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Impact of Riparian Revegetation on Soil Carbon Sequestration

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[2]Emma has always had a love of observing the natural world. Her passion for the environmental sciences was fostered by her family's love of the outdoors and participation in the student competition Science Olympiad in her youth. She graduated with a B.S. in Environmental Science and with a minor in Earth Science in June of 2024. Today, she lives on the coast of Oregon, working in a bakery, and pursuing a career in environmental conservation and research of coastal forests.

[3]Janet was born and raised in the heart of San Francisco. She then transferred to the University of Oregon and graduated with a Bachelor's Degree in Environmental Studies. Janet now works as a front desk receptionist in San Francisco and plans to stay there for roughly a year to help fund her master's degree in Marine Biology, while also enjoying the great outdoors with her loved ones. Once her master's degree is completed, she plans to pursue the research side of marine biology while upholding conservation, sustainable, and ethical values.

[4]Sydney Holtz grew up in Milwaukie, Oregon, where she spent her time hiking and interacting with the outdoors. She is set to graduate in Spring 2025 with a B.S. in Environmental Studies and minors in Geography and Earth Science. After graduation, she hopes to travel to different countries and collaborate with nonprofits focused on restoration and sustainability.

[5]Emily has been a research assistant and acting lab manager for the Soil Plant and Atmosphere (SPA) Lab since 2022. Emily is interested in the terrestrial and fluvial dynamics of riparian ecosystems and the long-term processes affecting habitat and function after restoration. Emily participated in the Environmental Leadership Program both as a student and as the SPA lab project manager for the Eugene Water and Electric Board's Forest Research site in Springfield, Oregon.

[6]Connor grew up in San Jose, California, where his love for the outdoors flourished. He spent his time hiking, playing baseball, and watching Animal Planet- fascinated by diversity, evolution, and how living things interacted with the environment. He graduated in the Spring of 2024 with a Bachelor of Science in Environmental Science, as well as minors in Anthropology, Biology, and Sustainable Business. Connor is now using his degree at a consulting company cleaning up oil spills in Colorado.

[7]Olivia was born and raised in the high desert of Reno, Nevada, where she spent her summers hiking and her winters skiing. She graduated with a Bachelor of Science in Environmental Sciences from the University of Oregon in the Spring of 2024 and is now doing seasonal work in the Lake Tahoe area. She is currently taking time away from academia but hopes to pursue her doctorate in the next couple of years.

[8]Morgan grew up outside the Rocky Mountains in Westminster, Colorado, where her love of the environment started. After three years at the University of Oregon, she will graduate in the Spring of 2025 with a B.S. in Environmental Studies and minors in Sustainable Business and Geography. She hopes to move back home and work for the U.S. Forest Service, or non-profits focused on forestry, soil conservancy, and restoration, specifically with local farms to incorporate sustainable agricultural practices.

[9]Ava grew up on a farm outside of Portland, Oregon, where she and her family maintained a small animal sanctuary. She graduated from the University of Oregon in 2024 with a B.S. in Environmental Sciences, focusing on the earth's physical processes, along with a minor in French. In her career, she hopes to promote ecological restoration and conservation, and to encourage sustainable agricultural systems, all while finding cool rocks to put in her pockets.

[10]Mason Ruggiero was born and raised in Eugene, spending most weekends growing up exploring Oregon and the Pacific Northwest. As a lifelong Duck, staying in Eugene for college was an easy choice, graduating from Oregon in December of 2024 with a bachelor's degree in Environmental Science. Mason is particularly interested in environmental law, sustainable energy development, and related fields, where he hopes to contribute to innovative solutions for environmental challenges.

[11]Camille Tommeraason grew up in Woodland, California, and came to the University of Oregon to follow in her grandfather's footsteps of becoming a Duck. In her free time, she enjoys crocheting, needle-felting, learning about insects, and spending time outdoors. After spending four years at the university, Camille is set to graduate with bachelor's degrees in Environmental Science and Biology in the spring of 2025. After graduation, she hopes to pursue a career in restoration ecology, entomology, sustainable agriculture, or a related field.

[12]Laurel grew up in Washington, at the heart of grunge and rock music in Olympia and Seattle. Her love for the environment was fostered as she explored hiking trails and visited Lake Cushman often in her childhood. In the spring of 2024, she graduated from the University of Oregon with a Bachelor of Science in Environmental Studies. She is currently working as an Engagement Organizer at the Oregon League of Conservation Voters. She is looking to see what career opportunities develop in the nonprofit world, hoping to get more involved with environmental justice efforts.

Abstract

Riparian forests hold unique potential for mitigating climate change effects, with revegetation and canopy cover playing key roles in influencing carbon and nitrogen storage within these systems. This study investigated multiple variables that assist in reducing the amount of carbon in the atmosphere via sequestering carbon in soils and connected carbon sequestration to continuing revegetation efforts in a riparian experimental forest site, which we hope could be more widely applied to projects of a similar nature. Our study parameters primarily examined the relationship between carbon sequestration, age of vegetation, and actively revegetated versus naturally regenerated sites. Additionally, we examined the correlation between canopy cover and soil carbon percentages. To gain insight into these questions, we collected soil samples, ran carbon and nitrogen analyses, and conducted canopy cover assessments across 5 phases of the study site, each planted at different times with different treatments. Our findings showed that soil carbon sequestration was highest in the old growth phases and the lowest in Phase 2, which consisted of hardwood saplings. The amount of soil nitrogen was also highest in old growth phases and lowest in Phase 2 but the margins were much smaller, with only 0.09 being the largest difference. As for canopy cover, the old growth had the highest amount, whereas the control had the lowest. This data will inform insights into the past and future restoration capabilities of this site through the continued research of carbon sequestration with vegetation, soil, and canopy cover. Considering these aspects comprehensively, we can effectively incorporate successful management practices for mitigating climate change impacts through riparian restoration.

1. Introduction

Highbanks, the study site for this research, is a riparian zone. A riparian zone is an area of land alongside a body of water, such as a river, stream, or lake. Riparian zones have unique vegetation and soil conditions, acting as intermediaries between aquatic and terrestrial ecosystems. Riparian zones play a crucial role in supporting biodiversity, maintaining water quality, and providing habitat; however, industrialization, agriculture, and mismanagement often degrade these areas through erosion, flooding, and overall environmental degradation, necessitating restoration efforts (Gregory et al., 1991; Dudgeon et al., 2006; Ruwanza et al., 2013; Wentzel & Hull, 2021).

As carbon dioxide and other greenhouse gases accumulate in the atmosphere, climate change becomes an imminent threat that demands investigation into possible mitigation solutions (Mora et al., 2018). Restoration of riparian zones is essential to help mitigate climate change because these zones can sequester carbon in their soil and biomass, reducing the amount of greenhouse gas in the atmosphere (Maraseni & Mitchell, 2015). Carbon sequestration is the pulling of carbon from the atmosphere via artificial or natural methods and storing it in a repository that holds more carbon than it emits, sometimes referred to as a carbon sink (Lal et al., 2015).

The largest terrestrial carbon pool is soil, storing two times the amount of carbon in the atmosphere and almost three times greater than aboveground biomass; soil stores carbon most efficiently in healthy ecosystems (Paul et al., 2023). Vegetation, through photosynthetic processes and foundational growth habits, enhances soil structure, stability, and carbon sequestration (Dhanwantri et al., 2015). The age, growth, and size of the vegetation in these soils significantly impact the amount of overall carbon stored between the soil and the plants (Dhanwantri et al., 2015; Gough et al., 2008). It is important to understand the impact of vegetation on the amount of carbon sequestration that can occur within the soil. Riparian zones, including Highbanks, contain a variety of soil types. Carbon sequestration can occur at different levels in different soil types. At Highbanks, our team observed different soil types sequestering different levels of carbon due to the different types of vegetation growing in the soil. Soil type impacts the vegetation that can grow in an area due to the soil texture, soil pH, and the organic matter within the soil. Soil type and its characteristics can directly impact the vegetation grown through its physical and chemical properties (Gatiboni, 2022).

Soil health is also impacted by canopy cover. Canopy cover is the percentage of land shaded by overhanging vegetation. The shading directly impacts the health of the soil, which can be determined through the amount of available nutrients such as soil carbon and nitrogen (Aponte et al., 2010). With more canopy cover over an area, we expect the amount of carbon stored within above-ground biomass to increase. Above-ground biomass is all the living plant parts on the above the soil. Heterogeneity in the ground cover through the diversity of trees and shrubs allows for a range in litterfall quantity and quality, bringing more opportunities for nutrients essential to plant growth to be incorporated into the soil (Aponte et al., 2010). Canopy cover also reduces the lateral momentum of erosive winds, redistributing the shear stress that could otherwise displace fine soil particles (Webb et al., 2021).

The importance of vegetation and canopy cover for soil health suggests methods for environmental restoration. Natural regeneration, the restoration practice where direct interference from humans is absent, presents a viable and cost-effective restoration strategy, especially in former agricultural fields, fostering carbon sinks over time. Natural regeneration requires less effort than active revegetation, in which native trees and shrubs are manually planted in the environment (Morrien et al. 2017). However, natural regeneration relies on seeds spread from existing plants; therefore, it is not guaranteed to occur in a fashion that facilitates ideal carbon sequestration conditions. Active revegetation and restoration of riparian ecosystems yield immediate benefits for soil health with long-lasting impacts that result in ecosystem self-sustainability (Osborne & Kovacic, 1993; Bieluczyk et al., 2023; Nolan et al., 2021; Ye et al., 2023). Therefore, while natural regeneration does provide benefits, it is not guaranteed to be successful in increasing carbon sequestration. In partnership, the University of Oregon's SPA lab and the Eugene Water and Electric Board (EWEB) have transformed Highbanks into an experimental forest. The project aims to investigate if active revegetation is an effective way to increase carbon sequestration, which EWEB could replicate at other sites to mitigate global climate change.

Through scientific experimentation, we can further understand how active revegetation helps with soil carbon sequestration via photosynthetic processes. We expect that soil carbon and nitrogen content will be higher in phases—areas of the study site—with more mature vegetation and that areas with active revegetation measures will show increased soil carbon compared to areas without. Additionally, we also expect that carbon sequestration levels will increase in tandem with canopy cover, allowing canopy cover to be used as rough estimates of carbon sequestration levels.

2. Study Site Description

2.1 Historical Background

Until the 1800s, the Highbanks land was inhabited and managed by Native groups such as the Molalla, who were displaced and forcibly removed by colonial settlers (Beckham, 2008). Originally, the land contained riparian hardwoods, grasslands, and savannas (Dawson, 2021). It now has communities of young trees and shrubs, streambanks, sloughs, and abandoned pastures.

2.2 Soil Description

Our on-site research occurred at Highbanks (44.06227°N, 122.93058°W), located in Springfield, northeast of the University of Oregon (Fig. 1). The site is adjacent to the McKenzie River; Cedar Creek, one of its tributaries, flows through the study area. Highbanks was predominantly a fallow field, a section of arable land left deliberately unplanted, before being acquired as part of the 140 acres the Eugene Water and Electric Board (EWEB) attained in 2020. The land is now used for educational purposes, focusing on restoration research in collaboration with restoring land to sequester carbon, as this research field is their Carbon Forestry Lab. EWEB partnered with the SPA lab to explore ways to sequester carbon by developing an experimental forest to apply to other EWEB sites (Dawson, 2021).

This research is part of a decade-long project that started in 2020 and contains 3 phases on their own sections of the property. Phase 1 was planted in 2021, Phase 2 in 2022, and Phase 3 in 2023 (Fig. 1). Each phase contains a mixture of different planting treatments. Each planting treatment type has its own specific mixture of native plant species. Hardwood treatment plots, which are the dominant treatment type in Phases 1 and 2, are planted only with native hardwoods. Mixed treatment plots, the dominant treatment type in Phase 3, are planted with a mixture of native hardwoods and native shrubs. These phases also include different planting densities, as shown by the different outline colors (Fig. 2). Old-growth plots, referred to as Phase 0, surround some portions of the perimeter of the study site and contain trees planted by a previous landowner that are an estimated 30–80 years old. Some areas within the phases were left unplanted as control sites, referred to as Phase 4.

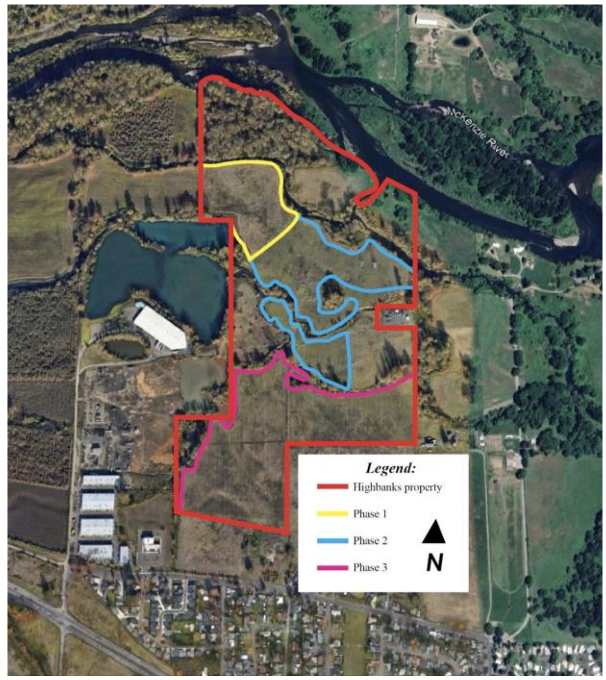

Fig. 1: Map of the research area in NE Springfield, Oregon, by H.R. Dawson.

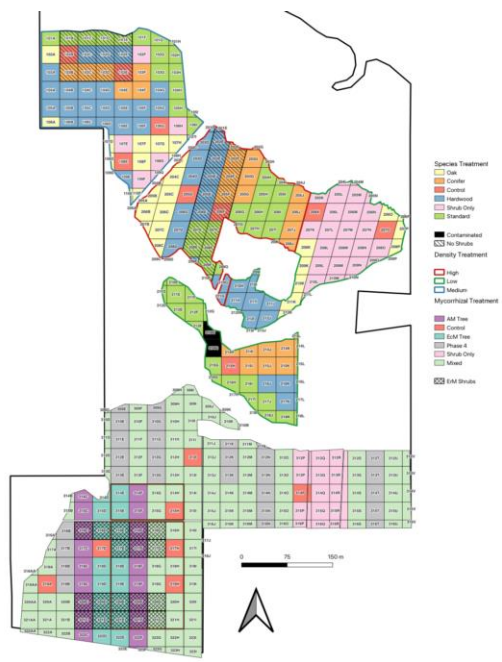

Fig. 2: Plots showing detailed treatments, by J. Odenthal.

3. Methods

3.1 Soil Sampling

We followed the SPA lab's Standard Operating Procedures (SOP) for all field and lab methods. Additionally, we documented the locations of our sites using the Avenza app to guarantee future site consistency when collecting our samples.

We collected samples at a depth of 20cm in the ground with a soil auger tool. This depth covers most of the soil's rhizosphere, the region containing the presence and activity of root structures where plant and soil interactions occur (VanDerZanden, 2019). Since this project aims to help identify methods for increasing carbon sequestration in soils, and soil nitrogen is an essential nutrient for plant growth, collecting these soil samples is necessary to record how the soils are performing in their respective species treatments over time. In future years, this data can be used to show the increase or decrease in soil carbon. We collected samples of soil cores for carbon analysis from the soil near trees or shrubs at each Highbanks collection point. We collected three samples from the control site (an unplanted, unaltered region of the study site), Phase 1 (planted in 2020), Phase 2 (planted in 2021), Phase 3 (planted in 2022), and the old-growth forest, totaling 15 samples. All samples collected in Phases 1 and 2 were collected from hardwood treatment plots, and all samples collected in Phase 3 were collected in mixed plots. Samples were taken from hardwood treatment plots in both Phases 1 and 2 in the interest of continuity; however, as Phase 3 does not have any hardwood treatment plots, samples were taken from mixed plots here.

3.2 Carbon-Nitrogen Analysis of Soil Samples

To analyze the soil samples for carbon-nitrogen percentages, we first placed our samples from the field into the drying oven to remove moisture. We then sieved and ground the samples into a fine texture to homogenize the sample for the most accurate readings and prepared these samples into vials. Next, we used the microbalance scale to weigh our soil samples and the calibration and reference material before running the Elemental Analyzer. We weighed the soil samples and soil reference material as close to 20mg as possible, and the calibration reference material was weighed at 1, 3, and 5mg. We packed the samples and standards into tin capsules and recorded the sample's final weight and cell location in the microtiter plate. The sample weight was recorded precisely for carbon-nitrogen readings, which was of the utmost importance because carbon and nitrogen were measured by percent weight.

We used the FlashSmart Elemental Analyzer 2000 to find the percentages of carbon and nitrogen in the soil samples. This equipment heated our samples to the degree that they combusted and pushed the remains through its system with helium as a carrier gas to a detector that records carbon and nitrogen values. It is important to set up a new calibration to ensure the analyzer is running accurately and calculating the data correctly. The calibration creates a curve, and once it plateaued, we could run our soil and vegetation samples. A calibration curve in the FlashSmart Elemental Analyzer links known standard concentrations to detector responses, allowing accurate quantification of unknown samples (*Thermo FlashSmart CHNS/O Elemental Analyzer,* 2020).

3.3 Canopy Cover

To analyze canopy cover, we used the Leaf Area Index (LAI), a hemispherical digital photograph that allows us to understand the amount of canopy cover in a phase. Our protocols for taking and editing LAI images were adapted from the Washington State Ecology protocols for field studies that quantified the Total Maximum Daily Load for forest and fish surveys using hemispherical digital photography (Stohr, 2019; Mathieu, 2019). To measure the LAI photos, we used digital hemispherical photography to take photographs of the vegetation canopy using a fish-eye lens. We marked the location on Avenza, as well as the coordinates and elevation. We set the camera tripod to face true north at a height of 1.24 meters, as this was our standard for each image. Next, we took the LAI photos in the center of the 8m radius circle, at the same location as the soil samples, totaling 15 pictures.

The next step was to remove imperfections in Adobe Photoshop. This step ensured that the software did not interpret imperfections as canopy cover along with the vegetation. After editing the photos, we ran them through the GapLight Analyzer (GLA) program, which analyzes digital hemispherical canopy photos to give us the percentage of canopy cover and the leaf area index (Frazer et al., 1999). We can compare the canopy cover and LAI to associated soil carbon values and the other phases with this data.

3.4 Data Management and Analysis

Data management involved the systematic transcription of information from physical documents into Google Sheets, organized by collection groups. This data was then exported to Microsoft Excel, allowing for the creation of redundant copies to bolster data integrity and accessibility. To ensure accuracy, team members conducted a thorough proofreading process, verifying that all values were correctly entered. Rstudio was used for all data analysis, which included the calculation of averages and the formation of figures.

4. Results

4.1 Carbon-Nitrogen in Soil

The average elemental percentages of carbon (Fig. 4) and nitrogen for soil (Fig. 5) had lower values in the older planted phases. The average nitrogen percentages for soil were fairly consistent throughout the phases, with the lowest being 0.20% for Phase 2 and the highest being 0.29% for Phase 0. Average carbon percentages in soil were slightly more variable, with the lowest at 2.55% for Phase 2 and the highest being 3.76% for Phase 0. Phase 2 had the lowest average carbon and nitrogen percentages, while Phase 0 had the highest average carbon and nitrogen percentages.

Soil Carbon			
Phase	Max Carbon	Min Carbon	Avg Carbon
0	6.435954	2.000569	3.76
1	3.235122	2.065588	2.62
2	3.890586	1.553887	2.55
3	4.276962	2.360507	3.15
4	5.721297	1.831597	3.52

Fig. 4: Table with Maximum, Minimum, and Average Soil Carbon Percentage by Phase

Soil Nitrogen			
Phase	Max Nitrogen	Min Nitrogen	Avg Nitrogen
0	0.4502616	0.1974038	0.29
1	0.2772633	0.1953057	0.24
2	0.2475881	0.1513207	0.20
3	0.3343065	0.2218660	0.26
4	0.3463190	0.1827519	0.26

Fig. 5: Table with Maximum, Minimum, and Average Soil Nitrogen Percentage by Phase

4.2 Canopy Cover

Across all phases, canopy cover ranged from 70.11% in Phase 0 to 11.62% in Phase 3. Phase 4, the control, had the lowest average canopy cover at 13.50%. Phase 0, the old growth, had the highest average canopy cover at 62.58% (Fig. 6).

Phase 0 contains the highest average for both canopy cover and soil carbon (Fig. 7). No other phase is correlated in this manner.

Canopy Cover by Phase			
Phase	Maximum	Minimum	Avgerage
0	70.11	53.17	62.58
1	26.14	17.49	22.58
2	21.53	18.56	20.41
3	17.39	11.62	13.82
4	14.28	12.04	13.50

Fig. 6: Percent Canopy Cover by Phase

Average Carbon and Canopy Cover by Phase		
Phase	Avg Carbon (%)	Avg Canopy Cover (%)
0	3.76	62.58
1	2.62	22.58
2	2.55	20.41
3	3.15	13.82
4	3.52	13.50

Fig. 7: Percent Canopy Cover by Phase

5. Discussion

5.1 Carbon-Nitrogen in Soil

The hypothesis was that the carbon and nitrogen percentages would be lowest in the control and increase sequentially through the phases, with the highest percentages in the old growth. Phase 0 did have the highest soil elemental carbon percentage as predicted; however, the next highest was Phase 4, the control plot, followed by Phase 3, Phase 1, and the lowest average soil elemental carbon percentage was recorded in Phase 2 (Fig. 4). The phase with the oldest vegetation showed the most carbon stored in the soil, supporting that carbon sequestration increases in storage as time goes on. However, the age of the vegetation did not accurately predict soil carbon in the other plots. Soil elemental nitrogen percentage was the highest in Phase 0, followed by Phases 4, 3, 1, and finally Phase 2. As previously mentioned, all samples for Phases 1 and 2 were collected from hardwood treatment plots, while Phase 3 samples were collected from mixed plots. Different plants may affect the sequestration or fluctuation of elemental carbon and nitrogen percentages in various ways (Shaw, 2024). The variation of these treatments could have influenced the overall average carbon and nitrogen percentages we observed. Moreover, Phases 1–3 were disturbed by tilling when the vegetation was initially planted in each phase. This tilling may have disturbed the elemental carbon and nitrogen percentages, as tilling is widely accepted as a practice that may disturb soil elemental carbon percentages (Bruce et al., 1999). Since Phases 0 and 4 have not been recently disrupted by tilling, it is possible that this could explain their higher soil carbon and nitrogen content. Other extraneous factors, such as the site's varied slope, past use of the soils, disturbances, growth of volunteer plants, and groundwater movement, could also have influenced the data.

5.2 Canopy Cover

Phase 4, the control, had the smallest average canopy cover. Average canopy cover then increased sequentially from the youngest actively revegetated phase, Phase 3, to the oldest phase, Phase 0 (Fig. 6). This shows that the plants within the phases continue to grow with age, which is a positive indicator that active revegetation efforts are proceeding successfully.

Phase 0 has both the highest soil carbon and canopy cover percentage, which is consistent with our hypothesis that soil carbon and canopy cover would be highest in older plots (Fig. 7). However, there appears to be no correlation between average canopy cover and average soil carbon content in the other phases. This could be due to discrepancies outlined in the above discussion of soil carbon. Additionally, the oldest tree in Phase 1 is no more than 4 years old, and the youngest tree in Phase 3 is no more than 2 years old. Therefore, it is likely that soil canopy cover could be used to roughly estimate soil carbon levels only as it applies to vast age ranges but falls short when comparing plants in closer succession.

6. Conclusion

Continued research is necessary to come to any conclusions on the capabilities of riparian revegetation sites in correlation with carbon sequestration and soil characteristics. This preliminary research will support this multi-year research project aiming to restore the land with strategic groupings of vegetation that are efficient at sequestering carbon. Our findings demonstrate that mature trees boast the highest soil carbon and nitrogen levels; however, the age of the plot did not consistently predict soil carbon and nitrogen levels. Although the soil containing the most mature plants contained the most carbon and nitrogen, we cannot conclusively claim at this time that areas with more mature plants will have the highest soil carbon and nitrogen levels or that ongoing revegetation efforts increase these levels. It is likely that tilling and other disruptions to the earth in the process of planting Phases 1–3 disrupted soil carbon and nitrogen levels, causing them to fall below the control site. Future research as these phases continue to mature is necessary to further investigate this question. This project is still in the early stages and the trends that we hope to see may eventually appear in long-term project monitoring.

Canopy cover proved to be correlated with plant age, with Phase 0 having the highest canopy cover percentage and Phase 4 having the lowest. Although, due to soil carbon content not increasing with age or active revegetation as hypothesized, our hypothesis that canopy cover percentage could be used to roughly estimate soil carbon content cannot be proven at this time. Overall, our study underscores the critical role of preserving mature vegetation, as it proves to be the most effective at sequestering carbon in riparian zones as a method of climate mitigation. Additionally, we hope that our study can highlight that the effects of active revegetation may not be immediately obvious and could take multiple years to become apparent. Preservation of existing trees, continuous monitoring, and adaptive management are essential to maximize carbon sequestration and ensure long-term ecosystem resilience.

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