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Characterizing streams and riparian areas with airborne laser scanning data

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ABSTRACT

The established position and increasing availability of Airborne Laser Scanning (ALS) as an important source of information including forest inventory, allows additional applications to be developed when such data are already available. One key focus area for the application of ALS data is the assessment of riparian ecosystems, due to their critical role for providing, regulating and supporting important ecosystem services. ALS data provide detailed and accurate digital terrain models (DTMs) under forest canopy, which in turn enable the characterization of detailed stream networks, stream properties, and associated vegetation characteristics in adjacent riparian ecotones. In a complex Pacific Northwest coastal forest, we demonstrate how ALS point clouds can be used to map a stream network and characterize stream properties including stream order, width, gradient, sinuosity, and solar shading. Of relevance to regulatory and sustainability related elements of forest management, we demonstrate the use of these data to identify stream classes and related riparian zones, as well as the fish-bearing potential of the stream. The total length of identified streams was 6421.8 km, of which 55% were of the lowest order streams. The median stream gradient was 16.4% with median stream width varying between 0.58 and 19.67 m for the smallest to largest streams respectively. Stream class and fish bearing potential were evaluated using independent data, with overall accuracies of 61.0% for stream class and 82.9% for fish-bearing potential. The median of stand height, canopy cover, and stand vertical variability within riparian management areas was 19.8 m, 88.6%, and 68%, respectively, and in general did not vary across stream orders. The majority of streams (74.4%) were not accessible for anadromous fish. For fish-bearing streams, we found that only 0.2% had a mean stand height < 2 m, while 2.4% had canopy cover of < 20%, and only 7.3% received < 10 h of shade. The ALS data thus enabled a holistic characterization of riparian ecotones, providing useful information on both stream and vegetation properties that can support sustainable forest management, inform on erosion risk, and become a foundation for the quantification of ecosystem goods and services.

1. Introduction

In recent years, Airborne Laser Scanning (ALS) data has become increasingly commonplace in supporting the development of forest inventories and guiding forest operations (Næsset, 2002; White et al., 2013; Woods et al., 2011; Wulder et al., 2013). ALS-based approaches have delivered accurate wall-to-wall predictions of forest stand inventory attributes including height, canopy cover, diameter, biomass, and volume (Evans et al., 2006; Lim et al., 2003; Reutebuch et al., 2005; Wulder et al., 2012). With the operational adoption of ALS technology for forest inventory (Næsset, 2014), the potential to provide additional insights into other forest and vegetation-related attributes not directly associated with forest inventories are increasingly being examined (Coops et al., 2016; Davies and Asner, 2014; Lang et al., 2012; Saarinen et al., 2015; Tattoni et al., 2012). This additional information can support sustainable forest management, protection of endangered species or vulnerable habitats, and can also inform on various forest related ecosystem services.

One key focus area for the application of ALS data is the assessment of riparian ecosystems. Riparian zones, defined as transition areas regularly influenced by fresh water, refer to biotic communities located at the banks of streams and lakes (Naiman and Decamps, 1997). These transition zones serve critical roles in providing, regulating, and supporting important ecosystem services. They act to stabilize stream banks, filter pollutants, serve as wildlife habitat, and mitigate stream flow (Naiman et al., 1993; Perry et al., 1999). By providing shade, they regulate stream water temperature (Davies-Colley and Rutherford, 2005), which is an important habitability factor for fish, including anadromous salmonids (Larson and Larson, 1996). Due to the narrow and fragmented nature of riparian forests, these important ecosystems are prone to a number of disturbances that can easily degrade their

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ecological function. In order to conserve the structure and ecological integrity of riparian ecosystems, specific silvicultural practices, management routines, and policies have been established (Ministry of Forests Lands and Natural Resource Operations, 1995; Tschaplinski and Pike, 2010).

Traditionally, stream and riparian vegetation have been described by a number of attributes grouped into several categories (Pike et al., 2010). These attributes, summarized in Table 1, are related to water channel and riparian vegetation characteristics including stream dimensions and shape, water properties, occurrence and habitat of water organisms, and characteristics of stream bank vegetation. Conventionally, a combination of stream sampling, water gauges, and aerial interpretation has been used to map these stream attributes, providing valuable data to both forest managers and regulators on the condition and habitat condition of these riparian ecotones. As is evident from Table 1, ALS data has demonstrated capacity for characterizing a number of these critical riparian attributes. First, ALS data enables the generation of accurate digital terrain models (DTMs), even under forest canopy (Reutebuch et al., 2003). These ALS derived models have been shown to be highly accurate both in horizontal and vertical dimensions, even under dense canopy cover conditions (Bater and Coops, 2009; Reutebuch et al., 2003; Su and Bork, 2006). The detailed gridded elevation data can be used to delineate stream networks and calculate stream flow direction and accumulation (Hohenthal et al., 2011; Notebaert et al., 2009). The accuracy of the derived stream networks, as well as the level of detail, rely directly on the quality of the DTM (Goulden et al., 2014; Murphy et al., 2008).

Existing studies have demonstrated that ALS data can be successfully used to characterize stream order and magnitude (James et al., 2007), gradient (Cavalli et al., 2008; Vianello et al., 2009), width (Biron et al.,

Table 1
Selected stream attributes, their description and the capacity of ALS data to characterize them.

Stream attribute	Description	Capacity of ALS to estimate attribute	Supporting references/comments
Related to stream dimensions, shape, location			
Order and magnitude	Property of stream network that describes the relative position of a stream segment. Stream network starts with the first order streams, which are the smallest and do not have tributaries. When two first order streams join, a second order stream is created.	High	(Goetz, 2006; James et al., 2007)
Gradient	Measured with a clinometer on a representative stream part of at least 100 m. Stream gradient is important as it is a useful guide to determine potential fish occurrence. In the absence of any fish inventory data, all streams with gradient of <20% are considered fish streams.	High	(Cavalli et al., 2008; Vianello et al., 2009)
Width	Stream width is determined based on normal, undisturbed channel width, as a horizontal distance between the tops of the stream banks. Average width is calculated from six width measurements within a homogenous part of a stream.	Moderate	(Biron et al., 2013; Johansen et al., 2010, 2011; Michez et al., 2013)
Class	Stream class determines the minimum RMA width. Six stream classes (S1 to S6, Table 2). Classification is based on two main criteria: presence of fish, and average channel width. In some cases a third criterion is used – occurrence in a community watershed.	Moderate	Can be derived based on width and gradient
Channel components and morphology	Components such as pools, riffles, steps, cascades or plane beds can be distinguished in different parts of stream channels. They are important for many organisms as they provide different habitat characteristics (different water flow velocity, different water depth). They also define stream morphology type (i.e. step-pool or riffle-pool)	Moderate	(Cavalli et al., 2008)
Sinuosity	The ratio between channel length and a straight distance between channel beginning and end.	High	(McKean et al., 2009)
Bank stability	Informs on possible erosion risk and sediment deposition	Moderate	(Johansen et al., 2013)
Related to water			
Water level, streamflow	Informs on the hydrological processes upstream. Is important for channel stability, sediment transport, and ecological function.	Low-moderate (requires bathymetric sensor)	(Hohenthal et al., 2011; Legleiter, 2012; McKean et al., 2009)
Water quality	Chemical, physical, and biological properties of water. Water quality is affected by tree cover, which provides shade and therefore influences water temperature. Trees are also a source of organic matter.	None	–
Sediment content	Content of particles <0.1 mm in diameter: clay, silt and fine sand.	None	–
Water temperature	Controls and influences many aspects of stream ecology. Temperature increase caused by removal of forest canopy has a negative effect on cold-water species such as salmonids	Low	Only indirectly, by characterizing incoming solar radiations or shading
Presence of fish, species, abundance	Fish (typically salmonids), are sampled to provide biological measure of the status of the ecosystem.	Moderate	Only indirectly, by linking with stream gradient
Wood, large woody debris	Functions as geomorphic structure, place of interception of the organic matter, as cover for fish and other water organisms, and as a substrate.	Moderate	(Riedler et al., 2015; Scheidl et al., 2008)
Related to riparian vegetation			
Tree species; stand type	Different tree species have different rooting characteristics and therefore provide different bank stability.	Low	(Michez et al., 2013)
Canopy cover (and Vegetation overhang)	Canopy cover determines the amount of shade that is cast on a stream	High	(Johansen et al., 2010, 2011; Michez et al., 2013; Riedler et al., 2015)
Stand dimensions and structure	Larger trees provide greater bank stability; stream shading depends on the dimension and structure of the riparian stand	High	(Michez et al., 2013; Riedler et al., 2015; Wasser et al., 2015, 2013)
Longitudinal continuity	Extent of a stream Function as corridors for plant dispersal	High	(Johansen et al., 2010; Michez et al., 2013)
Bank stability	Stream channels are stabilized by the vegetation growing along the riparian area. Roots increase soil stability, large trees can stop wood transported during floods.	Low	Indirectly, by relating to detected vegetation
Shading	Riparian vegetation influences water temperature by absorbing and reflecting incoming solar radiation.	High	(Greenberg et al., 2012)

Based on: (Goetz, 2006; Hohenthal et al., 2011; Ministry of Forest Lands and Natural Resource Operations, 2014; Pike et al., 2010). Threshold values and classification systems indicated may be specific to the Province of British Columbia, Canada only.

2013; Johansen et al., 2010, 2011; Michez et al., 2013), sinuosity, and channel morphology (Cavalli et al., 2008). ALS data also allow characterization of riparian vegetation including canopy cover, height, longitudinal continuity, horizontal and vertical structure, and stand type (deciduous/conifer) (Goetz, 2006; Johansen et al., 2010; Michez et al., 2013; Riedler et al., 2015; Wasser et al., 2013). Bank stability can be inferred based on tree size (larger trees can stop woody debris transported during increased water discharge) and stand type, as deciduous tree species provide more support for stream banks (Michez et al., 2013). Finally, shade cast by vegetation as a modifier of stream water temperature can be characterized by modelling shade or incoming solar radiation (Bode et al., 2014; Greenberg et al., 2012; Lee et al., 2009; Mücke and Hollaus, 2011).

ALS data is largely limited to those physical aspects of riparian ecosystems that do not require direct measurement. Many stream-level measurements including chemical composition, pH, sediment content, and temperature, are based on manual field measurements, which ALS sensors are not suitable, nor designed, to collect. There are however some aspects of stream water properties, like water level, that can be mapped using bathymetric lidar (Hohenthal et al., 2011; Legleiter, 2012; McKean et al., 2009). Other stream attributes can be characterized indirectly. For example, fish presence in streams is largely depends on topographical factors such as gradient, which can be determined using ALS data (Cavalli et al., 2008; McKean et al., 2009; Vianello et al., 2009).

Once collected, information on riparian ecotones is important for determining an appropriate riparian management area (RMA). In British Columbia, Canada, RMA classification systems are applied based on stream width and fish presence (Pike et al., 2010). RMA class determines forest management options within a given proximity of streams, and the British Columbia stream classification system (Table 2) (Ministry of Forest Lands and Natural Resource Operations, 2014) consists of six classes, with class S1 indicating large rivers, and class S6 indicating small streams with no fish presence. Although the presented classification system is specific to British Columbia, other locations of the Pacific Northwest apply systems that in many cases also require information on fish presence and stream size (Pike et al., 2010). Forest operations are therefore largely influenced by the presence of stream channels. The width of riparian management areas are defined in relation to the stream class, with higher order streams having wider riparian management areas (Table 2, Fig. 1). Within these broadly defined RMAs are specific riparian management zones and riparian reserve zones. A riparian reserve zone (RRZ) is established to protect fish, wildlife habitat, biodiversity value and water values, while a riparian management zone (RMZ) is established to conserve fish, wildlife habitat, biodiversity value and water values, and serves to protect the RRZ (Fig. 1). Generally, these zones imply restrictions on forest management practices. For example, roads typically cannot be constructed within RMAs and harvesting is generally prohibited within RRZs. Harvesting is permitted within RMZs, but a certain proportion of basal area must be maintained (e.g., 10–20%), depending on stream class. Existing studies that apply ALS data to describe riparian areas mainly focus on large streams or subsets of stream networks (Johansen et al., 2010, 2011; Michez et al., 2013; Wasser et al., 2013). It is noted that the inclusion of small streams is vitally important as they are a major contributor of water resources to lowland river networks and can be nesting grounds for anadromous fish (Allan and Castillo, 2007; Pike et al., 2010). Stream networks can be defined using digital terrain models (DTMs) derived photogrammetrically (Walker and Willgoose, 1999), with the scale of the photography limiting the spatial resolution of the DTM (Fisher and Tate, 2006). Small streams can be challenging to identify from coarse DTMs, particularly under dense forest canopy, as a function of both the spatial resolution and the inability to acquire ground observations under canopy.

The literature cited above confirms that large area riparian assessments performed using ALS data can provide a complementary technology to delineate and characterize riparian ecotones. A consideration of these analyses however is that they have been applied in disparate locations, and are not linked to an existing RMA system. Moreover, they have examined individual riparian attributes in general, rather than providing a more holistic characterization of riparian ecosystems. Further, these studies did not relate the extracted riparian characteristics to the implications for forest management. In this paper, our objective is to demonstrate how ALS data can be used to inform sustainable forest management, by characterizing streams and riparian zones in a complex Pacific Northwest coastal forest. The presented methodology describes the assessment of both stream and riparian vegetation conditions and therefore provides comprehensive information on the riparian ecosystem including potential fish occurrence, stream width, stream class, gradient, and shading characteristics. To do so, we first utilize ALS data to detect and describe streams with the identified characteristics. ALS data is then used to describe height, canopy cover, and vertical structure of surrounding riparian vegetation. By simulating sun position we calculate the total number of shaded hours a portion of stream receives. We conclude by discussing how the extracted attributes can be used to describe the provision and regulation of ecosystem services related to riparian areas and support sustainable forest management.

Table 2
Stream classification and riparian management area width (Pike et al., 2010, simplified).

Stream class	Fish occurrence	Average channel width [m]	Riparian reserve zone (RRZ) width [m]	Riparian management zone (RMZ) width [m]	Total width of riparian management area (RMA) [m]
S1[a]	Yes	>20	50	20	70
S2	Yes	>5; ≤20	30	20	50
S3	Yes	>1.5; ≤5	20	20	40
S4	Yes	<1.5	0	30	30
S5	No	>3	0	30	30
S6	No	≤3	0	20	20

[a] Class S1 can be further divided into S1-A and S1-B. Class S1-A represents large rivers, with average channel width over 100 m for >1 km of stream length. Since no large rivers are located in the study area, class S1 is limited to the specification of S1-B only.

2. Methods

2.1. Study area

The study area is located on northern Vancouver Island, British Columbia, Canada and is approximately 52,000 ha in size (Fig. 2). Located within the Coastal Western Hemlock biogeoclimatic zone (CWH), the

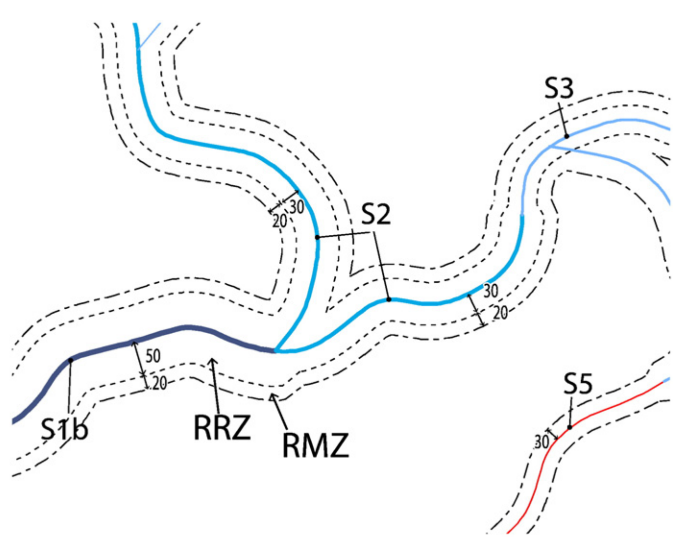

Fig. 1. A portion of stream network with Riparian Reserve Zone (RRZ) and Riparian Management Zone (RMZ) indicated with dashed lines. The width of RRZ and RMZ depends on stream class (here: S1b, S2, S3, S5). Together, RRZ and RMZ form Riparian Management Area (RMA)

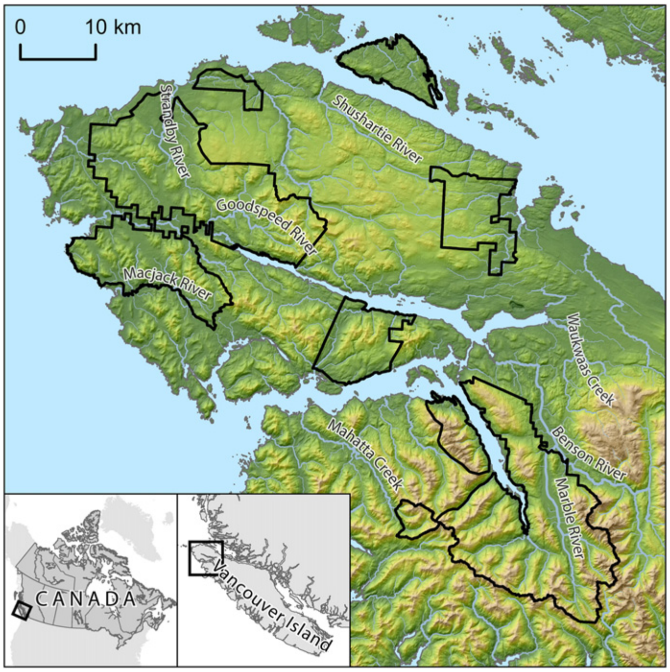

Fig. 2. Topography of northern part of Vancouver Island, British Columbia, Canada. Location of study area is indicated by black polygons.

study area is characterized by high annual precipitation (2228 mm), mild winters, and cool summers (Meidinger and Pojar, 1991). Elevation ranges from sea level to 1200 m, with rugged terrain and an average slope of 43.7%. The area is comprised of highly productive temperate rainforest dominated by western hemlock (*Tsuga heterophylla*) and western red cedar (*Thuja plicata*). The study area lies within the range of a number of salmonids, including Sockeye salmon (*Oncorhynchus nerka)*, Coho salmon (*Oncorhynchus kisutch*), Cutthroat Trout (*Oncorhynchus clarkii)*, and Rainbow Trout (*Oncorhynchus mykiss*) (Ministry of Environment, 2016). Forests in the study area are actively managed. The average age of stands was 144 years. More details on the study area are detailed in Tompalski et al. (2015).

2.2. Freshwater Atlas (FWA) and additional field-derived validation data

The BC Freshwater Atlas (FWA) is a freely available dataset containing British Columbia's hydrological features, including stream networks, wetlands, lakes, glaciers and watershed boundaries (Ministry of Forests and Lands, 2009). The FWA was created using a 25 m Digital Terrain Model (DTM) to delineate streams and watersheds. The DTM was derived using aerial photogrammetry, at 1:20,000 scale (Ministry of Forests and Lands, 2016). The FWA was developed in 2009 and provides a common source of freshwater feature data in the province, tying various freshwater-related activities to a common base.

The FWA provides information on stream location, order, and magnitude. Additional parameters important for forest management, such as stream class or fish presence are not included. These attributes are crucial for defining riparian management areas and forest management activities in adjacent forest areas. Forest managers use the FWA as a base layer, and derive attributes such as stream class according to the stream width and whether or not the stream is located within a community watershed. Fish bearing streams are determined as those streams that are frequented by particular fish species, or that connect to the Pacific Ocean or a lake known to support fish. The presence of fish is determined based on stream properties (gradient and width) and additionally checked in the field for streams with uncertain fish occurrence, especially to confirm fish absence in streams with low gradient. Field checks include visual sightings, angling, pole seining, trapping and electrofishing (Ministry of Forests Lands and Natural Resource Operations, 1998). The FWA stream network may be augmented when more detailed stream data is available. In this study we used the FWA stream network that was enriched with stream class definitions (and therefore also fish occurrence, Table 2). Stream class was assigned based on field observations and was available for 44% of the streams in the study area.

2.3. Deriving comprehensive information of the riparian ecosystem

Our aim is to describe how ALS data can be used to provide a comprehensive characterization of stream networks and riparian vegetation attributes (Fig. 3). Riparian ecosystems are complex systems including critical elements such as stream networks, fish biology, and forest practices. Stream properties determine fish habitat, fish occurrence influences forest practices, and riparian forest characteristics affect stream conditions. To provide a broad description of the riparian ecosystem using remote sensing technology such as ALS, each of the elements needs to be analyzed separately. We therefore start with describing how ALS data was used to derive stream networks and riparian zones. We then describe how stream networks and riparian forest stand attributes were extracted based on the point cloud. These individual characteristics are then merged in a concise database that contains all derived attributes for each stream section.

2.4. ALS point clouds and metrics

An Optech ALTM3100EA scanning system was used to acquire ALS point clouds in 2012. The average first return point density was 11.6 points/m^2 (details related to ALS data acquisition can be found in Tompalski et al. (2015)) with key elements shared below. Returns classified as "ground" were used to create a Digital Terrain Model (DTM). The DTM raster layer with pixel size of 1 m was then used to generate stream network (described in detail below) and to normalize point cloud heights to heights above ground level. ALS-derived metrics were calculated for 20 × 20 m cells using FUSION software package (version 3.42) (McGaughey, 2015). From the available metrics we chose those that describe forest height, cover, and vertical variability. 95th percentile of first returns was used to characterize stand height (denoted as

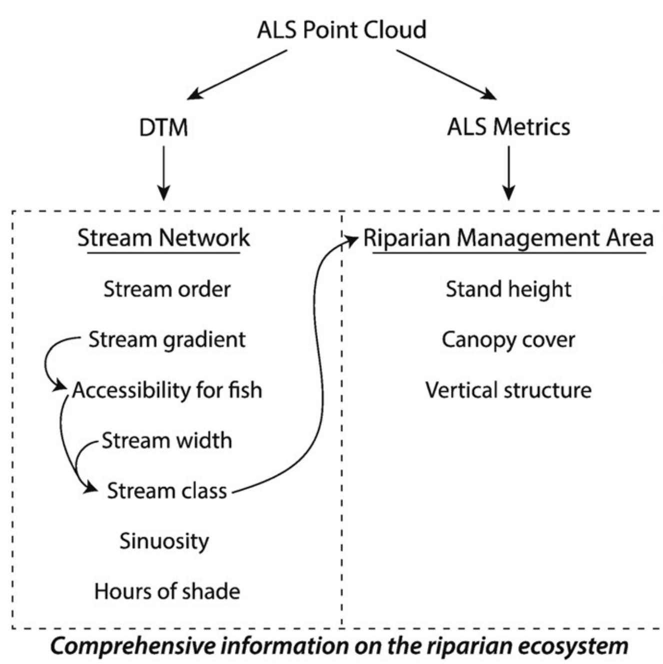

Fig. 3. Flowchart presenting how the riparian ecosystem is characterized based on ALS point clouds and extracted stream and forest stand attributes.

P95), while proportion of first returns above 2 m threshold was used as a descriptor of canopy cover (CC). Vertical variability was characterized with coefficient of variation of point heights (CV).

2.5. Delineating stream networks

To extract stream networks, a 1 meter-resolution DTM was submitted to a standard processing routine included in the ArcGIS software package. This workflow consisted of several steps. First, the DTM was corrected for imperfections by filling sinks—cells with undefined drainage direction. Then, a flow direction and flow accumulation were defined. To delineate streams an initiation area must be set, that defines an area of accumulated flow as a stream origin. In our study the stream initiation was set to 2 ha, following Jaeger et al. (2007), who delineated headwater source areas in the Washington Coast Range. They report that the median headwater source areas typically vary between 1.1 and 1.6 ha, with maximum values ranging from 2.3 to 6.1 ha. The choice of the stream initiation area was also based on the resulting stream order structure as well as the resulting drainage density as suggested by James et al. (2007). Stream orders, which inform on stream hierarchy, were assigned according to Strahler (1957).

The positional accuracy of the detected streams was assessed by comparing them to the stream network in FWA. We followed the approach proposed by Goodchild and Hunter (1997), whereby a reference linear feature is buffered consecutively and the created buffer zones are intersected with the tested linear feature. The percent of total length of the tested feature inside the buffered reference feature informs on the agreement between the two.

2.6. Riparian attributes

To provide comprehensive description of riparian areas we identified important attributes that are useful for forest management, describe important ecosystem services, and are possible to derive with ALS data (Table 3). We based this list on our experience in analyzing remote sensing data and the existing literature (e.g. Johansen et al., 2010; Michez et al., 2013; Wasser et al., 2013).

Table 3
Selected riparian zone attributes that were of interest in this study, together with data and metrics used to characterize them.

Riparian zone attribute	Data and/or metrics used to characterize attribute	Reference for applied method
Stream order	DTM	Standard processing routines embedded in GIS software (ArcGIS hydrology toolbox); stream order assigned after Strahler (1957)
Stream gradient	DTM	(Cavalli et al., 2008; Vianello et al., 2009)
Stream sinuosity	Derived stream segments	(Pike et al., 2010)
Potential accessibility for fish	Stream gradient	(Ministry of Forest Lands and Natural Resource Operations, 2014; Pike et al., 2010)
Stream width	DTM	(Johansen et al., 2011)
Stream class	Potential accessibility for fish, stream width	(Ministry of Forest Lands and Natural Resource Operations, 2014; Pike et al., 2010)
Vegetation height (P95)	Normalized ALS point cloud; 95th percentile of point heights	(Wulder et al., 2008)
Canopy cover (CC)	Normalized ALS point cloud; proportion of first returns above 2 m	(Wulder et al., 2008)
Vertical variability (CV)	Normalized ALS point cloud; coefficient of variation of point heights	(Wulder et al., 2008)
Total hours of shade	Raw ALS point cloud; points converted into voxel space	(Bode et al., 2014; Greenberg et al., 2012; Mücke and Hollaus, 2011)

The first set of attributes characterizes the stream channel. We calculated stream gradient and used it to define potential accessibility for fish. Stream shape was characterized by calculating sinuosity. Using object based image analysis tools (Blaschke, 2010) we calculated stream area and width, which in conjunction with fish accessibility, allowed for stream class designation. Riparian vegetation is described by the second set of attributes. From the stand characteristics that may be derived from ALS data, we chose to describe height, canopy cover, and vertical variability in riparian management areas. Finally, the water temperature regulating aspect of riparian vegetation was characterized with the total hours of shade a portion of stream received during a selected summer day.

2.6.1. Sinuosity, stream gradient and potential accessibility for fish

Stream channel sinuosity was calculated for each stream segment, by dividing total channel length by the length of a straight-line distance between the endpoints. A sinuosity value of 1 indicates a perfectly straight stream segment. Channels with sinuosity of 1.5 are considered sinuous channels. Higher ratios indicate meandering channels (Mueller, 1968; Wolman and Miller, 1960).

To calculate the stream gradient, stream segments detected with the DTM needed to be divided into homogenous parts. To do so we followed a logic proposed by Cavalli et al. (2008). Streams were first converted into points with a regular spacing of 1 m. Each of the points was assigned an elevation value from the ALS DTM. This set of points created a two-dimensional space defined by the distance from stream origin and elevation. Using linear regression, a line was fit to the set of points, representing a general gradient of the selected stream. Residuals of the model represented differences in elevation between the fitted line and the stream. Local extremes of the residuals were treated as the breakpoints and used to derive stream segments (Fig. 4).

In British Columbia, stream accessibility for fish is determined mainly by stream gradient (Ministry of Forest Lands and Natural Resource Operations, 2014), with a gradient of 20% over a distance of 100 m

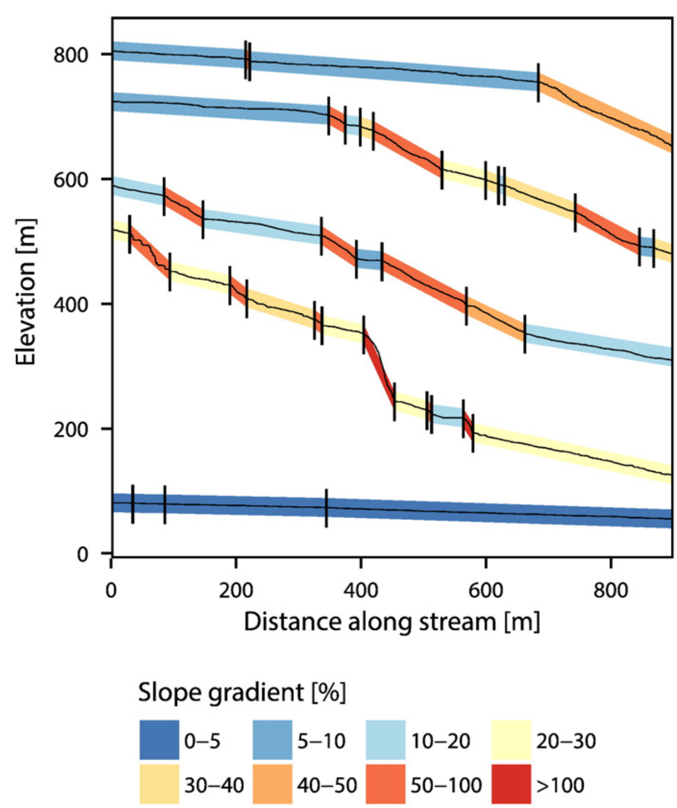

Fig. 4. Example of stream segments derived from ALS data.

defining streams deemed to be inaccessible for fish. Potential stream accessibility was determined for each stream, by following from stream end (lowest point on last segment with highest stream order) to stream source. If a segment exceeded 20% gradient and the segment length exceeded 100 m, the upstream network was considered inaccessible.

2.6.2. Stream width and stream class

Stream width was determined by expanding stream lines into areas of homogenous elevation using object based image analysis tools and following logic presented by Michez et al. (2013). First, terrain elevation from DTM was assigned to points representing stream center lines. After converting the lines to raster, each pixel was treated as a seed. Seeds were grown into neighboring DTM pixels with elevation difference less than or equal to 0.1 m. This resulted in stream polygons representing the area of each stream segment. Additional filtering was applied to exclude objects smaller than 5 m^2. Stream width was calculated by dividing stream area by stream length.

Potential accessibility for salmonids and derived stream width were used to assign stream class, using the official guidelines for British Columbia (Ministry of Forest Lands and Natural Resource Operations, 2014). This stream classification first categorizes streams into fish bearing (classes: S1, S2, S3, and S4) and non-fish bearing (classes S5 and S6). Further division is determined based on average channel width, with class S1 depicting large rivers, and classes S4 and S6 depicting narrow streams, with fish presence and absence, respectively.

Since the calculated channel width varied for stream segments, to avoid a situation where consecutive segments have very different classes, we performed the classification on longer stream sections first. Additionally, once a stream section was classified, the section further down the stream length could not be classified as a lower class.

2.6.3. Characteristics of stands next to streams

To characterize the vegetation within the riparian zones we extracted stand properties for the RMA, which was defined for each stream segment based on stream width and fish occurrence. Additionally, stand properties were extracted for the RMA sub-zones: the RMZ and RRZ, as well as for the stand located outside RMA, with the width of the outside zone being equal to the width of the RMA. This enabled assessment of differences between stands in each of the zones as a result of different management practices. Each stream segment was assigned ALS-derived attributes that included P95, CC and CV. These stand attributes provide a comprehensive characterization of stand conditions in the close vicinity of streams. This in turn allows to identify stream parts of low height or for which the vegetation cover is low, as well as to assess any differences in stand attributes across stream classes.

2.6.4. Stream shading

Stream shading was calculated based on raw point cloud data. We based our method on Bode et al. (2014) and Mücke and Hollaus (2011). For one selected summer day (August 1st), sun position was calculated at an hourly interval, based on the date and center location of ALS data. August 1st was chosen as a representative day for summer conditions, based on the average daily maximum temperatures in the study area and reported 30 year average temperature in the Fraser river (Fisheries and Oceans Canada, 2016). For each sun position, area shaded by vegetation was defined. To do so, the point cloud and the DTM were rotated using sun azimuth and zenith, so that the sun was located directly above. The point cloud was then converted into $5 \times 5 \times 1$ m voxels. Due to the initial rotation, shaded areas were calculated by counting the voxels above each of the DTM pixels. If the count exceeded 2, the pixel was considered shaded. The raster layer representing shaded areas was converted back to original 3D space. Shading determined for each hour was merged into final shading composite, with pixel size of 5×5 m determined by the chosen voxel dimension. Shaded pixels for each hour were summed up so that the final composite represented the total hours of shade calculated for each pixel (Fig. 5).

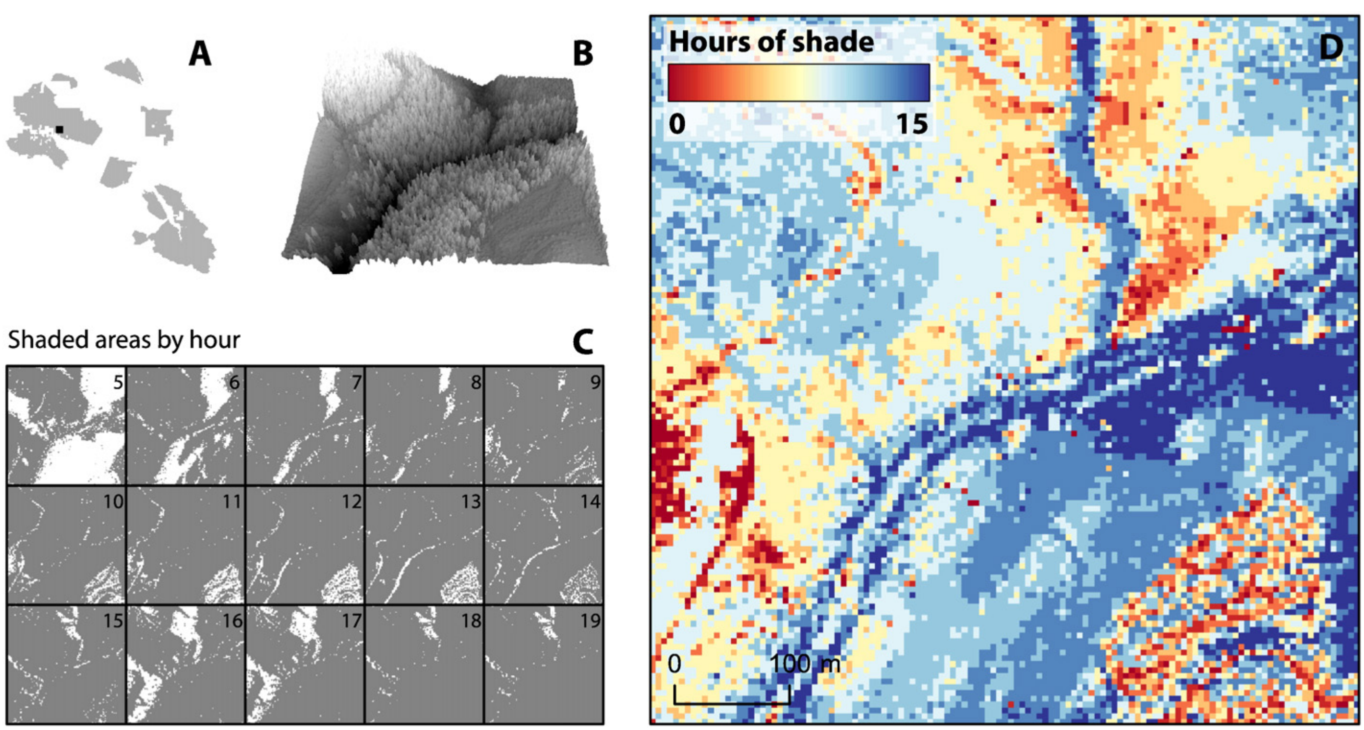

Fig. 5. Methodology of calculating hours of shade demonstrated on a subset of study area. (A) Location of the subset within the study area. (B) A 3D view of the digital surface model of the subset area. (C) For the shaded area by hour, grey colour indicates areas with shade, whereas the number in the top right corner indicates time during the day (24 h format). (D) The final raster layer representing total hours of shade is derived by summing hourly shade rasters.

Table 4
Summary statistics of the detected streams grouped by stream order.

Order	Total length		Median gradient [%]	Median sinuosity	Median width [m]	Median P95 [m]	Median CC [%]	Median CV	Median total hours of shade [hours]	Proportion inaccessible [%]
	[km]	[%]								
1	3533.6	55.0	20.94	1.12	0.58	19.12	86.72	0.68	11.86	46.5
2	1585.8	24.7	15.24	1.15	0.61	20.35	85.88	0.69	11.91	18.7
3	773.6	12.0	9.11	1.17	1.21	21.95	85.59	0.69	11.86	6.7
4	338.3	5.3	3.79	1.19	3.31	24.35	89.53	0.63	11.93	1.8
5	160.9	2.5	1.08	1.17	12.53	24.43	91.10	0.58	11.78	0.4
6	29.9	0.5	0.33	1.14	19.67	30.37	88.48	0.64	10.81	0.01
Total	6421.8	100.0	16.39	1.14	0.67	19.80	86.57	0.68	11.88	74.11

2.7. Validation of stream class and predicted fish occurrence

The potential fish occurrence and stream class derived with ALS data were validated using field-defined stream class delineated from the freshwater atlas database. The validation dataset consisted of both the fish presence/absence information and stream class. We first generated 1500 random points (10% of total number of reference streams) along randomly selected streams, with the number of points proportional to the total length of each stream class. We then compared the reference fish presence/absence information as well as field-defined stream class with corresponding attributes in the closest ALS-detected stream. This allowed the creation of a confusion matrix and to define the accuracy of the ALS-defined fish occurrence and stream class prediction.

3. Results

The total length of detected streams within the study area was 6421.8 km (Table 4). The median stream gradient was 16.4%, and the highest median stream gradient was for the lowest order streams (order = 1; 20.94%). Stream sinuosity was very similar for each stream order, although a slight decrease in sinuosity with increasing order values was observed. Stream width increased with increasing stream order and had a median value of 0.58 m for streams of the lowest order and 19.67 m for streams with the highest order. Median height (P95), canopy cover (CC) and vertical structure (CV) of stands next to streams were similar across stream orders, with lowest canopy cover for streams of order 6. Median hours of shade were similar across stream orders, with median value for all streams of 11.88 h (Fig. 6, upper panel). By analyzing the stream gradient from end to beginning of the streams, we estimated that 74.1% of stream total length was potentially not accessible for fish, due to a stream segment exceeding a gradient of 20% for at least 100 m. When grouped by stream order, only 0.01% of streams of order 6, and 46.5% of streams of the lowest order were not accessible (Table 4).

As the variances across order groups of the presented attributes were not equal, Kruskal-Wallis with Dunn's posthoc test was used to check if the differences between groups of calculated metrics were significant (Fig. 6). For this test we selected 50 random stream segments for each stream order. The differences between stream orders for the various attributes had different levels of statistical significance. For stream gradient and width, differences between most of the possible pairs of order values were significant. For stream sinuosity, CC, and CV, no significant differences were observed. For stand P95 and hours of

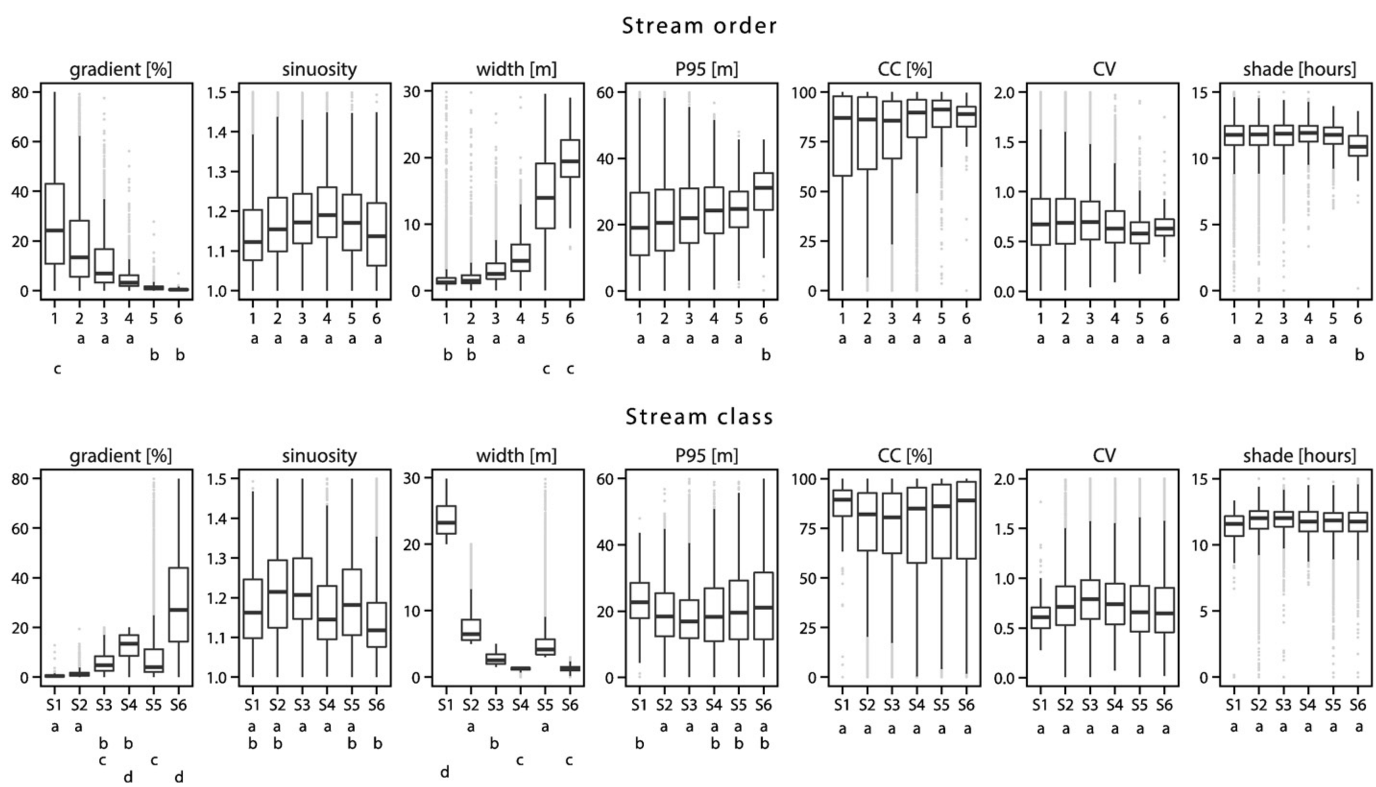

Fig. 6. Boxplots presenting selected attribute values across stream orders and stream classes. Different letters under the boxplots indicate significant difference between groups at $\alpha = 0.05$ determined with Kruskal-Wallis and Dunn's posthoc test. Groups that share the same letter are not significantly different. For example, stream gradient for streams of order 2, 3, and 4 is not significantly different, while streams of order 1 are significantly different from all order groups.

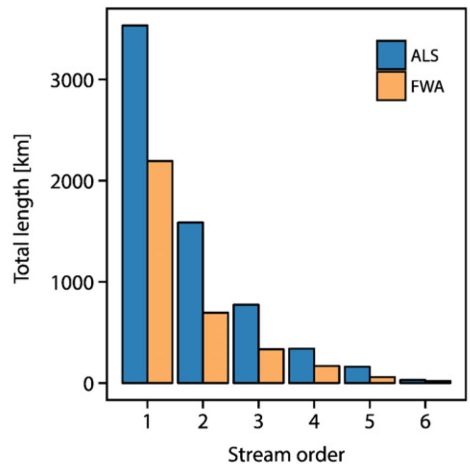

Fig. 7. Comparison of streams detected with ALS with streams in the FMA database, by stream order and stream class. Left panel: total length of streams by stream order in FWA database and detected with ALS. Right panel: relative length of streams by stream class in FWA and streams detected with ALS data.

shade, streams of order 6 differed significantly from streams of all other order groups.

The total length of detected streams was almost two times larger (96.5%) than the total length of streams in FWA database. The largest differences in total length were observed for streams of order 1 and 2 (Fig. 7). Visual comparison of detected streams data with the FWA database (Fig. 8) demonstrates the amount of detail in the channel network derived with ALS data. The result of the positional agreement analysis showed that 42.7% of the ALS-detected streams lie within 5 m of the FWA streams, and 70.1% of the ALS-detected streams lie within 10 m of the FWA streams. Approximately 95% of streams were located within a buffer of 18.6 m.

The higher level of detail in the ALS-derived DTM resulted in more detailed stream shapes. This had an effect on stream sinuosity, which for all stream order groups had larger values when compared to FWA (Fig. 9). The distribution of sinuosity of stream derived with ALS data had greater variability than sinuosity of FWA streams. Interestingly, largest values of sinuosity were observed for streams of order 3–5.

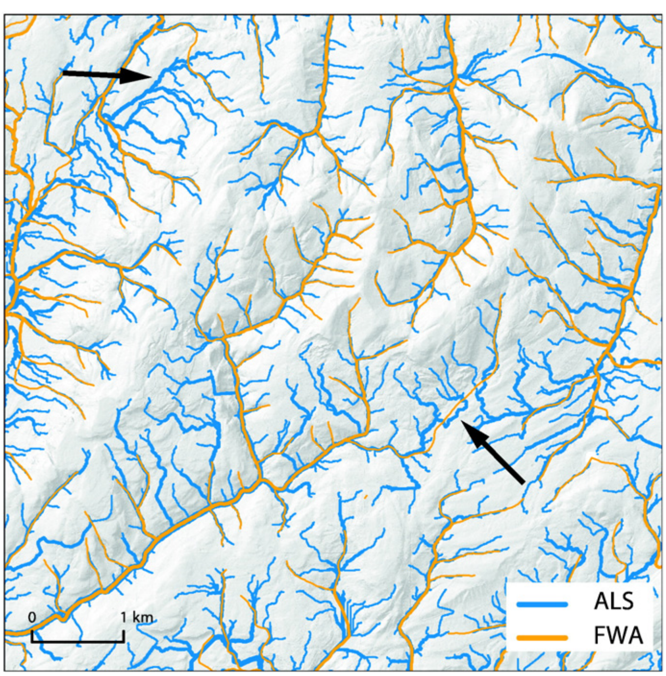

Fig. 8. A visual comparison of streams in FWA database and streams detected based on ALS-derived DTM. The arrows indicate areas where there are larger differences between the stream networks. The total length of streams presented on this figure is 294 km and 110 km for ALS and FWA, respectively.

Accessibility for fish (Fig. 11) and derived stream width were used to assign stream class according to (Ministry of Forest Lands and Natural Resource Operations, 2014) (Table 5). All streams in classes from S1 to S4 are considered to be fish-bearing streams, while streams in classes S5 and S6 are non-fish bearing streams. Most of the streams (57.0% of the total stream length) were classified as S6 (narrow, non-fish bearing). Together with class S5, these two classes summed to the total of 66.8% stream length of streams not accessible for fish. Class S3 was the most dominant fish bearing stream type, with 14.5% of the total stream length. Median stream gradient changed from <0.5% for classes S1, to over 7% for class S4. Maximum gradient values occurred, as expected, in non-fish bearing streams, with median of 24.6% for class S6. P95, CC, CV and hours of shade were similar across stream classes (Fig. 6, lower panel)

Some of the differences in the derived riparian attributes across stream classes were statistically significant. For the attributes describing stream channels, almost all differences between stream classes were significant for stream gradient and width and only some were significant for stream sinuosity. For attributes describing riparian vegetation (height, canopy cover, vertical structure, shade), significant differences were only observed for riparian vegetation height, for streams of class S1, S2 and S3 (Fig. 6).

Comparisons of the stand attributes between RMA and in the direct vicinity of RMA ("non-RMA"), as well as between RRZ and RMZ are presented on Fig. 10. The differences were analyzed with Wilcoxon paired test, for 50 randomly selected stream segments in each stream class. In general, stands located closer to the water channels were taller, especially for the larger streams. The differences in stand heights between RMA and non-RMA were significant for the majority of stream classes. The differences in height between stands in RRZ and RMZ were significant only for largest streams (class S1). Differences in canopy cover were significant for streams in class S1 and S4 (RMA versus non-RMA), with larger values for stands located in the direct vicinity of streams. Stand vertical variability (CV) was similar between RMA and non-RMA, as well as RRZ and RMZ, with none of the differences being significant.

Results showed that for the majority (82.9%) of streams selected for the validation, fish occurrence was correctly assigned (Table 6). Non-fish-bearing streams were assigned with lower omission and commission errors. Fish-bearing streams were in 26.0% cases misclassified as non-fish-bearing and in 55.1% cases were omitted.

Validation of stream class showed that 61.0% of streams were assigned the correct stream class, however the errors of omission and commission were larger than for defining fish occurrence, often exceeding 70% (Table 7). Classes S1 and S6 were classified with the highest accuracies. Stream class depends on stream width and fish occurrence with an error in either of these attributes contributing to the overall accuracy and observed misclassifications. Because of the class definitions (Table 2), error in class width will result in misclassification to a neighboring class (e.g. S2 or S4 instead S3), while error in fish occurrence will result in error in misclassification between class groups S1–S4 and S5–S6 (e.g. S5 instead of S2). This can be observed for example for class S2 – error in predicted fish occurrence lead to classification of 28 points as class S5.

Each stream segment was assigned a number of attributes that described both the stream and riparian zone characteristics. We present a selection of these attributes on Fig. 11 for a subset of the study area.

Using the derived stand attributes we were able to define the proportion of fish-bearing streams (by length) that do not exceed a certain height or canopy cover value. This in turn allows the identification of parts of riparian habitats that are not optimal for fish – information on low stand height and low canopy cover indicates that streams are open, potentially exposed for direct sunlight or may be at higher risk

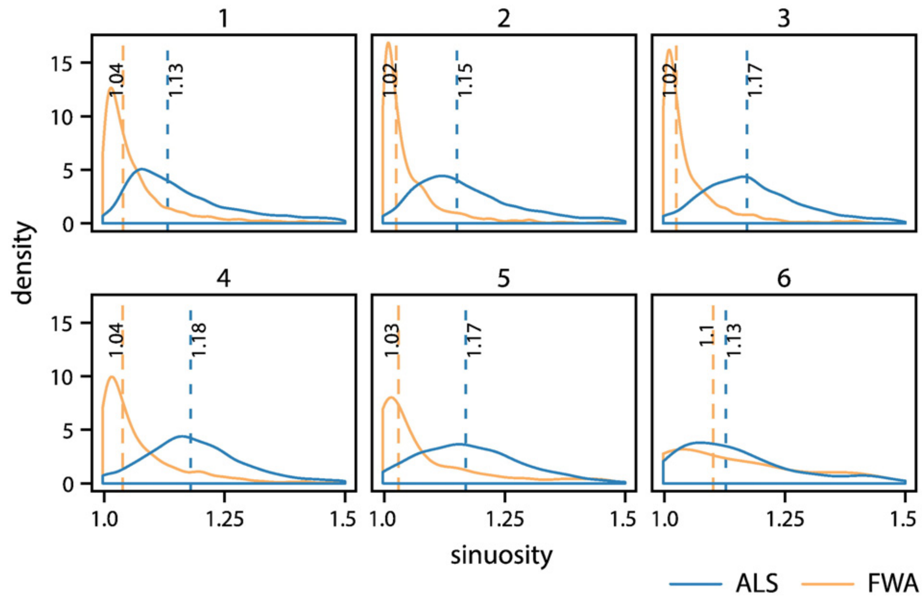

Fig. 9. Comparison (by stream order) of stream sinuosity between streams detected with ALS data and streams in FWA. Vertical lines and corresponding labels indicate median values.

of erosion. We found that 25% of total length of streams that are defined as potentially accessible for fish, have stand height below 12.7 m, canopy cover below 59.7. Only for 0.2% of the total length of fish-accessible streams the stand height is below 2 m, and for 2.4% the canopy cover is <20% (Fig. 13, panels A and B).

By calculating total hours of shade we were able to estimate the proportion of the day each shade segment receives. The analysis of stream shading showed little variability by stream order or stream class (Fig. 6, Table 4, Table 5). We illustrate how the hours of shade changed with the forest stand conditions in the direct vicinity (Fig. 12). Sections of streams passing through clearcuts or young forest stands, were shaded shorter and variability in stand conditions is reflected in the variability of calculated shade. Further, we calculated the proportion of cumulative fish-bearing streams length that receives particular amount of shade (Fig. 13, panel C). This analysis informs that 25% of total length of streams that are defined as potentially accessible for fish, receive at least 11.3 h of shade, with only 7.3% of fish-accessible streams receiving <10 h of shade.

4. Discussion

In this study we evaluated the use of ALS captured point cloud data to derive stream network and assign characteristics of streams and riparian zones in complex forests in Pacific Northwest. With the growing popularity of ALS data acquisition for wall-to-wall forest inventories, important riparian attributes that can inform sustainable forest management and derive additional value from the investment in ALS data. Herein, we demonstrated the suitability of ALS data for describing stream networks and characterizing riparian vegetation. The identified suite of feasible attributes to be extracted using ALS data is of high ecological value and forest management interest.

Our results showed that there is consistency between the derived stream network and the existing FWA data. The ALS-derived stream network was more detailed due to a finer scale DTM (1 m versus the 25 m DTM used to generate the FWA product). The differences to the FWA data were observed primarily for lower order streams and in the headwater of the watersheds.

A crucial stream attribute that many management decisions are based on is the occurrence of habitat suitable for fish. In this research, we developed an approach to estimate occurrence of fish habitat based on stream gradient, following the methodology that is used in British Columbia. The accuracy of terrain elevation from ALS data however allows the longitudinal profile of stream segments to be calculated. Stream segments that are above a segment with a gradient exceeding 20% gradient and longer than 100 m were defined as non-fish-bearing. ALS data therefore provides an opportunity to characterize not only structural, but also functional connectivity of the streams. The mountainous character of the study area resulted in a low percentage of fish-bearing streams (74% potentially inaccessible to fish). Validation against field data showed high accuracy of the fish occurrence classification; however, the high errors of omission for the fish-bearing streams indicated that for streams defined as fish-bearing additional field checks are also required to confirm the assigned value. The limited reference data only allowed the assessment of the positional agreement of streams with the FWA, presence of fish, and stream class.

There are two main reasons that cause the high error of omission for the fish-bearing streams. First – the fixed threshold of 20% over 100 m is recommended as a value to define fish barriers, however in some cases fish can still travel through these high gradient stream sections. Second,

Table 5
Summary statistics of the detected streams grouped by stream class.

Stream class	Total length		Median gradient [%]	Median sinuosity	Median width [m]	Median P95 [m]	Median CC [m]	Median CV	Median total hours of shade [hours]
	[km]	[%]							
S1	56.40	0.9	0.42	1.16	23.82	22.30	88.39	0.61	11.53
S2	563.23	8.8	0.79	1.21	7.20	18.12	80.98	0.71	11.86
S3	933.61	14.5	3.27	1.21	2.87	17.11	81.12	0.77	12.00
S4	577.39	9.0	7.75	1.13	0.48	19.58	87.21	0.68	12.00
S5	631.07	9.8	2.78	1.18	4.79	19.58	85.73	0.68	11.82
S6	3660.4	57.0	24.65	1.12	0.46	20.98	88.45	0.65	11.78
Total	6421.1	100.0							

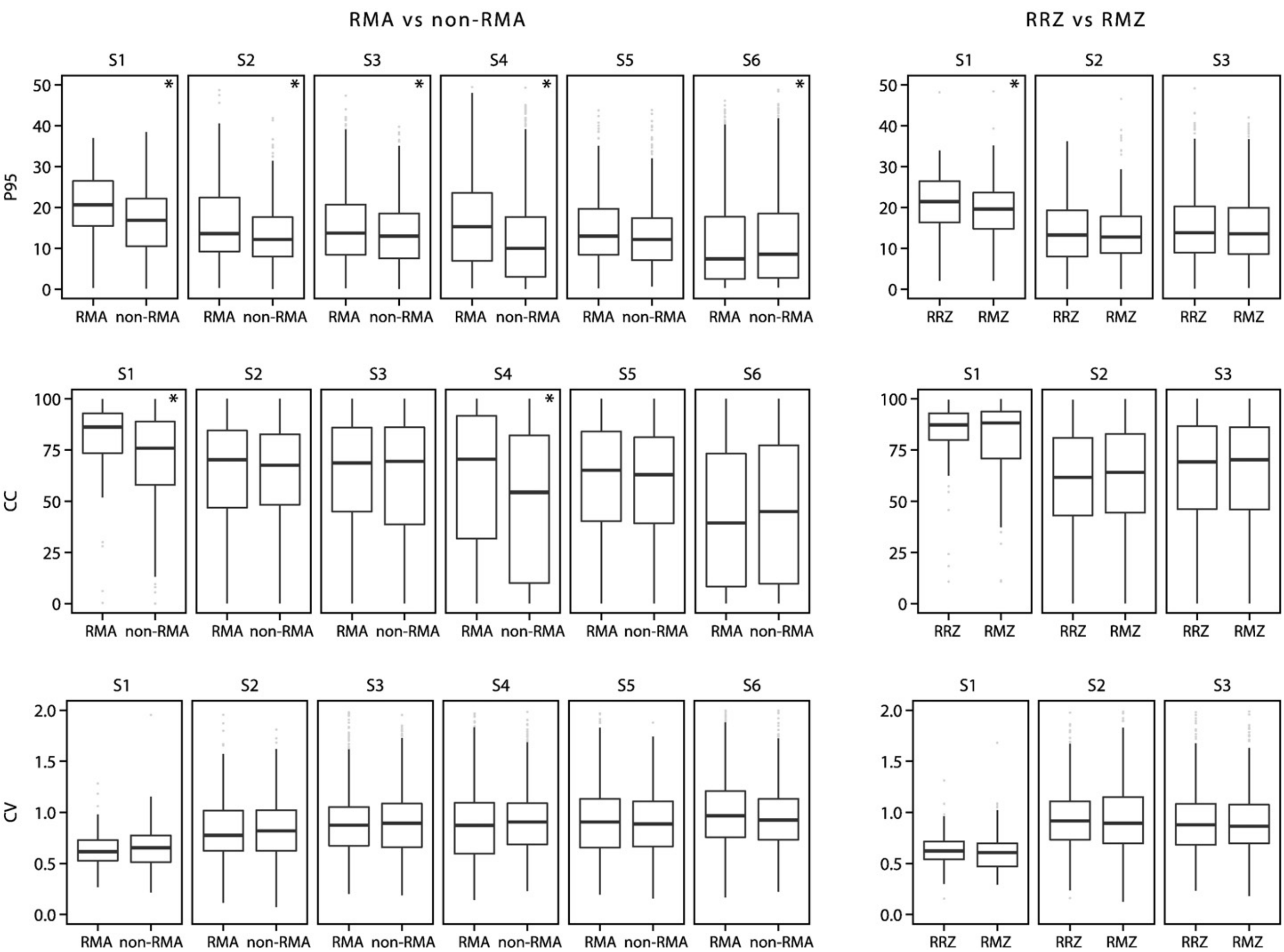

Fig. 10. Comparison of stand height (P95), canopy cover (CC), and vertical structure (CV), across stream classes. Comparison is performed between stands inside RMA and in direct vicinity of RMA ("non-RMA", left), and within the RMA zone – between RRZ and RMZ (right). Significant differences are indicated with asterisk.

although the ALS data we used was of high density, errors in DTM could still occur, especially under dense forest canopy. Errors in the DTM could influence the calculation of stream gradient and therefore cause misclassification of potential fish occurrence.

Based on the derived attributes a description of stream networks in the study area can be composed. First, because of the mountainous nature, streams of lowest orders typically have a high gradient, often exceeding 60%. The gradient decreases as distance from stream source increases, which is also reflected by the increase of stream order. High gradient, low order streams are narrow (median width of 0.58 m) and not accessible for fish (46.5%). With the gradient decrease in stream segments (and order increase) the proportion of fish-accessible streams increases—the largest streams are almost entirely fish accessible. When analyzed by stream class, the increase of stream gradient from classes S1 to S4, as well as larger gradient for S6 than S5, is strictly related to the classification scheme. Streams with larger width (and therefore also a higher classification) have a lower gradient. The larger variability of gradient for classes S5 and S6, which depict the parts of streams that are not accessible for fish, results from broader class definitions, especially for class S5, which consist of all non-accessible streams wider than 3 m.

Within riparian ecotones, vegetation height, canopy cover, and vertical variability were similar across the majority of stream orders and stream classes. Significant differences were observed for stand height between the largest streams and streams of lower order only. Stream shade was similar for all streams with slightly lower values observed for largest channels, which is related to their larger width and lower amount of overhanging canopies.

Table 6
Confusion matrix of the potential fish occurrence.

Prediction	Reference		
	Non-fish-bearing	Fish-bearing	Error of commission
Non-fish-bearing	1082	199	15.5%
Fish-bearing	57	162	26.0%
Error of omission	5.0%	55.1%	Overall acc: 82.9% (CI: 80.1%, 84.8%)

Table 7
Confusion matrix of the stream class.

Prediction	Reference						
	S1	S2	S3	S4	S5	S6	Error of commission
S1	2	0	0	0	0	0	0.0%
S2	2	14	27	22	0	1	78.8%
S3	0	12	31	8	2	15	54.4%
S4	0	4	25	15	1	38	81.9%
S5	1	28	47	17	37	44	78.7%
S6	0	21	58	27	185	816	26.3%
Error of omission	60.0%	82.3%	83.5%	83.1%	83.6%	10.7%	Overall acc: 61.0% (CI: 58.5%, 63.5%)

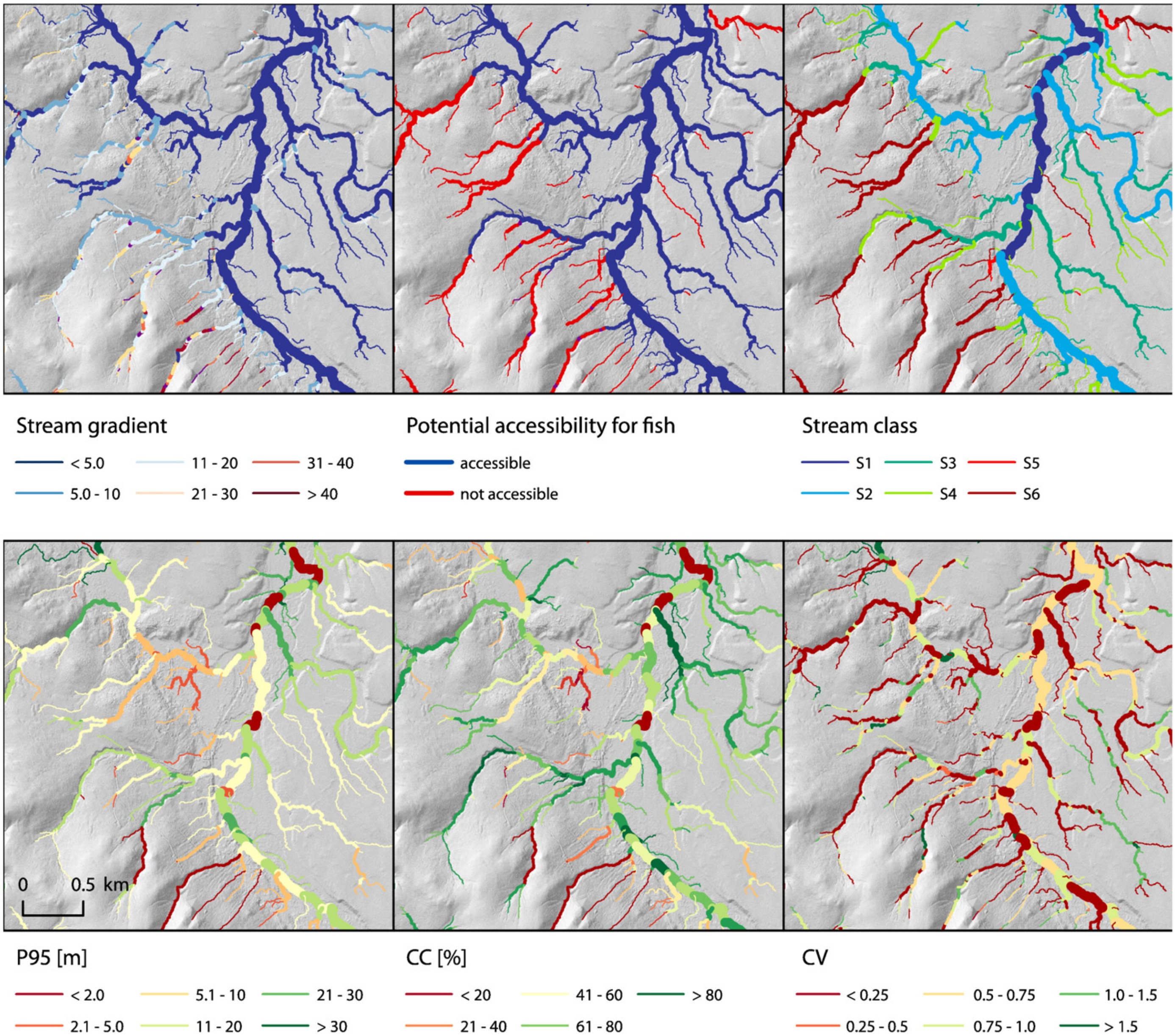

Fig. 11. Stream gradient, potential accessibility, class, stand height (P95), canopy cover (CC) and vertical variability (CV) m derived for each stream segment demonstrated on a portion of study area. Notice that for some streams segments of higher and lower gradient are alternating. Accessibility for fish for such streams is defined by the lowest segment exceeding 20% gradient. Height and canopy cover are calculated for stands in direct vicinity of streams (20 m buffer). Values are averaged for each stream segment.

We observed small, non-significant differences in sinuosity for streams of different orders or different classes. The slight increase in complexity of channel shape for streams of order 3 or 4 may be related to channel morphology typical for different locations within the watersheds. In the steep, headwater portion of the stream network, step-pool and cascade-pool dominate, which change into pool-riffle reaches in lower sections, where streams are wider and meander more (Pike et al., 2010). The higher sinuosity values for ALS-derived streams than for FWA, result from higher spatial resolution of the terrain model used to derive the stream network (1 m for ALS versus 25 m for the FWA).

Forest practices close to streams are determined by stream class. By combining potential fish occurrence with stream width derived by extending stream center line into pixels of homogenous elevation, stream class was derived. Although the class assignment was not ideal (overall accuracy 61%) the improvement over currently existing methods is evident. ALS-based stream class attribution is more detailed, objective, and can be applied over large areas. This outcome is likely the greatest interest for current forestry practices. For areas where ALS data is already available, the additional information on stream classes can be extracted at no additional cost. This in turn can lead to reducing operational costs related to harvest planning and other silvicultural activities. Additionally, extracted information on riparian vegetation can provide insights regarding areas with potential risk erosion, or inform on locations which have to be protected due to lower bank stability. As shown by Johansen et al. (2013), stream bank condition can be successfully characterized with ALS data integrated with high resolution optical images.

The differences in stand attributes between RMA and stands outside RMA were small, although still significant in some cases. The protection of riparian areas defined in existing regulations has a visible effect on stand height and canopy cover. In general, riparian stands adjacent to streams are taller and have larger canopy cover than stands outside the riparian area; however, measured vertical variability is not significantly different. Stream classes of S1, S2, and S3 are subdivided into RRZ and RMZ. The primary objective of this subdivision is to additionally

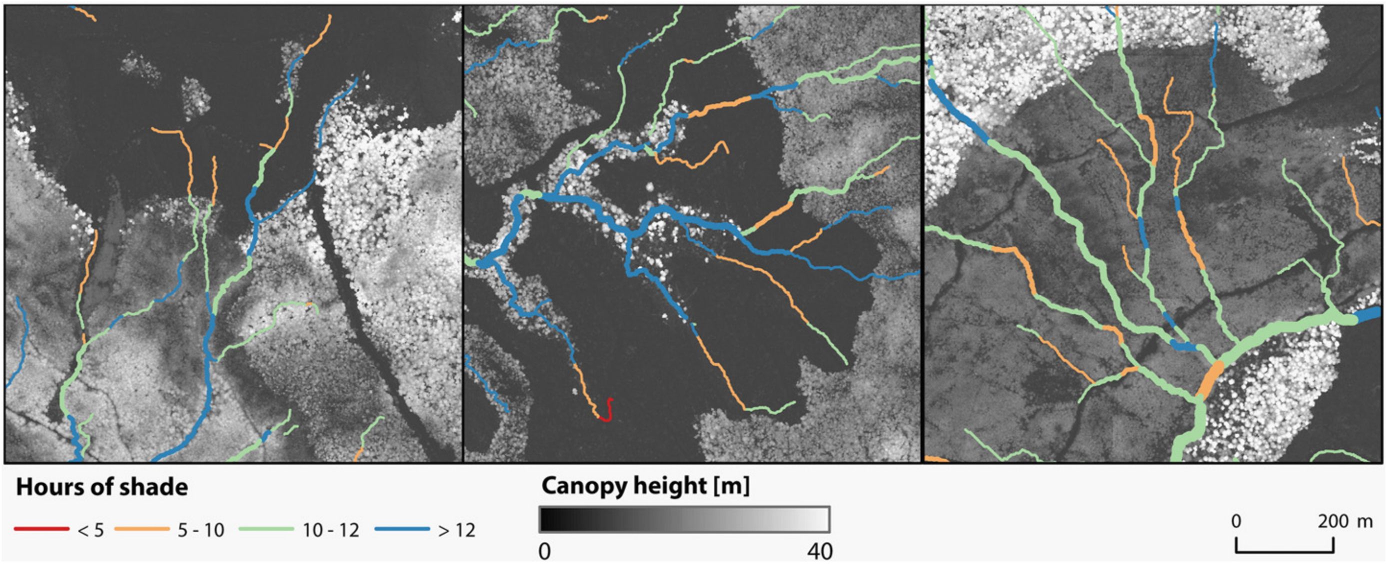

Fig. 12. Hours of shade classes assigned to streams. The three chosen subset of study area demonstrate how stream shading changes when streams pass through different forest stands.

regulate forest practices in the area adjacent to these stream classes. While in RMZ trees may be removed up to a specified limit in retained basal area, no harvesting activities are permitted inside RRZ. The RMZ serves as additional buffer to protect RRZ from windthrow and retaining wildlife trees (Ministry of Forest Lands and Natural Resource Operations, 2014). As a result, the stand attributes of RRZ and RMZ should not differ markedly. Indeed, our results show that significant differences existed only for class S1, where stand height was larger within RRZ than RMZ. For all other attributes stand attributes were similar.

By analyzing stand dimensions adjacent to streams and quantifying the shading they provide, we characterized streams with an absence of canopy cover, low vegetation, and few hours of received shade. These characteristics affect both water and habitat quality (Ghermandi et al., 2009). The total length of potentially fish-bearing streams that did not receive at least 10 h of shade during the day was very small, which was a confirmation of proper riparian management practices in the study area. In fact, the only examples of stream segments that received <5 h of shade we could find, were small headwater streams.

The presented methodology of analyzing riparian zones consists of identifying stream networks and characterizing them with ALS data. Contrary to existing research focusing on larger streams and rivers (Johansen et al., 2010; Michez et al., 2013), we presented a workflow that takes advantage of the accurate, ALS-derived DTM to delineate streams and characterize vegetation surrounding riparian vegetation. We therefore built-upon existing research (e.g. Vianello et al., 2009; Wasser et al., 2013) and integrated different techniques for the description of riparian ecotones. The ALS-derived stream network is highly detailed, providing valuable information for sustainably managing RMA and facilitating improved forest planning and operations. Foresters can take advantage of predicted fish occurrence and stream class, which defines the allowed activities within the close vicinity of water channels.

Apart from the forestry context, the function of riparian zones can be also integrated to the ecosystem service framework (Bastian et al., 2013). The detailed information provided by this analysis provides an in-depth understanding of the role water and riparian vegetation play in the environment, and how they influence of human well-being (Andrew et al., 2014). Ecosystem services related to riparian zones can be identified as the regulating service of canopy cover on water temperature, provisioning services of fish population and habitat and regulating service of stream gradient on fish occurrence. All three services are important and, as shown, can be characterized in detail with ALS data. Such information is the additional benefit of characterizing riparian areas more broadly, expanding their role and taking interdisciplinary aspects into account. Once identified, specific services may be better managed, protected and monitored.

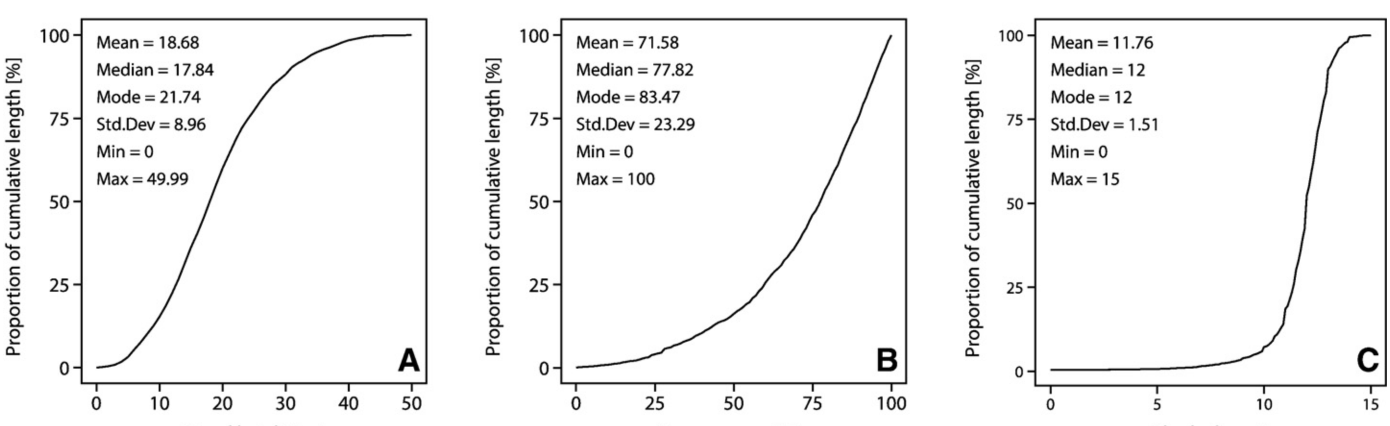

Fig. 13. Cumulative distribution of stand height, canopy cover and shade vs proportion of cumulative stream length for streams defined as accessible for fish. Graphs inform on the proportion of streams that does not exceed certain value of height, canopy cover or shade, respectively.

5. Conclusions

In this research we demonstrated how ALS data can be used to characterize riparian zones, by first delineating the stream network and then extracting a number of important stream and riparian vegetation attributes. The increasingly common collection of ALS data to meet forest management information needs allows for additional applications to be developed from these available data. Through the combination of both stream attributes and characteristics of riparian forest stands, we developed a methodology that provides a holistic assessment of forestry- and ecology-related aspects of riparian ecotones. The attributes that were derived using ALS point clouds described stream gradient, sinuosity, and width, as well as riparian vegetation height, canopy cover, vertical complexity, and the total hours of shade a stream receives. Each stream was identified for potential accessibility for fish, which is an important factor for forest managers (as it defines the size of the protected buffer zones adjacent to streams). Regarding spatial attributes of interest, the approaches implemented and tested here largely show an improvement over existing methods, with ALS-based approaches offering objectivity and consistency over large areas.

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