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Microbial Degradation of Organic Contaminants in Streambed/Floodplain Sediments in Passaic River—New Jersey Area

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Abstract

This paper is intended to explore soil organic matter and carbon isotope fractionation at three locations of the Passaic River to determine if microbial degradation of organic contaminants in soil is correlated to the surrounding physical environment. Microbial degradation of organic contaminants is important for the detoxification of toxic substances thereby minimizing stagnation in the environment and accumulating in the food chain. Since organic contaminants are not easily dissolved in water, they will penetrate sediment and end up enriching the adjacent soil. The hypothesis that we are testing is microbial activity and carbon isotope fractionation will be greater in preserved soils than urban soils. The reason why this is expected to be the case is the expectation of higher microbial activity in preserved environments due to less exposure to pollutants, better soil structure, higher organic matter content, and more favorable conditions for microbial growth. This is contrasted with urban soils, which are impacted by pollutants and disturbances, potentially inhibiting microbial activity. We wish to collect soil samples adjacent to the Passaic River at a pristine location, Great Swamp Wildlife Refuge, a suburban location, Goffle Brook Park, Hawthorne NJ, and an urban location, Paterson NJ. These soil samples will be weighed for soil organic matter (SOM) and weighed for isotope ratio mass spectrometry (IRMS) to test organic carbon isotopes. High SOM and δ13C depletion activity indicate microbial growth based on the characteristics of the soil horizon rather than the location of the soil sample which results in degradation of organic compounds.

Keywords

Organic Contaminant, PCBs, Microbial Degradation, Passaic River

1. Introduction

The Passaic River in Northern New Jersey is a river of contradictions. Stretching for 80 miles, the Passaic River flows through four of the most populated counties in New Jersey (Morris County, Passaic County, Bergen County, and Essex County) comprising swamps, suburbs, and cities.

The start of the river occurs as a trickle of water from a foot wide hole in Mendham. The river then passes through the pristine Great Swamp national wildlife refuge. Leaving this preserved gem, the Passaic River's water then contributes to the flood-prone towns known as the Passaic River Basin. The Passaic River is then transformed into the Great Falls, initially responsible for the industrialization of Paterson. Downriver, and before the last 17 miles of the Passaic River in Newark, is Dundee Dam which prevents dioxin from contaminating the river upstream. This cancer-causing dioxin was dumped into the Passaic River from 1951 to 1969 when the former Diamond Alkali site in Newark manufactured organic contaminants such as defoliants and Polychlorinated Biphenyl (PCBs). The tide would transport these contaminants up and down the Passaic River for 17 miles, and residual dioxin pollutants from the dumping remain. The Passaic River then flows past dioxin containment walls into the waters of Newark Bay which houses a plethora of cargo ships filled with containers [1].

Soil adjacent to the Passaic River needs microbes to biodegrade organic contaminants and deteriorate toxic substances. Microbes are microscopic organisms such as bacteria and fungi which require a healthy living environment to degenerate organic contaminants in sediments [2]. "Microorganisms decompose organic matter, detoxifying the toxic substance, fixing the nitrogen, transformation of nitrogen, phosphorous, potassium and other secondary & micronutrients are the major biochemical activities performed by microbes in soil." If organic contaminants, such as PCBs, are not biodegraded then these man-made chemical compounds remain in the sediment where they bioaccumulate and biomagnified in the food chain and contribute to detrimental health effects [3].

The 80 miles of the Passaic River is surrounded by a diverse physical environment consisting of pristine and natural habitats for wildlife; populated suburban towns prone to flooding; and dense industrialized urban areas heavily contaminated with environmental pollutants. The soil dynamics along the Passaic River at these locations are just as diverse in terms of organic contaminants and the ability of microbes to degrade these organic contaminants in sediments. We expect that the microbial activity at the Great Swamp national wildlife refuge will be greater than the industrialized city of Paterson and the suburb of Hawthorne. This research will contribute to other monitoring projects of microbial degradation of PCBs over time. This research can also have implications in relatively new areas of organic contaminant pollution, such as the train derailment near East Palestine, Ohio and the rate of microbial biodegradation in the surrounding creek soils affected by the derailment.

The Passaic River pollution source is most often caused by urban runoff that introduces pollutants to the water body. Urban runoff has been the second most frequent source of pollution in the United States. For the Passaic River specifically urban runoff is a significant source of metals, PAH, DDT sediment loadings with PCBs sediment loads being significantly higher than estimated from urban runoff [4].

There are many factors that influence the reactivity of microorganisms to decompose organic matter. The most related factor to this study, would be the impact of **anthropogenic and natural disturbances.** Modification of the environment could alter environment structure, decrease in species diversity and the reduction of stability and functionality of the ecosystem's carbon and nutrient cycling [5]. Disturbances, especially urbanization, could impact the quality and quantity of annual litter fall, affecting microbial decomposition process. This would significantly affect the areas along the Passaic River in regions with vegetation cover along its banks and floodplains.

Urbanization can also affect soil properties. Urbanization can lead to compaction, contamination, and altered nutrient content, which can affect microbial communities and their ability to decompose organic matter [5]. Studying how soil properties vary between an urban and pristin area could highlight the interactions between soil health, microbial activity and ecosystem services.

Urban areas exhibit **reduced plant species diversity** compared to more natural settings. This can influence the quality and quantity of litter fall. This variation in species diversity between urban and pristine areas along the Passaic River can be examined to observe litter fall composition and decomposition can provide insights on ecosystem functionality.

The concerns of organic contaminants (POPs - PCB, DDT, industrial chemicals…) are multifaceted and widely documented. Organic contaminants persist in the environment, resistant to the natural degradation process, and accumulate in the food chain ((U.S. Environmental Protection Agency, n.d.-a). According to the World Health Organization, organic contaminants also raise concern on its effects on human health causing increased cancer risk, changes in the immune system, reproductive disorders and increased birth defects (World Health Organization (n.d.).

The role of microbial degradation (**Figure 1**) is to bio-transform highly toxic and hazardous states of organic pollutants into a nontoxic product. Pollutants can be broken down in different ways (actinomycetes, algae, fungi, and bacteria). When searching for food, microorganisms can find food through a contaminated environment. They consume pollutants or contaminants as a source of carbon, which provides the nutrients to grow and survive in such harsh environmental conditions [6].

The concrete species of the microorganisms at the locations of the Passaic River has not been confirmed. It is assumed that widely spread bacteria like pseudomonas and sphingomonas can live in many environments. The assumption made is based on bacteria and other potential microorganisms known biodegradation capabilities and environmental prevalence, suggesting a potential

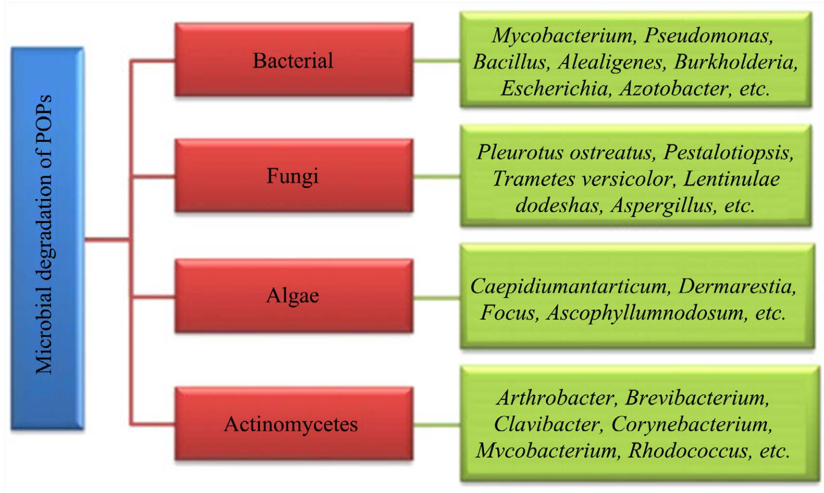


Figure 1. Microbial degradation of POPs.

role in the bioremediation of contaminated sites like the Passaic River. However, there is a lack of direct evidence from the Passaic River or its floodplain sediments that would require specific microbial analyses for confirmation of microbial species.

Literature Review

Soil will contain many microbes as long as there is a carbon source for energy. Decomposition of soil organic matter (SOM) is vital to the global carbon cycle. Carbon isotopic fractionation occurs during SOM decomposition. The lighter ^{12}C is enriched in the CO_2 released into the atmosphere while the heavier ^{13}C is enriched into the SOM which strengthens microbial degradation. Research has shown that soil carbon isotope variations relative to carbon-dynamic models can have biological and environmental significance. While environmental and biotic factors affect the decomposition rate of organic matter, there has been limited research on these factors affecting carbon isotope fractionation during SOM decomposition. One study completed [7] measured the carbon isotope ratios of soil and litter samples collected from soil profiles. These soil profiles showed trends of decreasing C concentration and increasing $\delta^{13}C_{SOM}$ with soil depth. Additionally, this study showed that carbon isotope fractionation factors tend to decrease with higher C/N ratios and ^{13}C enrichment is positively correlated to carbon isotope fractionation factors (**Figure 2**).

Understanding carbon isotope fractionation has been demonstrated to be helpful for also studying the global carbon cycle. According to Blaser and Conrad (2016), "degradation is achieved by a complex soil microbial community comprising many different biochemical pathways, which depend on the chemical nature of the organic substrate and the environmental conditions." Previously, to determine the amount of carbon flux pathways in soil, microbial function was proven by incubating soil samples. Research has shown that analysis of stable carbon isotope fractionation of microbial function may replace incubation in

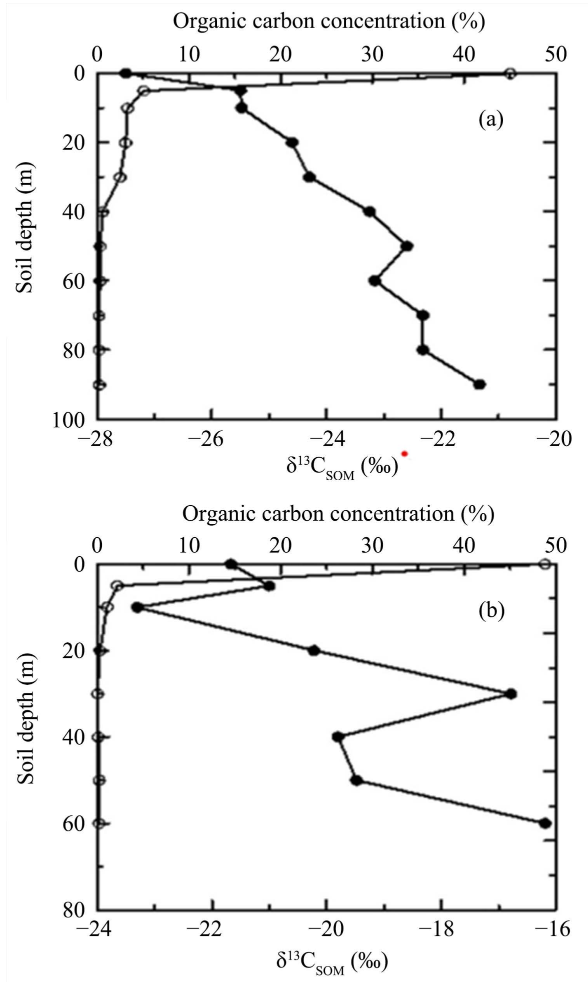


Figure 2. Open circles in the graphs above represent the vertical changes in $\delta^{13}C_{SOM}$ while closed circles represent organic carbon concentration.

soil samples since isotopic signatures partially reflect microbial functioning. Additionally, stable carbon isotope fractionation analysis may be able to differentiate between different organic substrates used for degradation such as the amount of root discharge fractionation factors quantify how much a given bio-chemical reaction discriminates against the substrate containing the heavy isotope ^{13}C. The compound specific stable isotope analysis (CSIA) of $\delta^{13}C$ requires an isotope ratio mass spectrometer (IRMS), which measures versus SOM degradation. However, some limitations would entail that different organic substrates need to be definitive in their isotopic compositions and the carbon flux pathways might only display small fractionation factors or might be identical for the different substrates.

The ^{13}C isotopic signature is given by its ratio $R = {}^{13}C/{}^{12}C$ and is denoted relative to a standard as $\delta^{13}C = 10^3(R/R_{st} - 1)$. The reactions in a biochemical pathway are displayed as enrichment fractionation factors ($e = 10^3[1 - \alpha]$) during the conversion of a substrate to a product. For reaction A --> B, the fractionation factor is defined as $\alpha_{A,B} = (\delta^{13}C_A + 10^3)/(\delta^{13}C_B + 10^3)$. Thus, fractionation factors quantify how much a given bio-chemical reaction discriminates against the substrate containing the heavy isotope ^{13}C. The compound specific stable isotope analysis (CSIA) of $\delta^{13}C$ requires an isotope ratio mass spectrometer (IRMS), which measures the $\delta^{13}C$ in CO_2 [8]. Determination of the fractionation factor for carbon biochemical pathways requires that there is no interference by other pathways. Additionally, fractionation factors in microbial cultures can cause practical problems and uncertainties which can have several consequences. To mitigate issues, a range of possible fractionation factors rather than a constant value should be used, and the interpretation of fractionation factors should be in accordance with these ranges in pure cultures. Another possible way of limiting fractionation uncertainties is to combine the fractionation of several stable isotopes together. For example, combining ^{13}C with ^{2}H or ^{18}O might resolve the anaerobic break-down of organic pollutants where the factors of fractionation of the individual isotopes are comparatively small or may be masked by other effects, for example, commitment to catalysis [8]. Ultimately, stable carbon isotope fractionation is a useful way to differentiate very strongly fractionating pathways between organic substrates and SOM microbial degradation.

2. Materials and Method

2.1. Equipment

Isotope spectrometry (IRMS);
Mixer Mill;
Mortar and pestle;
Plastic containers;
Analytical balance.

2.2. Chemicals/Reagents

Hydrochloric acid, HCl concentrated.

3. Experiment

3.1. Fractionation in Soil

Greater fractionation in preserved soils than urban soils likeliness of microbial activity would be greater in preserved soils than urban. Fractionation rates were varied based on the location much more than the specific characteristics of the soil, subsoil would have more soil organic matter and likeliness of microbial activity than topsoil.

Background: The Passaic River, Traveling the Passaic, a river of contradictions. Mendham, Great Swamp, Passaic River Basin, Paterson, Newark.

Organic Contaminants vs Microbes

Organic Contaminants

Organic Contaminants: Dioxins Furans, Polychlorinated Biphenyl (PCB), Vinyl Chloride.

Mostly generates as an unavoidable byproduct of industrial processes persist in the environment and accumulates in food chains and, is not easily dissolved in water and become enriched in sediment.

Microbes

Microbes: microscopic organism. e.g., bacteria, fungi, algae can be the mediums for biodegradation of organic compounds and detoxification of toxic substances. E.g., dechlorination Dehalococcoides & Chloriflexi strong correlation between microbe diversity and soil organic carbon content. Other dependents: soil depth, porosity.

Carbon Isotope Fractionation in Soil

Occurs during soil organic matter (SOM) decomposition ^{12}C enrichment in released CO_2 while ^{13}C enrichment in residual soil organic matter SOM decomposition could be subjected to environmental factors that would affect carbon isotope fractionation soil water content = greater fractionation.

Soil horizon characteristics are type of soil horizons & each horizon has its own characteristics.

Carbon isotope fractionation associated with preferential oxidation of different components of organic matter. Little fractionation during decay.

Increasing diagenesis

Methods

Soil auger for soil sampling boring down 60 cm into the soil horizons at each site Sampling bags for collected soil samples transported to a freezer to prevent mold Frozen soil samples kept in an electric oven to dry 24 hours Mortar and pestle used for grinding samples RBBt1, GS-Bt1, & P-Urban to avoid contamination Sample RB-Bt1 weighed in a crucible for Loss on Ignition (LOI) result Mixer Mill crusher used for grinding sample GBSub TB to avoid contamination Hydrochloric acid (HCl) added to each sample to eliminate carbonates.

Samples weighed for isotope ratio mass spectrometry (IRMS) to test organic carbon isotopes Results.

Loss on Ignition (LOI): 0.1065 (0.1065/2.0478 g) = 5.2% Organic Content; Sample RB-Bt1.

***Sampling*:**

We sampled from pristine environments Great Swamp (1): RB-Bt1 Great Swamp and Urban Paterson: P-Urban *and a tributary of the river* Goffle Brook: GB-Sub TB. Samples were tested on $\delta^{13}C$ organic (‰), $\delta^{15}N$ (‰), and loss of ignition (LOI).

Interpretation

5.2% soil organic matter (SOM) is a productive amount for maintaining a healthy living environment for microbes; therefore, Sample RBBt1 shows a positive ability to degrade organic containments in sediments.

2% - 3% Organic matter is the rational amount of SOM. However, different variables such as clay content could affect productivity of microbe communities.

Depleted ^{13}C value correlates to microbial activity.

Between urban and preserved soils, fractionation rates are variable based on the characteristics of the soil and not the location.

Soil water content differences between RB-Bt1, GB-Sub, P-Urban and, GS-Bt1 Soil horizons- possible that topsoil would have greater fractionation and organic soil matter than subsoil because of having a greater humus content due to decomposition of organic matter being greater at the surface Soil Organic Matter.

3.2. Experiment

The main objectives for this proposal are to 1) Measure soil organic matter (SOM) content 2) Conduct a carbon isotope fractionation analysis and 3) Compare soil profiles of the samples areas and characteristics that might affect SOM and carbon isotope fractionation. All objectives are used to have a scope of the likeliness of the abundances of microbial activity and a comparison of that between urban and preserved soils. For preemptive data, four samples (Great Swamp National Wildlife Preserve, Morris County, NJ, RB-Bt1 & GS-Bt1; Paterson Memorial Park, (P-urban), Paterson, NJ; and Goffle Brook Park, Hawthorne, NJ, GB-SubTB) were taken at flood plain and stream beds. All samples were taken 60 cm down the soil profile apart from the Great Swamp samples. Sample RB-Bt1 was used in a Loss on Ignition (LOI) to measure soil organic matter content.

The characteristics of the soil within the soil profile is one of the controlling factors on soil organic matter (SOM) content, carbon isotope fractionation, microbial growth, and activity. With the samples that were taken, the corresponding soil profile was recorded as the characteristics could give insight on factors that could affect carbon fractionation and SOM content. For the Great Swamp, the corresponding soil order is an Alfisol, more specifically the soil series is Aeric Ochraqualfs. Typical characteristics of this soil show signs of leaching, accumulation of clay in subsurface horizons, high native fertility, and found in areas that are humid. The profile consists of an Ap, Bt1, Bt2, (Bt3 in some places), C, and R. The Ap horizon means that topsoil is plowed or disturbed frequently while Bt1, 2 and 3 indicate an accumulation of clay.

The next soil profile is GB-SubTB at Goffle Brook Park, Hawthorne, NJ. The soil type is split between Fluvaquents-Udifluvaquents. This soil is frequently flooded and classified as hydric soil that has anaerobic conditions in the topsoil. It only consisted of two horizons, A (top soil horizon) and C (Parent material).

The last soil profile is P-Urban, Paterson Memorial Park, and Paterson, NJ. Most of the area falls under urban land that has no soil data. The next soil type is Typic Dystrudepts (Riverhead) which is an Inceptisol. This soil has minimal horizon development, a low pH, and an udic moisture regime. The soil horizons at the sample site were Ap, Bw, BC1, 2BC2, and 2C2. A new horizon name not mentioned before is Bw, which means that there is in situ weathering within this zone of accumulation.

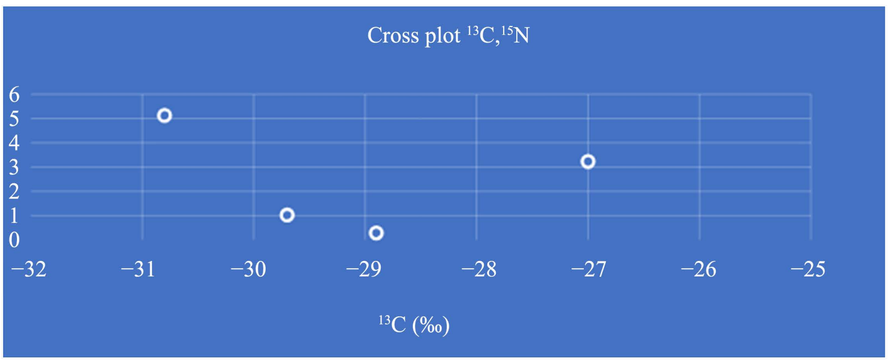
Factors highlighted in this proposal that could affect SOM contents and carbon isotope fractionation are soil water content and the characteristics of the soil. High soil water content leads to greater carbon fractionation; however, it can limit microbial growth and slow decomposition [7]. The reason for this is an example of a characteristic of soil is a weathered (Bw) horizon. Weathering can onset diagenesis due to early reactions of ground waters and secondary weathering products [9]. Generally, increased soil moisture can affect microbial activity and the solubility of gases, which in turn can influence the fractionation of carbon isotopes during the decomposition of soil organic matter.

The LOI test for RB-Bt1 gave a result of 0.1065 (**Table 1**). By dividing this value by the sample weight (2.0478g) the soil organic matter content is **5.2%**. From the literature, it is expected that soil organic matter percentage is between 1% - 5% but this also depends on the type of soil [10]. For the amount of SOM, it is a productive amount for maintaining a healthy living environment for microbes; however, clay content can affect microbial activity. For carbon isotope fractionation analysis the results for **δ^{13}C-organic (‰)** values are: RB-Bt1 = −30.8‰, GS-Bt1 = −27 (‰), GB-SubTB = −29.7 (‰), P-Urban = −28.9 (‰).

With the preemptive data, **between urban and preserved soils fractionation rates were variable based on the characteristics of the soil and not the location** because of 1) Soil water content differences between soil profiles. RB-Bt1, GB-Sub, GS-Bt1 were more saturated and to some extent completely flooded in contrast to GS-Bt1 which was mostly dry. This is reflected in the values with GS-Bt1 having lower fractionation despite being a preserved soil; and 2) from the data a depleted ^{13}C value correlates to microbial activity because during decomposition microbes will assimilate part of the existing organic carbon to build

Table 1. The LOI test for RB-Bt1.

Sample ID	Weight (mg)	δ^{13}C-organic (‰)	δ^{15}N (‰)
RB-Bt1 Great Swamp	3.09	−30.8	5.1
GS-Bt1 Great Swamp	2.96	−27	3.2
GB-SubTB Goffle Brook Park	2.9	−29.7	1.01
P-Urban Paterson Memorial Park	2.47	−28.9	0.3



their bodies, and remaining organic carbon is preferentially oxidized into CO_2 and H_2O (Wang *et al*., 2015). This proves our **hypothesis correct, the pristine location sample, RB-BT1 has the highest $\delta^{13}C$ value and therefore assumed to have the highest microbial activity.**

Research Methods

For field sampling, a clean soil profile is needed to accurately sample different soil horizons limiting mixing from other horizons. A soil auger will be used to make a soil pit, and using a ruler and a set of markers a group can separate apparent horizons. If horizons are not easily distinguished, Soil Web is an application that gives the dominant and minor soil types at a specific location. Soil samples will be collected, placed in sample bags, and then placed into a freezer to prevent mold. An estimated time to dig the soil pit with the augur and collect will take approximately 15 minutes. Within these 15 minutes notes on characteristics of the soil one can make in the field will be recorded with the soil profile as well.

Once all samples are in a laboratory setting, the frozen soil samples will be kept in an electric oven to dry for 24 hours. Once dry, a mortar and pestle will be used for grinding samples to avoid contamination. Pristine samples will be weighed in a crucible for the Loss on Ignition

(LOI) result. If need be, a Mixer Mill crusher can be used as well for grinding rough samples to avoid contamination. A 10% hydrochloric acid (HCl) bath will be added to each grinded sample to eliminate carbonates. Finally, samples will be weighed for isotope ratio mass spectrometry (IRMS) to test organic carbon and nitrogen isotopes. For the preemptive data presented, this is the strongest method that is known to the researchers of this proposal. However, if new methods are found that are proven to be more efficient, those will be either adopted or incorporated into the original methods.

For the preemptive data, access to sites like the Great Swamp was approved by Montclair State University, Earth and Environmental Science Department and the leaders at the Great Swamp National Wildlife Refuge. For any future sites, pre-approval must be acquired, and such locations will need to be surveyed to choose sample sub-sites. All samples will be tested at Montclair State University. For the case of going further within this study, testing the concentrations of organic contaminants at the same university can be accessed via tool availability to start testing.

4. Discussion

The implications of this research are far-reaching for the State of NJ and the immediate surrounding populations impacted by the Passaic River. Microbial degradation of organic contaminants is critical for the entire ecosystem of the Passaic River whether the location is a refuge for 244 bird species, a suburban enclave for homes and businesses, or a homeless tent encampment for those less fortunate who seek the safety of the Passaic River banks from city streets. Nine years ago, NJ had a plan to spend $1.4 billion on the cleanup of the Passaic River due to contamination by toxins which pose a threat to the environment and human health. Unfortunately, no major work has been done yet [10]. Comparing the characteristics of the soil horizon at various locations adjacent to the Passaic River coupled with measuring the SOM and conducting carbon isotope fractionation analysis will strengthen the research on microbes needing to biodegrade organic contaminants and deteriorate toxic substances. This research will aid in the $1.4 billion cleanup of the Passaic River as well as keep pristine areas such as the Great Swamp a natural refuge.

5. Conclusion

We set out to explore carbon isotope fractionation at three locations of the Passaic River to determine if microbial degradation of organic contaminants in soil is correlated to the surrounding physical environment; pristine vs. suburban vs. urban. We will first cover the dynamics of the Passaic River followed by the basics of organic contaminants and microbes relative to carbon isotope fractionation in soil. This is followed by field sampling and soil horizons at each site. This will then lead into a discussion about soil organic matter and carbon fractionation. Finally, we will explain future work which could benefit restoring the sediment in the Passaic River contaminated with PCBs.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Bedard, D.L. (2008) A Case Study for Microbial Biodegradation: Anaerobic Bacterial Reductive Dechlorination of Polychlorinated Biphenyls—From Sediment to Defined Medium. *Annual Review of* Microbiology, **62**, 253-270. https://doi.org/10.1146/annurev.micro.62.081307.162733

[2] Bhattarai, A., Bhattarai, B. and Pandey, S. (2015) Variation of Soil Microbial Population in Different Soil Horizons. J*ournal of Microbiology & Experimentation*, **2**, 75-78. https://doi.org/10.15406/jmen.2015.02.00044

[3] Blaser, M. and Conrad, R. (2016) Stable Carbon Isotope Fractionation as Tracer of Carbon Cycling in Anoxic Soil Ecosystems. *Current Opinion in Biotechnology*, **41**, 122-129. https://doi.org/10.1016/j.copbio.2016.07.001

[4] Walker, W.J., McNutt, R.P. and Maslanka, C.K. (2000) The Potential Contribution of Urban Runoff to Surface Sediments of the Passaic River: Sources and Chemical

Characteristics. *Environmental Science & Technology*, **34**, 4729-4736.

[5] Chen, W., Hu, H., Heal, K., Sohi, S., Tigabu, M., Qiu, W. and Zhou, C. (2023) Linking Microbial Decomposition to Dissolved Organic Matter Composition in the Revegetation of the Red Soil Erosion Area. *Forests*, **14**, 270. https://doi.org/10.3390/f14020270

[6] Boudh, S., Singh, J.S. and Chaturvedi, P. (2019) Chapter 19 - Microbial Resources Mediated Bioremediation of Persistent Organic Pollutants. In: Singh, J.S., Ed., *New and Future Developments in Microbial Biotechnology and Bioengineering*, Elsevier, Amsterdam, 283-294. https://doi.org/10.1016/B978-0-12-818258-1.00019-4

[7] Fallon, S. and Zehawl, T. (2023) The Passaic: A River of Contradictions. https://www.northjersey.com/picture-gallery/news/environment/2023/02/08/passaic-river-great-swamp-watershed-newark-great-falls/11089723002/

[8] Gasch, C. (2019). Soil Organic Matter in Cropping Systems. Extension at the University of Minnesota. https://extension.umn.edu/soil-management-and-health/soil-organic-matter-cropping-systems

[9] Nesbitt, H.W. and Young, G.M. (1989) Formation and Diagenesis of Weathering Profiles. *The Journal of Geology*, **97**, 129-147. https://doi.org/10.1086/629290

[10] PRB3Maps (2022) Passaic River Maps. Passaic River Basin. https://www.passaicriverbasin.com/prb3maps.html