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RESEARCH ARTICLE

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Handheld lidar as a tool for characterizing wood-rich river corridors

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Abstract

Wood accumulations influence geomorphic, hydraulic, and ecologic functions within a river corridor, but characterizing these accumulations presents challenges across a range of field and remote sensing methodologies. We evaluate the ability of handheld lidar scanners, specifically lidar-scanning capabilities of a fourth-generation iPad Pro, to collect three-dimensional wood accumulation data, which can be used to inform measurements of wood volume, porosity, complexity, and roughness. We discuss the potential and limitations of this novel methodology for river research and management. We found that handheld lidar presents a cost-effective input for data-processing workflows that field measurements of wood accumulation dimensions cannot as easily replicate including (1) a user-friendly means of data collection and visualization; (2) accurate comparisons of wood volume over time; (3) integration into workflows to measure porosity parameters; and (4) potential use in informing hydraulic and morphodynamic models. Consideration of study area constraints and intended use of scans are prerequisites to using handheld lidar as an effective tool. We identified some specific limitations of using handheld lidar scanners in wood-rich river corridors, including (1) scanners perform poorly when wood is under water or surrounded by dense vegetation; (2) scanners require physical access to areas of interest at distances less than 5 m; (3) scans need to be manually georeferenced; and (4) scans require manual measurements for any dimensional data, which still have associated user time and error. Handheld lidar as a scientific tool is rapidly developing and there is substantial room for expansion of applications, utilization, and advances in the use of this tool in river research and management.

KEYWORDS
handheld lidar, large wood, river characterization, river restoration, technology-assisted fieldwork, wood volume

1 | INTRODUCTION

Characteristics of wood accumulations (e.g., porosity, volume, dimensions) influence the geomorphic, hydraulic, and ecologic functions that wood can provide within the river corridor. We refer to wood accumulations here as both natural and human-built wood structures (e.g., beaver dam analogues, post-assisted log structures [PALS]) ranging in size from small accumulations composed primarily of coarse organic material to logjams with at least three pieces of large wood (>10 cm in diameter and 1 m in length). As scientific understanding has increased around the benefits of wood in river corridors, so has the collection of data addressing wood accumulation characteristics (Gurnell et al., 2002; MacVicar et al., 2009; Spreitzer et al., 2019; Wohl et al., 2019). The volume of research addressing wood in river corridors has also emphasized the challenges associated with characterizing wood accumulations across a diverse set of methods (Livers et al., 2020; Wohl et al., 2019) and the lack of common metrics for wood accumulation characterization (Wohl et al., 2010). Quantitative measurements of wood accumulations are still severely limited at a field scale (Wohl & Scott, 2017) and associated with great uncertainties (Livers et al., 2020). These limitations are mainly related to difficulties in data acquisition, which commonly contain unintentionally influenced (e.g., human impaired) measurements (e.g., bulk volume), assumed parameters (e.g., density, porosity), or rough transect estimates that all influence the quality of gained results. The need for methods that can efficiently and effectively characterize wood accumulations is timely and important for understanding the characteristics that drive specific processes and mechanisms in river corridors, particularly as wood is increasingly used in restoration contexts.

We present a novel methodology for characterizing wood accumulations in the field using handheld lidar and discuss the potential and limitations of this methodology in river science and management. Lidar, or light detection and ranging, is a remote sensing method that uses a laser to measure distances to Earth's surface, returning three-dimensional information about the surface characteristics (Wandinger, 2005). Apple Inc. introduced a built-in infrared lidar sensor to iPad and iPhone Pro devices in 2020, providing a cost-effective and portable tool for characterizing objects and environments in three-dimensional space. We refer to the technology built-in to these devices as handheld lidar but specifically use a fourth-generation (2020) iPad Pro in this study. Multiple methodological reviews (Luetzenburg et al., 2021; Tavani et al., 2022) have investigated the technical capabilities, comparative outputs, and in situ usability of handheld lidar in various environmental science applications (see Section 1.2). However, no studies, to our knowledge, have assessed the capability of handheld lidar scanners to provide useful data in river corridors, and more specifically as a tool for characterizing wood accumulations in these environments.

We investigate whether this new tool has the potential to enable rapid collection of high-resolution spatial data for wood accumulations at low cost with respect to equipment and personnel time. Specifically, we ask what attributes of a wood accumulation can be characterized using handheld lidar scans and how can we use these scans to learn more about the biophysical context of a river corridor. We evaluate whether handheld lidar can serve as an effective approach for measuring wood accumulation dimensions and as input into workflows (Spreitzer et al., 2022) for calculating wood volume and porosity. We briefly review the existing methodologies used to characterize wood in river corridors and the current utilization of handheld lidar in environmental applications. We further discuss the applicability of handheld lidar for river science and management as well as directions for advances in the use of this tool to address some of its current limitations.

1.1 | Existing methods for characterizing wood-rich river corridors

Within the river research community, there is a growing set of field methods for characterizing wood accumulations within river corridors (Ruiz-Villanueva et al., 2016). Manners et al. (2007) systematically dismantled natural logjams to understand the relationship between jam composition and the hydraulics around the wood accumulation. Wohl et al. (2010) defined key wood features to measure in the field for understanding the size and characteristics of natural wood accumulations, the geomorphic features of the channel and valley, and the ecological characteristics of the riparian zone adjacent to the study channel reach. Scott et al. (2019) developed a reproducible field protocol (WooDDAM) to survey wood accumulation characteristics and dynamics. Livers et al. (2020) reviewed a suite of methods for measuring wood accumulation porosity and volumes and pointed to the difficulty in collecting and reproducing field measurements. Broadly, field methods rely on the ability to physically access a site, measure variables directly at a site, and typically repeat methods over multiple wood accumulations or multiple timescales, all of which can be prohibitive with the cost of equipment, time, labor, and reproducibility between people.

To supplement field methods used to characterize wood accumulations, remotely sensed imagery and topographic data are often used to extract physical and ecological attributes of a river corridor and to detect change over time. Existing remote sensing tools for collecting wood characteristic data include using airborne lidar (Abalharth et al., 2015; Atha & Dietrich, 2016; Dakin Kuiper et al., 2023; Ulloa et al., 2015), terrestrial laser scanning (Grigillo et al., 2015; Tonon et al., 2014), or structure-from-motion (SfM) photogrammetry using images collected from drones (Sanhueza et al., 2018; Spreitzer et al., 2022) or mounted cameras (Spreitzer et al., 2019, 2020). Spreitzer et al. (2022) used SfM photogrammetry to develop an empirical approach for the approximation of wood accumulation characteristics (porosity, volume, packing arrangement) without needing to know the solid wood volume. However, gaps in remote sensing data collection techniques remain for accurate non-intrusive methods to quantify wood accumulation characteristics. Much like field methods, remote sensing methods come with their own set of trade-offs in spatial and temporal resolution. Lidar can outweigh many technical limitations for quickly measuring high-resolution three-dimensional surfaces, but the necessary equipment is expensive, requires expert operator training, and is typically flown onboard an aircraft or large drone (Tavani et al., 2022; Westoby et al., 2018). Resolving high resolution, complex, three-dimensional surfaces is challenging and, consequently, methodological limitations restrict current abilities to routinely characterize large wood characteristics using remote sensing methods (Steeb et al., 2017; Thevenet et al., 1998).

1.2 | Current utilization of handheld lidar in the Earth sciences

Handheld lidar has been quickly adopted for scientific applications as a novel methodology that bridges gaps in field and remote sensing methods. Three years after Apple's first release of the handheld lidar scanner, science and engineering-based applications have emerged in the disciplines of forestry (Gollob et al., 2021; Tatsumi et al., 2023), civil engineering (Chase et al., 2022; Riquelme et al., 2021), and the geosciences (Alijani et al., 2022; King et al., 2022; Luetzenburg et al., 2021; Tavani et al., 2022; Table 1). Yet, to our knowledge, the use of handheld lidar to characterize large wood accumulations is still unexplored in the literature.

2 | METHODS

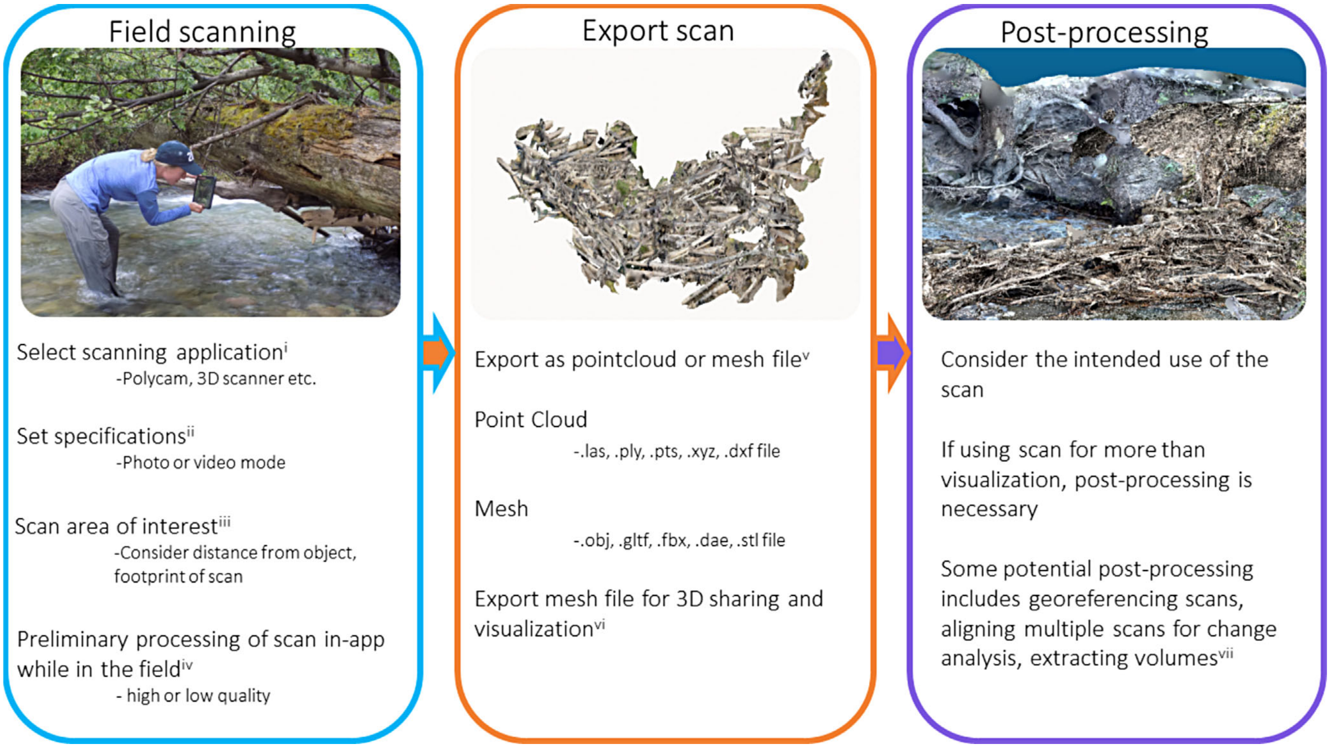
2.1 | Data collection

We selected 19 wood accumulations in five rivers and streams of the US Rocky Mountains for both manual field measurements and measurements extracted from handheld lidar scans. Our sites were selected based on ease of access, known wood accumulations, and locations of ongoing research. Wood accumulations varied in size, complexity, and type (natural vs. constructed; Supplemental Information). In Colorado, we collected scans at Elkhorn Creek (89 km^2 drainage area) and Little Beaver Creek (38 km^2 drainage area), both tributaries to the Cache La Poudre basin. In Montana, we collected scans at Lost Creek (85 km^2 drainage area) and Goat Creek (94 km^2 drainage area), both tributaries to the Swan River as well as the Swan itself (1676 km^2 drainage area). The watersheds of Little Beaver Creek and Elkhorn Creek were severely burned in 2021 following wildfire. The wood accumulations scanned at Little Beaver Creek represent locations where the wood accumulation remained intact but the characteristics of the accumulation changed substantially. The wood accumulations scanned along Elkhorn Creek are PALS that were constructed post-fire in the channel and floodplain as a restoration measure. All wood accumulations scanned for the Montana field sites are naturally occurring but range in size and complexity. The scan and field photos for each site are included as Supplemental Information.

We collected wood accumulation dimension measurements (length, width, and height) manually in the field using a hand tape, stadia rod, or Laser Technology TruPulse 360B laser rangefinder, depending on the size and access of the wood accumulation. We visually estimated porosity by evaluating the proportion of void space using the best-fit box method where wood accumulation volume is defined by a box or other simple geometric shape that best fits the accumulation but may not enclose all materials (Livers et al., 2020; Figure 1c). We acknowledge that field measurements can be both subjective and have associated error (Livers et al., 2020) and use this

TABLE 1 Current environmental applications using handheld lidar.

Source	Setting	Data acquired from handheld lidar scans	Functionality of handheld lidar scans
Alijani *et al.*, (2022)	Sandbed flume	Surface roughness	Surface roughness parameters measured from scans were comparable with more common approaches indicating that the resolution of handheld lidar was sufficient in this application
Gollob *et al.*, (2021)	Forest	Tree diameter measurements and spatial mapping of trees	Estimates of individual tree parameters were comparable between handheld lidar personal laser scanning (PLS). and manual methods. Time needed to use the handheld lidar for this application was longer than PLS but shorter than manual approach
King *et al.*, (2022)	Snow	Snow depth	Handheld lidar estimates and manual field measurements for snow depth was comparable with an absolute mean error of 2.5 cm between measurement methods
Luetzenburg *et al.*, (2021)	Coastal cliff	Cliff measurements	Comparable results between handheld lidar and traditional methods for surveying and reconstructing large cliffs (accuracy of 0.1 m). Concluded that the versatility of the tool outweighs the range of limitations
Riquelme *et al.*, (2021)	Rock slope	Orientation	Found optimal scan distance is less than 3 m for device to sufficiently detect rocky slopes
Tatsumi *et al.*, (2023)	Forest	Tree diameter measurements and spatial mapping of trees	Created a free mobile app that uses handheld lidar to survey forest inventory. Measurements were comparable to manual field methods and reduced the person-hours required
Tavani *et al.*, (2022)	Rock outcrop	Location, strike and dip, true bed thicknesses	Analyzed the performance of handheld lidar as a replacement for conventional geological instruments and concluded that while the performance of handheld lidar is acceptable for most field cases, the tool is most useful for more qualitative purposes without substantial additional post-processing



Field scanning

Select scanning application[i]
-Polycam, 3D scanner etc.

Set specifications[ii]
-Photo or video mode

Scan area of interest[iii]
-Consider distance from object, footprint of scan

Preliminary processing of scan in-app while in the field[iv]
- high or low quality

Export scan

Export as pointcloud or mesh file[v]

Point Cloud
-.las, .ply, .pts, .xyz, .dxf file

Mesh
-.obj, .gltf, .fbx, .dae, .stl file

Export mesh file for 3D sharing and visualization[vi]

Post-processing

Consider the intended use of the scan

If using scan for more than visualization, post-processing is necessary

Some potential post-processing includes georeferencing scans, aligning multiple scans for change analysis, extracting volumes[vii]

FIGURE 1 Workflow for using a handheld lidar scanner in the field and bringing scans from scanning device into post-processing software. For decision points in the workflow, we have underlined what we chose. For: (i) we use the Polycam app (Polycam Inc., 2023); (ii) we use video mode and maintain default specifications for maximum distance and scanning resolution; (iii) we make sure scan point can be safely accessed from multiple angles and break our scan into multiple parts using the "extend" option in Polycam if we are scanning a large area, making sure to have overlapping reference points; (iv) when possible, we process scans at high quality. High-quality processing changes add time and might not be feasible for the app if it is a large scan. It is possible to process a scan in the field (without data or WI-FI) and re-process it at a higher quality later. Workflow continues as (v) we use .las and .obj files in our processing. For Polycam, a paid Polycam Pro subscription is needed to download .obj and .las files, but the subscription is not needed to scan or share scans; (vi) we use Sketchfab (2023) for sharing and visualization of a 3D model; and (vii) we do all post-processing using open-source CloudCompare (2023). [Color figure can be viewed at wileyonlinelibrary.com]

as a relative comparison for resolving wood accumulation characteristics from scans rather than an absolute accuracy check.

We scanned each of our 19 wood accumulations in the field. Our process for collecting handheld lidar field scans is summarized in Figure 1 and described in the following steps:

2.1.1 | Field scanning and dimension measurements

Select scanning application

Scans were performed using the freely available *Polycam App in the iOS App Store (version 1.9.9) using iOS version 15.2*. We use Polycam, but numerous applications exist for lidar scanning (e.g., 3-D Scanner) that involve comparable workflow and considerations.

Set scanning specifications

We used the default scan setting in video mode with a maximum distance of 5 m between the scanner and area of interest. This activates the device's camera and lidar sensor, and the display shows the image in the camera overlain with a series of dots, which cover areas not yet scanned and stored in memory. In Polycam, this is the "mesh preview" and provides a helpful visual of what area has been scanned.

Scan area of interest

Point lidar scanning device toward area of interest and slowly start moving to capture the area from all angles. Moving the tablet around causes the dots in the "mesh preview" to disappear and they are replaced by a wireframe surface. It is important to move slowly and smoothly when collecting scans, otherwise the device's inertial measurement unit (IMU) positioning may become uncertain, leading to "drift" in the scan.

Preliminary processing

When the scan is complete, in-application processing produces a three-dimensional textured model viewable within Polycam. When scanning a larger area and using Polycam, the "extend" feature allows for multi-part scans. Basic data collection, such as measuring jam dimensions, can be done within the application without further post-processing.

Wood accumulation dimension measurements

We measured wood accumulation dimensions following preliminary in-app processing of the textured model using the ruler tool in Polycam. We relied on matching points between annotated field photos and scans for each site to ensure we were measuring from the same dimensional start and end points for length, width, and height in the scan and field.

2.2 | Post-processing and data analysis

Although 3D visualization may be sufficient for some purposes, exporting the scan-derived point clouds for post-processing greatly increases the utility of handheld lidar scans. We tested a few ways to export lidar scans and input them into post-processing workflows for further wood characterization. One aspect to note is that handheld lidar scans are exported from scanning applications without any real-world coordinate systems. The simplest way to project the scans into coordinates is by placing ground control points (GCPs) in the area prior to scanning. The location of the GCPs can be collected with real-time kinematic (RTK) survey equipment in addition to being captured in the scan. Both the surveyed GCP locations and the lidar scans can then be brought into post-processing software, such as CloudCompare, where the "Align" tool can be used to identify the targets in the point cloud, assign current satellite navigation (GNSS) coordinates, and compute a translation/rotation matrix, which is applied to the entire scan dataset. Even though there is not a need for the scan to be in real-world coordinates for many aspects of post-processing, such as comparative volumetric change, scanning points in the field that are not expected to change ensure that scans can be aligned for reproducibility and potential applications involving temporal change in wood accumulations.

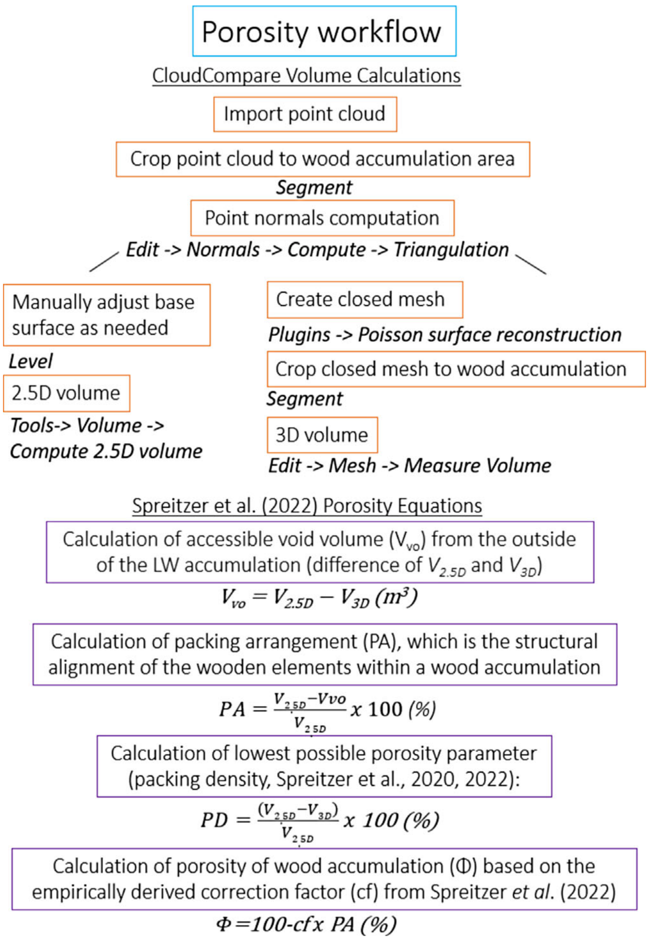


FIGURE 2 Workflow adapted from Spreitzer et al. (2022) for quantifying wood volumes and porosity from handheld lidar scans. In the step of the workflow, we used a conservative correction factor (cf = 0.5) for all wood accumulations based on results presented by Spreitzer et al. (2022) suggesting this correction factor as a better fit for the lower bound of the estimated porosity range. [Color figure can be viewed at wileyonlinelibrary.com]

We calculated volumes for each wood accumulation and compared volume calculations between the scan and the manual field measurements. For our field-derived wood volumes, we used the best-fit box method to compute wood volume from the field data using the length, width, height, and visual porosity estimates from field measurements (Dixon, 2016; Livers et al., 2020; Livers & Wohl, 2016; Scott & Wohl, 2018). We tested multiple ways of calculating volume using scan-derived point clouds and meshes. We first calculated volume using the aerial extent of the wood accumulation multiplied by the porosity estimated in the field (Livers et al., 2020). Aerial extent was measured directly in Polycam using the "area" tool, and field estimates of porosity were used. We used a simplified version of the Spreitzer et al. (2022) workflow to calculate approximate 2.5D and 3D volumes of each wood accumulation in CloudCompare (Figure 2). The 2.5D volume does not consider void space inside of wood accumulations and only accounts for a very limited amount of void space accessible from the surface (Spreitzer et al., 2020). We imported our handheld lidar point clouds into CloudCompare and isolated the points comprising the wood accumulation from background features using the "Segmentation" tool. After segmentation, we estimated point normals with respect to their surface position using triangulation for surface approximation. For 2.5D volume calculation, we used the built-in CloudCompare volume tool for each point cloud. We were only interested in the volume of wood above the base surface (i.e., the channel bed) and found that at times we needed to manually adjust the base surface using the "level" tool before calculating 2.5D volume. For 3D volume, we conducted surface meshing using Poisson surface reconstruction, keeping all parameters as default. Poisson surface reconstruction is robust to noise and used as a reliable surface reconstruction algorithm (Kazhdan & Hoppe, 2013; Spreitzer et al., 2020; Wolff et al., 2016). Following Poisson surface reconstruction, we calculated the volume of the mesh. This provided a closer approximation of 3D volume, but our decision to use a simplified rapid workflow excluded a step that completely closed the bottom of the mesh (Spreitzer et al., 2020) and thus limited the accuracy of this calculation. Once 2.5D and 3D volumes were calculated for each wood accumulation, we used the Spreitzer et al. (2022) workflow for calculating porosity parameters (Figure 2).

We used the dataset collected at our 19 wood accumulations (dimensions, porosities, and volumes) to compare handheld lidar scans to field measurements of the same wood accumulations. We calculated summary statistics of mean, median, variance, and standard deviation between field and scan measurements. We used Levene's test (1960) to determine whether field and scan measurements have equal variances. Given the non-normal distribution of the data, we used a Wilcoxon rank sum test (Wilcoxon, 1992) to assess whether there are comparable median dimension measurement values between the field and handheld lidar scans using R version 4.2.3 (R Core Team, 2023).

3 | RESULTS AND DISCUSSION

3.1 | Comparison of handheld lidar and manual field measurements

We investigated whether traditional field and handheld lidar scan measurements of dimensions, volumes, and porosities are comparable across a set of wood accumulations ranging in complexity of structure (Figure 3). All field and handheld lidar measurements are included as S1 in the Supplemental Information. We found no significant difference in medians or variance of wood accumulation measurements between field and lidar scans ($p = 0.90$ comparing medians and $p = 0.81$ comparing variances without porosity data included; $p = 0.29$ comparing medians and $p = 0.72$ comparing variances with all data included). This suggests that handheld lidar can effectively produce similar results as manual field measurements. We also compared summary statistics of scan and field measurements for constructed and natural wood accumulations to assess whether the structural complexity of an accumulation impacts the dimensional measurements of a scan (Table S2). We found that summary statistics were comparable regardless of whether the wood was constructed or accumulated naturally, but the variance in measurements for naturally occurring wood accumulations was higher than constructed wood accumulations. This suggests that the size and physical complexity of the wood accumulation did not affect the dimensional measurements within the Polycam application, although we expect that structural complexity has a greater impact on other potential applications, such as estimating porosity and incorporating wood characteristics into hydraulic and morphodynamic models. Although there was less variance in measurements for constructed wood accumulations between field and handheld lidar methods compared to measurements of natural wood accumulations, we suspect this was partly due to challenges in accurately measuring larger complex wood accumulation dimensions in the field and associated user error. The person collecting manual field measurements was periodically different than the person collecting lidar scans, which may have further caused differences in what we determined as the measuring extents, leading to greater variation between the two types of measurements. If conducting repeat scans, we recommend having clear right, left, upstream, and

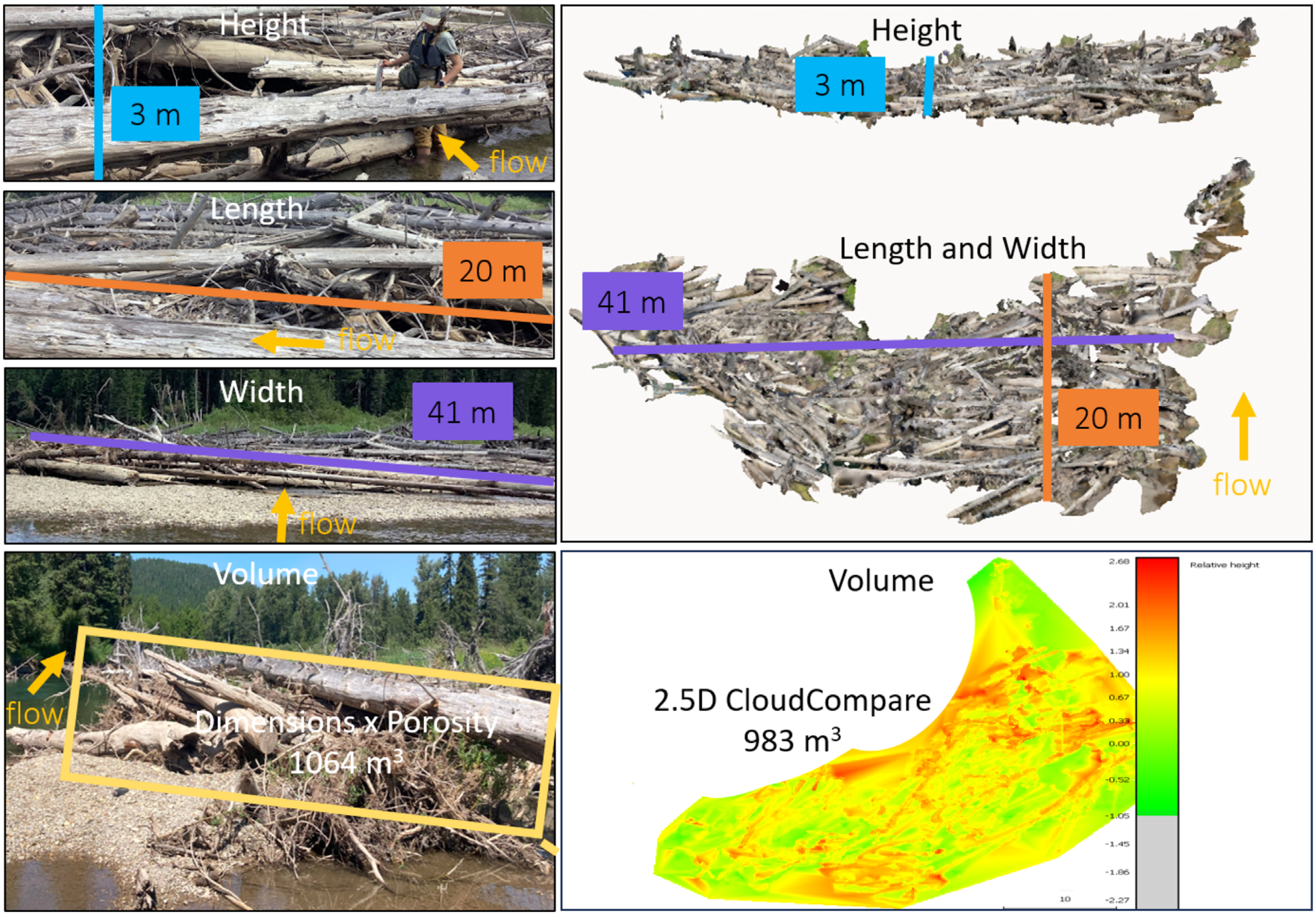


FIGURE 3 Comparing field and handheld lidar scan wood accumulation measurements for site Swan 6. [Color figure can be viewed at wileyonlinelibrary.com]

downstream points of measurements in the field to reduce human error in measurement comparisons from the scans.

For dimensional measurements, we saw the most variation between field and scan values when measuring height (Figure 3). In the field, we measured wood accumulation height from bed surface to top of wood accumulation, which included the submerged portion of the jam. With the scans, measuring the submerged portion of the wood accumulation was not feasible. All our accumulations were at least partly submerged, but we intentionally collected our scans at low flow when, on average, at least 70% of the jam height was above the water surface. Another point to note here is that some of the laser pulses do penetrate water even with the infrared sensor, and this was more common at our study sites where the water is very clear. Thus, in most of our scans, we can see through the water to detect wood but are still not able to easily include any wood below the water surface in the height measurements. The impact of water stage on scans is important to consider when using this methodology and, to the extent possible, conducting scans at low flows maximizes the volume of the wood accumulation visible above the water surface. We did not use a water-resistant device to scan accumulations in the field and did not explore whether such a feature might allow for some of the laser pulses emitted by the scanner to penetrate water if the device is submerged at a close range to the wood accumulation.

We adapted a workflow from Spreitzer et al. (2022) to calculate volumes from handheld lidar scans. It is important to note that our simplification of steps to compute volumes was at the expense of more accurate volumetric measurements. Our volumetric calculations were intentionally approximate because we were interested in knowing what was feasible with a simplified workflow using a single open-source software platform. Our approach allowed for a rapid assessment of wood volumes and porosities but we encourage users to consider the intended use of volumetric measurements and use the full workflow outlined in Spreitzer et al. (2022) for more accurate volumetric measurements. Not surprisingly, volume has greater variation between field and scan methods relative to our dimensional measurements (Figure 4). Field volumes were calculated with best-fit boxes and tended to overestimate the wood accumulation volumes, consistent with the findings of Livers et al. (2020). Determining the spatial boundaries of the best-fit box (e.g., average vs. maximum length, width, and height of the wood accumulation) or other shape can vary from person to person in the field, and reproducibility of this method is thus challenging (Scott et al., 2019). We used a visual estimate of porosity with our field volume calculation, which further adds to the subjectivity and potential sources of error. Our calculated 3D volumes typically corresponded with the lowest volumetric values of our approaches. We expect that this was an underestimate of volume because of our simplified workflow and subjectivity in closing the mesh bottom. Nonetheless, volume calculations across our 10 smallest wood accumulation were closely clustered around the mean for volume measurements across methods (Table 2). We see the largest

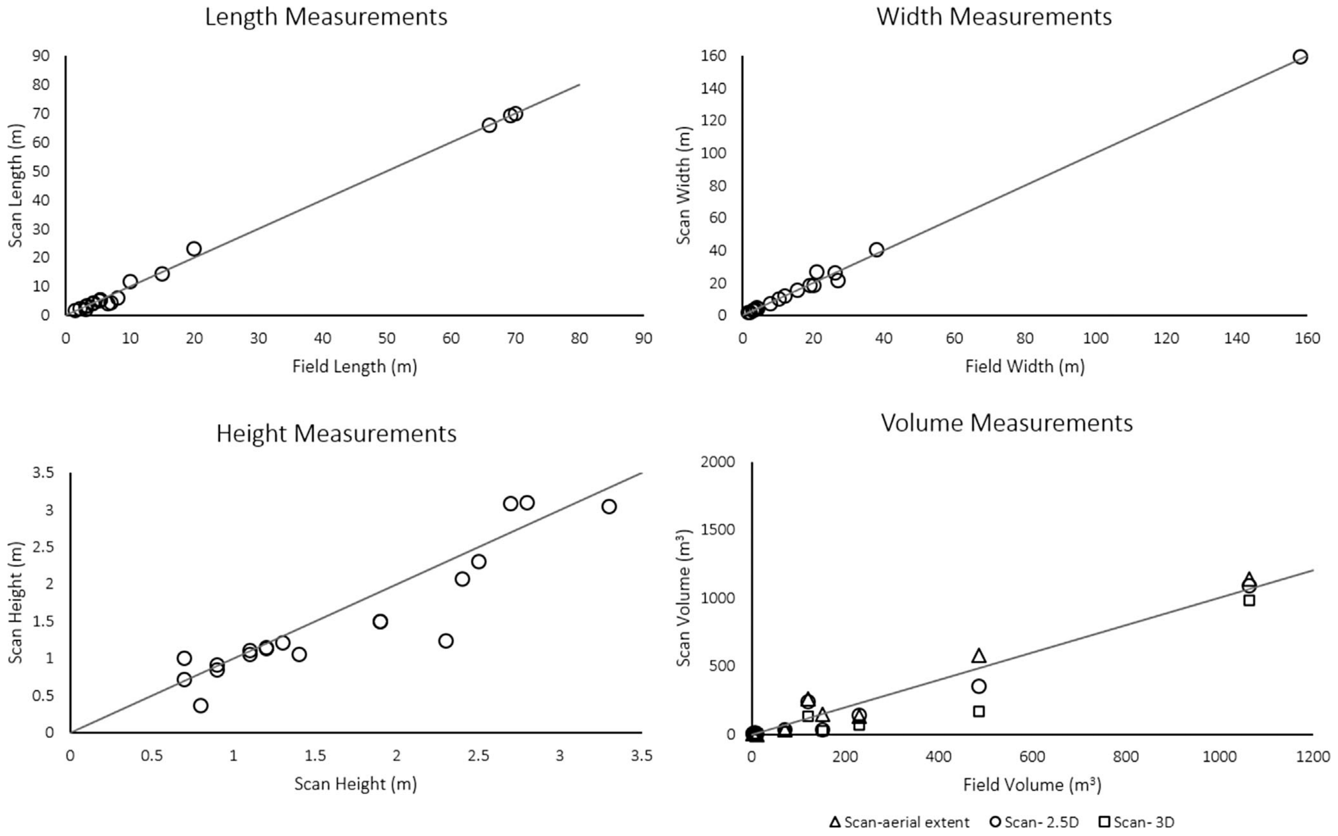


FIGURE 4 Comparison of field measurements to scan measurements for dimensions and volumes. Plots fit with a 1:1 line.

TABLE 2 Summary statistics of volumes (m^3) at each wood accumulation site across volume calculation methods (field bounding box, aerial volume, 2.5D volume, 3D volume).

Site	Type	Mean	Median	Variance	Standard Deviation
Lost 1	Natural	6.0	6.0	1.9	1.4
Lost 2	Natural	376.3	353.3	26039.5	161.4
Goat 1	Natural	141.3	136.1	3342.1	57.8
Goat 2	Natural	39.0	32.9	378.9	19.5
Swan 1	Natural	1821.3	1780.8	153652.8	392.0
Swan 2	Natural	1096.8	845.5	320892.7	566.5
Swan 3	Natural	78.9	37.9	4079.8	63.9
Swan 4	Natural	174.3	133.6	4700.3	68.6
Swan 5	Natural	8139.6	6442.5	14224832.3	3771.6
Swan 6	Natural	1067.8	1064.0	3231.6	56.8
LBC 3	Natural	7.6	6.4	5.3	2.3
LBC 4	Natural	5.8	6.6	6.9	2.6
Elkhorn 1	Constructed	2.0	2.5	1.3	1.1
Elkhorn 2	Constructed	2.3	2.1	1.6	1.3
Elkhorn 3	Constructed	7.0	6.6	5.7	2.4
Elkhorn 4	Constructed	3.5	3.4	1.3	1.1
Elkhorn 5	Constructed	3.5	1.8	17.6	4.2
Elkhorn 6	Constructed	4.3	5.4	7.4	2.7
Elkhorn 7	Constructed	4.3	3.1	7.5	2.7

variation in volume measurements at the largest wood accumulations, which is reasonable given the potential for increased user error in field measurements and greater complexity in the case of our sites (Table 2).

We tested whether handheld lidar scans can be used to calculate porosity without visual estimates and prior knowledge of solid wood volume using a workflow adapted from Spreitzer et al. (2022). Our results suggest that 2.5D and 3D volumes calculated from handheld lidar scans can be integrated into the approach developed by Spreitzer et al. (2022) and used to estimate upper and lower bounds of a porosity estimate. Spreitzer et al. (2022) used field measurements of volumes (i.e., wood accumulations chipped and measured in cubic meters) to calibrate a correction factor based on the structural alignment of the wooden deposit that translated their SfM-derived volumes to porosity. We did not go through the process of developing a correction factor for our wood accumulations and instead used the recommended conservative correction factor ($cf = 0.5$) for all wood accumulations. Our calculated porosity range was further impacted by our simplified workflow for 2.5D and 3D volumes, which likely contributed to the large range of calculated porosity values (Figure 5). However, for most wood accumulations, our field estimate fell within or close to the calculated range of porosities (<10% porosity difference between field estimates and calculated porosities). Porosity can be variable throughout wood accumulations and is a highly subjective field measurement (Livers et al., 2020). Thus, we find producing an upper and lower limit of porosity a beneficial way to represent the porosity of a wood accumulation.

3.2 | Potential and limitations of handheld lidar to characterize wood-rich corridors

Handheld lidar scanning, like any tool or methodology, comes with its own set of benefits and limitations. Handheld lidar is capable of realistically representing environments at >10 cm (Luetzenburg et al., 2021; Tavani et al., 2022), which makes it useful for resolving detailed characteristics of wood accumulations. The portability, equipment costs relative to most terrestrial lidar scanners of drone-based SfM, and ability to bring the output of a handheld lidar scan (raw point cloud and mesh) into existing workflows for quantifying wood accumulation characteristics, allows handheld lidar scanners to stand out as a tool. We find the greatest potential of the device is in the simple workflow for data collection, ability to quickly determine aerial extent (footprint) of wood accumulations, ease of comparisons of wood volume over time, and ability to feed these data into existing workflows to measure porosity, precise volumes, and potentially to inform hydraulic and numerical models.

Handheld lidar scanning is not without its limitations, and we found the need to manually measure dimensions (still subject to user error) and the need for post-processing to obtain a fully georeferenced model limitations to the tool's efficacy. When using the device in the field, we found that the handheld lidar scanners performed poorly when wood was under water and dense vegetation. This is consistent with most remote sensing tools (Abalharth et al., 2015). The specifications and performance of handheld lidar are not equivalent to survey-grade lidar tools in terms of maximum operational

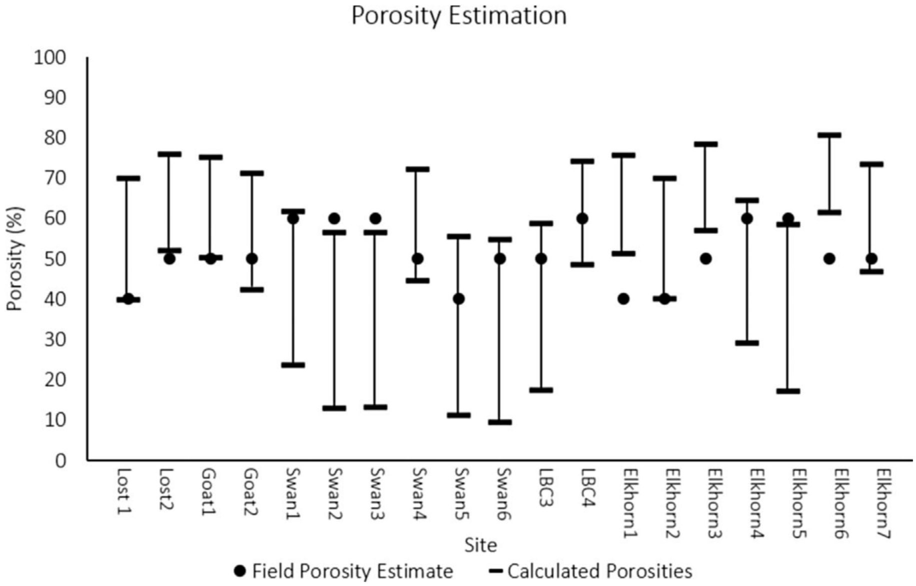


FIGURE 5 Porosity estimates for all wood accumulations. Visual field estimates are shown as single points while calculated porosities from scans are shown as a line with upper and lower bounds determined by ϕ and PD values.

range (presently <5 m) or noise characteristics (Tavani et al., 2022). Scans best represented the area of interest when we were able to capture the area from the most angles and the closest distance possible. This meant being able to physically access the area of interest at a distance closer than 5 m and often needing to climb on top of a wood accumulation to get a detailed scan. We did not attempt to use a pole-mounted device given the size of our scanner (a 12.9-inch iPad). Luetzenburg et al. (2021) mounted an Apple iPhone 12 Pro on a 1.5 m long selfie stick when scanning a cliff face and found that increases the extend of the model considerably, especially vertically along the cliff face. The utilization of a selfie stick is one simple solution to partly overcome the limitations in range. In cases where wood accumulations are unsafe to access or be near, handheld lidar scanning is not a feasible methodology.

Given that handheld lidar scans are not georeferenced, we found that using GCPs (targets or fixed points in the field) was an easy way to align multiple scans for comparison, repeat scans, and georeference scans using RTK survey instrumentation. Alternatively, point-pair-picking between models provided another method for aligning multiple scans for comparison that did not need to be georeferenced. The time needed to collect a handheld lidar scan ranged from approximately 5 min for a simple wood accumulation (e.g., Elkhorn 1–7) and 10 min for a small, but complex wood accumulation (e.g., Lost 1) to 1 h for a large wood raft (e.g., Swan 5). Any scan more than ~10 min in duration included too much data for our device and Polycam to process. This could be remedied by creating a multipart scan using the "extend" feature in Polycam. The time needed to scan a wood accumulation for the sole purpose of dimensions is not a cost savings relative to manual field measurements. However, the cost–benefit of handheld lidar outperforms many traditional field and remote sensing methods in the additional information one can easily glean from a scan through input into existing workflows quantifying wood accumulation characteristics such as volume and porosity (Spreitzer et al., 2022).

Our assessment of the potential and limitations of handheld lidar aligns with conclusions drawn by other studies. Luetzenburg et al. (2021) investigated the basic technical capabilities of handheld lidar and found that the versatility of the tool outweighs the range of limitations, making handheld lidar a cost-effective alternative to established techniques in remote sensing with possible uses for a wide range of Earth science disciplines. Tavani et al. (2022) analyzed the performance of handheld lidar in geosciences-related applications as a replacement for conventional geological instruments and concluded that, although the performance of handheld lidar is acceptable for most field cases, the tool is most useful for more qualitative purposes without substantial additional post-processing. However, handheld lidar applications are still relatively untested and there may be many opportunities to use the technology in natural sciences and engineering and more specifically in river research and applications.

3.3 | Applications for handheld lidar in wood-rich river corridors

We envision numerous potential applications and advances to the use of this tool for both research and management in wood-rich river corridors. For researchers, a detailed mechanistic understanding of wood accumulations is commonly constrained by the time needed to characterize wood accumulations in the field. Collecting scans of wood accumulations using handheld lidar provides the opportunity to bring detailed three-dimensional visualization of those accumulations out of the field. We found that scans can be easily imported into CloudCompare for simple analyses including georeferencing scans, aligning multiple scans for comparison, and volumetric comparisons of wood accumulations (Figure 6). The basic method of wood volume calculation performed in this study suggests that handheld lidar could be useful to monitor changes in natural wood accumulations and provide insight into our limited understanding of how wood accumulations evolve over time.

Handheld lidar offers a straightforward processing pipeline for high-resolution point clouds and meshes. Outputs from handheld lidar

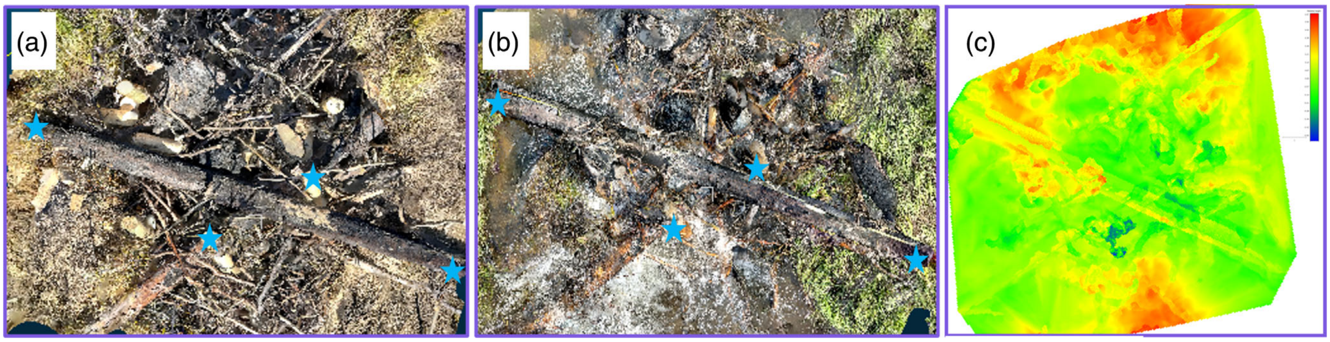


FIGURE 6 Example application of scans brought into CloudCompare for post-processing. In (a) and (b), we align scans of wood structures used in a restoration project before and after the snowmelt runoff (October 2022 and June 2023) to assess volumetric wood change. The blue stars represent the same points in the wood accumulation scanned on two different dates for analysis of change in volume. In (c), we conduct a volumetric comparison between (a) and (b) to observe how the volume of wood has changed with time. [Color figure can be viewed at wileyonlinelibrary.com]

scans can be input into existing workflows (Spreitzer et al., 2022) for computing 2.5D and 3D wood volumes and subsequent porosity parameters. This method reduces some of the human-introduced errors that accompany visual field estimates and provides higher credibility for computed results via a range of porosity parameters (Spreitzer et al., 2022).

For resource managers and river restoration practitioners, the availability and straightforward use of devices with built-in scanners introduces handheld lidar as a tool that can be used by communities and citizen science programs to monitor environmental change with unprecedented ease. One example where we anticipate this success is using handheld lidar scanners to monitor changes in area or volume of constructed wood accumulations, such as beaver dam analogues or PALS. Handheld lidar becomes an increasingly useful tool with the growing use of wood structures for process-based river restoration (Wheaton et al., 2019). Knowledge about volumetric measures and porosity parameters of wood accumulations is crucial for the prediction of hydraulic and geomorphic effects but, at present, our limited understanding of how wood accumulation characteristics relate to specific desired effects constrains our ability to evaluate whether constructed wood accumulations have comparable effects to natural wood accumulations. Part of this limited understanding comes from the challenges associated with collecting such data. Future work is needed to explore the ability to use scans in three-dimensional hydraulic and morphodynamic models. We expect that the ability to do this will provide enhanced detail in quantifying complexity and roughness in modeling space.

4 | CONCLUSIONS

We tested the ability of handheld lidar scans to capture the three-dimensional characteristics of wood accumulations efficiently and effectively in wood-rich river corridors. The methods presented to support a broad characterization of wood accumulations, remove some, but not all, of the subjectivity of manual field measurements, and provide a potential launching point for continued applications and inquiry utilizing handheld lidar in river corridors. We found that handheld lidar scans produce similar dimension, volume, and porosity measurements as traditional field measurements and can be a useful tool for rapid assessment of wood accumulations at a field scale. Handheld lidar scans have both potential and limitations as a tool for characterizing wood accumulations and consideration of study area constraints and intended use of scans is a prerequisite to using handheld lidar as an effective tool. Handheld lidar scans introduce opportunities for further quantitative analysis of wood accumulation characteristics that traditional field or remote sensing measurements cannot provide for the same cost–benefit. The scanners have a simple workflow for visualization and provide a user-friendly means of data collection. Outputs from the scans (point clouds, meshes) allow for accurate comparisons of wood volume over time, the ability to feed these data into existing workflows to measure porosity, and maybe even use these data to inform modeling approaches. When focusing on characterizing wood-rich river corridors, we also identified multiple limitations of handheld lidar. First, the scanner performs poorly when wood is under water or dense vegetation. Second, scans require physical access to the area of interest at less than 5 m and this limitation in range reduces the field of applications to close range and small- to medium-scale study sites. Third, the process is limited to scanning a small area of interest or multipart scans of a larger area due to file size limits for in-application processing. Fourth, dimensional characteristics still need to be manually calculated from the scan. Although handheld lidar can accurately replicate length, width, and height measurements of wood accumulations, dimensional measurements take longer than the traditional field methods, so time is not always saved on quantitatively characterizing wood accumulations using this method compared to directly in the field. One improvement to this feature would be if dimensions could be digitally calculated for an average. There is substantial room for expansion of applications, utilization, and advances to the use of this tool in river research and management and we call on both scientists and managers to contribute to an expected growing body of literature and practice that utilizes handheld lidar scans to characterize wood in rivers.

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DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, and further inquiries can be directed to the corresponding author.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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