Deer Creek Stage 0 Restoration Geomorphic Complexity Monitoring Report

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1. Executive Summary

Stage 0 restoration is a relatively new technique of restoring wide, depositional valley bottoms to an anastomosing state, and existing monitoring has not yet demonstrated its long-term efficacy. The Deer Creek Stage 0 restoration sought to increase valley bottom geomorphic complexity by adding large wood, removing anthropogenic channel confinement, and reshaping the existing channel. Existing monitoring techniques may not adequately capture these processes that Stage 0 restoration seeks to influence. To develop and test appropriate metrics for monitoring Stage 0 restoration, we used a combination of post-restoration field surveys and remote imagery to measure spatial heterogeneity and to observe wood jam characteristics and channel lateral migration. Specifically, to determine the impacts of Stage 0 restoration along Deer Creek, we evaluated: (1) how the restoration directly altered valley bottom spatial heterogeneity; (2) the variability, or dynamism, of valley bottom morphology and spatial heterogeneity before and after restoration; (3) the trajectory of valley bottom spatial heterogeneity before and after restoration in the context of estimated flow history; and (4) wood dynamics. We also compare methods for quantifying geomorphic complexity and collecting relevant monitoring data.

The Stage 0 restoration substantially increased the ratio of active channel area to valley bottom area of the treated reaches of Deer Creek and increased valley bottom patch diversity in the upstream of the two treated reaches. This direct impact has provided the river more room to erode and deposit sediment across its valley bottom and, in the upstream treated reach, created a more diverse assemblage of geomorphic units that may provide the basis for a more diverse fluvial ecosystem. While the restored reaches are not uniformly more dynamic than pre-restoration, they show no trend towards a return to their pre-restoration, less complex state after two years of low to moderate flows. However, the absence of high flows post-restoration prevents determination of whether these short-term impacts will be sustained. The lack of high flows and field surveys of wood or channel morphology similarly limit our ability to quantify wood dynamics and sediment erosion and deposition post-restoration. However, we observed complex and likely relatively stable wood jams that substantially interact with channel margin landforms and living trees and that could induce substantial geomorphic change when high flows that can reshape the channel occur in the future.

To characterize valley bottom spatial heterogeneity, we determine: (1) the ratio of channel length to valley bottom length; (2) the number of vegetated islands per valley bottom length; (3) the ratio of channel to valley bottom area; and (4) the Shannon equitability index, a measure of the relative abundance of morphologic patches across the valley bottom. We found the ratio of channel to valley bottom area and the Shannon equitability index to be most robust to mapping errors and provide information directly relatable to ecogeomorphic processes such as channel migration, avulsion, widening, vegetation establishment on deposited sediment, and vegetation recruitment from eroded surfaces. Thus, we recommend these indices or similar ones (e.g., channel to floodplain area, or Shannon diversity index) as robust measures of valley bottom spatial heterogeneity that can be used to monitor Stage 0 restoration effectiveness. However, we caution that these metrics of spatial heterogeneity are sensitive to the selection and definition of valley bottom patch types.

The observations needed to measure geomorphic complexity can be made using a variety of methods, ranging from expensive and time-consuming (e.g., bathymetric LiDAR) to cheap and rapid (e.g., field transects of patch abundance). We recommend a combination of field measurements of valley bottom patch abundance and mapping of freely available imagery as a cost-effective means of measuring spatial heterogeneity. We also recommend direct observation of wood jam dynamics (e.g., repeat surveys to determine how wood jams change after high flows) and channel morphological change (e.g., tracking lateral erosion in imagery, noting bar deposition during field surveys) to contextualize measurements of spatial heterogeneity.

2. Introduction

The Deer Creek, OR Stage 0 restoration, completed in Summer 2016, sought to increase valley bottom spatial heterogeneity and increase hydrologic connectivity by restoring large wood and filling incised channels with sediment removed from natural and anthropogenic deposits to create a more anastomosing planform. Stage 0 restoration is a novel method to restore low-gradient, unconfined reaches to a dynamic steady state that maximizes sediment, water, and nutrient retention time (Powers et al., 2018). Such a dynamic steady state should show no consistent, long-term trend in spatial heterogeneity or morphologic adjustment, but still vary through time as channels migrate and avulse. Many river systems naturally exhibit locally broad valley bottoms and relatively dynamic channel morphologies that perform these retentive functions (Wohl et al., 2017), and anthropogenic disturbance such as forestry, road building, levee construction, and stream cleaning have generally simplified and artificially confined such valley bottoms (Bilby and Ward, 1991; Burns, 1972; Wohl, 2014). This motivates a restoration approach that restores a stream to a sustainable state of high geomorphic complexity.

A challenge of Stage 0 restoration is that it seeks to restore dynamic processes that monitoring can struggle to robustly characterize. Stage 0 restoration alters the entire valley bottom to restore the dynamic geomorphic processes that underpin fluvial ecosystems (Powers et al., 2018). These processes include: (1) channel migration and avulsion, which can produce freshly scoured surfaces for vegetation colonization and recruit mature trees to act as downed wood (Latterell et al., 2006; Van Pelt et al., 2006); (2) sediment deposition and resulting retention of nutrients and organic matter (Wohl et al., 2017; Wohl and Scott, 2016); (3) lateral hydrologic connectivity, including delivery of sediment, nutrients, and water via overbank flooding (Covino, 2017) and low flow wetting of side channels, which can provide key fish habitat (Groot and Margolis, 1991; Morley et al., 2005); (4) and wood accumulation, which can drive avulsion and migration (Abbe and Montgomery, 2003; Bertoldi et al., 2009; Collins et al., 2012; Gurnell et al., 2005; Sear et al., 2010), hydrologic connectivity, and create important habitat for aquatic and riparian species(Jones et al., 2014; Pilotto et al., 2014). Simple metrics, such as the number of pools per unit valley length, the number of channels per valley length, or cross-sectional topography variability may not adequately capture the magnitude or direction of these processes. While biotic monitoring (e.g., fish and macroinvertebrate diversity and abundance estimates) may evaluate desired end result of restoration, it does not explicitly measure the geomorphic foundation on which fluvial ecosystems exist (Kondolf and Micheli, 1995).

The complex processes described above all tend to increase the spatial heterogeneity, or the variability in biotic and physical forms, across the valley bottom. In lieu of costly efforts to directly observe those processes, metrics that quantify geomorphic complexity (e.g., Wohl, 2016) may be useful to evaluate whether Stage 0 restoration restores geomorphic processes and whether a stream exhibits a sufficiently complex state to support the varied habitat types that can then support a diverse ecosystem (Brown, 2003; Herdrich et al., 2018; Venarsky et al., 2018; Ward and Stanford, 1995).

We describe geomorphic complexity as a combination of spatial variability in biologic and physical forms (spatial heterogeneity) and temporal variability in those forms (dynamism) (Figure 1). Geomorphic spatial heterogeneity here refers to the diversity of patches of physical and biologic forms in a river valley bottom (Wohl, 2016). Spatial heterogeneity can be described using a combination of more traditional geomorphic complexity metrics related to the number or morphology of channels as well as metrics that have more traditionally been used to describe ecologic diversity, such as the Shannon diversity and equitability indices (Maddock et al., 2008; Wyrick and Pasternack, 2014). Diversity indices measure richness (the number of morphologic patch types), abundance (the proportion of valley bottom occupied by each morphologic patch), and evenness (the relative proportion of each morphology patch).

These spatial heterogeneity metrics describe the valley bottom at a given point in time. However, a fully functioning valley bottom likely changes through time, necessitating that temporal analysis also be a key part of monitoring geomorphic complexity. Geomorphic dynamism consists of variability in morphologic metrics like spatial heterogeneity as well as variability in morphology through time (e.g., point bar growth, migration, avulsion). Such variability through time can also include consistent trends (Figure 1) in spatial heterogeneity or morphologic evolution, which could indicate whether a system has been restored to a dynamic steady state or is potentially undesirably returning to pre-restoration conditions.

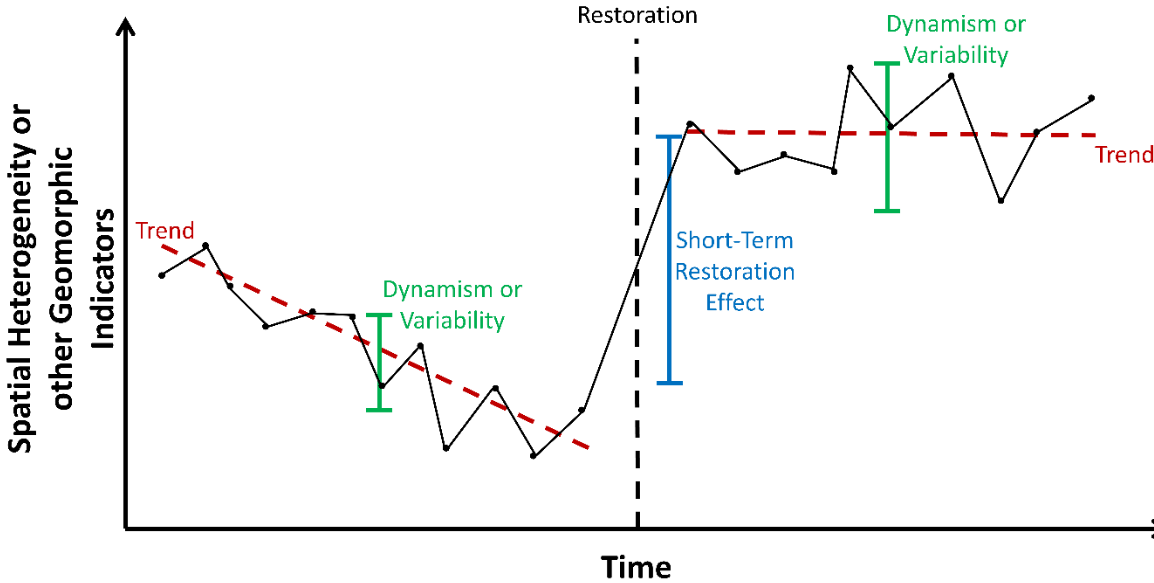

Figure 1: Conceptual plot showing spatial heterogeneity of a stream reach through time. Stage 0 restoration has a short-term restoration effect (shown in blue) but may also sustainably alter spatial heterogeneity. Restoration sustainability can be measured by the trend (red dashed line) in spatial heterogeneity as well as variability in valley bottom spatial heterogeneity, or the dynamism of reach-scale morphology (shown in green). In this figure, a hypothetical stream with a pre-restoration trend towards a simpler state (lower spatial heterogeneity) and low dynamism is restored to a sustainable (no positive or negative trend) state of high spatial heterogeneity and dynamism.

While a valley bottom could be restored to a spatially heterogeneous state, if it is completely static (i.e., has no dynamism), over time the geomorphic processes that build diverse habitats will fail to function and the system will fail to support a diverse ecosystem. Only a sustainably spatially heterogeneous *and* dynamic valley bottom meets the key goals of Stage 0 restoration. To address the challenge of robustly monitoring Stage 0 restoration effects on spatial heterogeneity, we utilized a variety of remotely sensed and field data sources to compute multiple measures of spatial heterogeneity and dynamism. Our objectives were to:

1. Determine the short-term geomorphic impact of the Deer Creek Stage 0 restoration by comparing the spatial heterogeneity and wood load of post-restoration treated reaches to pre-restoration and untreated reaches.
2. Compare multiple metrics of spatial heterogeneity and temporal dynamism of Deer Creek to determine the most robust means of monitoring the geomorphic complexity of a Stage 0 restoration.
3. Compare multiple means of collecting the geomorphic data that feed metrics of spatial heterogeneity and temporal dynamism as the basis for recommendations on the most effective protocols for monitoring Stage 0 restoration effects on geomorphic complexity.

3. Methods

3.1 Study Site

The Deer Creek Stage 0 restoration took place just upstream of the confluence between Deer Creek and the mainstem of the McKenzie River in the western Oregon Cascade Range (Figure 2) and sought to restore the river from a simplified state to a more complex, anastomosing planform. The pre-anthropogenic-disturbance state of Deer Creek is poorly known, but relict side channels and islands on terraces may indicate that the restoration reach was formerly anastomosing. Near the confluence, a large flood that reshaped the valley bottom in 1964 produced a multithread channel that filled much of the valley bottom (Bianco, 2018). Road building and forest harvest, beginning in the mid 19th century, more recent berm construction along the active channel, construction of an electricity transmission line that runs through the reach, and active wood removal has likely decreased wood supply and load. This may have led to lateral confinement of the channel, producing the recent pre-restoration condition of a single to multiple thread channel with a single incised main channel and poor lateral hydrologic connectivity.

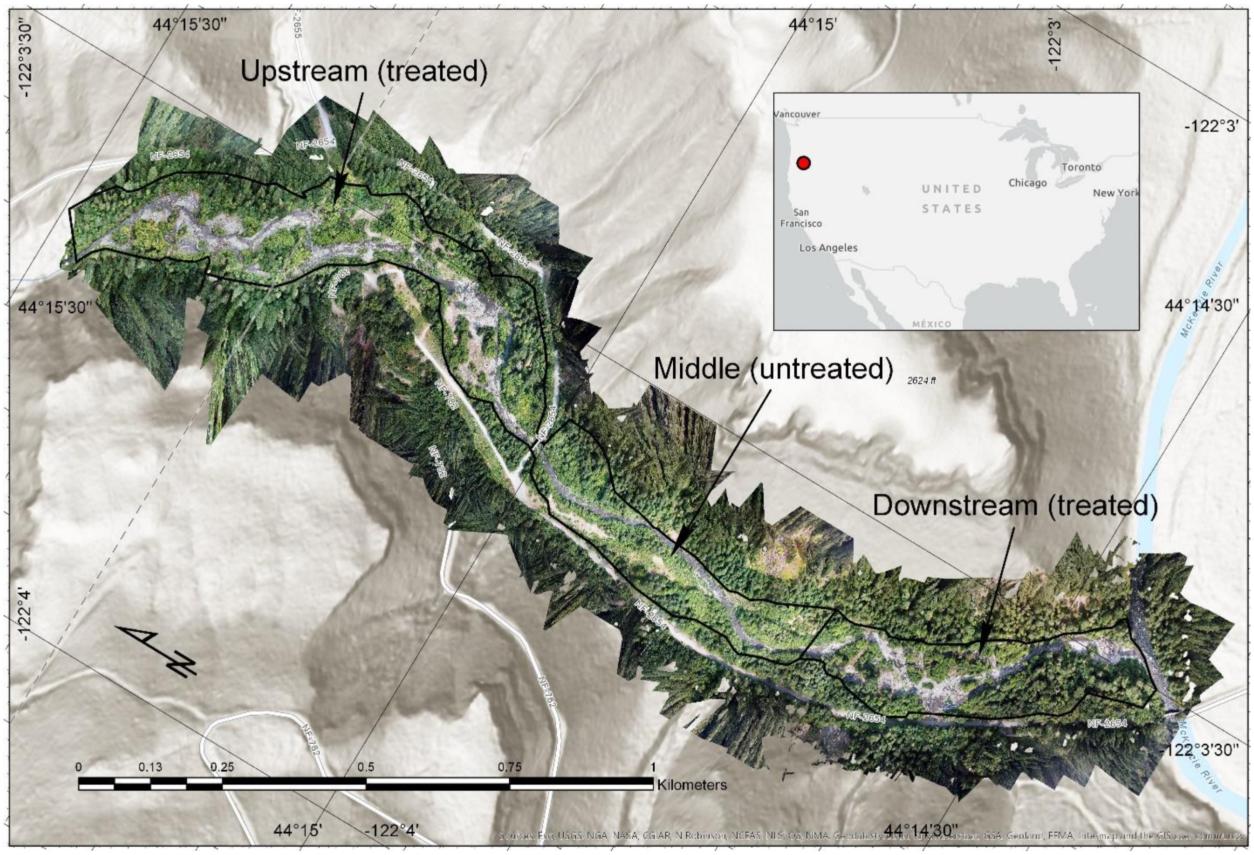

Figure 2: Map showing the three reaches of the Deer Creek Stage 0 restoration project overlaid on a drone-derived orthomosaic from August 2018. Inset shows Deer Creek (red circle) location. Black boundaries delineate the valley bottom extent mapped for each reach.

The restored segment of Deer Creek drains a basin of approximately 59 km^2 spanning an elevation range of 1055 to 1628 m (U.S. Geological Survey, 2019). The valley bottom at the restoration site has a gradient of approximately 1.8% over a length of 2.15 km, and ranges in width from approximately 20 to 154 m. Prior to restoration, the active channel was confined to a small proportion of the total valley bottom area (20 – 30 % of the valley bottom) by berms. Restoration sought to give the active channel more room to migrate, thus increasing geomorphic and hydrologic lateral connectivity.

The Stage 0 restoration of Deer Creek occurred in Summer 2016 and involved earth moving to remove berms, reactivate side channels, and fill in the incised main channel, followed by the placement of substantial amounts of unanchored large wood in active channels, floodplain, and on vegetated islands (desired placement was at least 200 logs per km). The restoration occurred along only the upstream and downstream portions of the lower 2.15 km of Deer Creek, leaving a middle reach unrestored. For two years post-restoration, 13 large conifers were pulled over (felled without cutting off the root bole) from the valley wall into the channel, providing relatively stable potential key pieces, supplementing wood load and delivering minor quantities of sediment.

3.2 Mapping Deer Creek Valley Bottom Morphology and Wood

To quantify spatial heterogeneity and dynamism in Deer Creek, we manually mapped a combination of historical aerial imagery, high-resolution satellite imagery, and low-altitude drone imagery (e.g., Figure 3) collected both shortly before and for 2 years following restoration. We utilized Google Earth and USGS EarthExplorer to identify and access high resolution orthoimagery of the restored reach. Due to the moderate size of the stream, we excluded non-color images (in which active channel was difficult to distinguish), overly shaded images, and images of too low resolution. We also used three existing drone imagery datasets (described in Bianco, 2018) from just prior to restoration to 2017, supplemented by our own drone flight in August 2018, conducted with a DJI Mavic Pro flown at altitudes ranging from 30 to 120 m above ground level.

Table 1 summarizes imagery sources. Using these imagery sources, we were able to observe Deer Creek's morphologic evolution for 11 years pre-restoration, and 2 years post-restoration. The baseline data provided by the 11 years of pre-restoration observations is essential for understanding the effects of Stage 0 restoration on the trend and dynamism of Deer Creek's morphology.

Table 1: Summary of imagery data used to map the valley bottom of Deer Creek. We assumed that the valley bottom extent mapped in 2018 drone imagery and 2018 bathymetric LiDAR applied to all time periods.

Date	**Imagery Resolution (m)**	**Imagery Source (USGS: USGS Earth Explorer, GE: Google Earth, D: Drone)**	**Reaches Covered (U: upstream, D: downstream, M: middle)**	**Morphologic Units Mapped (1: active channels; 2: vegetated islands; 3: pools; 4: wood; 5: floodplains; 6: terraces; 7: valley bottom)**
07/2005	1	USGS	U, D	1, 2
06/2009	1	USGS	U, M, D	1, 2
08/2011	1	USGS	U, M, D	1, 2
07/2012	1	USGS	U, M, D	1, 2
07/07/2013	0.3	GE	U, M, D	1, 2
09/2014	1	USGS	U, M, D	1, 2
04/2016	0.03	D	U, D	1, 2, 3, 4, 5, 6
06/27/2016 (pre-restoration)	0.3	GE	U	1, 2, 4
07/2016	1	USGS	U, M, D	1, 2
07/14/2016	0.3	GE	U, M, D	1, 2, 4
07/26/2016	0.3	GE	U, D	1, 2, 4
09/2016	0.03	D	U, D	1, 2, 3, 4, 5, 6
09/2017	0.03	D	U, D (partial)	1, 2, 3, 4, 5, 6
08/2018	0.03	D	U, M, D	1, 2, 3, 4, 5, 6, 7

Figure 3: Comparison of imagery sources used to measure geomorphic complexity and wood along Deer Creek. Images show the same rightward bend in the upstream reach of Deer Creek.

To enable accurate mapping and comparison with other imagery sources, we processed the low-altitude drone imagery of Deer Creek to produce orthorectified mosaics (orthomosaics) of the study site using Agisoft Metashape Professional. We first identified and eliminated blurry, out-of-focus, overly oblique, and poorly exposed imagery, then aligned photos by matching points. Following alignment, we manually edited the points that tie images together to eliminate erroneous points, then generated a dense, three-dimensional point cloud. Using a DEM generated from the dense point cloud, we orthorectified images to create an orthomosaic. We detail our workflow for this process in Appendix A. Because these orthomosaics are only georeferenced using the drones' on-board GPS unit, we used ArcGIS Pro to align the orthomosaics from 2016 and 2017 to the 2018 orthomosaic, which had the most extensive coverage and the best georectification to imagery data (based on alignment of roads and other assumedly permanent features). We detail our workflow for this process in Appendix B.

To supplement aerial imagery and more accurately map the extent of the valley bottom, we utilized a 1 m bathymetric LiDAR-derived ground-surface DEM collected in 2018. We detrended this DEM separately for each reach (upstream, middle, and downstream) by fitting a linear plane to 3 points along the valley bottom and subtracting that linear plane from the original DEM. Detrending enabled clearer observation of height above the channel bed, helpful for differentiating floodplains from terraces.

We used ArcGIS Pro to manually map the valley bottom, terraces, floodplains, vegetated islands, pools, and wood using imagery and detrended LiDAR DEM data. For 1 m imagery, it was possible to accurately differentiate terrace and floodplain surfaces but not accurately resolve pools and wood. Thus, for those imagery datasets, we only mapped active channels and vegetated islands (

Table 1). We assumed that the extent of the valley bottom was unchanged from its 2018 extent for the period of study and assumed that terraces were unchanged from their 2018 extent since 2016. These assumptions are supported by the absence of mass movements on the valley walls and the absence of noticeable bank erosion from 2016 to 2018, other than the direct effects of the restoration, which did not appear to substantially influence terraces. We define each morphologic unit mapped in Table 2.

Table 2: Definitions of morphologic units mapped in remotely sensed imagery for Deer Creek.

Valley Bottom	The area encompassing active channels, floodplains, and terraces, bound laterally by hillslopes above the highest terrace. Does not include terraces that are considered perched on hillslopes (i.e., far above the modern valley bottom and likely inaccessible by modern fluvial erosion).
Terrace	Quasi-planar surfaces (although they may be hummocky or covered by hummocky deposits) higher in elevation than the contemporary floodplain that show evidence of being shaped by the same river currently occupying the valley bottom (to differentiate from alluvial fans) but are distinctly less active than contemporary floodplains. Terraces should not show evidence of recent flooding (e.g., fluvial deposition by the same river currently occupying the valley bottom), and generally exhibit distinct vegetation communities compared to contemporary floodplain (i.e., a greater abundance of flood-intolerant species). Anthropogenic features such as roads should not be *de facto* mapped as terraces. Also note that tributary channels may be actively reworking surfaces that should be mapped as terraces for the main stream in a valley, and that the choice of stream being mapped will determine whether such surfaces should be mapped as terraces or active floodplain.
Floodplain	Quasi-planar surfaces lower than adjacent terraces that show evidence of recent fluvial reworking are likely inundated at flows just above bankfull stage, are not entirely scoured bare of vegetation (although small patches of vegetation scour are permitted, and care should be taken to distinguish anthropogenic from fluvial vegetation removal).
Vegetated Islands	Floodplain surfaces that are vegetated and likely surrounded on all sides by recently active (although not necessarily active at low flow) channels. Note that side channels (channels that separate from and rejoin the main channel) obscured by canopy can be inferred from the presence of exposed diffluences or confluences surrounding islands. Mapped edges of vegetated islands should try to approximate the actual banks of the islands, not the edge of the canopy cover obscuring the bank and should thus be between the edge of the canopy cover and the center of trees on the edges of islands. Vegetated islands must appear to be at least 3m across in any one direction to avoid mapping of overhanging canopy.
Wood	Any accumulation of fine logs (with visible edges), accumulation of large and fine wood (large being over 1 m in length and 10 cm in diameter), or single piece of large wood. Small gaps in accumulations less than approximately 0.5 x 0.5 m are treated as part of the accumulation.
Pool	Depressions in the active channel that appear as more still water (i.e., less whitewater, fewer exposed cobbles/boulders), finer textured, and darker colored (indicating higher water depth) than other regions of the wetted channel. Pools are mapped from imagery

	even when detrended DEM shows no depression as long as there is substantial wood covering the pool that could obscure the channel bed from LiDAR.

After mapping morphology unit polygons, we computed active channel and valley bottom length by creating centerlines for those mapped polygons for each time period. We manually cleaned these centerlines to eliminate unrealistic sinuosity, confluences, or difluences and ensure that they spanned the entire longitudinal distance of each polygon.

We measured wood jam characteristics to make qualitative predictions of their dynamics post-restoration. While we lacked detailed wood jam characteristics data for 2016 and 2017, we conducted a survey of wood jam dynamics using the Wood jam Dynamics Database and Assessment Model (WooDDAM) protocol (Scott et al., 2019) in August 2018. WooDDAM consists of a field survey protocol to survey wood jam characteristics and resurvey how wood jams change through time, or wood jam dynamics. These data are uploaded to a public, online database that can be used to contextualize measurements (e.g., compare jam characteristics to jams in similar regions). The online database drives machine-learning based statistical models to predict how wood jams change through time. While these models are only preliminary at this time, the database will likely be sufficient to produce robust estimates of the probability of wood jams experiencing various modes of change (e.g., accumulating wood, mobilizing) in the near future, partly using data from ongoing monitoring of Deer Creek.

We surveyed every wood jam (3 or more touching pieces of wood with diameter over 10 cm and length over 1 m) for the first 400 m of the upstream reach of Deer Creek (30 jams), then subjectively chose jams that we judged likely to influence channel morphology to survey downstream of that point to the confluence with the McKenzie River (19 jams). WooDDAM surveys measure characteristics of wood jam structure, geometry, and interaction with valley bottom landforms while also recording characteristics of the valley bottom and watershed hydrology. This survey allows us to describe typical wood jams in Deer Creek and determine whether they exhibit features that may regulate wood jam dynamics, based on previous observations of wood jam dynamics in the WooDDAM database.

3.3 Quantifying Stage 0 Restoration Effects on Valley Bottom Geomorphic Complexity

We used four metrics of spatial heterogeneity to quantify the geomorphic effects of the Stage 0 restoration on Deer Creek (see section 4.2.1 for a detailed comparison of these metrics). Two of these metrics, the ratio of channel length to valley bottom length and the number of vegetated islands per unit valley bottom length, are proxies for the number of channels present across the valley bottom. These metrics represent the abundance of features such as vegetated islands and side channels that can potentially trap wood (Scott and Wohl, 2018). The ratio of active channel area to valley bottom area represents the lateral extent in which the stream is currently shaping its valley bottom. A simplified, constrained stream will exhibit a low ratio of active channel to valley bottom area, likely indicating minimal migration and avulsion, whereas a complex, anastomosing stream will exhibit a high ratio of active channel to valley bottom area, representing recent active migration and avulsion that maintains a high proportion of active channel area relative to floodplain, vegetated island, and terrace area. Finally, we use the Shannon Equitability Index,

$$Equitability = -\sum_{i=1}^{N} \frac{p_i \ln p_i}{\ln N},$$

where p_i is the proportion of the total area (in this case, the valley bottom area) occupied by a particular morphologic unit patch type and N is the total number of morphologic unit types present, or richness. The Shannon Equitability Index is normalized by the maximum possible diversity, making it an easily interpretable value between 0 and 1. Values near 1 indicate a nearly even distribution of morphologic unit types, whereas values near 0 indicate that one morphologic unit type dominates most of the valley bottom. A valley bottom with an equitability closer to 1 should exhibit an even distribution of morphologic patches and resulting habitat patches that can sustain biodiversity.

Geomorphic diversity indices are only as powerful as the data that are used to compute them: namely, the choice of how to define different morphologic units. Past studies have dominantly chosen primarily channel-centric morphologic units, including patches of sediment size (Scagliotti, 2019), bedforms (Wyrick and Pasternack, 2014), in-stream habitat morphology, cover, and hydraulics (Maddock et al., 2008). This choice of morphologic unit definition will only indicate diversity within the active channel. Laurel and Wohl (2018) apply diversity indices using geomorphic units that cover a range of valley bottom forms, mainly representing hydrologic connectivity and the spatial heterogeneity of inundation during various stages of flow. We define morphologic units on a broad scale to enable us to compute spatial heterogeneity and diversity metrics that:

1. represent the spatial heterogeneity of morphologic units that are essential for supporting diverse habitat types,
2. are readily comparable between diverse valley bottoms, including both single and multithread streams,
3. indicate planform roughness in terms of the abundance of vegetated islands and other features that can trap wood (Scott and Wohl, 2018), and
4. are likely to be sensitive to the processes targeted for restoration by Stage 0 restoration efforts, including wood dynamics and vegetation recruitment (by bank erosion or avulsion into forested surfaces) and establishment due to channel migration and avulsion.

While more detailed morphologic units could provide more information about specific habitat types, vertical (as opposed to lateral) changes in morphology, hydrologic connectivity, or other potential factors of interest, we defined our metrics by considering the data available for this site and to maximize the applicability of our metrics of spatial heterogeneity to the processes that Stage 0 restoration seeks to restore. The major processes our metrics miss are hydrologic connectivity, as we lack data on floodplain and side channel inundation frequency, depth, etc, and vertical changes to channel morphology, as we lack a reliable time-series of high-resolution DEM data.

We statistically analyzed these metrics of spatial heterogeneity using the R Statistical Package (R Core Team, 2019). To measure the short-term, direct effects of restoration, we compared 95% confidence intervals (CI) for mean estimates of spatial heterogeneity between pre- and post-restoration time periods and between treated and untreated reaches. To quantify dynamism in spatial heterogeneity, we computed the absolute range of the data and the coefficient of variance (CV), which is the standard deviation divided by the mean and scales to the magnitude of the variable being analyzed. Finally, to evaluate trends in spatial heterogeneity, we computed Spearman rank-correlation coefficients and associated 95% confidence interval uncertainty of each metric through time for the pre- and post-restoration period for each reach. A Spearman rank-correlation coefficient of -1 indicates a perfectly consistent negative trend, a coefficient of 1 indicates a perfectly consistent positive trend, and a coefficient of 0 indicates no evident trend. This coefficient is ideal for basic trend analysis, as it does not differentiate between linear or various types of nonlinear trends. For our purposes, we simply wanted to determine whether spatial heterogeneity was increasing or decreasing through time, as opposed to the precise nature of that increase or decrease.

We evaluated change in heterogeneity metrics through time (dynamism and trend) in the context of the magnitude and timing of flows Deer Creek likely experienced over the period of study. Geomorphic change is a function of the driving force of flow magnitude and the characteristics that set a reach's resistance to change, such as channel planform, bank and bed stability, wood and sediment regimes, and vegetation growth (Wolman and Gerson, 1978). Thus, we interpret changes to Deer Creek in the context of our best estimate of its hydrology: flow data from nearby Lookout Creek. Lookout Creek is a 62 km^2 watershed adjacent to Deer Creek that ranges in elevation from 436 to 1622 m and likely experiences a similar climatic regime. Because it is gaged, we use it as a flow history analog to Deer Creek.

3.3.1 Comparing Methods for Collecting Morphologic Data to Evaluate Stage 0 Geomorphic Response

While we derived the results presented here from manual mapping of geomorphic units described above, we also compare our methods to various automated, semi-automated, and ground-based data collection techniques. For mapping imagery, we explored the feasibility of using pixel-based and object-based image classification in ArcGIS Pro. For classifying DEM data, we explored the feasibility of automated geomorphic unit extraction based on surface topology. Using two years of post-restoration valley bottom transect measurements of sediment size and vegetation patch abundance, we compared our remote mapping to ground-based field mapping. We also use ground-based images and expert knowledge from the period directly following restoration to check the accuracy of our valley bottom maps. Finally, we use a survey of wood jam characteristics from August 2018 to predict wood dynamics and suggest future field-based monitoring for the Deer Creek Stage 0 restoration.

4. Results and Discussion

4.1 Deer Creek Stage 0 Restoration Effects on Valley Bottom Geomorphic Complexity, Wood Load, and Wood Dynamics

We evaluate the effects of the Stage 0 restoration on Deer Creek in terms of how the restoration directly altered: valley bottom spatial heterogeneity (section 4.1.1); the variability, or dynamism, of valley bottom spatial heterogeneity and morphology before and after restoration (section 4.1.2); the trajectory of valley bottom spatial heterogeneity before and after restoration in the context of flow history (section 4.1.3) and wood dynamics (section 4.1.4), which could be a driver for both the dynamism and trend of morphologic change following restoration. These aspects are all equally important in judging the effectiveness of the restoration at creating a more geomorphically complex valley bottom.

4.1.1 Direct Impacts of Stage 0 Restoration on Deer Creek Spatial Heterogeneity

The Stage 0 restoration regraded much of the valley bottom, increasing the area occupied by active channels and vegetated islands while also introducing substantial amounts of large wood. This resulted in an increase to valley bottom spatial heterogeneity compared to the 2005 to 2016 (pre-restoration) period and compared to the control reach as measured by channel to valley length ratio, channel to valley area ratio, and vegetated island count (Figure 4). It is important to note that the treated reaches started out significantly more spatially heterogeneous by these metrics than the untreated reach before restoration (Table 3), and the restoration significantly increased the existing disparity between the treated and untreated reaches.

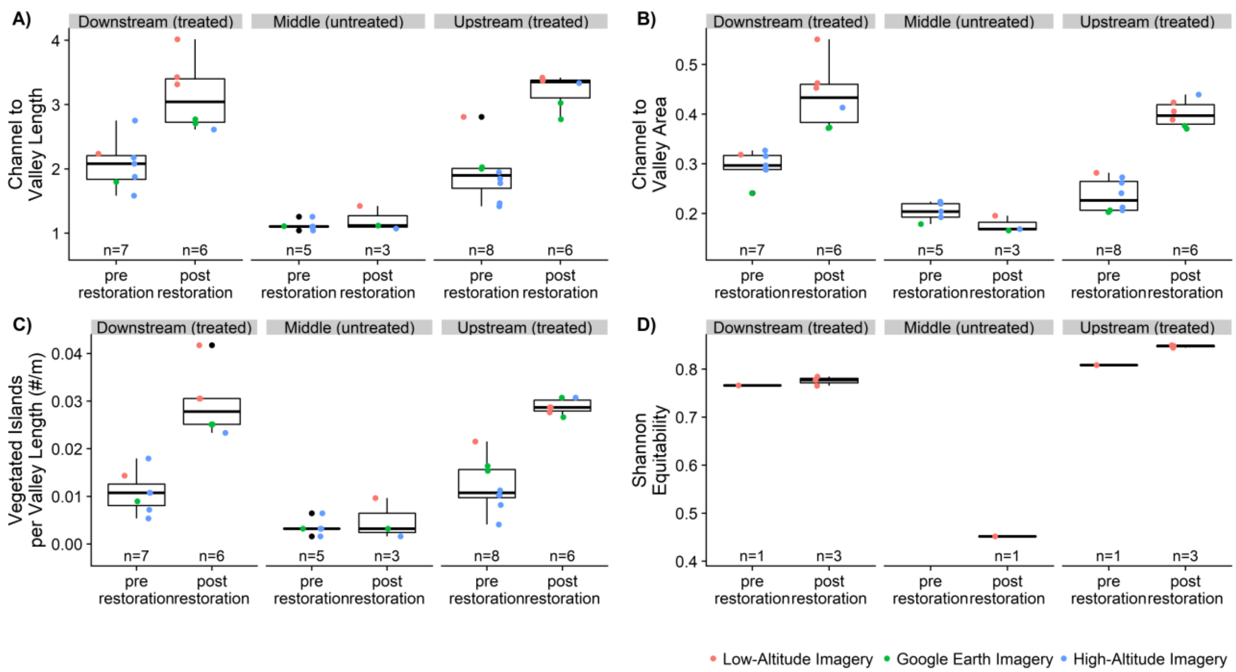

Figure 4: Boxplots showing four metrics of spatial heterogeneity for pre- and post-restoration Deer Creek, grouped by reach. Colored points show raw data, sorted by imagery source. n values for each boxplot show sample size. See Table 3 for mean and 95% confidence interval for each boxplot shown here.

Table 3: Mean, 95% confidence interval (in parentheses after mean, where applicable), and sample size for spatial heterogeneity metrics shown in Figure 4. Significant differences are judged by comparing confidence intervals and are noted for each metric in each reach. A positive change is represented by +, no change is represented by 0, and comparisons that are not applicable are marked with N/A.

Metric	Reach	Pre-Restoration Mean	Pre-Restoration n	Post-Restoration Mean	Post-Restoration n	Change Pre- to Post-Restoration	Different than Untreated Reach Pre-Restoration	Different than Untreated Reach Post-Restoration
Channel to Valley Length	Upstream (treated)	1.91 (1.55 - 2.27)	7	3.22 (2.94 - 3.49)	6	+	+	+
	Middle (untreated)	1.12 (1.02 - 1.22)	5	1.20 (0.73 - 1.68)	3	0	N/A	N/A
	Downstream (treated)	2.07 (1.72 - 2.42)	8	3.14 (2.57 - 3.71)	6	+	+	+
Vegetated Island Count per Valley Bottom Length	Upstream (treated)	0.24 (0.21 - 0.26)	7	0.40 (0.37 - 0.43)	6	+	+	+
	Middle (untreated)	0.20 (0.18 - 0.23)	5	0.18 (0.14 - 0.22)	3	0	N/A	N/A
	Downstream (treated)	0.30 (0.27 - 0.32)	8	0.44 (0.37 - 0.51)	6	+	+	+
Channel to Valley Area	Upstream (treated)	0.01 (0.01 - 0.02)	7	0.03 (0.03 - 0.03)	6	+	+	+
	Middle (untreated)	0.00 (0 - 0.01)	5	0.00 (-0.01 - 0.02)	3	0	N/A	N/A
	Downstream (treated)	0.01 (0.01 - 0.01)	8	0.03 (0.02 - 0.04)	6	+	+	+
Shannon Equitability	Upstream (treated)	0.81	1	0.85 (0.84 - 0.85)	3	+	unknown	+
	Middle (untreated)		0	0.42	1	unknown	N/A	N/A
	Downstream (treated)	0.77	1	0.78 (0.75 - 0.8)	3	0	unknown	+

While the restoration converted substantial floodplain area to active channel in both the upstream and downstream reaches (Figure 4B), this increased the equitability of valley bottom patches more in the upstream treated reach than it did in the downstream treated reach (Figure 4D, Table 3). However, the single datum from the pre-restoration period may not be representative of the general pre-restoration condition, making this comparison uncertain. Restoration reduced floodplain area more substantially in the downstream reach than the upstream reach, allowing active channel area to now dominate the valley bottom and producing a less even distribution of patches (Figure 5). This does not necessarily mean that the downstream reach lacks the diverse morphology necessary for a diverse ecosystem. While the downstream valley bottom may not be more diverse compared to pre-restoration conditions, the increase in active channel area may result in greater morphologic dynamism in response to future high flows, which may sustain a patchy valley bottom with more space for diverse active channel habitats (Figure 4B). If slight dominance by active channel area in the downstream reach is preferable from a geomorphic or ecologic standpoint, then this nonuniformity in restoration effects on spatial heterogeneity may be ideal. This demonstrates the importance of carefully considering the data that drive heterogeneity metrics when monitoring Stage 0 restoration (Figure 5).

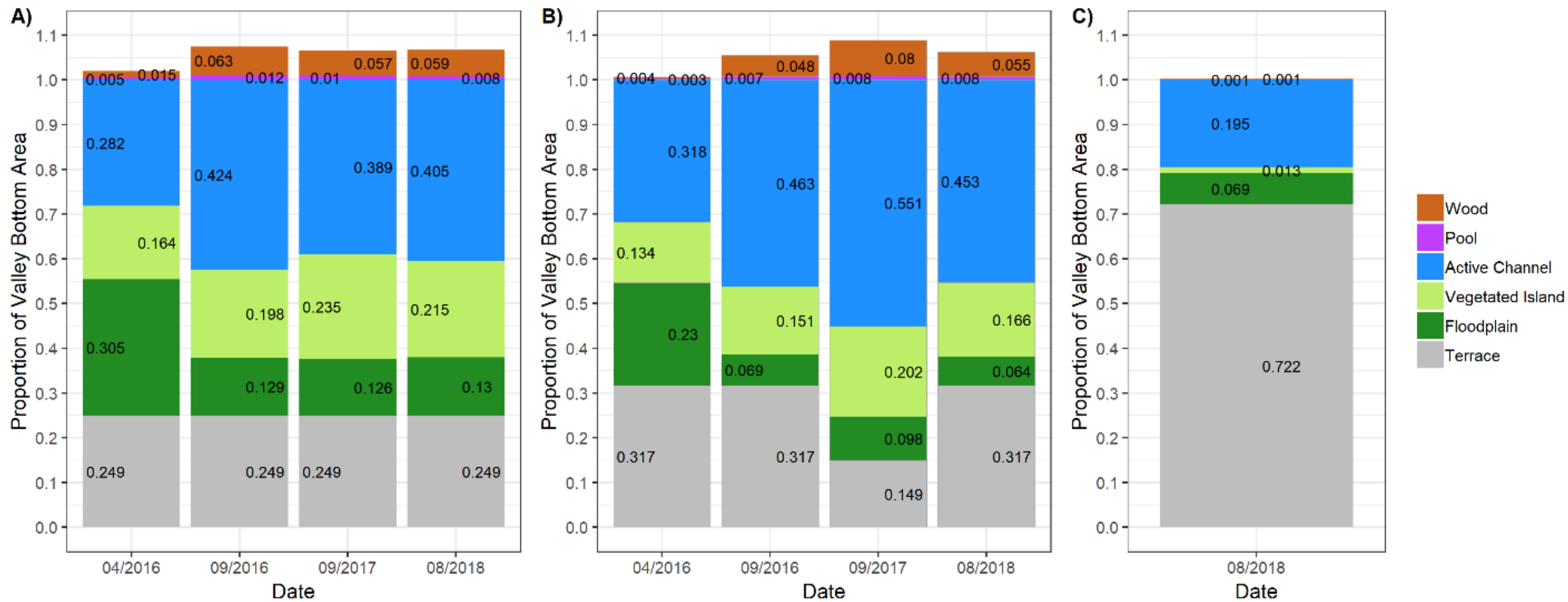

Figure 5: Stacked barplots showing the relative distribution of valley bottom patches mapped in low-altitude drone imagery for the upstream (A, treated), downstream (B, treated), and middle (C, untreated) reaches of Deer Creek. Numbers on plot show the proportion of valley bottom area occupied by each patch type. Note the greater dominance of active channel area in the downstream reach compared to the upstream reach and the dominance of terrace area in the middle reach, which reflects its incised, simple morphology. Note that the 09/2017 drone imagery of the downstream reach covered only part of that reach, and thus has a different proportion of terrace area even though that proportion likely did not change throughout the study period.

4.1.2 Valley Bottom Geomorphic Dynamism

Stage 0 restoration sought to restore Deer Creek to a dynamic, anastomosing planform in which scour and deposition would rearrange the valley bottom periodically. We evaluate change through time in Deer Creek's geomorphic dynamism by comparing the variability in spatial heterogeneity metrics since 2005 with the flow history in Lookout Creek, which we use as a surrogate for Deer Creek's flow history.

Lookout Creek experienced at least one flow over 2000 cfs (corresponding to a 39% annual exceedance probability based on 60 years of Lookout Creek annual peak flow data) in most years from 2005-2016. The redistribution of sediment in these high flows and vegetation establishment during low flow periods appear to have induced substantial geomorphic change in Deer Creek during the pre-restoration period (Figure 6, Table 4). Qualitative observations of this change while mapping imagery indicate that bar deposition and erosion along with associated vegetation establishment and recruitment was the dominant mechanism of change pre-restoration.

While restoration substantially altered the valley bottom, we have yet to observe substantial natural geomorphic adjustment in the treated reaches. The restoration substantially increased wood loading, the number of channels, and the proportion of the valley bottom occupied by active channel, all of which has likely increased hydrologic connectivity and increased roughness. This increased complexity may drive sediment deposition and retention (Wohl et al., 2017; Wohl and Scott, 2016), which could then result in avulsion and/or channel widening via bank erosion. However, from restoration (July 2016) until the most recent survey (August 2018), maximum annual flows in Lookout Creek have only been around 1500 cfs. Until we observe flows capable of rearranging the valley bottom, we will be unable to determine whether Stage 0 restoration made Deer Creek more geomorphically dynamic or whether the direct increase in spatial heterogeneity is sustained over the long-term.

We also note that we were unable to quantify our error in mapping the Deer Creek valley bottom using aerial imagery due to a lack of repeat, comparable imagery datasets. It is likely that variable shading, canopy foliage, and lighting introduced variability in our delineation of patch boundaries that could explain some of the changes that we attributed to dynamism (e.g., Draut et al., 2008). Our current estimates of dynamism are thus likely over-estimates due to this variability in the extent to which valley bottom features were obscured on different images.

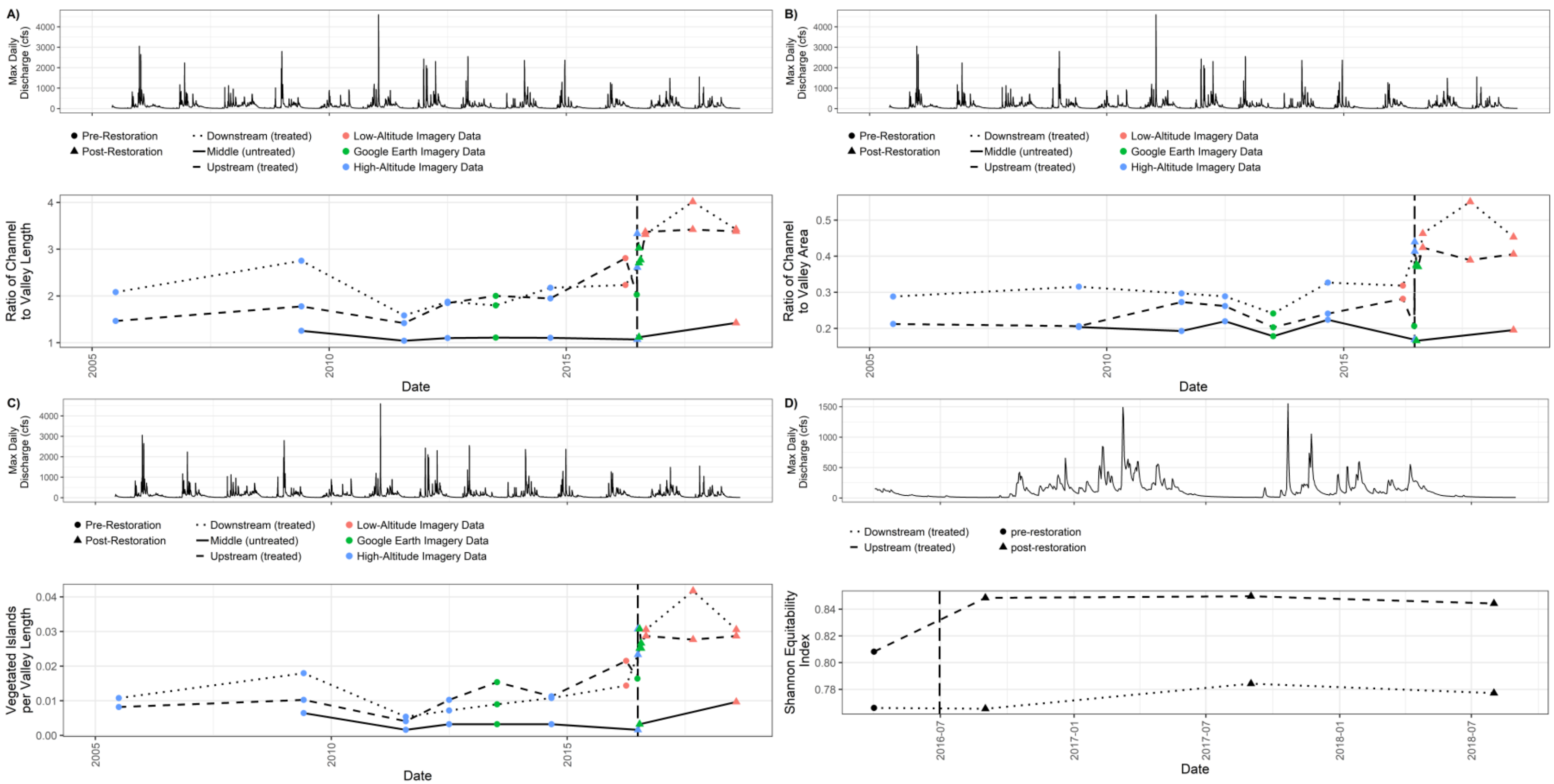

Figure 6: Line plots showing metrics of spatial heterogeneity for the period of available data, alongside line plots showing the maximum daily discharge of Lookout Creek, which we use as a proxy for flows in Deer Creek. Data are grouped by reach (line type), data source (point color), and pre- versus post-restoration (point shape). The vertical dashed line in each plot delineates the time of restoration.

Table 4: Coefficient of variance and range for each metric of spatial heterogeneity and reach for pre- and post-restoration. Coefficient of variance describes a scaled measure of how much each metric changed during a period of time, whereas range provides an absolute (unscaled) measure of total variability. Bolded green indicates a greater dynamism post restoration, and italicized red text indicates lesser dynamism post-restoration. Black text represents values that are likely too similar to be significantly different, although we note that we cannot evaluate uncertainty in this metric due to a lack of repeat measurements.

Metric	Reach	Pre-Restoration Coefficient of Variance	Post-Restoration Coefficient of Variance	Pre-Restoration Range	Post-Restoration Range
Channel to Valley Length	Upstream (treated)	*0.18*	*0.05*	*1.00*	*0.30*
	Middle (untreated)	**0.07**	**0.18**	**0.21**	**0.33**
	Downstream (treated)	0.18	0.17	1.17	1.16
Vegetated Island Count per Valley Bottom Length	Upstream (treated)	*0.12*	*0.02*	*0.07*	*0.02*
	Middle (untreated)	**0.09**	**0.11**	0.05	0.03
	Downstream (treated)	**0.10**	**0.16**	**0.09**	**0.15**
Channel to Valley Area	Upstream (treated)	*0.43*	*0.03*	0.01	0.00
	Middle (untreated)	**0.50**	**0.85**	**0.00**	**0.01**
	Downstream (treated)	*0.40*	*0.25*	**0.01**	**0.02**
Shannon Equitability	Upstream (treated)		0.00		0.01
	Middle (untreated)				
	Downstream (treated)		0.01		0.01

4.1.3 Valley Bottom Geomorphic Trajectory

The lack of high flows and the short period since restoration also makes evaluating Deer Creek's post-restoration geomorphic trajectory difficult. Current observations do not indicate that the spatial heterogeneity of this portion of Deer Creek is following a consistent trend through time either before or after restoration (

Table 5).

Table 5: Spearman Rank-Correlation Coefficient and 95% Confidence Interval on that coefficient for each metric of spatial heterogeneity in each reach for the pre- and post-restoration time period. These coefficients represent trends through time in spatial heterogeneity. Bold green text represents metrics that likely increased through time for a given reach and period. Note that while some metrics increased over time, there are no consistent trends in spatial heterogeneity pre- or post-restoration. Table cells are blank where data are insufficient to evaluate a trend.

Metric	Reach	Pre-Restoration Spearman Coefficient	Pre-Restoration Spearman Coefficient 95% Confidence Interval	Post-Restoration Spearman Coefficient	Post-Restoration Spearman Coefficient 95% Confidence Interval
Channel to Valley Length	Upstream (treated)	**0.88**	**0.44 - 0.98**	0.71	-0.26 - 0.97
	Middle (untreated)	-0.10	-0.91 - 0.87		
	Downstream (treated)	0.11	-0.72 - 0.81	**0.94**	**0.54 - 0.99**
Vegetated Island Count per Valley Bottom Length	Upstream (treated)	0.14	-0.64 - 0.78	-0.09	-0.85 - 0.79
	Middle (untreated)	0.30	-0.81 - 0.94	0.50	
	Downstream (treated)	0.46	-0.47 - 0.91	0.60	-0.44 - 0.95
Channel to Valley Area	Upstream (treated)	**0.86**	**0.38 - 0.98**	-0.53	-0.94 - 0.52
	Middle (untreated)	-0.22	-0.93 - 0.83		
	Downstream (treated)	0.05	-0.74 - 0.79	**0.88**	**0.22 - 0.99**
Shannon Equitability	Upstream (treated)			-0.50	-0.94 - 0.55
	Middle (untreated)				
	Downstream (treated)			0.50	-0.55 - 0.94

Continued monitoring over the next 5-10 years (assuming high flows occur during that period) is necessary to determine whether the Stage 0 restoration's increase in spatial heterogeneity is sustained. A successfully restored reach should ideally exhibit a dynamic steady state: showing no consistent, long-term trend in spatial heterogeneity or morphologic adjustment, but still varying through time as channels migrate and avulse. While current observations suggest that this is the case, we stress that the probable lack of geomorphically effective flows and the short period of examination (2 years post-restoration) make this judgement very uncertain.

4.1.4 Wood Dynamics in Deer Creek Following Stage 0 Restoration

Our imagery mapping of wood loads shows results similar to that from the wood load monitoring of Bianco (2018) (Figure 7): wood load increased substantially due to restoration and has maintained a high magnitude post-restoration, with some minor variability from year to year. Sustained high wood loads, as we have observed so far, are more likely to feed back on channel evolution, creating more spatial heterogeneity in morphologic units and vegetation communities (Fetherston et al., 1995; Montgomery et al., 2003; Scott and Wohl, 2018; Wohl et al., 2018). Thus far, wood introduced to Deer Creek appears to be forming relatively large jams that interact substantially with channel margins (bed and banks), living trees, and valley walls, especially in areas of high trapping efficiency (sensu Scott and Wohl, 2018) across the valley bottom, such as the heads of vegetated islands and the margins of side channels. The wood introduced was largely intact (i.e., included root boles), which may lend to the relative stability of many jams from year to year (Merten et al., 2010), despite the limited transport of individual pieces observed shortly after restoration by Bianco (2018).

We lack the quantitative observations necessary to rigorously evaluate the role of wood dynamics in causing geomorphic change or creating or maintaining spatial heterogeneity. In a natural anastomosing system, wood should likely at least partially drive channel migration, avulsion, and vegetated island stabilization (Collins et al., 2012; Wohl et al., 2018), but Deer Creek has not experienced substantial natural lateral erosion post-restoration, likely due to the lack of high flows. While geomorphic change associated with wood is evident on post-restoration imagery in some segments of the active channel that appear to be aggrading sediment around wood jams and vegetated islands, we lack the field data to robustly evaluate this.

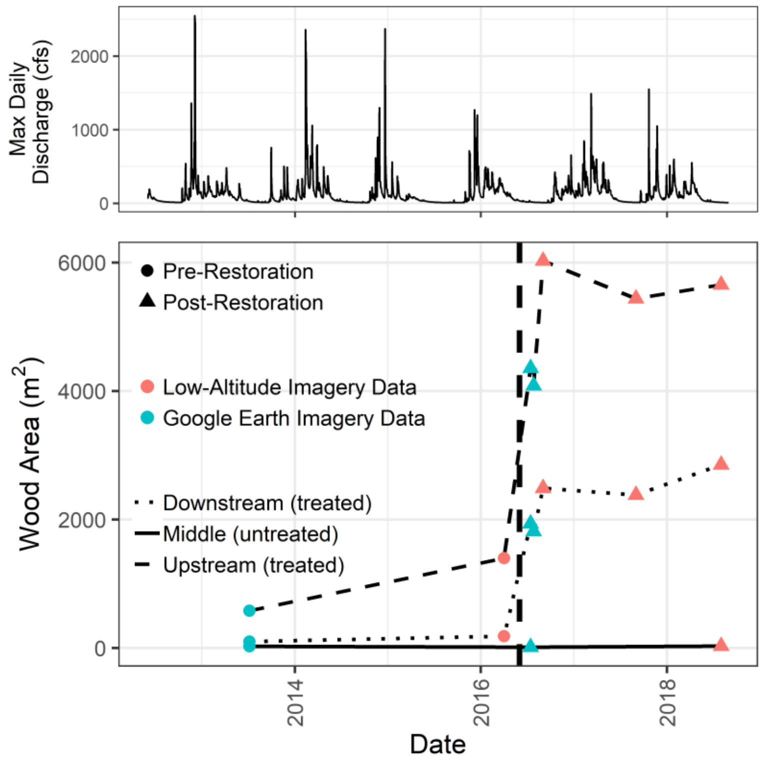

Figure 7: Wood area across the valley bottom through time, plotted alongside maximum daily discharge in Lookout Creek, a proxy for Deer Creek flows. Data are organized by reach (line type), data source (point color), and pre- versus post-restoration (point shape).

That the wood load has been consistently high post-restoration may be in part due to the lack of high flows that are likely to substantially rearrange Deer Creek's valley bottom. Bankfull stage acts as a threshold for wood mobility, whereby wood jam mobilization is unlikely below bankfull stage (but not necessarily guaranteed above it; Kramer and Wohl, 2016; Scott et al., 2019). Due to the lack of high flows post-restoration, we are unable to determine if the introduced wood will be stable over the long-term. However, we can make some inferences from our observations of wood jam characteristics.

Our analysis of the census of 30 wood jams we surveyed in August 2018 in the upstream-most 400 m of the upper treated reach of Deer Creek suggest that wood may be effectively stored in the now more spatially heterogeneous valley bottom of Deer Creek post-restoration. Of these 30 jams, 23 (77%) touch both the channel bed and floodplain or vegetated island surfaces, indicating substantial interaction with channel margin elements that could help resist mobilization during high flows. 14 of the 30 jams (47%) span at least one active channel, which may make them more likely to accumulate sediment (Wohl and Scott, 2016). 17 of the 30 jams (57%) are at least partially buried in sediment, 25 of the 30 jams (83%) are pinned on a likely immobile object (e.g., living trees and large boulders), and all 30 jams still have key pieces with rootwads attached, all of which likely indicate a higher probability of these jams not mobilizing during the next high flow (Merten et al., 2010). All 30 jams also have had a noticeable morphologic impact on the surrounding channel (e.g., bar deposition or pool scour). A complete summary of the data collected for these and other wood jams is available from the WooDDAM database (Scott et al., 2019), hosted at https://www.fs.fed.us/biology/nsaec/products-tools.html.

4.2 Recommended Methods for Evaluating Valley Bottom Geomorphic Complexity of Stage 0 Restoration

Monitoring for Stage 0 restoration must robustly evaluate the dynamism and trend of spatial heterogeneity, as well as the immediate impacts of restoration on the valley bottom, to evaluate whether restoration meets project goals over the long-term. Here, we discuss both the metrics and observations that are likely to meet these requirements as well as the data sources required to compute those metrics.

4.2.1 Recommended Metrics to Evaluate Valley Bottom Spatial Heterogeneity and Dynamism

We evaluated the suitability of metrics of spatial heterogeneity for use in monitoring Stage 0 restoration based on what processes they represent and their benefits and drawbacks (Table 6). Channel to valley length and vegetated island count per unit valley length are proxies for the number of channels present across the valley bottom, which is monitored on the assumption that a valley bottom with more channels (or more vegetated islands) is inherently more complex and can support a greater diversity of habitat patches. If remotely mapped, both metrics suffer from being sensitive to mapping errors caused by errors in identifying side channels on imagery (due to shading, low resolution, canopy cover, or variability in flow stage between images), and both metrics may fail to quantify heterogeneity in broad, wetland systems. However, these metrics require only low-resolution, generally freely available remotely sensed imagery. The ratio of channel to valley bottom area is more robust to mapping errors and is more representative of geomorphic processes like bank erosion, especially when evaluated through time, but requires higher resolution imagery. Finally, diversity indices such as the Shannon Equitability Index provide the most holistic evaluation of spatial heterogeneity, but are most difficult to collect data for (requiring high resolution imagery, DEM, and/or field survey data) and are sensitive to the choice of morphologic unit types being observed.

Table 6: Comparison of metrics of Spatial Heterogeneity used in this study. Metrics are listed (from top to bottom) in order of difficulty to compute (i.e., collect data for).

Metric	Evaluates	Pros	Cons
Channel to Valley Length	Degree to which valley bottom sustains multiple channels	• Low data requirement (imagery, or a GPS-tracked walk of the valley bottom)	• Sensitive to mapping errors • Limited representation of geomorphic processes • Misses channel width changes
Vegetated Island Count per Valley Bottom Length	Presence of vegetated islands	• Low data requirement (moderate resolution imagery, or GPS-mapping of valley bottom in field) • Directly measures abundance of a common wood trapping site (island heads)	• Sensitive to mapping errors • Limited representation of geomorphic processes • Misses channel width changes
Channel to Valley Area	Proportion of valley bottom that is actively being reshaped by the stream	• Robust to mapping errors due to shading, canopy cover, etc. • Captures both lateral migration and avulsion • Sensitive to channel width changes	• Moderate data requirement (moderate-resolution imagery, or detailed field surveying)
Shannon Equitability	Richness, Abundance, and Evenness of geomorphic units, but most sensitive to evenness	• Easy to interpret (scales from 0 to 1) • Captures heterogeneity of the foundation of biodiversity, if morphologic units are chosen appropriately • Comparable across sites with varying geomorphic characteristics, data quality • Can be tailored to monitor most sites, depending on choice of morphologic units measured	• Requires high resolution data, or intensive field measurements (transects) • Requires interpretation of multiple data sources using expert knowledge • Sensitive to selection of morphologic units and definitions

Along with monitoring of spatial heterogeneity, robust monitoring of Stage 0 restoration should include observations of spatial heterogeneity changes through time, both in terms of temporal variability (dynamism) and long-term trends. While most measures of variability (standard deviation, 95% confidence interval, coefficient of variance) will function for measuring dynamism in spatial heterogeneity, the coefficient of variance works well because it is normalized by the magnitude of the data. However, metrics like the absolute range in the data may be easier to interpret. To evaluate trends, we recommend a non-parametric coefficient, like the Spearman rank-correlation coefficient used here. Trend analysis such as regression can detect a specific type of trend and could be useful after testing for a consistent trend of any type but may miss consistent trends simply because they do not conform to the specific type of regression analysis used.

With all these analyses, uncertainty should be quantified using confidence intervals (on repeat-measurements of dynamism, or correlation coefficients for trends), as opposed to the sole use of confidence level (p-value) thresholds (Wasserstein and Lazar, 2016). As with most statistical analyses, we recommend using multiple lines of evidence to confirm statistical tests, such as visual evaluation of trends and dynamism via plots of spatial heterogeneity (e.g., Figure 4 andFigure 6) and using multiple means of quantifying a given variable (e.g., using both the coefficient of variance and absolute range in data to quantify dynamism).

Dynamism and morphologic trends through time should also be evaluated with direct observation of geomorphic change to contextualize and check metrics of spatial heterogeneity. Monitoring of Stage 0 restoration should ideally include observation of both lateral migration/avulsion and vertical sediment erosion and deposition. While quantitative, objective evaluation of the spatial distribution of elevation change throughout a reach (i.e., erosion and deposition; Wheaton et al., 2010) are ideal, such analyses require detailed and accurate data, which can be difficult to collect. Qualitative or semi-quantitative observation of geomorphic evolution, such as the tracking of avulsion occurrence, measurement of migration rates (e.g., Schook et al., 2017), and observation of where bars develop and where vegetation establishes or is recruited to the active channel can serve as powerful indicators of geomorphic process magnitude and direction. These more qualitative and semi-quantitative data can be collected using simple repeat-photography, imagery analysis, and timelapse camera monitoring, and can be used to check metrics of spatial heterogeneity. For example, if monitoring of active channel to valley bottom area shows a consistent upwards trend through time, one should check that there is also evidence of lateral migration or avulsion that could explain such a trend. Or, if spatial heterogeneity seems to be decreasing, one could look to direct observations of channel change to determine the cause of such a decrease (e.g., channel incision and narrowing) to guide adaptive management.

We recommend using different metrics depending on available data, budget, and objectives. For example, channel to valley length, vegetated island count per valley bottom length, and active channel to valley area can be readily measured from freely available satellite imagery sources (NAIP imagery or imagery hosted on Google Earth). With greater access to data collection resources (e.g., field transects, higher resolution imagery, or drone imagery), more holistic diversity indices, like the Shannon Equitability index used here, can be computed and used to provide a more complete picture of spatial heterogeneity. However, diversity indices are sensitive to decisions regarding the data that drive them, and data collection must be tailored to the geomorphic processes restoration seeks to influence.

While our analysis focused on Deer Creek, an anastomosing stream with relatively defined channels, we note that some Stage 0 restoration results in broad, less-channelized wetland valley bottoms. In these cases, our analysis suggests that channel-centric metrics like channel to valley length or vegetated island count per valley bottom length will likely miss potential geomorphic change through time. Instead, more holistic metrics like channel to valley area and Shannon Equitability index are likely more appropriate. These two metrics capture processes such as bank erosion and adjustments to the ratio of active channel to typically non-inundated floodplain surface. Shannon Equitability, in particular, can be tailored to measure the distribution of geomorphically-relevant patches across the valley bottom. For a wetland, as opposed to a more channelized valley bottom, those patches may be delineated by vegetation type, inundation degree, or hydrologic connectivity, for example. Even more than in a channelized valley bottom, metrics of spatial heterogeneity and dynamism in a broad, wetland valley bottom would need to be contextualized by direct observations of geomorphic change, as detailed above.

4.2.2 Recommended Data Collection Techniques to Facilitate Metrics of Spatial Heterogeneity and Dynamism

The metrics described in section 4.2.1 can be data intensive. Generally, they require information about the spatial abundance of pre-defined patch types across the valley bottom. However, this information can come from a variety of field and remote sensing data collection techniques. At a minimum, to measure spatial heterogeneity, data collection should:

1. either census or randomly sample the areal or linear abundance of defined patch types across the valley bottom,
2. be comparable to pre-restoration and/or historical data sources to enable comparison to baseline pre-restoration conditions,
3. enable repeat measurements for multiple years post-restoration to evaluate variability and trend in spatial heterogeneity,
4. optionally include direct observations of the geomorphic processes that spatial heterogeneity metrics should represent, such as channel lateral adjustment, sediment dynamics, and vegetation dynamics, and
5. optionally include direct observations of wood load and wood jam dynamics due to the potential for wood to be a fundamental driver of spatial heterogeneity.

4.2.2.1 Field Measurement of Spatial Heterogeneity

The most versatile and repeatable method of determining valley bottom patch abundance is on-the-ground field measurement. Evenly spaced transects randomly placed along the valley length can facilitate measurement of the proportion of valley width occupied by different morphologic units, substrate types, vegetation communities, or other patches (e.g., Laurel and Wohl, 2018). Comparing our two-dimensional drone-derived vegetation abundance (the sum of floodplain, vegetated island, and terrace area) to such transect measurements of vegetation abundance (Figure 8), we find that drone estimates of vegetation abundance tend to be 1 to 2 times higher than transect-based estimates. Overhanging canopy cover, which we attempted to avoid when mapping active channel edges from drone imagery, likely skewed our estimate of vegetation cover slightly higher than ground observation. This highlights a key deficiency with remotely sensed data in valley bottoms that have substantial canopy cover: imagery cannot accurately resolve morphology beneath canopy.

In terms of resource cost, transect measurements require only cheap equipment (tape, stakes, flagging), whereas low-altitude, high-resolution imagery generally requires a drone (although some high-resolution, freely available satellite imagery could work for this purpose, especially for larger sites). We flew Deer Creek (0.19 km^2) in approximately 3 hours with a drone, whereas transect measurements of the same area at a density of 12.6 transects per km took approximately 6.75 hours (Kate Meyer, Personal Communication, 2019). However, drone image processing generally took 1-3 hours of office work over 1-4 days (including processing time) plus another 1.5-4 hours of manual mapping, whereas transect data can be analyzed shortly after collection. For especially large restoration sites, other sampling methods, such as stratified random sampling of plots, may be more feasible than transects. While field transects to obtain morphologic unit data may be faster and cheaper than manually mapping drone imagery, drone imagery can also provide subsidiary products, including: (1) a detailed orthomosaic of the entire study area; (2) a DEM, if ground control points are surveyed (e.g., Javernick et al., 2014); (3) data that can be used later for spectral or other imagery analysis), and in general collects a more complete picture of the study area (a census, as opposed to a sample).

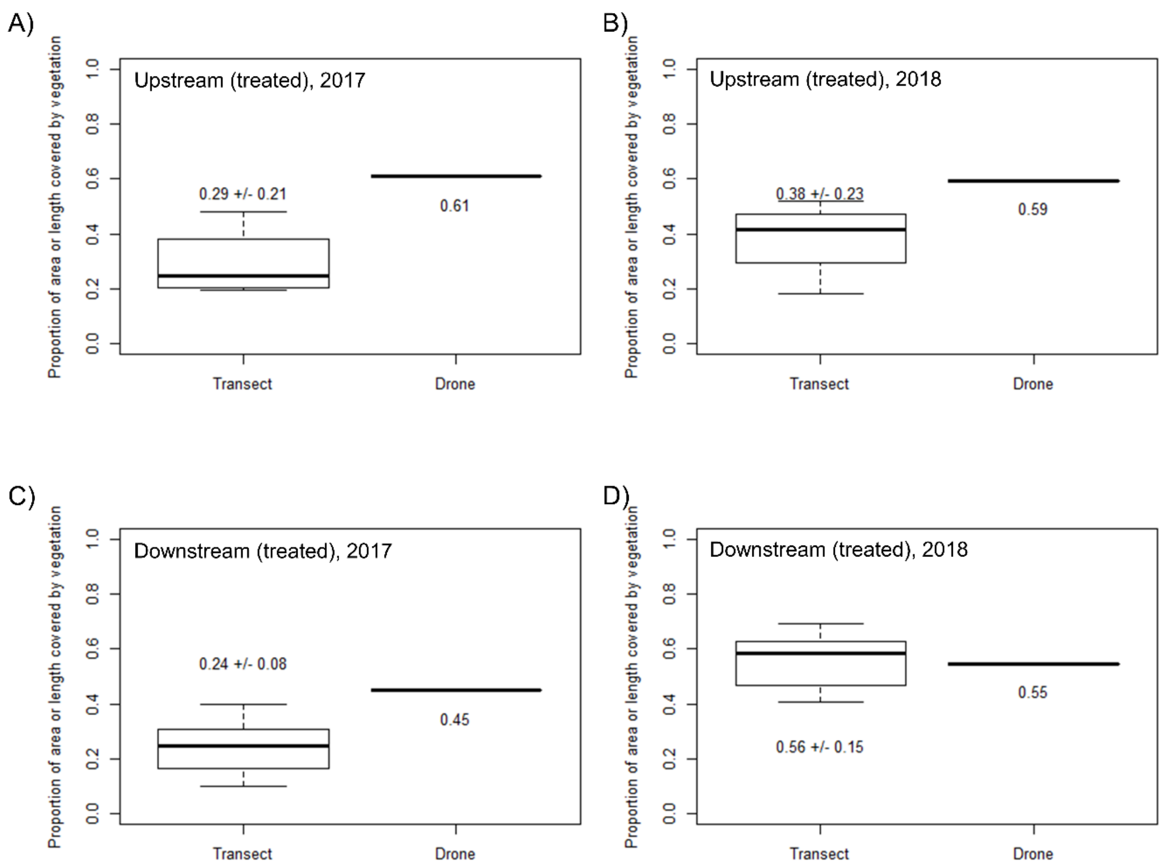

Figure 8: Boxplots comparing transect to drone measurements of vegetation abundance in the valley bottom of Deer Creek. For each boxplot of transect data, the mean vegetation abundance and 95% confidence interval uncertainty are shown. Note that drone estimates tend to be either close to or an overestimate of transect data, likely due to the effects of overhanging canopy.

While field measurement can be versatile, cheap, and effective, one may more directly compare remotely sensed data to historic data sources such as aerial and satellite imagery, as we have done here. Assuming that transect data are not collected for years prior to restoration, this enables one to obtain a historic perspective on the effects of restoration and long-term trends in the spatial heterogeneity and morphology of the site (Downs et al., 2011). Transect data collected alongside drone data can also calibrate drone data and correct for errors due to canopy cover if morphologic units are defined similarly.

4.2.2.2 Remote Sensing Measurement of Spatial Heterogeneity

The abundance of remotely sensed imagery for Deer Creek made manual mapping of patch abundance an effective means of gathering data to drive spatial heterogeneity metrics. When experts with field experience evaluated our naïve (having never visited the site pre-restoration) mapping of the upstream treated reach in 2016 pre-restoration drone imagery, we found only one part of a side channel had been improperly designated as a channel (it was a relict channel). We also found disagreement between field-based and imagery-based classification of pools. While these errors are relatively minor, they highlight the value of ground-truthing remotely sensed data whenever possible.

Both semi-automated and manual methods can serve to analyze imagery and DEM data depending on site conditions, budget, and data quality. In testing semi-automated image classification to map patches covered by wood versus vegetation, we found that pixel-based methods performed poorly on Deer Creek, where wood and exposed sediment often had a similar spectral signature. However, such classification may work better in larger systems with more contrast between wood and sediment (e.g., Smikrud and Prakash, 2006). Object-based classification worked better, but required substantial time to tune (i.e., adjust classification parameters) to achieve an only somewhat accurate result. Object-based classification accurately detected some wood, but we were never able to satisfactorily classify wood versus other patch types in the drone imagery we used. Semi-automated image classification may work more effectively if sites are evenly illuminated, patches to be classified can be clearly distinguished, and imagery is consistent enough to apply similar classifications across the entire site. While semi-automated methods may also be more ideal for large sites, such sites could also be measured manually using randomly or stratified-randomly sampled plots as an effective method of sampling patch abundance from imagery.

DEM-based classifications of morphologic units could also be a useful tool in collecting data to drive metrics of spatial heterogeneity and track morphology change through time. However, existing methods (Bangen et al., 2017; Demarchi and Bizzi, 2016; Wyrick et al., 2014) are generally focused on channel morphologic units and require high-resolution DEM data to run effectively. In exploring the use of these methods on Deer Creek, we found that the 1 m bathymetric LiDAR available for 2018 did not accurately resolve the ground surface beneath dense accumulations of wood, which are abundant across the active channel. This prevented us from applying an automated method of DEM classification, as we lacked measurements of the ground surface beneath wood. However, examining images visually, we were able to discern pools (based on water color, surface roughness, and sediment size) beneath wood that did not appear on the LiDAR DEM. As DEM-based classifications become better developed, they may be able to accurately map detailed morphologic unit patches for restoration monitoring. However, we found that manual mapping required less data and still achieved our goal of capturing relevant morphologic units to ensure that our spatial heterogeneity metrics represented the geomorphic processes that Stage 0 restoration sought to restore in Deer Creek.

4.2.2.3 Measuring Channel Morphologic Adjustments to Evaluate Geomorphic Dynamism

Monitoring for morphologic dynamism should ideally include tracking of channel lateral and vertical change to evaluate sediment transport and retention processes. A major drawback of our analyses here was our inability to assess vertical morphologic change. While we obtained DEMs from structure-from-motion processing of drone imagery, we were unable to accurately georeference these DEMs in three dimensions, preventing quantitative analysis of elevation change. The variability in stage between images and only minor morphologic change post-restoration prevented us from making definitive judgements of where the stream had aggraded or degraded based on our qualitative observations of morphologic change. Drone imagery, when processed using Structure-from-Motion techniques, can yield high-resolution, bathymetric DEMs when properly calibrated to water depth and accurately georeferenced (Dietrich, 2017). Airborne bathymetric LiDAR or detailed surveying using a total station or high-resolution GPS (Wheaton et al., 2010) can also provide sufficiently high-resolution DEMs to evaluate vertical patterns of sediment storage and erosion.

These methods of generating high-resolution DEMs are costly and time-consuming, motivating the use of qualitative or semi-quantitative field surveys of channel morphologic change with cheaper, faster field methods such as the transects mentioned above. Such integration could simply include measurements of bankfull dimensions for each channel crossed in a transect or repeat photo points aimed at qualitatively detecting likely deposition or erosion in a reach. Qualitative tracking of channel vertical change could also be integrated with surveys of wood jam dynamics and could potentially enable statistical analyses of the spatial distribution of channel change. While such analyses would not be as informative as distributed measurements of actual channel morphologic change, they could serve as an approximate indicator of whether a system is net depositing or eroding sediment, which could then motivate more detailed analyses if deemed necessary.

4.2.2.4 Measuring Wood Dynamics

Wood is a fundamental driver of channel morphologic change, and wood monitoring should likely be included in Stage 0 restoration monitoring where wood is reintroduced to channels. Both transect and imagery mapping methods can produce estimates of wood load, but not wood jam dynamics. While our predictions of wood jam dynamics (section 4.1.4) based on their characteristics are based on field experience and prior studies of wood jam mobility (Merten et al., 2010), the WooDDAM framework will likely be able to provide more data-driven, probabilistic predictions of wood jam dynamics in the near future. Surveying the 49 jams along Deer Creek took approximately 8 hours using the WooDDAM field survey protocol. The WooDDAM framework can be especially useful if applied to a random selection of wood jams within a restoration reach, with the aim of making unbiased inferences about the characteristics and dynamics of all wood jams within a reach. The primary advantage of WooDDAM is its uniformity and open design, whereby multiple operators can conduct surveys reproducibly and surveyed wood jams can be examined in the context of the other wood jams in the online database (Scott et al., 2019).

4.2.2.5 Summary of Data Collection Technique Recommendations

We recommend different data collection methods depending on budget and site characteristics (Table 7). If possible, an ideal geomorphic complexity monitoring strategy would include: (1) repeat airborne bathymetric LiDAR before, then at regular intervals after restoration; (2) drone-based imagery collection and field transects to map valley bottom patches and calibrate drone imagery for comparison with pre-restoration satellite imagery data; and (3) repeat monitoring of wood jam dynamics using a standardized framework such as WooDDAM (Scott et al., 2019). However, this would be costly and time-intensive. To maximize cost and monitoring effectiveness, repeat transect-based data collection, used in conjunction with high-resolution and freely available satellite imagery, could provide effective means of mapping valley bottom patches, channel lateral change, and potentially qualitative vertical change. If canopy cover does not obscure the site, one could use only satellite and historic aerial imagery to at least derive the ratio of channel to valley bottom area, channel to valley length, and the number of vegetated islands. However, if steep valley walls confine the site and produce shading issues in imagery or canopy cover is too dense, field transects and/or airborne LiDAR are likely the best methods for obtaining monitoring data.

Based on our analysis of Deer Creek, we suggest that cost-effective future monitoring of this and similar sites involve a combination of field-based transects, wood jam dynamics surveys, and mapping of either freely available satellite imagery or, if feasible, drone imagery. Field transects will robustly and rapidly measure the abundance of valley bottom patches, as defined above (Table 2) to drive metrics of spatial heterogeneity and, if integrated with repeat photography along transects, could enable qualitative observations of channel morphologic change. Mapping of remotely sensed imagery will enable more complete tracking of the ratio of active channel to valley bottom area (note that this requires substantially less office time than mapping all valley bottom patches on imagery). Wood jam dynamics surveys using the WooDDAM protocol (Scott et al., 2019) should be conducted either on a census of jams or a random sample of jams along the restoration reaches. These surveys will enable detailed tracking of whether wood jams tend to be accumulating wood, losing wood, remaining stable, or mobilizing throughout the project reach, and could provide annual information to drive adaptive management if wood jams in the restored reach begin to destabilize. Integrating these monitoring techniques on an annual basis for 5-10 years (or, to save cost, only after floods of a specified magnitude likely to reshape the channel) will provide a comprehensive evaluation how Deer Creek’s geomorphic complexity and wood dynamics evolve post-restoration without requiring overly expensive data collection measures such as bathymetric LiDAR. However, a high-resolution bathymetric DEM for the site could provide a robust evaluation of these methods if collected.

Table 7: Comparison of methods for obtaining data to drive spatial heterogeneity metrics (Table 6). See Figure 3 for a comparison of various imagery sources for Deer Creek.

Method	**Measures**	**Pros**	**Cons**
Satellite or Historic Aerial Imagery	• Active channel • Vegetated islands • Possibly terraces and valley bottom extent (from low-resolution DEMs)	• Low cost or free for many regions • Can be quickly mapped due to lower resolution • Often allows for data collection long before restoration to establish baseline conditions	• Cannot resolve detailed patches in valley bottom • Hampered by shading, canopy cover, etc. obscuring valley bottom • May be unfeasible for densely canopied or small valley bottoms
High-Resolution Satellite or Drone Imagery	• Pools • Wood • Active channel • Vegetated islands • Possibly terraces and valley bottom extent (from low-resolution DEMs)	• Resolves most of the relevant fundamental geomorphic units for an anastomosing system • Can provide subsidiary and helpful data products (e.g., structure-from-motion derived dem) • Low field-time required	• Costly (proprietary imagery, drone investment) • Hampered by shading, canopy cover, etc. obscuring valley bottom • May be unfeasible for densely canopied or small valley bottoms • Can require substantial office-time to process and map imagery
Airborne LiDAR or Densely Spaced Topographic Survey (e.g., Total Station)	• Pools (if unobscured by wood) • Vegetation (if lidar point clouds are used) • Detailed and objective geomorphic units, especially in channel • Terraces • Valley bottom extent	• Provides detailed topography under water and vegetation • Can be used to determine terrace and valley bottom extent for further imagery mapping	• Does not capture wood, vegetation (for ground-based topographic survey), or other potentially relevant valley bottom patch types • Abundant wood can cause errors in measuring ground surface • High time and cost requirement to obtain and process data
Systematic, Randomly Sampled Field Transects	• Pools • Wood • Sediment caliber • Morphologic units (subjective) • Vegetated islands • Terraces • Valley bottom extent	• Cheap, easy to implement • Unaffected by canopy cover or lighting conditions • Possibly the only effective method of mapping patches when site is obscured by dense canopy • Easy to design to be able to collect relevant data for describing spatial heterogeneity at the same time as other potential monitoring goals (e.g., habitat delineation, flow measurement)	• May require substantial field-time • Data represent a sample (hopefully unbiased, if properly randomly sampled) as opposed to a census, like other methods

5. Conclusion

The Deer Creek Stage 0 restoration has substantially altered the valley bottom, making it more spatially heterogeneous and wood rich. Our observations of spatial heterogeneity indicate that the restoration has substantially increased the ratio of active channel to valley bottom area and likely has provided the river more available space to rearrange its valley bottom. However, the lack of high flows in the two years since project completion means that the restoration has effectively gone untested. This lack of high flows combined with the short period of study post-restoration and the likely variability in our data make it difficult to determine whether Stage 0 restoration has produced a sustainably dynamic and anastomosing valley bottom along Deer Creek.

Stage 0 restoration goals and monitoring objectives should guide the definition of valley bottom patches in computing spatial heterogeneity metrics. Metrics such as channel to valley bottom area (or a similar measure, such as channel to floodplain area) and Shannon equitability are robust to data collection errors and can help determine the presence or absence of desired geomorphic processes, such as channel migration and avulsion. Such processes reshape valley bottoms over many years, necessitating robust analysis of geomorphic dynamism and the trend in spatial heterogeneity through time.

Data to drive the metrics of geomorphic complexity discussed here can be collected using a range of field and/or remote sensing techniques. More costly data collection can yield high resolution and more spatially distributed data. However, relatively inexpensive field methods such as transect sampling, especially in conjunction with mapping freely available imagery, can adequately determine the state and temporal evolution of geomorphic complexity. Regardless of how spatial heterogeneity is measured, observations of wood dynamics, the relative abundance of geomorphic units, channel morphologic change, and vegetation dynamics can help contextualize spatial heterogeneity metrics and their trends through time.

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