Widespread Wood Placement and Regrading Drive Lateral Connectivity and Reworking of the Channel and Floodplain in a Valley Bottom Reset to Stage 0

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Abstract

Valley bottom process reset, or the excavation of high surfaces and fill of incised channels combined with large wood addition, is a new method for creating multi-channel river-wetland corridors (also referred to as Stage 0 valley bottoms). Valley bottom process reset seeks to increase lateral flow and sediment connectivity to retain flow and sediment and kickstart geomorphic processes that may sustain aquatic and riparian habitat. This anthropogenic intervention provides an opportunity to examine relationships among wood-induced hydraulic roughness, valley bottom topography, and geomorphic processes such as overbank flow and sediment transport, avulsion, sediment retention, and pool scour. Here, I present a 6-year case study of a two-phase valley bottom process reset along Deer Creek, OR indicates that kickstarting processes that reshape the floodplain requires a substantial increase in roughness and hydrologic connectivity. A first phase of construction enhanced hydrologic but not sediment connectivity, largely failing to kickstart avulsion and floodplain reworking even during a likely 2- to 5-year recurrence interval flood. A second, more intensive phase of construction substantially reduced the threshold flow necessary for overbank flow and incision of floodplain reworking, as evidenced by the occurrence of these processes after only a < 2-year recurrence interval flood. During this flood, a spatially distributed wood lattice rearranged into discrete jams that scoured pools, retained sediment, and drove geomorphically effective overbank flows. While valley bottom regrading likely contributed to these geomorphic effects, the spatial correlation between newly incised floodplain channels and areas of wood aggregation indicates a substantial role of wood-induced hydraulic roughness and channel blockage. Wood drove floodplain reworking via two mechanisms: in-channel wood jams backwatered and constructed flow into the floodplain, and small wood jams formed in the floodplain forest further constricted flow through nascent channels to facilitate channel incision.

Key Points:

- Valley bottom reset can reduce the flow threshold required for restoring lateral hydrologic and sediment connectivity, which may increase the likelihood of a multi-channel, river-wetland corridor being sustained over a longer time period.
- Wood drives floodplain reworking by two mechanisms: first, diverting flow out of existing channels and into floodplain forests, and second, concentrating flow in floodplain forests to facilitate channelization.
- Removal of anthropogenic barriers and limited wood placement may be insufficient to fully restore lateral hydrologic and sediment connectivity, which may require much more substantial roughness and in-channel regrading.

1 Introduction

Valley-bottom restoration to Stage 0, or a multi-channel, sediment- and water-retaining valley bottom (Cluer & Thorne, 2014), has recently become a common goal of stream management in the western United States, from beaver-dominated headwaters to large, lowland rivers capable of sustaining such a condition (Flitcroft et al., 2022; Wheaton et al., 2019). If this style of restoration can create sustained multi-channel, wood-rich, heterogeneous riverscapes, then it may not only enhance habitat for aquatic and riparian biota (Stanford et al., 2005), but also mediate fluxes of sediment (Flannery et al., 2017; Fryirs et al., 2007), wood (Guiney & Lininger, 2022; Scott & Wohl, 2018), water, and nutrients (McClain et al., 2003; Sutfin & Wohl, 2017). By mediating these fluxes, this style of restoration may drive lateral sediment, water, and nutrient connectivity necessary to rework the floodplain and sustain the riparian ecosystem (Amoros & Bornette, 2002; Cadol & Wine, 2017; Collins et al., 2012). Enabling these riverine ecosystem functions can benefit downstream biota, including humans (Entwistle et al., 2018; Wohl et al., 2018, 2021) and can increase certain aspects of riverscape resilience, or the ability to absorb disturbances without compromising riverscape function (Fuller et al., 2019; Hall et al., 2018).

Restoration to Stage 0 seeks not only to enhance riverine habitat in the short-term: The primary goal is to restore the fluvial geomorphic processes, like lateral sediment and water connectivity, sediment retention, and floodplain reworking, often driven by wood, that can sustain such a condition (Collins et al., 2012; Wohl, 2011; Wohl et al., 2021). However, because of the limited monitoring of sites restored to Stage 0 (e.g., Flitcroft et al., 2022) both the short-term effects on valley-bottom geomorphic character and moderate-term effects on geomorphic process activity remain unclear.

In forested, multi-channel riverscapes, wood is a key element that can sustain a Stage 0 valley bottom: it creates spatial and temporal heterogeneity (Fausch & Northcote, 1992; Wohl et al., 2022), maintains lateral connectivity (Keys et al., 2018), mediates flows of water and sediment (Ader et al., 2020; Davidson & Eaton, 2013; Wohl & Scott, 2017), and drives channel migration and floodplain reworking (Collins et al., 2012). The presence of wood (especially channel-spanning wood; Livers & Wohl, 2021) strongly correlates with the geomorphic processes that restoration to Stage 0 seeks to sustain. However, the mechanisms by which wood sustains these processes are only vaguely understood. For example, wood may retain sediment and block channels, driving avulsions (Brummer et al., 2006), but how does wood accumulation on the floodplain itself (e.g., Lininger et al., 2021) affect avulsions and floodplain reworking? When placed in a loose, spatially-distributed pattern across the valley bottom, how does wood rearrange and form jams that can provide discrete geomorphic impacts? Answering these questions could help develop a more mechanistic understanding of how wood provides geomorphic functions in multi-channel riverscapes, which could then guide wood placement as part of restoration to Stage 0.

Valley bottoms that experience restoration to Stage 0 present valuable field laboratories to explore how riverscapes respond to disturbance. One method of creating a Stage 0 valley bottom is the valley bottom process reset style restoration using the geomorphic grade line (GGL) design method (Powers et al., 2019). The GGL method involves fitting a GGL surface to elevations of historical indicators of the pre-disturbance valley bottom to approximate the historical valley grade. Areas of the valley bottom that are higher than the GGL (e.g., terraces, anthropogenic berms, etc.) are then excavated, and areas lower than the GGL are filled with sediment. Wood sourced from on-site tree tipping and off-site harvest is then placed to provide hydraulic roughness and retain sediment that can support riparian vegetation establishment. This large wood is typically placed without artificial anchors (e.g., chain, boulder ballast, threaded rod, etc.), meaning that it can move downstream. However, some logs are often buried or left interacting with the valley wall or remaining riparian vegetation, which can reduce their ability to move downstream (Carah et al., 2014; Dixon & Sear, 2014; Merten et al., 2010). Monitoring this valley-scale alteration can provide insights into how riverscapes respond to changes in topography and wood storage.

1.1 Objectives

Here, I present 6 years of monitoring of restoration to Stage 0 along Deer Creek. I analyze the spatial arrangement and change of geomorphic units across the valley bottom using a geomorphic heterogeneity framework (Scott et al., 2022) to quantify how different phases of restoration set up the valley bottom’s geomorphic response to subsequent high flows. By mixing quantitative analysis of geomorphic spatial and temporal heterogeneity and qualitative observations of the spatial correlation between wood and geomorphic change, I examine how wood rearrangement alters the lateral connectivity of water and sediment and reworking of both the channel and floodplain. I examine not only how valley bottom process reset alters the arrangement of landforms across the valley bottom but also whether it is effective at kickstarting the geomorphic processes that may sustain a Stage 0 condition. In doing so, I seek to advance our understanding of how topography, wood, and vegetation interact to spur lateral connectivity and floodplain reworking and provide suggestions for future efforts to create Stage 0 valley bottoms.

1.2 Site Description

This study focuses on the lower 2.5 km of Deer Creek upstream of its confluence with the McKenzie River (Figure 1). This segment drains a 59 km^2 watershed, has a valley gradient of approximately 2% and a valley bottom width of 60 – 150 m. The channel ranges in surface grain size from boulder- to sand-bedded.

Restoration here was motivated by a desire to restore salmonid habitat after intensive anthropogenic habitat degradation. There is little direct evidence of what Deer Creek looked like or the ecosystem it sustained prior to human disturbance, but relict side channels and islands on terraces indicate that the restored segment used to be complex, with multiple channels and a diverse floodplain forest. Road building and forest harvest, beginning in the mid-19th century, berm construction along the active channel, construction of an electricity transmission line, and direct wood removal likely decreased wood supply, load, and function, as well as artificially confined the channel. This likely produced the pre-restoration condition of a dominantly single thread channel with poor lateral connectivity (i.e., limited transport of water, sediment, and wood between the channel and floodplain). The exception to that state in the pre-restoration period was a large flood that reshaped the valley bottom in 1964 and produced a multithread channel that filled much of the valley bottom (Bianco, 2018), before roads were repaired and the stream again confined to a single thread.

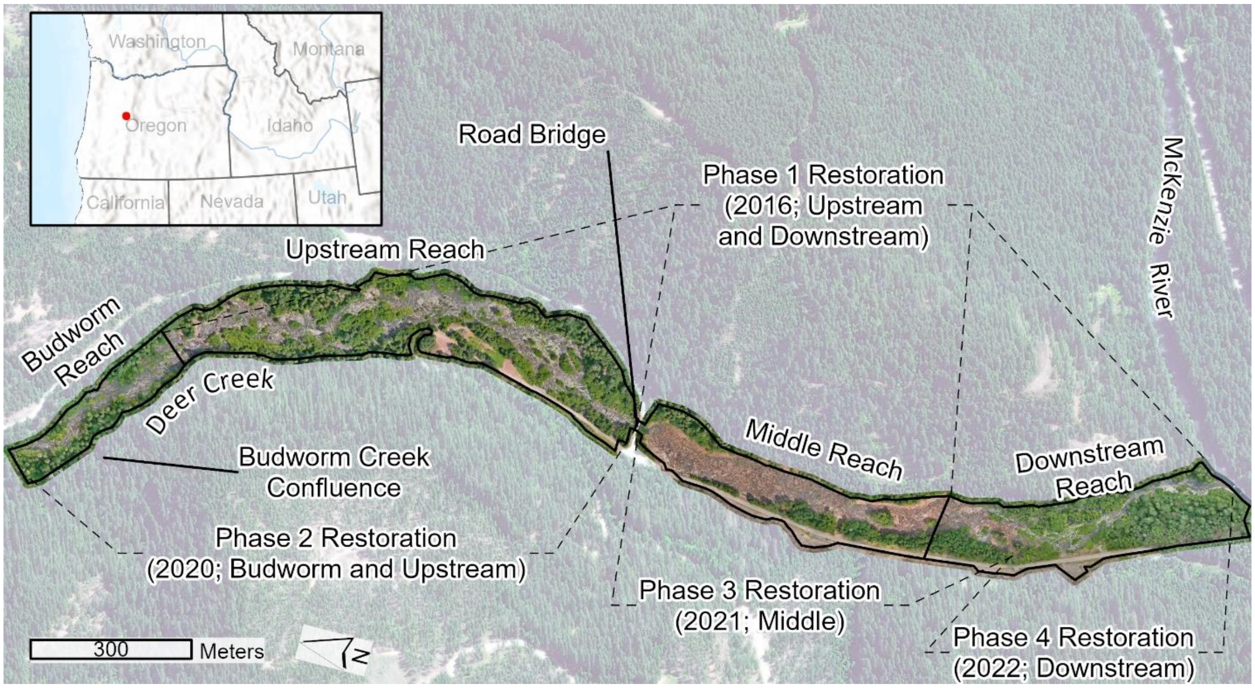

Figure 1: Map of Deer Creek, OR. Inset shows location in the Western United States. Imagery around the creek shows the 2021, post-phase 2 restoration condition, and lighter colored imagery shows the 2016 condition of the valley walls.

1.3 Process Reset Restoration to a Stage 0 Condition along Deer Creek

Restoration along Deer Creek sought to restore a Stage 0 valley bottom condition using the process reset to GGL method described above. This study documents two phases of restoration in 2016 (upstream and downstream reaches) and 2020 (Budworm and upstream reaches). From 2016 to 2020, this study tracks the evolution of the upstream and downstream reaches (Figure 1). I then shift the focus of the study to only the upstream and Budworm reaches to discuss the impacts of phase 2 restoration and two years of subsequent evolution. A subsequent third and fourth phase of restoration not documented in this study took place in 2021 and 2022 along the middle and downstream reaches.

Both phases 1 and 2 of restoration along Deer Creek had similar overall objectives but differed in approach and scope. While phase 1 restoration removed anthropogenic berms and filled in low portions of the channel, it did not reach the GGL-derived valley surface in many locations, as the GGL method was still in development at that time. It also only involved placement of a moderate quantity of wood (planned placement was 200 logs per km), although 13 large conifers were also pulled over (felled without cutting off the rootwad) into the channel in the two years following restoration. Phase 2 restoration, in contrast, was designed using a 2018 topobathymetric LiDAR digital elevation model (DEM) and the recently developed GGL method. It was designed to reach the GGL-derived valley surface across a much larger area, and it involved approximately quadrupling the existing wood load.

2 Methods

2.1 Data Collection and Analysis

I used a combination of remote sensing and field data to characterize the spatial distribution of geomorphic units and wood across the valley bottom. I conducted combined drone and ground surveys each summer during low-flow conditions from 2018 through 2022, with two surveys in summer 2020 to characterize pre- and post-phase 2 conditions. For the two surveys in 2016 to characterize pre- and post-phase 1 conditions and the survey in summer 2017, I used drone imagery, written and verbal site descriptions, and ground photos collected by others to characterize site conditions.

To characterize the geomorphic form of the site and infer geomorphic process activity, I applied a geomorphic heterogeneity framework (Scott et al., 2022), focusing on the diversity (evenness and richness) and spatial configuration (namely fragmentation) of geomorphic units. This framework relies on mapping the wall-to-wall extent of geomorphic units across the valley bottom that indicate relevant forms (in this case, those that define a multi-channel riverscape and indicate lateral connectivity) and processes (in this case, avulsion and local scour and deposition around wood). See Table 1 for definitions of this geomorphic unit schema.

Table 1: Definitions of geomorphic units mapped along Deer Creek

Unit	**Definition**
Terrace	quasi-planar surface showing no morphologic or vegetative signs of recent inundation, including terrace benches (i.e., terraces not on the valley margin)
Floodplain	quasi-planar, quasi-horizontal surface showing morphologic and/or vegetative signs of recent flood inundation, categorized by canopy height into low (< 1 m), medium (1 – 5 m), and high (> 5 m) canopy
Vegetated Island	floodplain surfaces surrounded by the channel, categorized by canopy height into low (< 1 m), medium (1 – 5 m), and high (> 5 m) canopy
Overbank Channel	channel (i.e., displaying bed and banks and typical fluvial bedforms) on a floodplain or vegetated island surface whose upstream-most elevation is closer to that of the surrounding floodplain or vegetated island surface than the nearby channel and that shows morphologic or vegetative evidence of being recently reshaped by overbank flow (i.e., is not a relict channel)
Pool	deep, concave-up, and baseflow-wetted portions of the below-bankfull channel
Undifferentiated Channel	shallower portions of the below-bankfull channel, including bars, riffles, runs, and glides

I also mapped the area occupied by downed, dead wood visible in drone imagery where that wood intersected non-terrace geomorphic units (i.e., I did not map wood solely resting on terraces). From this, I computed wood load as the ratio of wood area to non-terrace valley bottom area.

This wood load estimate is underbiased, as I missed downed wood tpdfhat was completely obscured by vegetation in the floodplain. I observed wood rearrangement between observations and via the use of 1-hr interval timelapse camera imagery.

To map geomorphic units and wood, I used a combination of field ground truthing and interpretation of remote sensing data, including: a 6 ft resolution LiDAR digital elevation model (DEM) from 2008, a 1 m resolution bathymetric LiDAR DEM from 2018, and approximately 3 cm structure-from-motion (SfM) derived drone orthomosaics and digital surface models. Drone imagery collected in April 2016 (just before phase 1 restoration), September 2016 (just after phase 1 restoration, September 2017, August 2018, July 2019, June 2020 (before phase 2 restoration), August 2020 (just after phase 2 restoration) and August 2021. Ground truthing involved walking the valley bottom and taking georeferenced notes and photos coincident the 2018 – 2021 drone surveys. I mapped geomorphic units in ArcGIS Pro by manually drawing polygons around geomorphic units based on the aforementioned definitions. I used ground truthing and the SfM-derived digital surface model to differentiate canopy heights of floodplain and vegetated island surfaces.

I computed the abundance (area divided by valley bottom area) and total perimeter length of all geomorphic unit patches to compute spatial heterogeneity metrics. I also intersected the geomorphic unit maps from all observations to compute a metric of temporal heterogeneity: the proportion of each reach that changed from observation to observation. To provide context for measurements of heterogeneity, I computed fluvial process space and utilization of that space. Table 2 describes the metrics computed in this study.

Table 2: Geomorphic heterogeneity metrics, definitions, and units.

Geomorphic Heterogeneity	Definition	Interpretation	Units

Metric			
Vegetated island density	Count of vegetated islands divided by valley bottom area	Like braiding index, a measure channel density	# islands / ha
In-channel edge density	Perimeter length of all pool and undifferentiated channel patches divided by the total area of all pool and undifferentiated channel patches	Fragmentation or disaggregation of the active channel — higher values indicate a more fragmented active channel, both in terms of topographic variation (pools versus undifferentiated channel) and planform variation (channel edge around islands and banks)	m / m^2
Wood density	Proportion of active channel and floodplain surfaces (i.e., all non-terrace surfaces) covered by large wood	Wood load. Given the likely lack of wood transport out of the studied reaches (with the exception of the Budworm reach, discussed below), this metric also indicates aggregation (lower aerial coverage with the same overall wood load indicates that wood is more aggregated into jams).	-
Canopy height evenness (Simpson	Probability of two randomly selected points being in floodplain or vegetated island units with	Vegetation succession, or the establishment of young vegetation patches. Higher values indicate a	-

Diversity Index)	different canopy heights. Simpson diversity index was computed as $1 - \sum_{i=1}^{R} p_i^2$, where r is the total number of classes and p_i is the proportion of area occupied by the ith class. With 3 possible classes, this index can range from 0 to 0.66, with 0.66 representing complete evenness.	more even distribution of vegetation age classes, indicating that vegetation is emerging on bars or that mature vegetation is preferentially being eroded.	
Proportion of reach changed since last observation	The proportion of the reach area that experienced a change in geomorphic units. Change from floodplain to island (or vice versa) and changes in canopy height are not counted for this metric.	Temporal heterogeneity — higher values indicate a greater degree of change, and when interpreted in context of preceding flow magnitude, indicates sensitivity to disturbance.	-
Fluvial process space	Area of non-terrace geomorphic units divided by total valley bottom area	The proportion of the valley bottom over which fluvial processes can readily cause geomorphic change.	-
Utilization of fluvial process space	Area of undifferentiated channel, pool, and overbank channel units divided by area of non-terrace units	The proportion of fluvial process space in which flow is actively carving or maintaining channels.	-

2.2 Streamflow Estimation

The force driving geomorphic change at a site, in this case, high winter flows, is key context to interpret post-restoration site evolution. Unfortunately, Deer Creek lacks a streamflow gage, so I used the adjacent Lookout Creek watershed as a flow analog (USGS gage 14161500). Lookout Creek is a 62 km^2 (comparable to Deer Creek's 59 km^2) watershed that shares a drainage divide with Deer Creek. Its watershed ranges in elevation from 436 to 1622 m (comparable to Deer Creek's range of 1,055 to 1,628 m) and likely experiences a very similar climatic regime. Like Deer Creek, it has a history of forest harvest (Frady et al., 2007). See Supplement S1 for a comparison of Lookout Creek peak for magnitude to relative stage observed in timelapse imagery on Deer Creek.

3 Results and Discussion

Here, I present a combined qualitative and quantitative assessment of the geomorphic change resulting from each phase of restoration in the context of flows that occurred after each phase. I use the spatial relationship between wood and geomorphic change to infer how wood altered flow and sediment transport patterns, leading to geomorphic change in both the channel and floodplain.

3.1 Phase 1 Restoration

Phase 1 restoration removed anthropogenic berms, filled incised channels, and added a substantial amount of large wood to the upstream and downstream reaches. This created new channels bifurcating from the former mainstem and locally inundated (reconnected) forested floodplains, creating diffuse forested side channel networks. Wood additions were primarily in the form of loose, separated accumulations, or jams, with large gaps between jams. Tree removal and channel infilling created wide, open channel areas interspersed with large, vegetated islands (Figure 2, Figure 3).

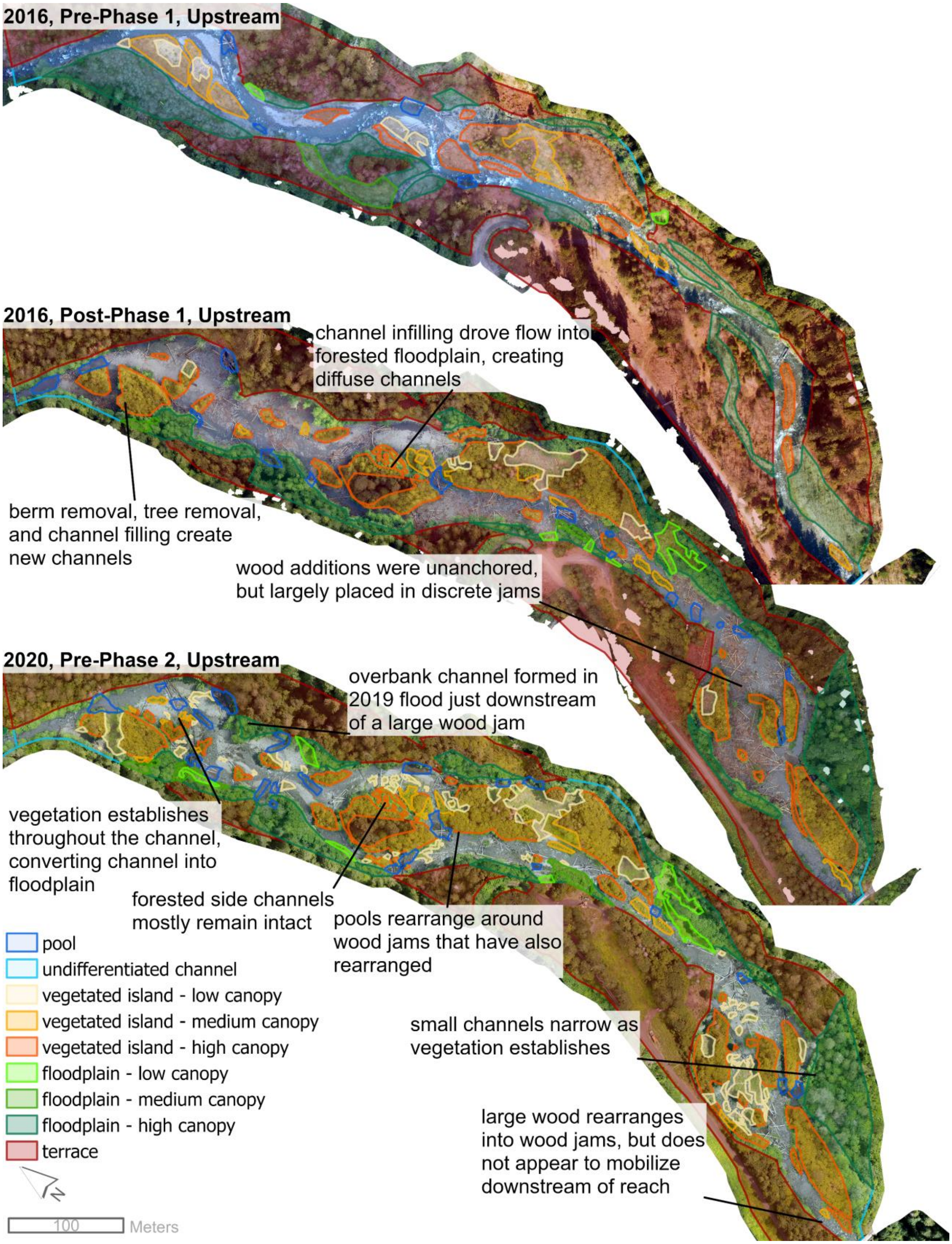

Figure 2: Maps showing change in the upstream reach from 2016 to 2020 (pre-phase 1 to pre-phase 2).

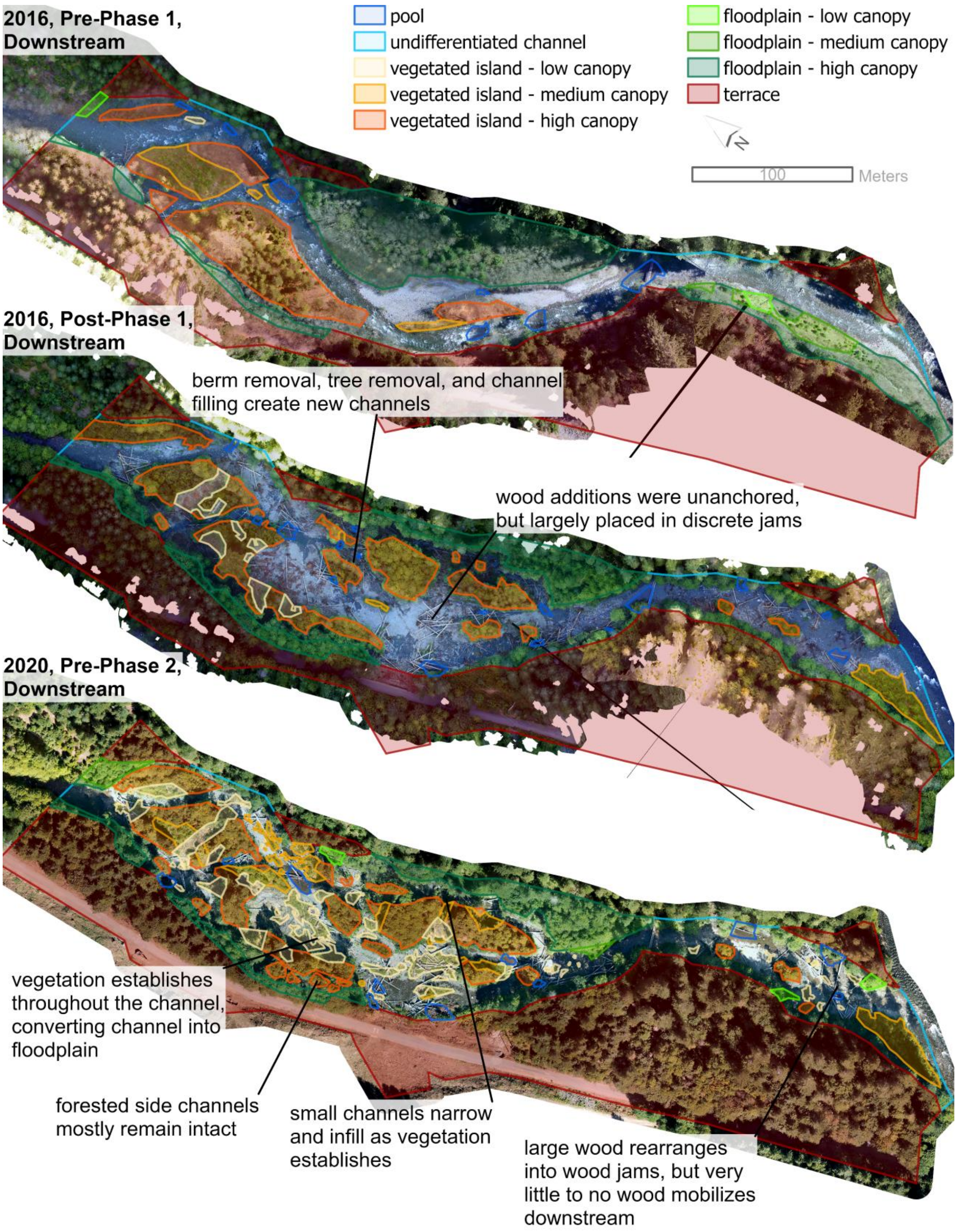

Figure 3: Maps showing change in the downstream reach from 2016 to 2020 (pre-phase 1 to pre-phase 2).

If restoration had restored lateral hydraulic and sediment connectivity and provided the roughness necessary to enable significant rearrangement of the channel and floodplain, I would have expected to see rearrangement of pools, sediment deposition around wood that could help drive overbank flow, and channel incision or overbank sediment deposition on floodplains. Instead, the primary geomorphic response in the 4 years following Phase 1 restoration was vegetation establishment in the channel, even through a 2- to 5-year recurrence interval flood, indicating that Phase 1 did not fully restore lateral connectivity or drive significant reworking of the channel or floodplain.

While floodplains were inundated after the April 2019 flood, as evidenced by fine detritus racked on floodplain vegetation, they were only minimally rearranged by the formation of overbank channels. Only one small floodplain overbank channel incised to a depth of only a few cm through a protrusion of terrace just downstream of an especially large log that ramped up on the bank (Figure 2). This overbank channel rapidly vegetated during the low flow period from summer 2019 to summer 2020.

In the channel, wood was slightly rearranged, but jams largely remained where they were placed, likely due to stability provided by buried logs, pieces ramped on valley walls or floodplains and terraces, or pieces racked on vegetation (Carah et al., 2014; Dixon & Sear, 2014; Merten et al., 2010). Very little wood entered the upstream reach from further upstream to supplement placed wood, and bank erosion recruited only a few trees in the downstream reach. Observations of the downstream-most, channel-spanning wood jams in each treated reach indicate that wood mobilization out of each reach was unlikely: each of those jams extended above the maximum stage reached during this period, remained stable, and racked wood from upstream (see Figure 11 in Flitcroft et al., 2022).

Because pools are often maintained by wood in wood-rich riverscapes (Montgomery et al., 2003; Pess et al., 2022), this lack of wood rearrangement may have led to the lack of channel bed rearrangement and new pool formation. Pool area largely did not change (ranging from 1 – 1.4% of the valley bottom for the upstream reach and 0.8 – 1% for the downstream reach) during this time, and pools largely did not change positions, indicating a lack of in-channel rearrangement.

Vegetation establishment increased landscape fragmentation, but did not provide sufficient roughness to reactivate geomorphically effective flows on the floodplain. Restoration itself increased the number of vegetated islands per unit area (analogous to the density of channels, or braiding index; Figure 4B) and fluvial process space (Figure 5). Edge density rapidly increased post-restoration due primarily to the growth and establishment of new of vegetated islands, as reflected by an increase in canopy height evenness, which tends to increase as new vegetation (low canopy height) establishes (Figure 6). Fluvial process space remained essentially constant after the initial increase during phase 1 restoration, and utilization of that space decreased as vegetation established (Figure 5C).

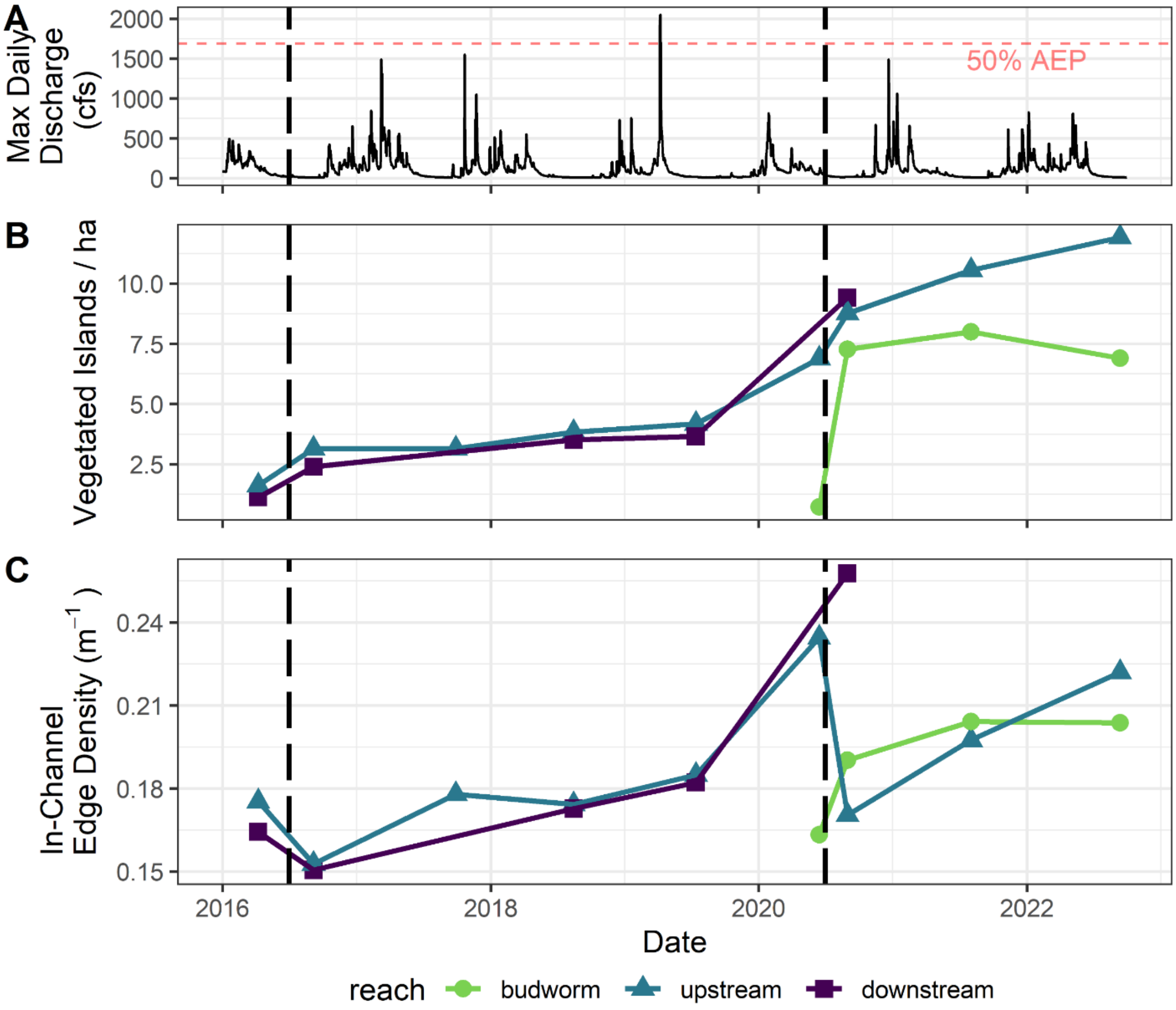

Figure 4: Estimated flow history (from Lookout Creek) (A), vegetated island density (B), and in-channel edge density (C) over time. Dashed lines indicate phases 1 and 2 of restoration.

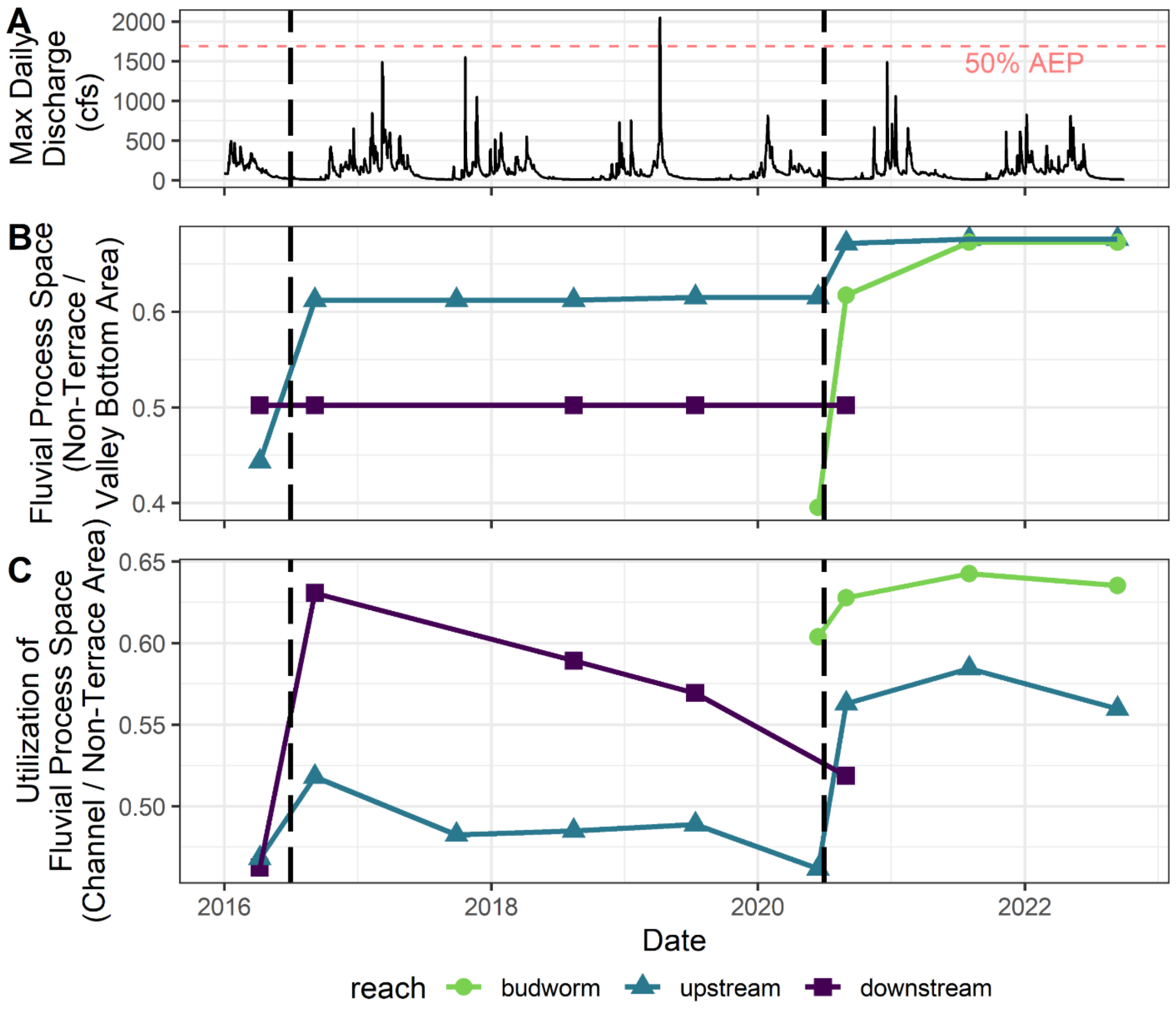

Figure 5: Estimated flow history (from Lookout Creek) (A), fluvial process space (B) and utilization of fluvial process space (C) through time. Dashed lines indicate phases 1 and 2 of restoration.

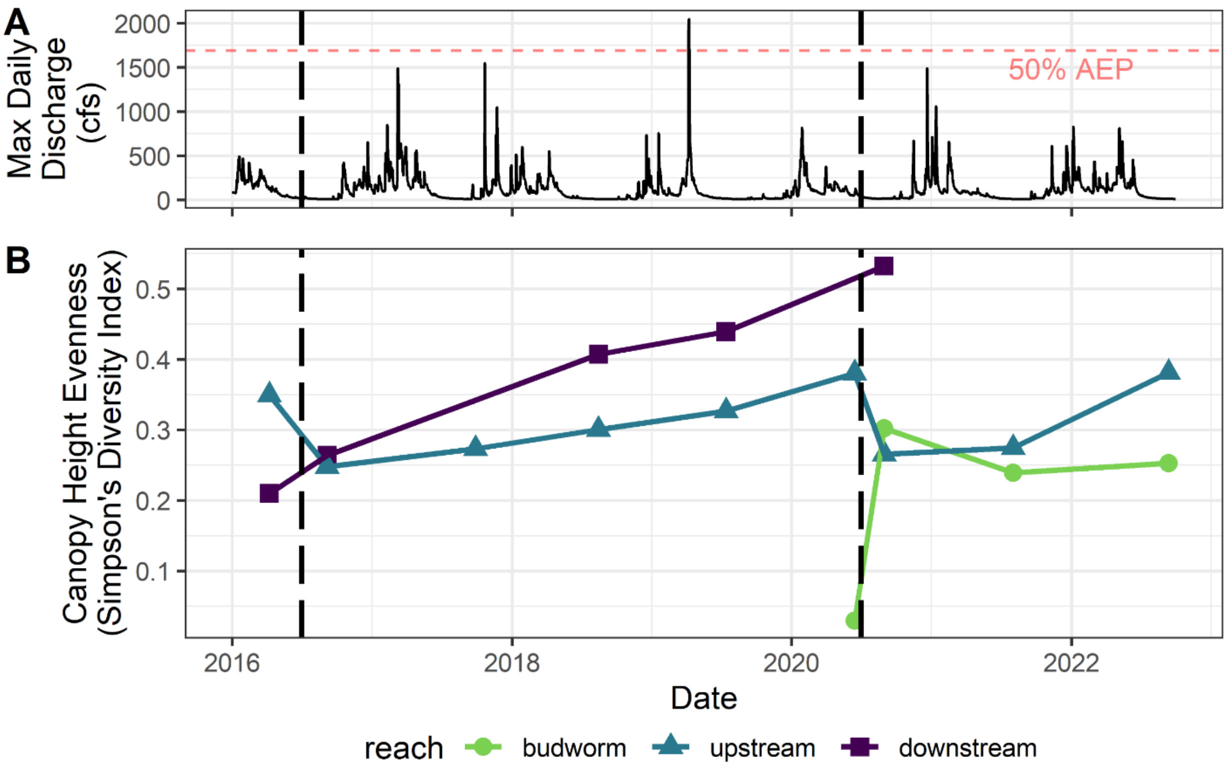

Figure 6: Estimated flow history (from Lookout Creek) (A), and evenness of vegetation canopy height across the valley bottom through time (B). Dashed lines indicate phases 1 and 2 of restoration.

3.2 Phase 2 Restoration

Phase 2 restoration of the upstream and budworm reaches was more intensive than phase 1, involving excavation of terraces and floodplains and infilling of channels, as well as the placement of much more wood. Total wood load increased by a factor of 4 in the upstream reach and a factor of 7 in the previously unrestored budworm reach (Figure 7). Wood placement formed a wood lattice, defined as a spatially well-distributed arrangement of logs at an approximately homogenous areal density, lacking, for the most part, discrete jams, or lower porosity zones.

The flows following phase 2 restoration not only rearranged placed wood and the channel bed, but also inundated and reworked the floodplain. In the year following phase 2 restoration, peak flow along Lookout Creek only reached approximately 1,500 cfs, less than the approximately 2,000 cfs peak that occurred between phase 1 and phase 2 (Figure S2). However, the geomorphic impact of this lower flow was much greater than that of the larger flood in April 2019, and change occurred over a large extent (14% and 7% of the valley bottom for the Budworm and upstream reaches, respectively; Figure 8).

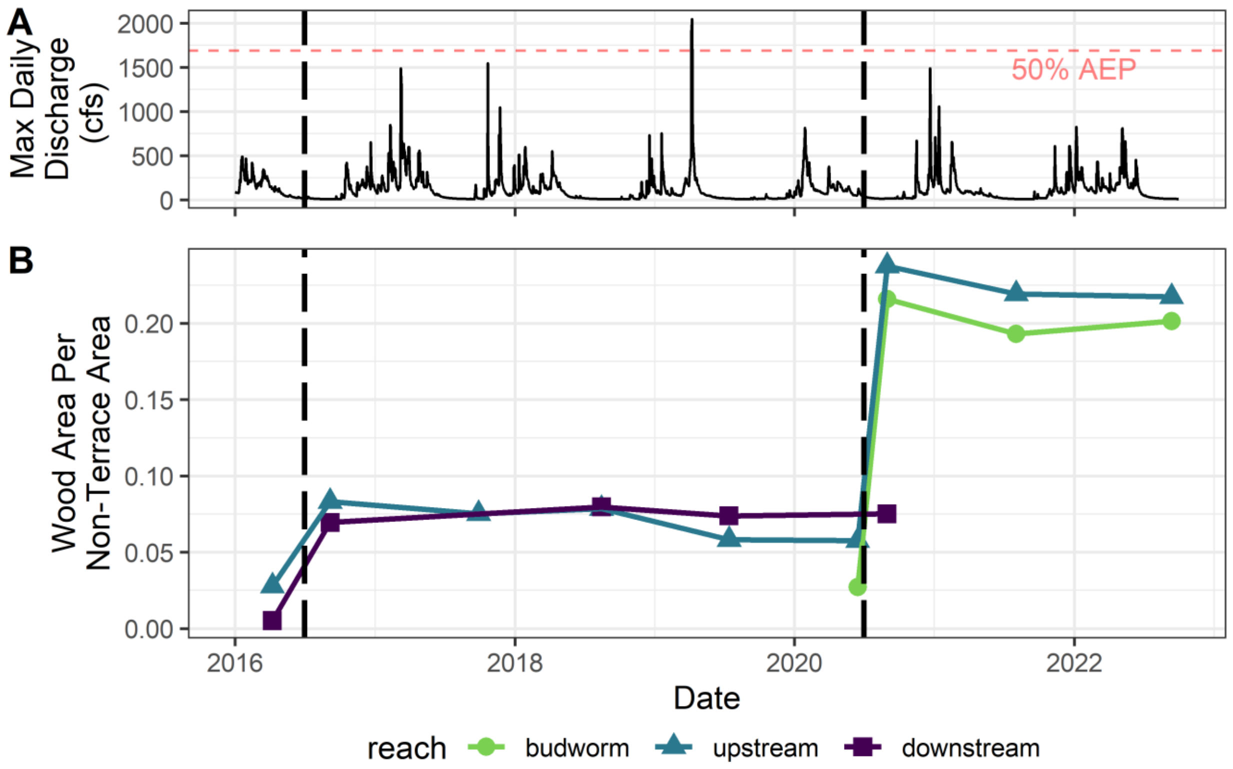

Figure 7: Estimated flow history (from Lookout Creek) (A), and wood density through time (B). Dashed lines indicate phases 1 and 2 of restoration.

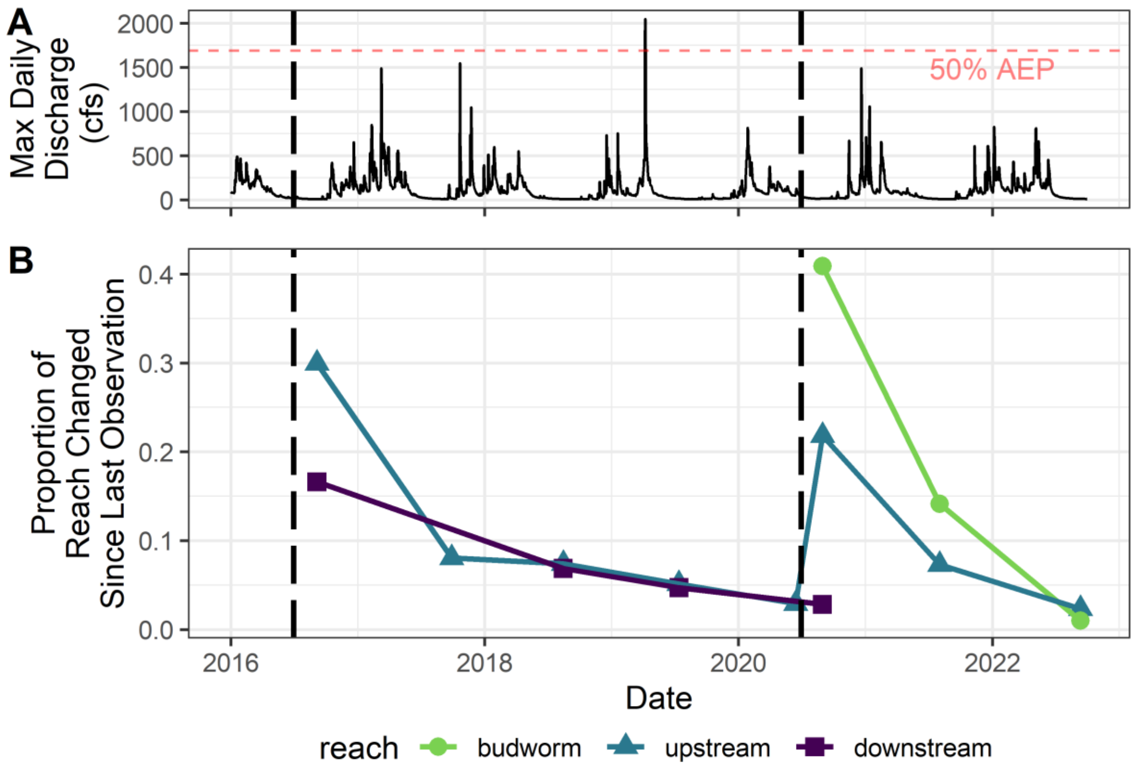

Figure 8: Estimated flow history (from Lookout Creek) (A), and proportion of each reach changed since the preceding observation (B). Dashed lines indicate phases 1 and 2 of restoration.

The December 2020 high flow rearranged the wood lattice and significantly reshaped the channel bed. Much of the wood lattice mobilized, although again, like after Phase 1, the tall, channel-spanning jam at the downstream end of the upstream reach remained stable and racked wood, indicating no net loss of large logs from the reach (no such jam existed at the downstream end of the Budworm reach). Rearrangement of the wood lattice created large gaps and formed wood jams (Figure 9), decreasing the total wood area in both reaches (i.e., wood became more densely packed, but total wood load likely did not decrease significantly; Figure 7). This rearrangement occurred quickly during the rising limb of the December 2020 flood (Supplemental Section S2), allowing newly formed wood jams formed to alter hydraulics and sediment transport during the peak of the flood. Wood rearrangement appeared to form more discrete jams in the Budworm reach compared to the upstream reach, possibly due to the narrower valley bottom in Budworm resulting in a higher flow depth (and thus a higher likelihood of log floating).

Wood jams appeared to dominantly form around logs that in some way interacted with less mobile elements in the valley bottom, usually living trees or the valley walls, or logs that were buried. This correlation implies that relatively stable elements, or nucleation points, that allow wood jams to form can be crucial in enabling a wood lattice to rearrange into discrete wood jams. I hypothesize that these nucleation points were key in preventing substantial downstream mobilization and keeping wood on site, where it could drive lateral connectivity and reworking of the floodplain. This hypothesis broadens the key piece concept (i.e., that wood jams form primarily on large, stable logs; Abbe & Montgomery, 2003) by acknowledging that other relatively immobile elements, such as living riparian vegetation or even small logs that interact with valley walls or are buried, can rack wood to form wood jams, and follows similar observations from other systems with riparian vegetation that is well exposed to flow (Gurnell & Bertoldi, 2020).

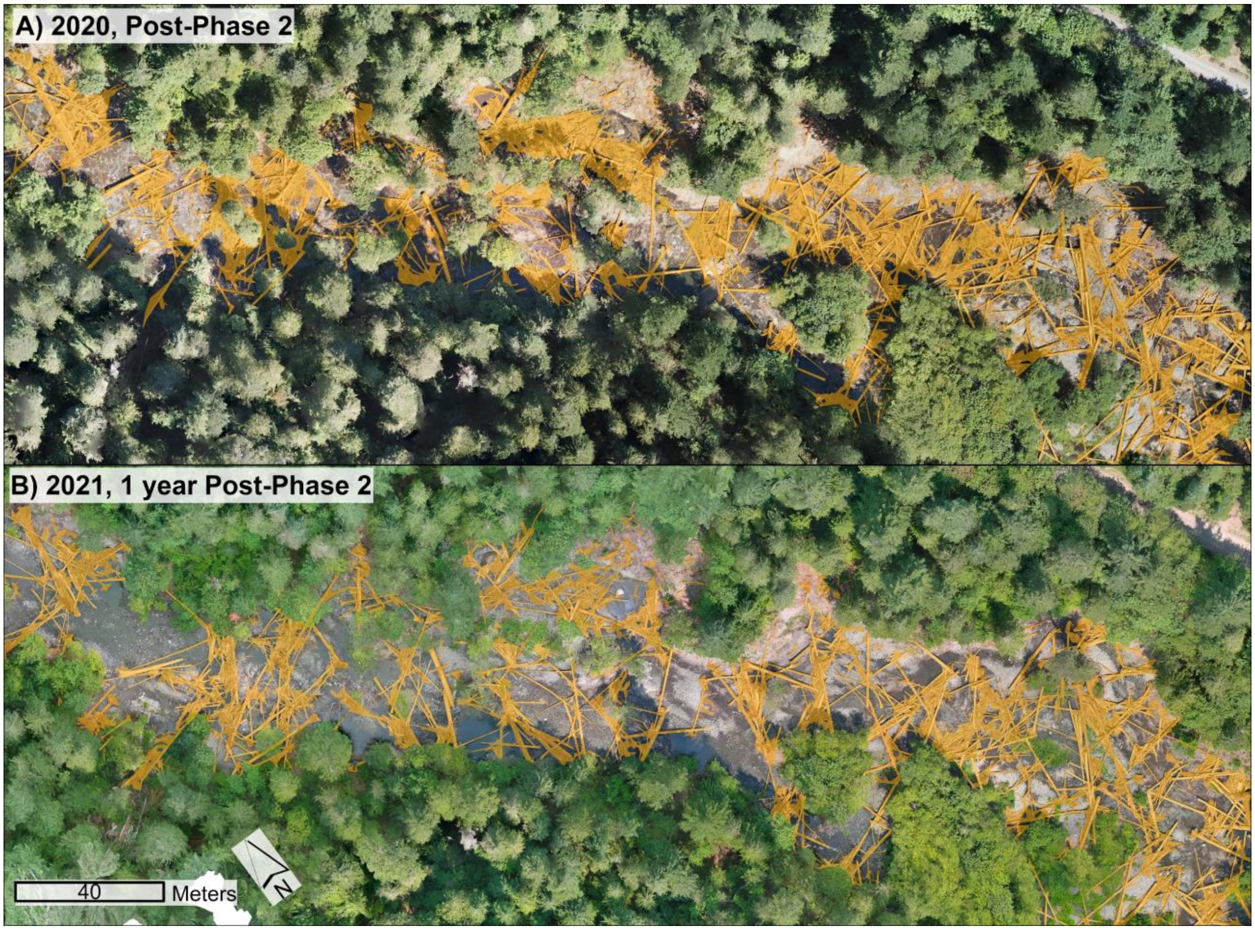

Figure 9: Map highlighting wood (orange overlays) in the transition from the Budworm to upstream reach, showing the originally placed wood lattice (A) and the rearrangement of that lattice to form wood jams (B).

Wood rearrangement into jams spatially correlated with the formation of new pools and sediment retention, as indicated by qualitative observations of gravel and sand bars and sediment wedges upstream of newly formed wood jams. Pool area increased from 6.6% to 8.2% of the valley bottom (an increase of 438 m^2) and from 3.2 to 4.1% (an increase of 1,113 m^2) in the Budworm and Upstream reaches, respectively. A significant portion of this increase can be accounted for by the formation of new pools or the expansion of existing pools either upstream of (i.e., backwaters) or downstream of (i.e., likely formed by plunging flow) newly formed wood jams (Figure 10, Figure 11). Correspondingly, in-channel edge density also increased (although part of this increase is likely due to avulsion, discussed below; Figure 4C). This indicates the importance of wood rearrangement and jam formation in enabling rearrangement of the channel bed, similar to other systems in which wood has been observed to constrict, plunge, and backwater flow to create pools (Livers & Wohl, 2021; Martens & Devine, 2022; Pess et al., 2022).

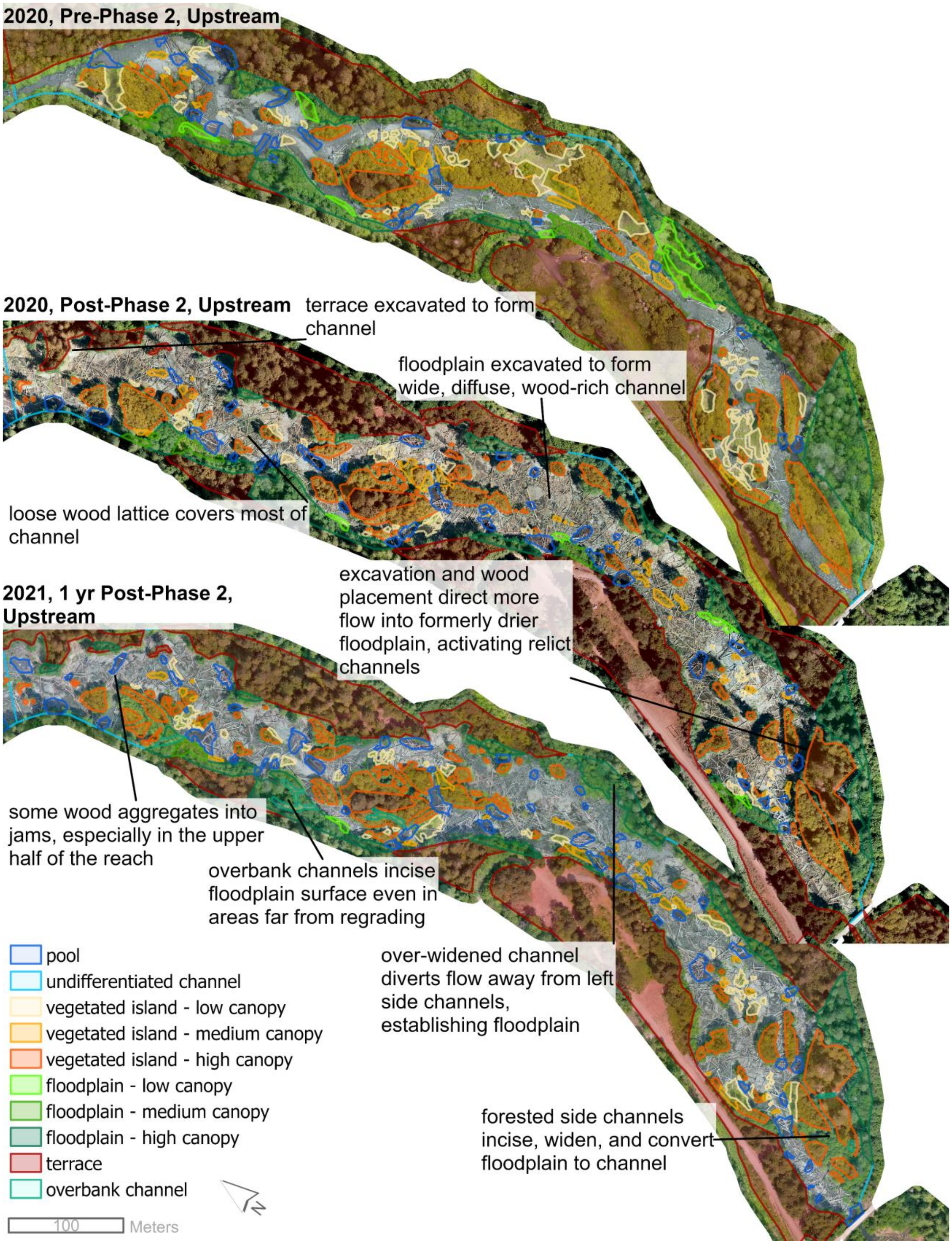

Figure 10: Maps showing change in the upstream reach from 2020 to 2021 (pre-phase 2 to 1 year post-phase 2).

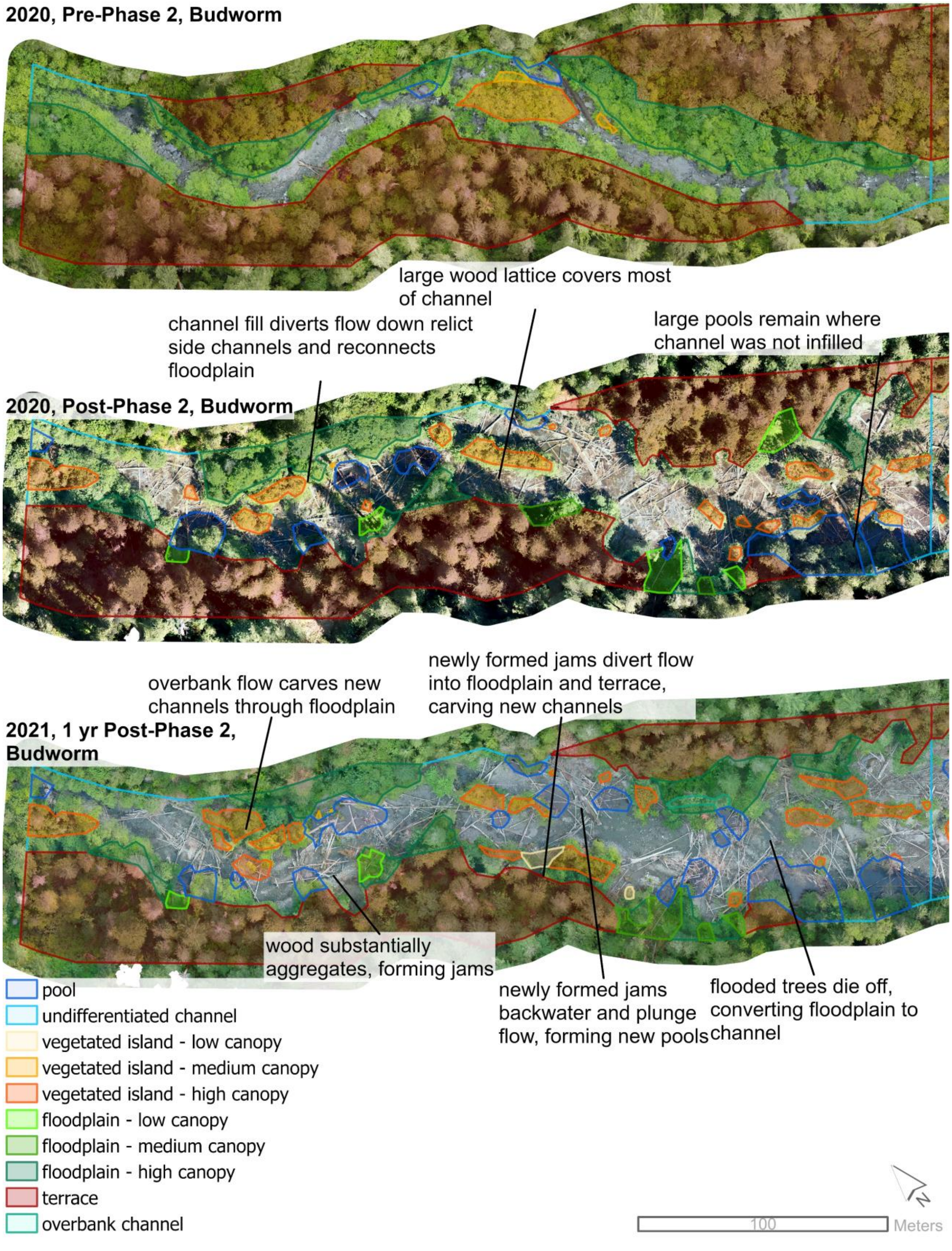

Figure 11: Maps showing change in the budworm reach from 2020 to 2021 (pre-phase 2 to 1 year post-phase 2).

Wood rearrangement in the channel along with the significant regrading done in phase 2 drove substantial floodplain inundation and reworking. Lateral hydrologic and sediment connectivity were indicated by overbank sand deposition, leaves and sticks racked on living vegetation, channel incision into formerly unchanneled floodplain (See Supplemental Section S3), scour and deposition on the floodplain, and nascent channels incised into floodplain and even terrace surfaces (Figure 10, Figure 11).

For the first time since restoration began, fluvial processes converted terrace into floodplain and even new low flow channels via avulsion, thus increasing fluvial process space (Figure 5B) and the density of bifurcations (Figure 4B). The creation of new channels on floodplain surfaces (e.g., Figure 12, Figure 13) also increased the utilization of that fluvial process space (Figure 5C), without a corresponding increase in vegetation canopy height evenness (Figure 6), indicating that these changes were primarily driven by the formation of new channels, as opposed to the vegetation establishment that occurred following phase 1.

Figure 12: Picture looking upstream (A) at a newly formed side channel branching off into the floodplain on right river (left side of picture) and downstream at that same side channel's inlet (B) (August 3, 2021). Blue arrows show flow directions.

Figure 13: Picture looking downstream at a channel inlet newly carved into a former floodplain surface (A) and, just downstream of that inlet, looking left at a low flow wetted area scoured into what was formerly a fully vegetated floodplain surface (B) (August 2, 2021). Arrows show flow direction.

In the second year after phase 2 restoration, flows were unusually low. Similarly low flows in 2019/2020 prior to phase 2 restoration led to widespread vegetation establishment in the active channel and did not produce overbank flow. However, even these lower flows after phase 2 restoration deposited organic matter on the floodplain, pushed over dead floodplain grasses, expanded an existing overbank channel, and incised a new low flow channel in the Budworm reach and the upper, slightly more laterally confined portion of the upstream reach. This indicates that after phase 2 restoration and the fluvial rearrangements in 2020/2021, lateral hydrologic and, to a more limited extent, sediment connectivity was maintained at even relatively low flows. I also saw no evidence of the channels that newly formed in 2020/2021 infilling with sediment or vegetating — they tended instead to experience rearrangement of the small wood jams that had formed in them, indicting substantial flow (Figure 14). While vegetation establishment was widespread in the open portions of the active channel, a combination of persistent low flow and canopy cover may have inhibited vegetation establishment in newly formed forested floodplain channels.

Figure 14: Repeat photos from 1 year (A) and 2 years (B). after phase 2 implementation, showing newly racked wood in a new low flow channel created during the December 2020 flood. Yellow lines highlight similar features to reference the two photos.

In summary, avulsion, floodplain reworking, and rearrangement of the active channel not only further fragmented the valley bottom, making it more heterogeneous, but also expanded the area over which fluvial processes may be active (fluvial process space), the proportion of that space experiencing active channel-formation and maintenance processes (utilization of fluvial process space), and the lateral hydrologic and sediment connectivity between the floodplain and channel. That these changes occurred during a moderate flow (< 2-year recurrence interval on Lookout Creek) but failed to occur during a higher flow (2- – 5-year recurrence interval on Lookout Creek) prior to phase 2 restoration suggests that phase 2 restoration lowered the threshold discharge required to reshape the channel and floodplain, thus making it more likely that the channel and floodplain will be reworked more frequently in the future.

3.3 The Role of Wood in Driving Lateral Connectivity and Reworking of the Channel and Floodplain

Some combination of increased roughness due to higher wood density and regrading that infilled channels led to the substantial decrease in the threshold required for geomorphically effective floodplain flows (i.e., an increase in lateral connectivity). Differentiating these two influences definitively is not possible at this site, but the spatial arrangement of wood in relation to both in-channel and floodplain reworking as well as qualitative observations can shed light on the role wood played.

Wood appeared to have influenced lateral connectivity and the prevalence of floodplain reworking in two key ways. First, in-channel wood jams likely backwatered and drove flow overbank that led to avulsions or floodplain overbank channel incision, similar to observations in other forested mountain streams (Abbe & Montgomery, 2003; Brummer et al., 2006; Collins & Montgomery, 2002). Every avulsion or newly formed overbank channel had a low porosity and often channel-spanning wood jam shortly downstream of their inlet (Figure 10, Figure 11). Even if regrading alone may have been sufficient to drive overbank flows, the location of in-channel wood controlled where those flows carved new channels. Many of these jams formed in places where wood was not particularly clustered or closely spaced post-restoration, highlighting the importance of wood mobility (Wohl et al., 2023) and likely a range of wood sizes (leading to lower porosity; Livers et al., 2020) and interactions with less mobile elements (i.e., jam nucleation points) in determining the spatial distribution of morphologic change and lateral connectivity.

Second, wood transported into and down newly incised floodplain channels itself was interacting with floodplain vegetation in a way that likely encouraged channel development and helped maintain lateral connectivity. Accumulations of smaller logs and branches racked on floodplain trees and interacted with exposed root networks (similar to observations of Hawley & MacMannis, 2019; Jeffries et al., 2003; Lininger et al., 2021) to regulate floodplain flow pathways, constrict flow, and form small scour pools throughout these floodplain channels (Figure 15, Figure 14). Scour pools formed just within or near nascent channel inlets by wood-induced flow constriction or plunging flow may also help maintain a greater low flow duration through these side channels by keeping their inlets better connected to nearby low flow channels, possibly preventing vegetation establishment and maintaining channel conveyance (Figure 12). Importantly, these floodplain wood jams were dominantly formed by small wood < 10cm in diameter and < 1m in length (although small wood occasionally racked on larger logs protruding into floodplain forests). Such small wood also racked on and filled in in-channel wood jams, likely reducing their porosity (Livers et al., 2020; Spreitzer et al., 2020) and thus increasing their ability to divert flow into the overbank.

Figure 15: Pictures of wood accumulations in forested floodplain channels that are backwatering (A) and constricting (B) flow. Blue arrows show flow direction.

I summarize how wood influenced lateral hydrology and sediment connectivity and the reworking of channels and floodplains in Figure 16. This conceptual diagram highlights the importance of both in-channel and floodplain wood accumulations in both driving lateral hydrologic connectivity and then enabling overbank flows to carve new channels, reworking the floodplain. Those processes required a certain set of ingredients, or necessary conditions, including: the initial condition of a spatially distributed wood lattice with abundant wood of various sizes that could be rearranged into wood jams, nucleation points for those jams to form, and sufficient fluvial process space (a lack of confinement) to allow overbank flows. Given the observed morphologic influences of small wood jams that formed in nascent floodplain channels, I hypothesize that they contributed to lowering the peak flow threshold required to induce geomorphic change on the floodplain. A lack of small wood and the floodplain jams that wood can form would likely result in a higher threshold discharge required to rework the floodplain.

This conceptual diagram and the findings of this case study are limited to a short time period, and thus raise the question of whether the observed lateral connectivity and widespread floodplain reworking will continue over a longer time period (i.e., the dashed line in Figure 16). Given which ingredients seem to have been required to drive these processes in the short-term, I hypothesize that some combination of wood supply (to replenish wood jams as they decay, break, and mobilize downstream), sediment supply (to prevent channel incision), and riparian vegetation establishment will be necessary to sustain the stream’s ability to rework itself and sustain a multi-channel, Stage 0 valley bottom over the long-term. While sediment supply is likely to be sufficient in this intensively logged watershed (Goodman et al., 2023; Jaeger et al., 2023), and there are no apparent factors limiting riparian vegetation establishment, almost no wood was observed to enter the treated reach during my observations from 2018 to 2022, indicating a potential lack of upstream wood supply. It remains to be seen if wood function will persist as wood decays, breaks, and mobilizes downstream.

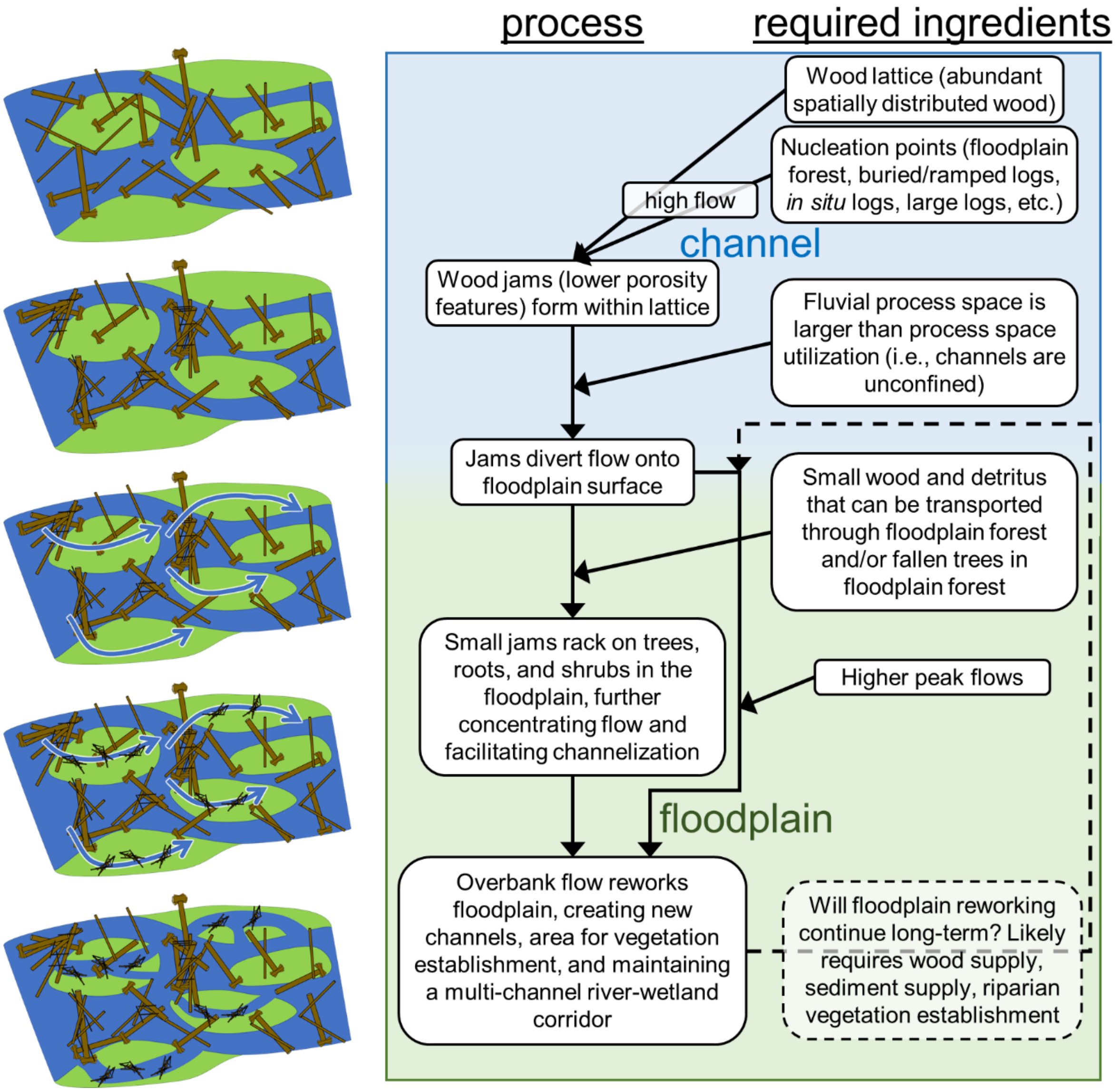

Figure 16: Conceptual diagram illustrating how wood rearrangement from a wood lattice into jams followed by small wood jam formation on floodplains leads to lateral connectivity and floodplain reworking.

4 Conclusions

A second, more intensive phase of wood placement and channel regrading along Deer Creek enabled wood rearrangement and jam formation that drove significant reworking of the channel bed and sufficient overbank flow to rework the floodplain. The fact that the floodplain inundated and changed much more in December 2020 than it did in the higher flow of April 2019 indicates that phase 2 restoration substantially increased lateral hydrologic and sediment connectivity. Even after the much lower winter flows in 2021/2022, new overbank and low flow channels formed in the Budworm reach, indicating that it maintained lateral connectivity at that lower flow. Although it is difficult to untangle the relative importance of regrading versus wood density and arrangement, the spatial correlation between wood jams and nascent channels as well as inferred morphologic change in floodplain channels themselves from smaller wood jams points to an important role for wood in regulating the occurrence and location of floodplain reworking, avulsion, and lateral sediment connectivity.

Wood rearrangement from a wood lattice (spatially distributed pieces) to an assemblage of discrete wood jams likely played a key role in backwatering and concentrating flow into floodplain forests as well as pool scour and bar deposition in existing channels. Such rearrangement was likely possible because of the high proportion of relatively stable logs (e.g., buried, racked on living trees, or ramped up on the valley wall) and patches of trees that could trap wood. Smaller wood interacting with the floodplain forest further concentrated flows, possibly enabling a greater degree of incision and channel development. These observations imply that a range of wood sizes, from large logs that can span the channel to small wood that can move through floodplain forests, is important for developing and maintaining lateral hydrologic and sediment connectivity.

More broadly, the lack of off-site wood mobilization and significant wood trapping on nucleation points throughout the treated sites raises the question of whether full wood mobility could occur in a system such as Deer Creek. Full mobilization of the placed wood downstream in a single large flood could present a significant hazard to infrastructure (De Cicco et al., 2018). However, the complex channel network and substantial interaction between wood and both valley walls and riparian forests could retain most wood on-site, even if much of it mobilizes and travels a short distance downstream. The substantial hazard posed by a full mobilization off-site and the tendency of restoration to Stage 0 projects to place wood lattices (Flitcroft et al., 2022) warrant further investigation of wood lattice mobility in heterogeneous, multi-channel systems.

From the perspective of implementing floodplain reconnection and restoration to Stage 0 projects, these findings imply that a substantial increase in in-channel roughness and regrading can be necessary to fully establish lateral hydrologic and sediment connectivity. These short-term findings show not only the importance of substantial wood placement, but also likely the effectiveness of the GGL method at evening out valley cross-sectional elevations (Powers et al., 2019). In addition to adding wood and regrading the valley bottom, it is likely that a mix of wood sizes and providing nucleation points (e.g., patches of remaining floodplain forest) both played important roles in driving geomorphically effective overbank flow and enabling scour and aggradation in the channel. These interventions enabled reworking of existing channels to create a more fragmented and heterogeneous channel bed and reworking of the floodplain to create a more heterogeneous valley bottom. The inundation and incision of terraces also expanded the overall fluvial process space in the valley bottom. These processes are all likely necessary to sustain a multi-thread river-wetland corridor.

By reducing the flow threshold required for those processes to activate, it stands to reason that this form of restoration has increased the likelihood of this condition sustaining itself for at least the period over which the placed wood will be geomorphically and hydraulically effective. This period may be up to multiple decades, assuming typical rates of decay and breakage for in-stream wood (Harmon et al., 1986; Hyatt & Naiman, 2001; Iroumé et al., 2017; Merten et al., 2013; Sass, 2009; Scherer, 2004). It also remains an open question whether the wood on-site will withstand a higher-magnitude peak flow or mobilize *en masse* downstream. Even if wood load and function decrease, riparian vegetation could continue to provide roughness and lateral connectivity, although it is unclear to what degree. Longer-term monitoring, especially reevaluations after higher flows, will be needed to evaluate those questions. For sites with a known lack of wood supply, adaptive management in the form of wood replacement, ideally coupled with long-term forest management to restore wood supply, may be necessary to sustain the wood-driven processes observed here.

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6 Data Availability

Data presented in this paper will be available via a public repository upon publication.

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