Research Article

Analysis of Ecological Impacts of a Stream Restoration on Riparian Vegetation in Baltimore County, Maryland

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Abstract: Riparian forests play a vital role in supporting wildlife, managing runoff, and enhancing human well-being, yet they have been degraded by urban development and engineered stormwater systems. Stream restorations have emerged as nature-based solution to water management, but their effect on adjacent riparian ecosystems requires more research. This study evaluates the ecological impact of the Upper Jones Falls Stream Restoration in Baltimore County, Maryland, USA, using satellite and aerial imagery to assess vegetation health and land cover. Vegetation health during the period between 2015 and 2025 was assessed using the normalized difference vegetation index (NDVI), derived from high-resolution multispectral PlanetScope satellite imagery. Results show that although mature forest canopy was substantially lost, vegetation steadily regenerated, with NDVI returning to baseline in less than 10 years. Land cover analysis confirmed some tree plantings closest to the water have been thriving in recent years and also revealed the persistence of exposed water and barren zones. These findings show that NDVI is a useful metric for monitoring vegetation recovery post-restoration, while emphasizing the importance of integrating land cover classification and direct observation. This study highlights the need for more nuanced evaluation of riparian restoration outcomes, including the use of evolving remote sensing technologies and modeling.

Keywords: riparian zone, stream restoration, remote sensing, NDVI, urban ecology

1. Introduction

1.1. Background

Set at the interface between aquatic and terrestrial ecosystems, riparian zones provide a cornucopia of vital ecosystem services including primary production, habitat, flood control, access to water, recreation and a connection to nature for humans (Cadenasso *et al.*, 2007; Ferreira *et al.*, 2023). In the urban environment, these services are scarce, and because of that, more valuable. Yet even in an extensively developed city, small patches of riparian forest can support a diverse number of species with rich spatial and temporal heterogeneity of landforms and habitat (Pennington *et al.*, 2010; Rusnák *et al.*, 2022).

Rivers and riparian zones have been heavily altered by human activity. In many cities, the built environment limits their utility for both humans and nature (Kaushal & Belt, 2012; Morin *et al.*, 2022). Common stressors include dams, flow regulation, agriculture and irrigation, human-induced modifications, and land use changes (Murphy *et al.*, 2022). These changes disrupt natural patterns that support riparian function. In particular, stormwater in Baltimore has been managed through the construction of extensive concrete infrastructure, replacing 1st- and 2nd-order streams (Pickett *et al.*, 2020). Increased volumes and velocity of stormwater then lead to erosion, lowering the water table and disconnecting urban streams from the riparian zone, impacting soil, vegetation, and microbial processes and therefore nutrient cycling (Kaushal & Belt, 2012). This outcome is known as urban stream syndrome, and is marked by rapid flow changes, lack of flood control, higher levels of pollutants and nutrients, altered stream channels, and lower biodiversity with more pollution-tolerant species (Walsh *et al.*, 2005). Because water is diverted, riparian zones are disconnected from their floodplains, streams become incised deeper into the ground due to erosion, and streams in concrete channels deny water to adjacent vegetation, degrading primary production, habitat, flood

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control and other ecosystem services provided by riparian systems. This degradation has prompted cities like Baltimore to implement restoration projects to reverse this degradation (Abdul & Kang, 2023).

The objectives of many urban stream restoration efforts are focused on meeting stormwater quality standards set by the Clean Water Act, which regulates a total maximum daily load of sediment, nitrogen, phosphorous and polychlorinated biphenyls (PCBs) into major waterways. With the focus on water quality, the extent to which restorations benefit riparian ecosystems is limited (Kenney *et al.*, 2012). As an example, the city of Baltimore, MD, has undertaken major urban stream restoration projects across all local watersheds (Baltimore City Department of Public Works, 2009), successfully reducing pollution drained into the Chesapeake Bay. While replanting of destroyed forest patches is standard practice, scientists and community stakeholders are increasingly concerned that some restorations do more harm than good, particularly when large swaths of mature forest habitat are removed to facilitate the restoration (Friends of Herring Run Parks, 2022). As a relatively new engineering practice, approaches to stream restoration should continue to evolve as new information and ideas come to light.

Remote sensing is a powerful and cost-effective method for studying the landscape functionality of ecosystems (del Río-Mena *et al.*, 2023; Iskin & Wohl, 2023). Multispectral remotely sensed imagery is increasingly used to generate detailed land use and land cover (LULC) maps (Claggett *et al.*, 2022) and to measure key indicators of ecological condition. One such indicator is the normalized difference vegetation index (NDVI), a widely used metric of vegetation health. NDVI has also been applied to classify vegetation types and assess both vegetation condition and landscape structure (Pace *et al.*, 2022). The ability to observe and measure land cover at high spatial and temporal resolution makes remote sensing particularly useful for understanding the potential of riparian systems to recover following stream restoration. Recent advances in very high-resolution drone-based multispectral imaging now allow for reliable species-level identification of riparian vegetation using machine learning (Rommel *et al.*, 2022). NDVI time series analysis can reveal the trajectory and pace of vegetative regrowth across disturbed and undisturbed areas (Fitts *et al.*, 2025), making it a valuable tool for evaluating the long-term effectiveness of restoration projects.

1.2. Research Questions and Hypothesis

Stream restoration projects, while often necessary to meet regulatory water quality standards, can cause significant disturbances to riparian ecosystems. For example, the removal of concrete channels and the excavation of new stream channels require the destruction of mature trees and displace aquatic and riparian organisms. As a result, forested areas are necessarily replaced with grass or pioneer species, reducing overall vegetation biomass. This raises the question; how severely are riparian forests impacted by stream restoration, and how does their recovery unfold over time? A key justification for this research lies in the need to quantify the ecological impact of restoration activities in order to refine and improve current methods. The hypothesis is that riparian ecosystems will require a significant time to recover after restoration, due to the loss of forest cover and leading to sustained reductions in NDVI values.

Despite prior efforts to monitor stream restoration effectiveness, there remains a gap in the literature regarding the specific ecological impacts of restoration activities on riparian vegetation health. This study aims to address that gap by leveraging high-resolution remotely sensed data to observe riparian vegetation dynamics over time at the stream-reach scale. The objectives of this study are to: (1) Examine a specific stream restoration case study in Baltimore County, Maryland. (2) Measure the extent and magnitude of deforestation resulting from restoration activity using remote sensing technology. (3) Observe the rate and spatial patterns of re-vegetation following the restoration.

2. Study Area and Methods

2.1. Study Area

This study evaluates the condition of a 11,190m^2 area alongside a stream restoration site along the Upper Jones Falls, restored by Blue Water Baltimore in 2016 (BWB Communications, 2016) (Figure 2A). As a representative example of similar efforts across Baltimore and the region, the site offers a valuable case study for assessing ecological outcomes.

The Upper Jones Falls Stream Restoration Project is located in a suburban neighborhood of Baltimore County, Maryland (Figure 1A). Jones Falls is a spring-fed stream in a temperate climate in the Montane-Piedmont floodplains ecosystem, originating in the Greenspring Valley of Baltimore County. The surrounding watershed is relatively undeveloped, characterized primarily by large estates. To illustrate the site's ecological significance. The Maryland Department of Natural Resources Fisheries Service has recorded the highest standing crop of wild trout in any Maryland stream within the Jones Falls (MDTU, 2020). The restoration project was managed by Blue Water Baltimore and executed by Environmental Quality Resources. The process involved diverting the stream, removing a 152m (500ft) section of concrete channel, then excavating a new channel with a more natural form Figure 2B. Large stones were implemented to regulate water flow, reducing erosion and pollution. After the restoration, 600 native plants were planted (Figures 1C−E). The aim was to improve aquatic habitat, and enhance water quality, as well as monitor for changes in water quality (BWB Communications, 2016). Restoration work took place between May and October of 2016, and the restored stream segment is located at 39°23'45"N, 76°39'52"W.

A site visit was conducted on February 12, 2025 and again on June 4, to observe the landforms and vegetation and document the current state using small unoccupied aircraft system (sUAS) imagery. There is a stand of American Sycamore (*Plantanus occidentalis*) extending approximately 100 meters along the northern side of the riverbank in the restored area, while further up from the stream, saplings of Swamp White Oak (*Quercus bicolor*) and Black Cherry (*Prunus serotina*), have been planted more recently, which is evidenced by the protective grow tubes (Figure 1D). In contrast, undisturbed regions supported mature stands of American Elm (*Ulmus americana*), and Bush Honeysuckles (*Genus Lonicera*), suggesting a different successional stage. These direct observations of vegetation patterns inform interpretation of remote sensed data.

2.2. Data Sources

This study integrates remote sensing techniques using two primary data sources. Multispectral imageryfrom PlanetScope, a constellation of Earth-observing satellites with high spatial and temporal resolution, was used to calculate the NDVI and assess vegetation health following the restoration until 2025. High-resolution aerial imagery from the National Agricultural Imagery Program (NAIP) complements this by enabling detailed land cover classification and detection of landscape changes over time (See Supplementary Data Sheet 1 for a complete list of data sources).

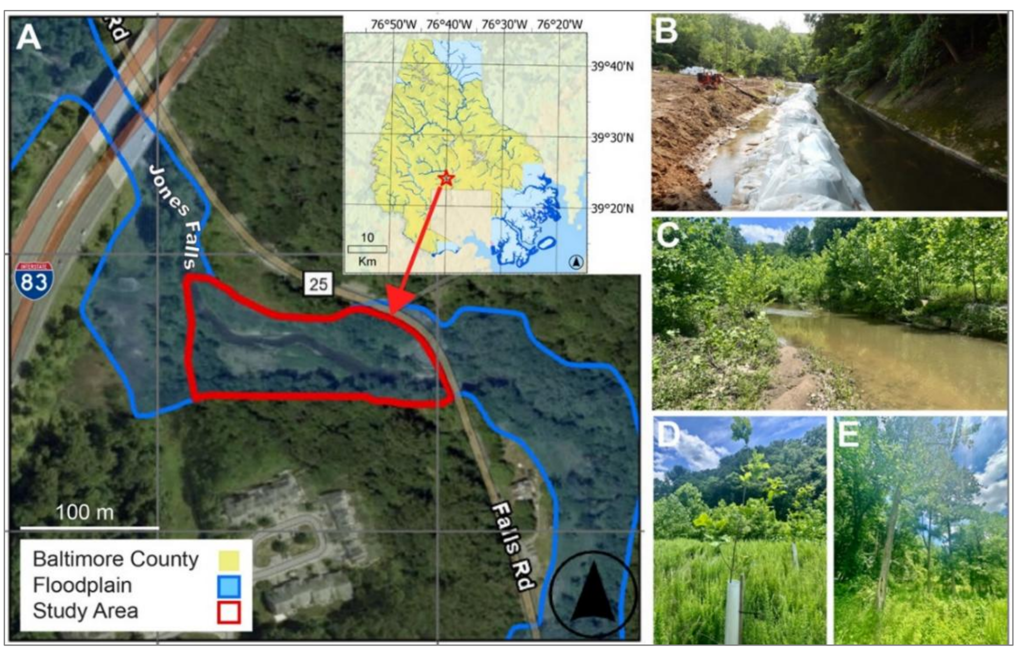

Figure 1. Study area: Upper Jones Falls stream channel removal and stream restoration. (A) The study area is bounded in red, within the floodplain (blue) located at the red star in Baltimore County, MD USA (inset, yellow). (B) Stream restoration construction in 2016, white sandbags on left for diverting the stream path, on the right is the concrete channel. Image used with permission of Blue Water Baltimore. (C) The restored channel in 2025, sycamore trees grow on both banks. (D) New plantings of oak and cherry in the meadow above the stream. (E) American elm in the older riparian forest not affected by the restoration.

The NAIP orthophotos were obtained from USGS EarthExplorer website (USDA, 2023). These high spatial resolution images are useful for identifying fine-scale characteristics of stream restoration sites, such as stone or concrete embankments, sandbars, and new tree plantings. Each image includes four bands: Red (R), Green (G), Blue (B), and Near-Infrared (NIR). Aerial image acquisition occurred before and after the restorations, on the following dates: 2015-07-24, 2017-06-11, 2021-06-17, and 2023-05-25 (Figures 2A−E). The USDA produced no images for this location in 2019, instead an aerial photo for that cycle was taken in 2018-11-06, but was not utilized for analysis because the acquisition date is well past the peak vegetation and the image is obscured by long shadows.

To obtain the most up-to-date observations of the study area, an aerial photographic survey of the study area was conducted on 2025-06-04 using a DJI Mini4Pro sUAS. The final orthorectified image was composed of 187 tiles mosaicked using PixPro software (Figure 2F).

The extent of the riparian zone was defined using the Federal Emergency Management Agency (FEMA) 100-year floodplain shapefile (Baltimore County, Maryland, 2018) from Baltimore County Open Data (Figure 2G), as the floodplain represents the area most likely to support riparian conditions due to its regular exposure to stream flow and flooding.

PlanetScope (PS) satellite imagery sourced from Planet.com (Figure 2H) was available beginning in October 2016, shortly after the restoration. This data set consists of Analysis-Ready PlanetScope imagery (Level 3B products); 3m spatial resolution, resampled from ~3.5m ground sampling distance (GSD), orthorectified surface reflectance product, radiometrically harmonized and spectrally aligned with Sentinel-2 bands: Blue (B2, 490 nm), Green (B3, 560 nm), Red (B4, 665 nm), and Narrow NIR (B4, 865 nm), facilitating consistent time-series comparisons (Planet, 2021).

Because PlanetScope images only became available beginning in 2016 after the restoration, additional images from the RapidEye satellite, also sourced from Planet.com, were used to assess vegetation conditions prior to restoration. These are orthorectified, and radiometrically corrected surface reflectance images at 5-meter spatial resolution (resampled from ~ 6.5m GSD) images (Level 3A products. The imagery includes five spectral bands: Blue (B1, 440–510 nm), Green (B2, 520–590 nm), Red (B3, 630–685 nm), Red Edge (B4, 690–730 nm), and Near-Infrared (B5, 760–850 nm) (Planet, 2019).

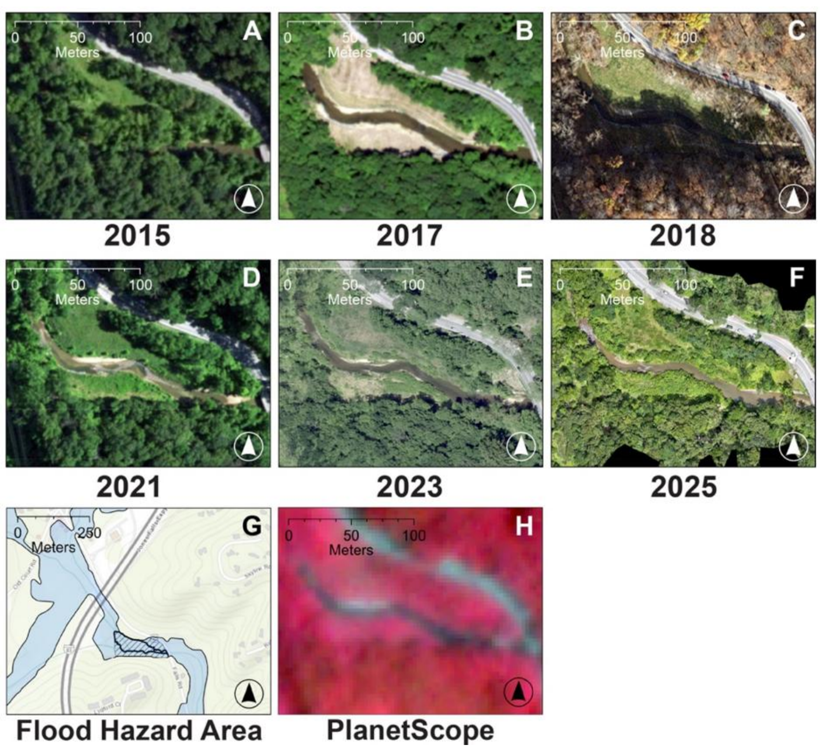

Figure 2. Data sources. (A–E) NAIP aerial orthophotos taken in the year below image. (F) sUAV aerial orthophoto taken in 2025. (G) FEMA 100-year floodplain, hatched area denotes the restoration area. (H) A representative multispectral satellite image, n=555 PlanetScope images.

2.3. Methods

To assess land cover changes, the study area was classified based on NAIP images from 2015, 2017, 2021 and 2023 and using the sUAV aerial mosaic from 2025. Images from 2015 and 2017 were first resampled from 1-m spatial resolution to 0.3-m resolution, to match the 2021 and 2023 images. The 2025 sUAV aerial mosaic was also resampled to 0.3m resolution. Images were then classified using Classification Wizard in ArcGIS Pro. Segmentation was unsupervised with spectral detail: 20, spatial detail: 10, and min. segment size: 10. Classification method was iso cluster, max. classes: 12, max. iterations: 50, max. merges 5, max. merge distance: 0.5, max samples per cluster: 2 and skip factor: 2. All classified images were then reclassified manually, to correct errors and reduce the number of classes to seven land cover classes, based on vegetation structure and surface characteristics: Canopy, Mixed Forest, Pioneer/Understory, Herbaceous, Barren, Developed, and Water (Table 1). Manual classification was informed by direct field observation and extrapolation between sequential years. These categories reflect different stages of vegetation, disturbance, and land use relevant to stream restoration monitoring.

Table 1. Land cover classification.

Class	Description	Rationale
Canopy	Tallest trees with whole crowns visible; dense upper layer of woody trees	Represents mature forest and urban forest canopy habitat
Mixed Forest	Intermediate sized vegetation; mix of small pre-canopy vegetation and shrubs	Reflects transitional forest zones and areas dominated by shrubs or low woody plants
Pioneer	Small woody vegetation, newly planted trees, or leafy understory vegetation	Indicates regrowth areas post-restoration or after disturbance, or exposed understory in canopy gaps
Herbaceous	Grass and groundcover with little vertical relief	Indicates lawns, mowed areas, and early successional vegetation
Barren	Bare ground, sandbars, trails, rocks, erosion control, recently cleared areas	Identifies unvegetated zones in the stream as well as disturbed areas
Developed	Road, bridges, guardrails, exposed concrete channel	Represents all artificial landforms in and around the area of interest
Water	Exposed water, not obscured by canopy in imagery	Marks stream channel presence

In order to focus the study on a representative area of interest, the reach of riparian zone near the removed channel was delineated using the FEMA 100-year floodplain shapefile (Figure 3). The cleared area was defined as all the Barren, Herbaceous and Water land cover that appeared in the 2017 NAIP imagery, and then intersected with the floodplain boundary to define the final cleared area shapefile. Water was included in the cleared area because it was canopy-covered in 2015 but fully exposed in 2017. As the study focuses on vegetation change, canopy removal over water is treated equivalently to that over bare ground.

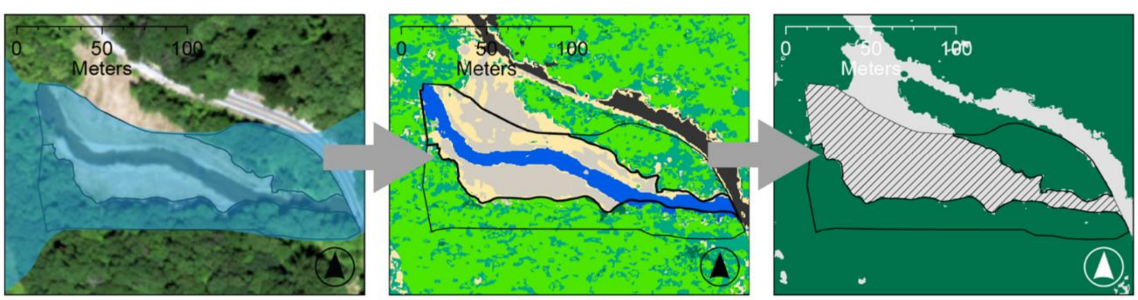

Figure 3. Generation of land cover and restoration extents. Land cover image was classified shortly after restoration using the NAIP image from 2017-06-11. The contiguous area within the floodplain classified as barren, herbaceous or water was identified as the cleared area, an uncleared region of equal size and within the floodplain was defined as the uncleared area. Both patches were converted to shapefiles for use as boundaries in subsequent analysis.

The boundary was smoothed to remove aliasing, resulting in a cleared region with an area of 5,595 m^2. As a reference area, an uncleared portion of adjacent riparian forest was also defined within the floodplain. The uncleared area serves as control to distinguish effects that are a direct result of deforestation and channel rerouting from any indirect effects like annual variations in precipitation, or from artifacts in the images like shadows. The NDVI value of the cleared area at any time point was interpreted relative to the uncleared control, rather than a theoretical baseline. One assumption is that prior to the restoration, the cleared and uncleared area had very similar properties in terms of land cover and mean NDVI. The uncleared area was drawn so that it covered the same surface area as the cleared area. These areas were then generated as shapefiles for further analysis and comparison of the cleared and uncleared areas.

To measure the impact of restoration on cleared and uncleared vegetation in the riparian zone, multispectral images from Planet were evaluated to measure NDVI for each area in each image (Figure 4). A total of 541 cloud-free and snow-free images from PlanetScope (PS2 and PS2.SD) constellations were acquired for dates between 08/14/2016 and 08/10/2025. The images were clipped using the cleared and uncleared boundaries with the Extract by Mask geoprocessing function in ArcGIS pro, then converted to NDVI rasters using the equation NDVI = (NIR−Red)/(NIR+Red). For each raster, the mean NDVI was calculated and taken as a representation of the overall vegetation index for that area. When multiple images were available for a single day, the average of their mean NDVI was used for that day, so that only one mean NDVI value was reported for each day in the time series. Because there were no PlanetScope images available prior to the restoration, four RapidEye images from 7/10/2015−8/4/2015 were used to establish a pre-restoration baseline (Supplementary Data Sheet 2 shows images used for specific dates and single image NDVI statistics). For RapidEye images bands 3 and 5 were used, for PlanetScope images bands 3 and 4 were used for red and NIR respectively. The files were batch processed using a custom ArcPy script.

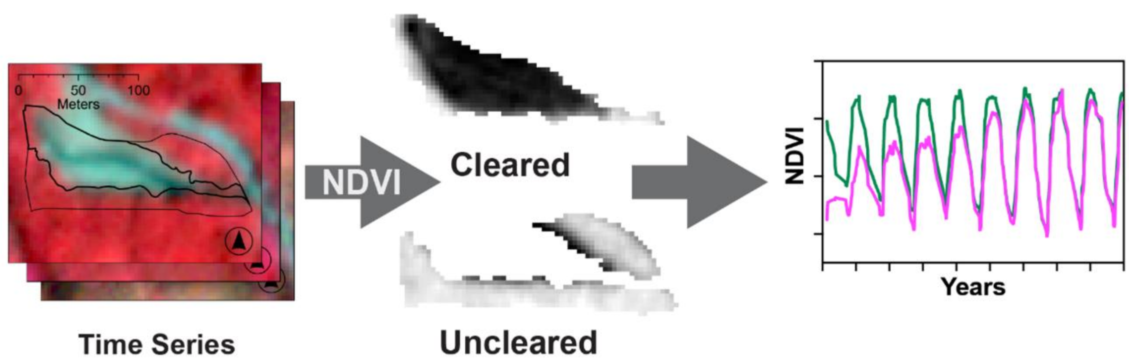

Figure 4. Calculation of NDVI. A PlanetScope image of the study area is shown in false color, where red represents the near infrared band and green represents the red band. The cleared or uncleared shapefile was used to clip a portion of the satellite images, which was then converted to an NDVI raster using the red and NIR bands. Then, mean pixel value was extracted from the layer statistics and compiled to generate a time-series.

3. Results

3.1. Land Cover Classification and Changes

Prior to clearing the area for stream restoration construction, most of the floodplain was forested. Approximately half of the areas of both the uncleared and to-be-cleared zones were classified as Canopy, with another quarter in each zone classified as Mixed Forest (Figures 5A & 5B, Table 2). The remaining land cover consisted mainly of exposed Pioneer vegetation along forest edges and a patch of Herbaceous vegetation in the area designated for clearing (Figure 4C). Notably, only a small fraction of the study area was classified as exposed Water, since nearly the entire length of the stream was shaded by late-successional canopy vegetation.

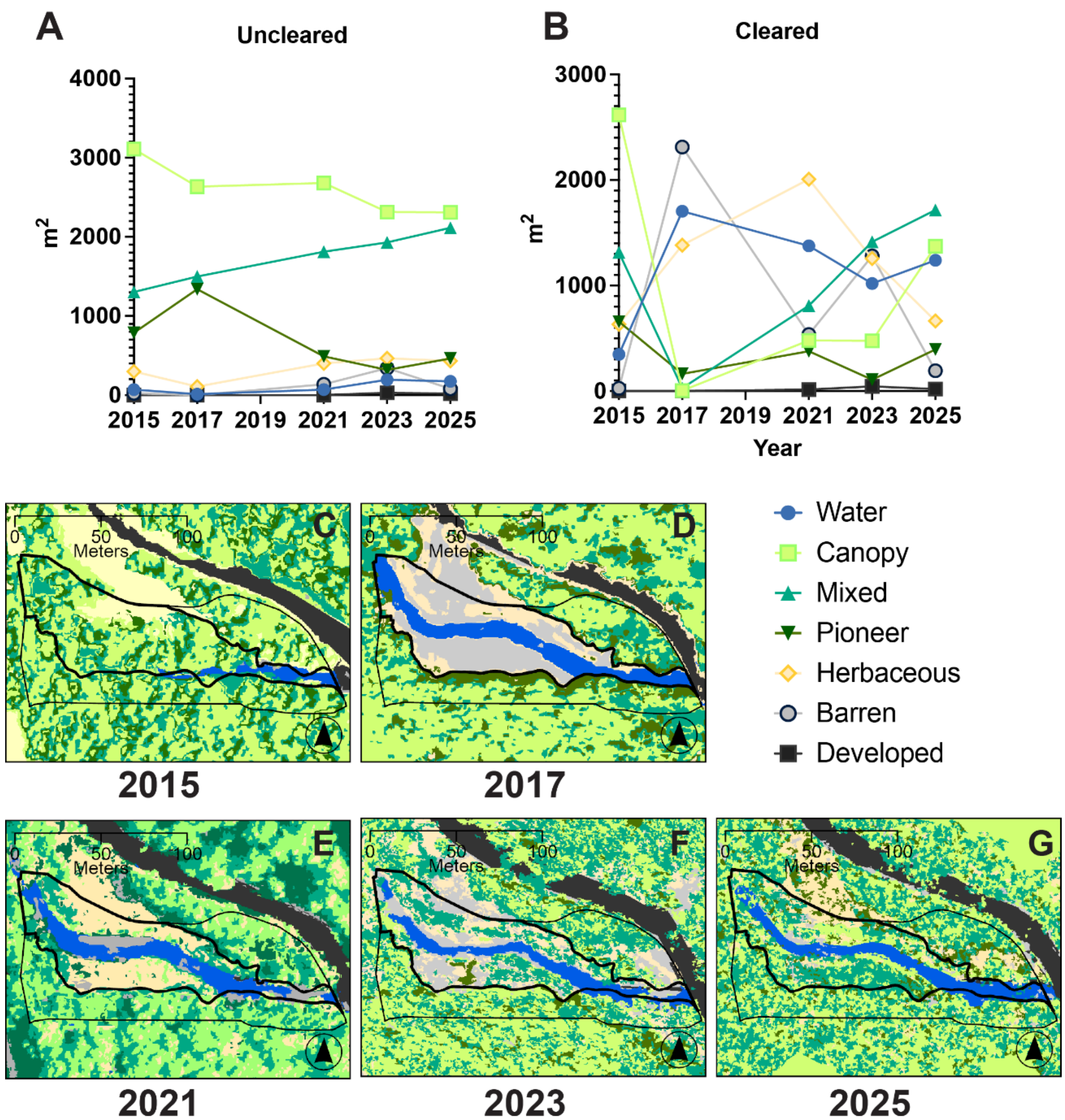

Figure 5. Land cover changes and maps. (A) Square meters of land cover for the uncleared riparian area over a 10-year timespan. (B) Square meters of land cover for the cleared area. (C−G) Land cover maps for each year that NAIP imagery was available.

Land cover was drastically altered following restoration. Forest clearing initially caused a complete loss of Canopy, Mixed Forest, and Understory vegetation within the defined cleared zone. In 2017, the first year following construction, land cover in this area consisted of 41% Barren ground, 30% open water, 25% Herbaceous vegetation, and 4% other land classes (Table 2, more detailed land cover data are in available Supplementary Sheet 3). Recovery of the Canopy and Mixed Forest classes progressed slowly through 2021 and 2023, while Pioneer vegetation expanded at a roughly linear rate. The Water area peaked in 2017 and remained relatively stable in the following years, with variation primarily driven by stream hydrology rather than canopy coverage. Between 2023 and 2025, significant vegetation recovery occurred: the cleared area regained 1,372 m^2 of Canopy (25% cover) and 1,715 m^2 (31% cover) of Mixed Forest. However, nine years post-restoration, Canopy cover remained 48% below 2015 levels, and exposed Water was still 257% greater than before the restoration.

Land cover also changed in the uncleared area over the course of the study. A loss of 477 m² of Canopy was observed in 2017, followed by another marked decline in tall trees in 2023. This decline coincided with a gradual increase in the Mixed Forest class, a decrease in Pioneer vegetation, and some gains in the Herbaceous class. A stand of trees on the north side of the stream, adjacent to the road, was removed prior to 2023 for unknown reasons (Figures 2E & 5F). The additional canopy loss in 2023 was accompanied by a 29 m² increase in Developed area, corresponding to newly visible sections of the bridge and remnants of the old concrete channel.

Overall, land cover analysis reveals that while vegetation in the cleared area is gradually returning, the landscape remains significantly changed in both structure and composition. The restoration led to substantial initial disturbance, followed by slow but measurable regrowth of forest classes. Meanwhile, even the uncleared area experienced notable shifts, underscoring the broader and more complex impacts of stream restoration on riparian land cover.

Table 2. Land cover area and change.*

Year	Class	Area (m^2)		Change Since 2015	
		Uncleared	Cleared	Uncleared	Cleared
	Total Area	**5595**	**5595**		
2015	Water	70	347		
	Canopy	3111	2618		
	Mixed	1304	1315		
	Pioneer	789	657		
	Herbaceous	298	632		
	Barren	23	26		
	Developed	0	0		
2017	Water	13	1703	–81%	391%
	Canopy	2634	5	–15%	–100%
	Mixed	1500	28	15%	–98%
	Pioneer	1338	162	70%	–75%
	Herbaceous	107	1383	–64%	119%
	Barren	0	2312	–98%	8760%
	Developed	2	1	**	**
2023	Water	194	1018	175%	193%
	Canopy	2315	475	–26%	–82%
	Mixed	1929	1414	48%	8%
	Pioneer	319	108	–60%	–84%
	Herbaceous	465	1256	56%	99%
	Barren	341	1281	1388%	4807%
	Developed	31	44	**	**
2025	Water	175	1239	149%	257%
	Canopy	2309	1372	–26%	–48%
	Mixed	2114	1716	62%	30%
	Pioneer	464	394	–41%	–40%
	Herbaceous	431	664	45%	5%
	Barren	80	192	249%	635%
	Developed	20	19	**	**

* More detailed land cover data are available in Supplementary Sheet 3.

** Percent land cover change was not reported because the Developed area coverage in 2015 was 0 m^2, therefore calculation was not possible.

3.2. NDVI Time Series Trend of NDVI

NDVI was analyzed over time to evaluate vegetation health dynamics in response to stream restoration (Figure 6A). Mean NDVI values for both cleared and uncleared areas, provide insight into the impacts of the restoration activity and recovery. Peak NDVI for both uncleared and cleared regions occurred during the months of July and August, indicated by the circled data points in Figure 6A. A minimum NDVI value was reached in the winter months, usually January.

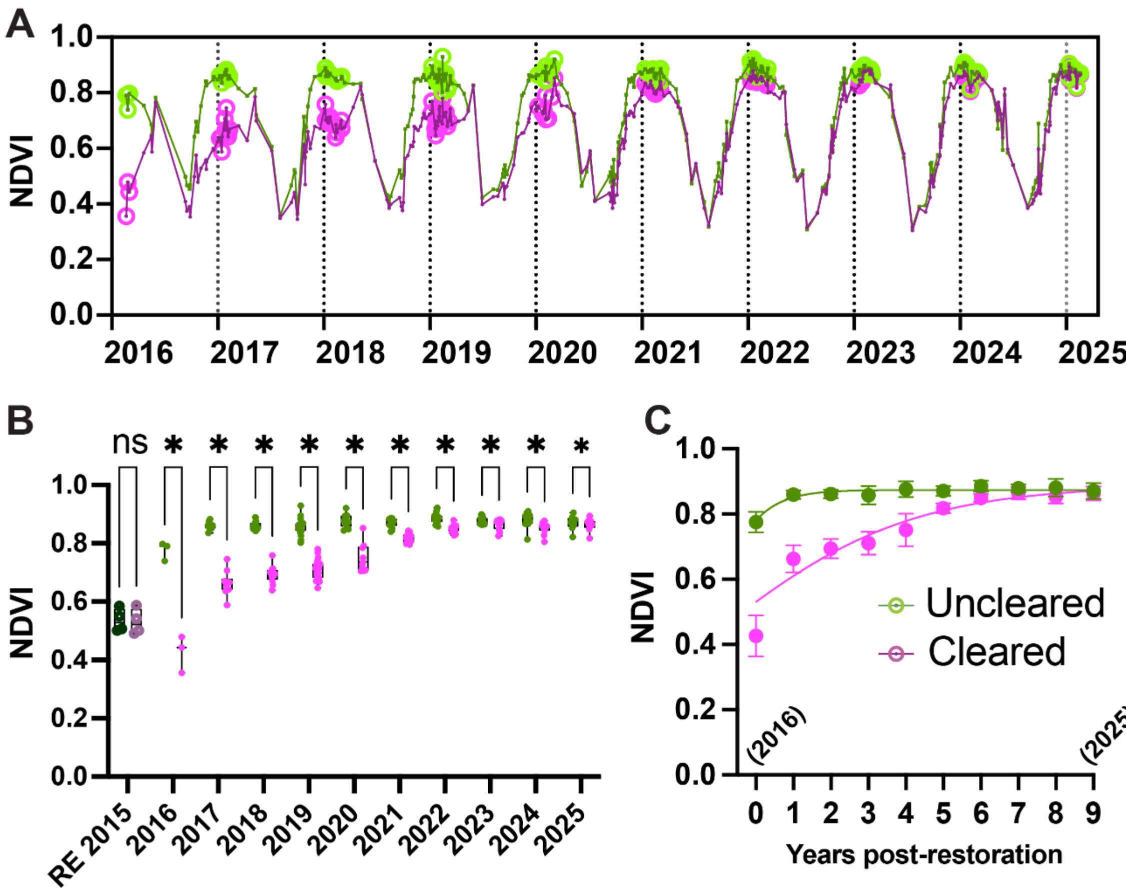

Figure 6. Restoration impacts on NDVI. (A) Time series of PlanetScope mean values for cleared and uncleared sections, n=362 days, circled points are peak vegetation days in July and August, dotted lines represent July 1st (B) Comparison of cleared and uncleared areas during peak vegetation, 2015 data is from RapidEye images, all other years are from PlanetScope, n=115 days, asterisks represent significant differences, multiple t-tests, *p*-value <0.001. (C) Logistic regression of NDVI over time, points represent mean NDVI during peak months, error bars show standard deviation, R^2= 0.3459 for uncleared and R^2= 0.8350 for cleared.

Prior to restoration in peak season 2015, the mean NDVI detected by RapidEye was not significantly different in the cleared versus the adjacent uncleared reference area (p = 0.284) (Figure 6B), indicating comparable vegetation cover at baseline. The restoration process caused a sharp decline in vegetation cover in the cleared area, as shown by the significant drop in NDVI following disturbance. In the first peak season following restoration the mean NDVI, was 0.78 and 0.43 for uncleared and cleared areas respectively. However, the cleared zone then experienced rapid vegetative growth, driven by replanting efforts and expansion of early successional species. By peak season of 2025, nine years post-restoration, NDVI in the cleared area had nearly reached equivalence with the uncleared reference zone; mean NDVI in the cleared area was 0.86, compared with 0.87 in the uncleared (Figure 6B), though it remained statistically lower (p < 0.001, t-test). The uncleared area also saw an initial reduction in mean NDVI, followed by a gradual increase during the study period, although less dramatic.

4. Discussion

4.1. Land Cover Changes

The classification of land cover within the riparian area captures the impact of the restoration activities on vegetation structure and spatial distribution. The most striking change is the complete removal of big trees in a continuous swath between the road and the stream. Water, Barren and Herbaceous classes remained dominant in the cleared area until 2025, when Mixed, Canopy and Water were the largest classes (Figure 5B). It is significant that 10 years post-restoration that canopy cover directly over the stream has not returned in a measurable way (Table 2). The loss of canopy over water is significant as streams lacking shade tend to become warmer, resulting in a loss of aquatic biodiversity (Fanelli *et al.*, 2019) and threatening the health of wild trout in particular (MDTU, 2020). In 2023 there is a spike in Barren land cover and a decrease in Herbaceous, correlated with a decrease in water coverage in the cleared area (Figure 5B); this is possibly a result of drought conditions during much of 2023 (NOAA, 2025). The recovery of canopy in 2025 to 25%, half of the 2015 coverage in the cleared area, is mainly due to the growth of the Sycamore trees along the streambanks, which accelerated between 2023 and 2025 (Figures 1D & 5F−G)), however these trees have not nearly reached the stature of the trees present before the restoration, such as the tall Elms (Figure 1E).

Changes in the uncleared portion may be influenced by clearing adjacent forest, but no direct link was demonstrated here. The first decrease in Canopy (Figure 5B) between 2015 and 2017 is most likely due to phenological differences, since the 2015 NAIP image was taken at peak growth on July 24th, while the 2017 NAIP image was acquired earlier in the year on June 11th, so the fullness of vegetation was greater in the 2015 image (Figures 2A & 2B), resulting in an apparent reduction of this class. The second decrease in canopy occurred between 2021 and 2023 when a stand of trees was removed from the northeast end of the uncleared area (Figures 2D & 5F). The expansion of Mixed class vegetation by 62% between 2015 and 2025, and the decrease in Pioneer by −41% could be due to a combination of factors, such as natural succession of understory to larger plants, and the reduction of canopy trees revealing the smaller mixed type of vegetation.

4.2. Recovery of NDVI in Cleared and Uncleared Areas during Peak Growth

The sharp NDVI decline in the cleared area immediately after restoration activity, confirms a substantial ecological disturbance. Prior to restoration, NDVI values in the cleared and uncleared zones were statistically indistinguishable ($p = 0.284$), suggesting comparable baseline vegetation cover and affirming that subsequent differences were attributable to the restoration activity. One caveat that should be addressed is the low absolute NDVI values observed in the uncleared and cleared areas prior to restoration in 2015 (Figure 6B); these values likely reflect sensor-specific calibration differences between RapidEye and PlanetScope imagery. However, it can be assumed that relative NDVI comparisons remain valid across sensors, and incorporation of RapidEye data was necessary to capture pre-restoration conditions, as PlanetScope imagery was not available prior to 2016. In the first peak season after restoration, PlanetScope images were used to measure NDVI, and they showed that the mean NDVI in the cleared zone dropped to 0.43, compared to 0.78 in the uncleared area. Over the following eight years, NDVI in the cleared section increased steadily, reaching 0.86 by the 2025 peak season. This value approached, but did not fully match, the uncleared zone's NDVI of 0.87, and the difference remained statistically significant ($p < 0.001$), indicating that recovery was strong but still incomplete. Notably, the uncleared reference area also experienced NDVI fluctuations, with a modest decrease followed by gradual increase. These changes may reflect indirect effects of the restoration, such as altered hydrology or edge effects, or broader landscape dynamics.

Seasonal variation was consistent across both zones, with NDVI peaking in July and August and reaching annual minima in the winter months, reinforcing that the observed long-term changes reflect true vegetation dynamics rather than seasonal fluctuations (Figure 6A). Between one and six years after restoration, NDVI in the cleared region began rising from the winter minimum earlier than in the uncleared area and reached peak values sooner, suggesting a shift in phenological timing potentially driven by early successional species. A recurring late-season spike in NDVI around November is also observed but is likely an artifact caused by long shadows in the imagery during that time of year (Figure 2C).

4.3. Logistic growth model predicts NDVI recovery following disturbance

To model NDVI recovery following stream restoration, a logistic model was fitted to the data using GraphPad Prism (Figure 6C). Literature has established that a logistic model is effective for evaluating bounded growth and decay of remotely sensed NDVI (Verma *et. al.*, 2016). Therefore, the logistic regression was chosen because it best captures the observed dynamics of a rapid initial recovery that slows as vegetation matures (Equation 1). In the cleared restoration area, the logistic model estimated a maximum NDVI (Y_m) of 0.8888, a starting value (Y_0) of 0.5306, a growth rate (k) of 0.3905, with a strong model fit ($R^2 = 0.8350$). In contrast, the uncleared area showed less overall change over time, with $Y_m = 0.8740$, $Y_0 = 0.7803$, k = 1.492, although a weaker fit ($R^2 = 0.3459$).

$$Y_{NDVI} = \frac{Y_m Y_0}{(Y_m - Y_0)e^{-kt} + Y_0} \tag{1}$$

This model predicts that the cleared area would reach the same NDVI value (Y_{NDVI}) after 9.44 years, a number that agrees with the observed result, suggesting that the logistic model effectively characterizes vegetation recovery in the cleared and uncleared areas, where growth followed a non-linear pattern (a table of logistic model results and example calculations are available in Supplementary Data Sheet 4). In contrast, the model showed a less precise fit for the uncleared area, consistent with more stable conditions and less directional change over time. Overall, these findings demonstrate that replanting efforts facilitated rapid vegetation regrowth in the cleared zone, though full ecological recovery, particularly in terms of vegetation density and structure, remains incomplete. According to the logistic model the mean NDVI in the cleared and uncleared areas is predicted to converge approximately 9 years post-restoration, and by year 10, the cleared zone is projected to slightly exceed the uncleared in NDVI (Supplementary Data Sheet 3). The model estimates that the uncleared area will reach its asymptotic NDVI value (Y_m) by year 25, which appears to be a reasonable recovery timescale given the observed NDVI trends and land cover changes. These results highlight the value of NDVI as a straightforward and effective metric for tracking riparian forest recovery over time.

4.4. NDVI Time Series Compared with Land Cover Analysis: Correlation and Contradiction

When interpreted alongside land cover data, the NDVI time series reveals important limitations in using greenness alone as a proxy for ecological recovery. Although NDVI values in the cleared area dropped sharply following restoration and then rebounded to nearly pre-disturbance levels, this trajectory does not fully capture the extent or quality of vegetation recovery. Prior to restoration, the cleared and uncleared areas had similar mean NDVI values (Figure 6B), which is expected given their comparable vegetation structure: 56% of the uncleared area and 47% of the cleared area were classified as Canopy (Table 2), and other land cover types were similarly distributed across both zones (Figure 5A).

A decade post-restoration, the apparent convergence of NDVI values between cleared and uncleared zones might suggest successful regrowth. However, the land cover data tells a more nuanced story. The sharp decline in biomass caused by the removal of mature trees was not reversed by the regrowth of equivalent vegetation; rather, much of the recovered NDVI can be attributed to early successional vegetation such as grass and shrubs, as well as young, small-diameter trees. These plant types have lower structural complexity and biomass than the mature forest they replaced but can nonetheless produce high NDVI values due to their chlorophyll content. Thus, the NDVI recovery reflects a return of vegetative cover in terms of greenness, but not necessarily in terms of forest structure, carbon storage, or habitat quality.

Interestingly, the NDVI in the cleared zone rebounded despite the addition of a widened stream channel, an area classified as Water, which would be expected to lower the average NDVI due to its non-vegetated surface. That NDVI still increased under these conditions highlights the dominance of low-stature, fast-growing vegetation in boosting spectral greenness measurements.

These findings challenge the initial hypothesis that NDVI would remain low in the cleared area due to the long-term loss of canopy. While NDVI recovered quickly, this appears to reflect a shift in vegetation type rather than a true return to pre-restoration forest conditions. The land cover analysis was essential for identifying persistent physical changes, such as the exposure of the streambed and the emergence of Barren and Water classes, which NDVI alone cannot resolve. For example, while the Water class peaked in 2017 immediately following construction, it remained elevated throughout the study period, with stream hydrology driving year-to-year variation more than canopy closure. By 2025, exposed water area was still 257% greater than in 2015.

Despite signs of vegetative regrowth, forest recovery remains incomplete. Between 2023 and 2025, the cleared area regained 1,372 m^2 of canopy forest (25% cover) and 1,715 m^2 (31% cover) of mixed forest. However, this still represents a 48% reduction in canopy cover compared to baseline levels from 2015. These figures underscore the importance of supplementing NDVI time series with land cover classifications and structure-sensitive remote sensing tools to better evaluate restoration success. While NDVI is useful for tracking general vegetation recovery, it lacks the specificity to distinguish between grasses, shrubs, and mature forests, or to detect ongoing structural deficits in recovering ecosystems.

5. Conclusions

This study examined the Upper Jones Falls stream restoration, a project which replaced a concrete channel with a more natural stream form (BWB Communications, 2016). This construction involved significant ecological disruption, especially the removal of mature forest cover. The replacement of trees with grass or pioneer species reduced vegetation biomass and restructured the landscape, raising important questions about ecological impact and recovery. Replanted vegetation showed signs of health and gradual recovery over time, with NDVI values steadily increasing post-restoration.

In summary, the restoration clearly had a profound impact on riparian vegetation, initiating a rapid rebound in NDVI values. Although NDVI values returned to near pre-restoration levels, suggesting a recovery in greenness, this did not fully align with land cover analysis, which indicated a shift in vegetation type rather than a return to pre-disturbance forest conditions. This highlights a key limitation of NDVI: while it offers a useful approximation of restoration progress, it lacks ecological specificity without contextual land cover data. This study helps establish a baseline for remotely monitoring stream restoration and suggests that a minimum 10-year window is likely required to recover a certain level of ecological complexity.

Stream restoration is still a relatively new development in environmental engineering and landscape design, with new approaches being implemented rapidly. This study provides actionable insights for restoration contractors, advocacy groups, residents, and municipal agencies aiming to design projects that balance water quality goals with habitat connectivity, biodiversity, and long-term ecosystem health. Selection and placement of replanting species could be used strategically to restore canopy shading over the stream, accelerating the return of this important riparian ecosystem service. Certain vegetation types may be more effective in restoring canopy cover, especially those that extend over the stream path, these should be preserved when possible or prioritized for rapid recovery. It may be better to leave some patches of established vegetation, rather than clearing a large contiguous swath. Restoration progress can be monitored remotely and could provide an indicator that informs managers when intervention is required, by adding new saplings or helping replanted vegetation to establish.

As technology continues to advance, it would be possible to automate much of this analysis in order to create a dashboard for city managers to continuously monitor restorations and parklands, similar to how transportation departments monitor traffic with cameras and sensors. Integrating citizen science and on-the-ground observations could provide useful context to complement remote sensing data, including information about species presence, plant health, and wildlife activity. Looking forward, evaluating landscape metrics like heterogeneity at a fine scale could provide a measure of ecological resilience and also serve as a useful tool for restoration design. Future work should also examine how restoration affects urban wildlife corridors and movement patterns, not only vegetation metrics.

Data Availability: Supplementary data are available in the attachment and at https://bit.ly/4nyfji8.

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