannot be a proper representation of nutrient storage in a restored wetland, since the variation within the habitat is comparable to the difference between restored and disturbed sites.

There was a perfect relationship between carbon and nitrogen within all habitats (r = 0.99), which is similar to observations made from a restored mangrove wetland where total organic carbon and nitrogen were positively correlated, depending upon the planting density and species (Guo et al., 2018). The small variation in TC:TN ratios observed, 10.6 to 12.0, implies that there is nitrogen storage due to organic matter accumulation, whereby habitats that store carbon also store nitrogen at a constant ratio. Here, carbon content can be used as a practical indicator of nitrogen storage for monitoring purposes, but not in the case of phosphorus.

Carbon and nitrogen enrichment compared to cropland is also reflective of gradual organic carbon accumulation noted for a constructed river wetland that had started with a low background organic carbon content, while the adjacent natural river wetland was relatively stable (Cao et al., 2015). In the comparison, the rate of accumulation was a function of carbon inputs and decomposition. The same can be suggested for the study areas because the enrichment has been calculated with respect to a cultivated reference where organic matter content had been depleted. This means that the same concentration may be considered high for one area while relatively low for another.

Phosphorus separation from carbon and nitrogen is reflected in practice. In three out of five restorations, phosphorus levels were less than those on cropland, while in two restored floodplain wetlands, the difference in phosphorus was 28%, but the difference for carbon was in the opposite direction. The differences in the water source and its pathway could explain this situation, as the restoration cells have directed tile drainage, while the floodplain wetlands also have overbank flooding; and the literature analyzed in Section 2.3 shows that the storage of phosphorus is dependent on location regarding the source of nutrients. However, this explanation cannot be confirmed through the means of habitats. An example of an estuarine reed wetland, where the sediments' total phosphorus content had a distinct spatial gradient and regular seasonal variation associated with reed growth, also supports the idea that only one point of sampling may reflect one particular phase of phosphorus signal (Lu et al., 2022).

Given that there is no reference site with an undisturbed condition in this dataset, it is impossible to evaluate the degree of recovery compared with an undisturbed reference point. From the national synthesis and the paired data analyzed in sections 1 and 2.1, it appears that even after 11 to 20 years of restoration, the wetlands are typically around 50 % below natural conditions for carbon and nitrogen. This implies that just because the enriched sites in this study show higher nutrient content than the croplands, they should not be considered to have attained their undisturbed state. The sites with less phosphorus compared with cropland should not necessarily be considered to be poorly performing, as the low phosphorus may just imply absence of legacy fertilizer phosphorus.

These are three major implications that result from this study of restoration monitoring. The first implication is that the sampling should always be stratified based on the habitat and hydrologic positions with replicated samples being taken in each strata since the differences in the habitats in this particular study were greater than the sampling error in the habitats. Secondly, there needs to be a separate report of carbon, nitrogen, and phosphorous with the interpretation of nitrogen being done based on carbon and that of phosphorus being done based on hydrology and sorption.

These findings also have implications for design considerations for wetlands restoration. Since nutrient retention is not constant depending on the type of water source, the location of inflow, cell arrangement, and the heterogeneity of habitat types would affect not only the amount of nutrient storage but also its spatial distribution. Restoration designs involving the creation of heterogeneous habitats would result in the accumulation of carbon and nitrogen in certain areas and phosphorus in others, and performance indicators set up for the entire restored wetland would have to differentiate which nutrient is to be stored in which area. In this way, monitoring based on average values would not show any such differentiation and, consequently, performance indicators can be fulfilled in name only while each individual habitat fails to reach its target.

Such an approach is also needed in reporting. The presentation of sediment nutrients as one index or even basing the estimation of phosphorus retention on carbon is not appropriate since it would hide the independent behavior discovered here. Separate analysis of each element along with its baseline and sampling arrangement is necessary for comparisons between different restorations and future meta-analyses.

There are also some restrictions associated with the research. First of all, the quantitative part of the research is based on a single published database for only one agricultural landscape. Moreover, areal stocks were not analyzed – only the concentrations; the upper layer of 7.5 cm of the sediment was considered; and

no time comparison was possible since there is no such data. Furthermore, the correlation between habitats means can be considered descriptive only since n=6. Consequently, conclusions regarding spatial structure are only indicative and should be verified through proper sampling.

VI. Conclusion

Nutrient storage in sediment differed greatly among restored wetlands and between restored wetlands and the cropland reference. Total carbon and total nitrogen were greater than cropland in all restored wetlands, up to 69 % and 50 % higher, respectively, and both were almost perfectly correlated across wetlands (r = 0.99) with a very tight carbon-to-nitrogen ratio. Total phosphorus behaved independently of both of these nutrients, varying between 499 and 831 mg kg^{-1} and being lower in three out of five restored wetlands compared to cropland, and thus yielding nearly twofold nitrogen-to-phosphorus ratios. Nutrient storage in sediment differed greatly among restored wetlands and between restored wetlands and the cropland reference. Total carbon and total nitrogen were greater than cropland in all restored wetlands, up to 69 % and 50 % higher, respectively, and both were almost perfectly correlated across wetlands (r = 0.99) with a very tight carbon-to-nitrogen ratio. Total phosphorus behaved independently of both of these nutrients, varying between 499 and 831 mg kg^{-1} and being lower in three out of five restored wetlands compared to cropland, and thus yielding nearly twofold nitrogen-to-phosphorus ratios. The differences between sites belonging to the same habitat type category were just as large as the differences between categories, demonstrating that one mean value per restoration site can give a highly misleading impression of the nutrient storage in a restored wetland. The current literature review suggests that restoration sites are normally far from the natural benchmarks of carbon and nitrogen for one to two decades after disturbance, while the collected data does not have a comparison with a natural habitat and therefore cannot tell us how far we are from the natural benchmark. It is thus clear that restoration studies should differentiate their samples by habitats and hydrological positions, assess separately the levels of carbon, nitrogen and phosphorus, consider both disturbed baselines and natural benchmarks, and carry out measurements repeatedly.

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