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Characterizing streams and riparian areas with airborne laser scanning data

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A B S T R A C T

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.