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Laser vision: lidar as a transformative tool to advance critical zone science

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Lidar as a transformative tool

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Abstract

Laser vision: lidar as a transformative tool to advance critical zone science. Observation and quantification of the Earth surface is undergoing a revolutionary change due to the increased spatial resolution and extent afforded by light detection and ranging (lidar) technology. As a consequence, lidar-derived information has led to fundamental discoveries within the individual disciplines of geomorphology, hydrology, and ecology. These disciplines form the cornerstones of Critical Zone (CZ) science, where researchers study how interactions among the geosphere, hydrosphere, and ecosphere shape and maintain the "zone of life", extending from the groundwater to the vegetation canopy. Lidar holds promise as a transdisciplinary CZ research tool by simultaneously allowing for quantification of topographic, vegetative, and hydrological data. Researchers are just beginning to utilize lidar datasets to answer synergistic questions in CZ science, such as how landforms and soils develop in space and time as a function of the local climate, biota, hydrologic properties, and lithology. This review's objective is to demonstrate the transformative potential of lidar by critically assessing both challenges and opportunities for transdisciplinary lidar applications. A review of 147 peer-reviewed studies utilizing lidar showed that 38 % of the studies were focused in geomorphology, 18 % in hydrology, 32 % in ecology, and the remaining 12 % have an interdisciplinary focus. We find that using lidar to its full potential will require numerous advances across CZ applications, including new and more powerful open-source processing tools, exploiting new lidar acquisition technologies, and improved integration with physically-based models and complementary in situ and remote-sensing observations. We provide a five-year vision to utilize and advocate for the expanded use of lidar datasets to benefit CZ science applications.

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1 Introduction

Complex interactions among the geosphere, ecosphere, and hydrosphere give rise to present-day landforms, vegetation, and corresponding water and energy fluxes. Critical Zone (CZ) science studies these interactions in the zone extending from the bottom of groundwater to the top of the vegetation canopy. Understanding CZ function is fundamental to characterizing regolith formation, carbon-energy-water cycles, meteorological controls on ecology, linked surface and subsurface processes, and numerous other Earth surface processes (NRC, 2012). Improved understanding of CZ functions is thus important for quantifying ecosystem services and predicting their sensitivity to environmental change. However, observing CZ processes is difficult because they occur at second to eon time scales, centimeter to kilometer spatial scales, and require multi-disciplinary measurement approaches (Chorover et al., 2011). Emerging technologies, such as Light detection and ranging (lidar), can be helpful in this regard because they generate precise three-dimensional information on the Earth's surface characteristics.

Lidar allows for simultaneous measurements of aboveground vegetation structure and human infrastructure, as well as the topography of the earth surface, including soils, bedrock, stream channels, and snow/ice pack. Depending on the data collection system and platform, observations can be made at the landscape scale (> 1000 km^2) and at spatial resolutions capable of capturing fine-scale processes (< 10 cm). Acquisition capabilities are increasing exponentially (Stennett, 2004; Glennie et al., 2014) and new ground-based (terrestrial laser scanning, TLS) and aerial platforms (airborne laser scanning, ALS) are leading to increased availability of lidar datasets with CZ-relevant information content. Consequently, lidar-derived information has dramatically improved understanding of processes governing Earth science disciplines.

The objective of this paper is to present a five-year vision for applying lidar to advance transdisciplinary CZ research questions. To accomplish this, we first provide an overview of the range of scientific insights offered by disciplinary-specific lidar research. We present key advances in geomorphology, hydrology, and ecology made possible by the availability of lidar datasets in Sects. 1.1, 1.2, and 1.3, respectively. This is followed in Sect. 2.1 by an exploration of transdisciplinary studies that utilized complimentary lidar-derived datasets. These results indicate exemplar transdisciplinary studies that can guide future research. In Sect. 2.2 we describe how lidar-derived information is uniquely suited to advance three CZ research topics: (1) quantifying change detection, (2) parameterization and verification of physical models, and (3) improved understanding of CZ processes across multiple scales. These topics are limited by a set of common impediments that we outline in Sect. 2.3. Finally, in Sect. 2.4, we present a vision to advance CZ science with lidar using examples of transdisciplinary research questions and provide a set of recommendations to guide CZ community usage and advocate for greater lidar resources over the next five years.

1.1 Key advances in geomorphology

High-resolution topographic datasets derived from lidar have greatly contributed to understanding geomorphic change, identifying geomorphic features, and understanding ecohydrologically-mediated processes. Broadly, lidar technology has been useful in studying geomorphic response to extreme events such as fire and storm events (e.g., Pelletier and Orem, 2014; Elina et al., 2015; Sankey et al., 2013; Perignon et al., 2013; Staley et al., 2014), human activities (e.g., James et al., 2009), and past climatic and tectonic forcings (e.g., Roering, 2008; Belmont, 2011; West et al., 2014). Meter and sub-meter scale time-varying processes, often derived from TLS, have been quantified in the response of stream banks to flooding events (Elina et al., 2015) and in the formation of microtopography due to feedbacks with biota (e.g., Roering et al., 2010; Pelletier et al., 2012; Harman et al., 2014). Examples of larger scale change detection applications, typically ALS-derived, include measuring changes in stream channel pathways resulting from Holocene climate change and anthropogenic activities (e.g., Day et al., 2013; Kessler, 2012; James 2012; Belmont et al., 2011), rates of change in migrating sand dunes (Pelletier, 2013), the influence of lithology and climate on hillslope form (e.g., Marshall and Roering, 2014; Hurst et al., 2013; Perron et al., 2008;

West et al., 2014), and channel head formation (e.g., Pelletier et al., 2013; Pelletier and Perron, 2012; Perron and Hamon, 2012). Automated tools to identify geomorphic features (i.e., floodplains, terraces, landslides) and transitional zones (i.e., hillslope-to-valley, floodplain-to-channel) have been used in conjunction with high-resolution elevation datasets from lidar, including Geonet 2.0 (Passalacqua et al., 2010), ALMTools (Booth et al., 2009), and TerrEX (Stout and Belmont, 2014).

1.2 Key advances in hydrology

Research utilizing lidar has advanced fundamental process understanding in snow hydrology (Deems et al., 2013), surface water hydraulics (Lane et al., 2004; Nathanson et al., 2012), and land-surface-atmosphere interactions (Mitchell et al., 2011). Lidar-derived snow depths (derived by differencing snow-on and snow-off elevations) over large ($>1\,km^2$) spatial extents from both ALS and TLS (Deems et al., 2013), have yielded unprecedented views of spatial snow distributions (e.g., Fassnacht and Deems, 2006; McCreight et al., 2014) and provided new insights into underlying processes determining spatial patterns in snow cover (Trujillo et al., 2009; Kirchner et al., 2014), accumulation and ablation rates (Grunewald et al., 2010; Varhola and Coops, 2013), snow water resources for planning (Hopkinson et al., 2012), and estimating the effects of forest cover and forest disturbance on snow processes (Harpold et al., 2014a). Change detection techniques have been effective for determining glacier mass balances (Hopkinson and Demuth, 2006), ice surface properties (Williams et al., 2013), and calving front movements (e.g., Arnold et al., 2006; Hopkinson et al., 2006). High resolution topographic information from lidar has proved important for channel delineation (Kinzel et al., 2013), rating curve estimation (Nathanson et al., 2012), floodplain mapping and inundation (Marks and Bates, 2000; Kinzel et al., 2007), and topographic water accumulation indices (Sørensen and Seibert, 2007; Jensco et al., 2009). Micro-topography measured using lidar shows potential for improving soil property and moisture information (e.g., Tenenbaum et al., 2006), surface and floodplain roughness (Mason et al., 2003; Forzieri et al., 2010; Brasington et

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al., 2012; Brubaker et al., 2013), hydraulic dynamics and sediment transport (Roering et al., 2012; McKean et al., 2014), surface ponding and storage volume calculations (Li et al., 2011; French, 2003), and wetland delineation (e.g., Lane and D'Amico, 2010). Certain hydrological modeling fields are well-poised to utilize high-resolution topography, such as movement of water in urban environments (Fewtrell et al., 2008), in-channel flow modeling (Mandlburger et al., 2009; Legleiter et al., 2011), and hyporheic exchange and ecohydraulics in small streams (e.g., Jensco et al., 2009). Finally, high-resolution, three-dimensional lidar measurements of canopy and vegetation structure (Vierling et al., 2008) have direct implications for modeling energy balances (Musselman et al., 2013) and evapotranspiration processes (Mitchell et al., 2011).

1.3 Key advances in ecology

Lidar-based remote sensing of vegetation communities (e.g., Lefsky et al., 2002; Maltamo et al., 2014; Streutker and Glenn, 2006) has transformed the way ecologists measure vegetation across multiple spatial scales. Substantial work has been undertaken using lidar to map vegetation structure and biomass distributions (see reviews by Seidel et al., 2011 and Wulder et al., 2012). These include the estimation of Leaf Area Index (LAI) (Riaño et al., 2004, Richardson et al., 2009; Hopkinson et al., 2013), vegetation roughness (Streuker and Glenn, 2006; Antonarakis et al., 2010), alpine tree lines (Coops et al., 2013), and total carbon storage and sequestration rates (Asner et al., 2012a; Baccini et al., 2012; Mascaro et al., 2011; Simard et al., 2011; Antonarakis et al., 2014) in forest, grassland, savannahs and/or shrubland communities. ALS has been used to characterize wildlife habitat in tree and shrub canopy (Hyde et al., 2005, Bork and Su, 2007; Vierling et al., 2008; Martinuzzi et al., 2009; Zellweger et al., 2014) and aquatic systems (McKean et al., 2008; Wedding et al., 2008; McKean et al., 2009). ALS has been a critical tool in modeling catchment scale water-availability for vegetation at fine (Harmon et al., 2014) and broad spatial scales (Chorover et al., 2011). Radiation transmission and ray-tracing models utilizing lidar provide ecologists with better tools to quantify in-canopy and below-canopy light environments (Lee et al., 2009; Bittner et

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al., 2014; Musselman et al., 2013; Bode et al., 2014; Moeser et al., 2014). Additionally, ecologists are beginning to quantify the impact of vegetation on micro-topography (Sankey et al., 2010; Pelletier et al., 2012; Harmon et al., 2014), as well as larger landform processes (Pelletier et al., 2013). Broad-scale lidar data allows for quantification of patches and mosaics amongst plant functional types across landscapes (Antonarkis et al., 2010; Dickinson et al., 2014). Ecologists have fused data from hyperspectral imaging and lidar to enable species classification for close to a decade (e.g., Mundt et al., 2006). However, new opportunities exist to link species-level detail and plant functional response through emerging technologies including co-deployment of hyperspectral and lidar sensors (Asner et al., 2012b), and hyperspectral (supercontinuum) laser technology (Kaasalainen et al., 2007; Hakala et al., 2012). By linking lidar with additional observations, researchers have begun to quantify species-level detail and plant health estimation (Cho et al., 2012; Féret and Asner, 2012; Olsoy et al., 2014) and carbon fluxes (Antonarkis et al., 2014).

2 Current toolkits and open questions for lidar in CZ science

Research based on lidar-derived information accounts for substantial advances within the cornerstone CZ disciplines. However, many open questions in CZ science require linked investigations across multiple disciplines. For example: what controls soil properties and processes? How do CZ fluxes and stores of carbon move in response to climatic variability? What will be the response of the CZ structure to disturbance and land use change? These CZ science questions demand a transdisciplinary approach capable of elucidating feedbacks among the geosphere, ecosphere, and hydrosphere.

A key advantage of lidar for understanding feedbacks is the coupling of previously unprecedented coverage over both broad temporal and spatial scales (Fig. 1). The utility of lidar for geo- eco- and hydrosphere investigations is dependent on the platform (e.g., TLS, ALS, or space-based laser scanning, SLS), with cross-platform observations capable of resolutions from 10^{-3} m to continental scales (Fig. 1). In terms of

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temporal extent, TLS, ALS and SLS are capable of employing weekly to sub-hourly scan rates (Fig. 1). Technologies allowing for faster scan rates will typically limit the spatial extent (Fig. 1). Advances in technology described in Sect. 2.3 will increase the spatial and temporal resolutions for all lidar platforms in the next five years (Fig. 1). The intersecting process scales shown in Fig. 1 demonstrate the viability of extracting transdisciplinary information from lidar given thoughtful experimental design and data collection.

2.1 Lidar as multi-disciplinary CZ tool

We conducted ta literature review of 147 peer-review papers that employed lidar datasets in the pursuit of improved process-based understanding. Our review found that most current lidar studies have a single disciplinary objective and rarely utilize the overlapping information in space and time generated by lidar available for transdisciplinary CZ research (Fig. 1). This is not surprising given the progress made in the cornerstone CZ disciplines using lidar datasets (Sects. 1.1 to 1.3). We organized the literature reviewed for this paper into a scoring system of geomorphic, hydrologic, and ecologic process knowledge advanced through individual lidar-based studies. For each paper we assigned 10 points among the three disciplines to capture potential transdisciplinary lidar use. For example, a study leading purely to hydrologic process advances would rank as 10 in the hydrology category and zero in the ecology and geomorphology categories. A transdisciplinary study balancing the process-based inferences among the three disciplines, with a more prominent ecological focus, would have been assigned scores of 3, 3, and 4 for geomorphology, hydrology, and ecology, respectively. Of course, this is a subjective scaling based on author opinions. To limit potential impacts of subjectivity, three different authors of the current paper assigned independent scores to each study and we used the average score to place each paper in the relative ranking triangle (Fig. 2).

The motivation for developing the conceptualization in Fig. 2 is to facilitate identification of studies employing transdisciplinary overlap (e.g., lie within the internal triangle)

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and motivate future collaborative research. The review showed 38 % of 147 studies were focused (score of 6 or higher) in geomorphology, 18 % in hydrology, 32 % in ecology, and the remainder having a more interdisciplinary focus. The few studies in the center of the triangle (i.e., studies receiving a minimum of 20 % in each discipline) could be considered as potential exemplars of CZ science using lidar as they balance well among each cornerstone discipline. Several studies were transdisciplinary in nature, but focused on lidar-derived topography and did not maximize information content on hydrological and ecological processes from lidar: Pelletier et al. (2012); Persson et al. (2012); Brubaker et al. (2013); Pelletier (2013); Coops et al. (2013), Rengers et al. (2014); and Pelletier and Orem (2014). Three of the studies reviewed could be qualified as potential exemplars through our simple (yet potentially subjective) analysis and can serve as possible roadmaps to guide future transdisciplinary investigations using lidar datasets (Fig. 2): Harman et al. (2014); Pelletier et al. (2013) and Perignon et al. (2013).

The potential exemplar CZ studies (Fig. 2) combined complementary information on geomorphologic, hydrologic, and ecologic processes from lidar datasets. For example, Harman et al. (2014) applied TLS to investigate coevolution of lidar-derived microtopography and hydrologic routing, vegetation (biovolume), and soil properties at two 100 m long semi-arid hillslopes. Utilizing lidar and limited field measurements, Harman et al. (2014) found that both alluvial and colluvial processes were important in shaping vegetation and soil dynamics on hillslopes. Pelletier et al. (2013), investigated landscape-scale ($> 10\,km^2$) variability in above-ground biomass, hydrologic routing, and topography derived from lidar at two mountain ranges in southern Arizona and applied a landscape evolution model to demonstrate the need to include ecological processes (e.g. vegetation density) to correctly model lidar-derived topography and biomass. Perignon et al. (2013) investigated topographic change following a major flood along a 12 km stretch of the Rio Puerco in New Mexico. They found that sedimentation patterns reflected complex interactions of vegetation, flow, and sediment at the scale of individual plants. These exemplar studies demonstrate the utility of lidar for trans-

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disciplinary process investigations at scales ranging from hillslopes (e.g., Harman et al., 2014), to stream reaches (e.g. Perignon et al., 2013), to mountain ranges (e.g., Pelletier et al., 2013). We provide additional examples to illustrate the overlapping processes observable with lidar that are motivated by CZ science questions in Sect. 2.4.

2.2 Analytical tools using lidar

Through our literature review and subsequent conceptualizations (e.g., Fig. 1) we have identified three clear areas where lidar observations have the potential to advance CZ science in the next five years: (1) quantifying change detection, (2) parameterization and verification of physical models, and (3) improved understanding CZ processes across multiple scales. Applying these tools is not mutually exclusive and each has seen different levels of previous research and development. For example, change detection utilizing lidar has received notable use in the CZ science community, particularly by geomorphologists analyzing topographic change over time. The use of lidar to quantify scaling relationships and thresholds remains relatively unexplored, despite robust scaling theories and analysis tools from other fields that are portable to lidar datasets. Similarly, integration of lidar datasets for either parameterization or verification has seen limited development within CZ-relevant models.

2.2.1 Change detection

Lidar-based change-detection analyses (CDA), i.e., mapping landscape adjustments through time in multi-temporal ALS and TLS datasets, have provided comprehensive measurements of snow depth (e.g., Harpold et al., 2014b; Tinkham et al., 2014) and ablation (Egli et al., 2012), co-seismic displacements after earthquakes (e.g., Oskin et al., 2012), changes in aeolian dune form and migration rates (e.g., Pelletier, 2013), fluvial erosion (e.g., Anderson and Pitlick, 2014; Pelletier and Orem, 2014), earthflow displacements (e.g., DeLong et al., 2012), knickpoint migration in gully/channel systems (e.g., Rengers and Tucker, 2014), cliff retreat along coasts (Young et al., 2010), permafrost degradation (Levy et al., 2013; Barnhart and Crosby, 2013), forest growth (Yu et al., 2004; Næsset and Gobakken, 2005) and changes in biomass (e.g., Meyer et al., 2013; Olsoy et al., 2014). Traditionally, lidar point clouds have been rasterized prior to differencing (e.g., Wheaton et al., 2010) using open-source processing toolkits (e.g., GCDv6) available to facilitate raster-based differencing. However, new methods such as Iterative Closest Point (Nissen et al., 2012), particle image velocimetry (Aryal et al., 2012), and Multiscale Model to Model Cloud Comparison (Lague et al., 2013) enable direct differencing of point clouds. It is likely that continued methodological advances will drive improved understanding of CZ processes by progressing the capabilities and quality of CDA. Structure from Motion (SfM) estimates three-dimensional structures from two-dimensional images providing an easily portable and low-cost method for making high-frequency change detection measurements (Westoby et al., 2012; Fonstad et al., 2013). There is also potential to apply time-series hyperspectral lidar datasets to quantify changes in forest health over time. Similarly, integration of bathymetric lidar with ALS opens the potential to monitoring dynamic changes in river flow and sediment transport (Flener et al., 2013). Although researchers often implement CDA using historic datasets (Rhoades et al., 2009), challenges arise from sparse metadata and reduced accuracy, thereby limiting the datasets usefulness (e.g. Glennie et al., 2014). Future CDA may be improved by further establishing, through repositories such as OpenTopography and UNAVCO, best practices for dataset sharing and archiving.

2.2.2 Scaling CZ processes

While researchers have harnessed existing scaling theories and tools utilizing lidar datasets, there is room for expansion using the range of scales afforded by lidar technologies (Fig. 1). Two complementary techniques, characterizing fractal patterns (e.g., Deems et al., 2006; Glenn et al., 2006; Perron et al., 2008) and process changes expressed as fractal breaks (e.g., Drake and Weishampel, 2000), benefit from the extensive breadth of spatial scales offered by lidar data. Self-similar patterns across scales indicate consistent processes and thus, provide a framework for sampling, modeling, and re-scaling processes. Variograms and semi-variograms are commonly employed to plot lidar-derived attributes of interest such as snow distribution (e.g., Deems et al., 2008; Harpold et al., 2014a) or forest spatial patterns (e.g., Boutet et al., 2003) against scale. Fractal and fractal deviations, as well as the length-scales of landscape structure (Perron et. al., 2008), convey important CZ information, e.g., the effect of tree-root spacing through time on soil production (Roering et al., 2010), patterns in tree gap-formation (Plotnick et al., 1996; Frazer et al., 2005), and underlying abiotic and biotic controls on forest fractal dimensions (Drake and Weishampel, 2000). Within the CZ framework, lidar allows consideration of topographic variation and biomass distribution (Chorover et al., 2011), and spatial thresholds for interactions among vegetation, hydrology, lithology, and surface processes ranging from the grain to landscape scale (e.g., Musselman et al., 2013; Pelletier et al., 2013; Harman et al., 2014). Zhao et al. (2009) developed a scale-invariant model of forest biomass, which illustrated the utility of scale-independent methods. However, we caution that one scientist's signal may be another's noise (Tarolli, 2014). Signal recognition may involve smoothing at one scale to quantify a relevant landscape metric, such as hillslope curvature (and derived erosion rates) (Hurst et al., 2013), which in turn limits valuable information at another scale, such as hydrologically-driven surface roughness or the spacing of tree-driven bedrock disruption (Roering et al., 2010; Hurst et al., 2012). Overall, lidar datasets retain the promise of up- or down- scaling feedbacks among multiple processes.

2.2.3 Model parameterization and verification

The wealth of recently collected lidar data has potential to inform the choice of physically-based model parameters and verify model output. Improved terrain representation has helped characterize hysteretic relationships between water storage and contributing area in large wetland complexes within parameterized runoff models (Shook et al., 2013), improve mapping in and along river channels to parameterize network level structure and flood inundation models (French, 2003; Kinzel et al., 2007;

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Snyder, 2009; Bates, 2012), and expand investigation of geomorphological change in floodplains (Thoma et al., 2005; Jones et al., 2007). Lidar provides vertical information that permits the direct retrieval of forest attributes such as tree height and canopy structure (Hyyppä et al., 2012; Vosselman and Maas, 2010) that can be used to model canopy volume (Palminteri et al., 2012), biomass (Zhao et al., 2009), and the transmittance of solar radiation (Essery et al., 2008; Musselman et al., 2013; Bode et al., 2014). Lidar has also proven to be instrumental in the verification of model states. For example, lidar datasets have been used to verify physically-based models, including landscape evolution models (Pelletier et al., 2014; Pelletier and Perron, 2012; Rengers and Tucker, 2014), aeolian models (Pelletier et al., 2012; Pelletier, 2013), physiological models (Coops et al., 2013), and snowpack energy balance models (Essery et al., 2008; Broxton et al., 2015). Simpler, empirical models have also been developed using lidar-derived estimates of soil erosion (Pelletier and Orem, 2014) and snow accumulation and ablation (Varhola et al., 2014). Better recognition within CZ modeling of the potential benefits of lidar for model calibration and verification could lead to increased utilization and targeted acquisitions in the future.

2.3 Adoption and utilization of lidar datasets

New and improved lidar datasets are more likely to result in transformative CZ science if a number of key opportunities (and impediments) are recognized. The research topics discussed in Sect. 2.2 require attention to four key areas in order to maximize the applicability of lidar in CZ science: (1) emerging data acquisition technology, (2) availability of processing and analysis techniques, (3) linkages to in situ observations, and (4) linkages to remote sensing observations. The first two areas recognize the importance of technological advances and information sharing to enhance lidar's data quality and coverage. The second two areas demonstrate the potential to extend scientific inferences made from lidar with linkages to multiple, complementary observations.

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2.3.1 Data acquisition technology

Future advances in data acquisition technologies will provide greater information and spatiotemporal coverage from lidar (and lidar-like) datasets. Several new lidar technologies are rapidly increasing data quality (accuracy, precision, resolution, etc.) and information content. Full waveform lidar data promises to provide better definition of ground surface and vegetation canopy (Wagner et al., 2008; Mallet and Bretar, 2009). Utilizing blue-green light spectrum, lidar systems are capable of bathymetric profiling (McKean et al., 2009; Fernandez-Diaz et al., 2014) and potentially determining turbidity and inherent optical properties of the water column. Lidar systems have demonstrated the benefits of combining point clouds with alternative data sources by, for example, including intensity and/or RGB cameras (Bork and Su, 2007) that collect data synchronously with the lidar and provide metadata for each point in the cloud. Less expensive and more adaptable lidar systems (Brooks et al., 2013) and alternative 3-D remote sensing techniques, such as SfM or low-cost 3-D cameras (Mankoff and Russo, 2013; Javernick et al., 2014), promise to allow high resolution monitoring at finer temporal resolutions and lower costs. Increasingly, lidar observations are being combined with passive electro-optical multispectral and hyperspectral images (Kurz et al., 2011). Lidar technology already includes active multispectral laser systems and hyperspectral laser observations of object reflectance are likely only three to five years away (Hakala et al., 2012; Hartzell et al., 2014). These systems promise to lessen the need for multiple sensors, thus reducing uncertainties due to data registration, lowering costs, and reducing processing time. The combination of these technologies hold promise to cost-effectively monitor aspects of the CZ at time scales of days or less, with information content that includes not only 3-D structure, but also spectral information that is potentially capable of determining vegetation composition and health, soil and bedrock composition, and water content.

In addition to emerging lidar acquisition systems, new and existing collection platforms are substantially broadening data coverage. Collection of lidar from fixed-wing

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aircraft is expanding to national scales through programs such as the U.S. Geological Survey's 3-D Elevation Program (3DEP), Switzerland's national lidar dataset collected by the Federal Office of Topography, Sweden's Lantmateriet (http://www.lantmateriet.se), Netherlands' Public Map Service (http://www.pdok.nl/en/node), Denmark's Geodata Agency (http://gst.dk), Finland's National Land Survey (http://www.maanmittauslaitos.fi/en/maps-5), United Kingdom's Environment Agency (http://www.geomatics-group.co.uk/GeoCMS), and Australia's AusCover (http://www.auscover.org.au/). Additionally, acquisition of aircraft and lidar systems by institutional research programs have led to greater capabilities for ecological research by the National Ecological Observatory Network (Kampe et al., 2010) and snow water resources via NASA's Airborne Snow Observatory (http://aso.jpl.nasa.gov). Institutional systems and operational expertise are also available for short-term research projects across a range of Earth science applications (Glennie et al., 2013) by the National Center for Airborne Laser Mapping (NCALM) and UNAVCO. Of particular interest to the CZ community is the development of unmanned aerial systems (UASs) that are capable of mounting small lidar systems for rapid deployment (Lin et al., 2011; Wallace et al., 2012). Long-range UASs offer the potential for repeat lidar acquisitions at a fraction of the cost of current ALS platforms.

2.3.2 Data access, processing, and analysis

The crux in successfully leveraging a flood of new lidar (and other high-resolution topographic information) data for CZ science (e.g., Stennett, 2004) will be the ability to extract meaningful information from these rich and voluminous datasets. These new lidar datasets require data processing and analysis tools be optimized to handle increasingly large datasets with greater information content. Processing limitations are likely to reduce the size and frequency that very high information content datasets can be collected, e.g. waveform or multispectral datasets pose processing challenges at the continental scale that may be manageable at the watershed-scale. Further, new software and workflows need to be developed to enable scientists to incorporate lidar data into detailed models of the CZ without expertise in remote sensing. The CZ science community must engage in a concerted effort to develop (and/or adopt from other domains) new open source tools that leverage high performance computing resources available through programs such as NSF's XSEDE (https://www.xsede.org/home). By increasing the scalability of CZ lidar-oriented processing and analysis tools, computationally intensive analysis and modeling at the highest resolution of the lidar datasets will be possible. In addition to increasing software scalability, new processing tools are necessary to take advantage of new data types, such as full waveform lidar (Wagner et al., 2008; Mallet and Bretar, 2009) and hyperspectral laser technology (Hakala et al., 2012). Cloud computing and the "big data paradigm" that is increasingly common in both industry and academia (Mattman, 2013) present opportunities for the CZ lidar community. Due to efforts such as NSF's OpenTopography (Crosby et al., 2011), there is a large volume of CZ-oriented lidar online and feely available to the community. OpenTopography already offers on-demand processing services (Krishnan et al., 2011) that permit users to generate standard and commonly used derivatives from the hosted lidar point cloud. By coupling data processing with data access, users are not required to download large volumes of data locally or have the dedicated computing and software resources to process these data. Although many CZ-oriented lidar datasets are already available to the community through resources such as OpenTopography in the US, there are numerous other lidar datasets that are not accessible because they are not available online or access is restricted. Many of these "legacy" datasets are likely to be important temporal baselines for comparison against future data focused on understanding CZ processes (Glennie et al., 2014; Harpold et al., 2014a).

2.3.3 Linkages to in situ observations

Many CZ studies have incorporated in situ observations to extend or confirm inferences made with lidar-derived datasets. In situ measurements are time consuming to collect, often expensive to analyze, and limited in terms of spatial coverage. As a result, researchers must be judicious with in situ data collection and maximize integra-

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tion with lidar datasets. Physical and chemical properties of soil and rock are among the in situ observations commonly integrated with lidar datasets. For example, lidar-based studies have integrated distributed measurements of soil hydraulic properties (Harman et al., 2014) and soil thickness (Roering et al., 2010; Pelletier et al., 2014; West et al., 2014), as well as radioactive isotopes in soils (West et al., 2014). Lidar datasets have also been used to extend in situ observations of snow depths (Harpold et al., 2014a; Varhola and Coops, 2013) and carbon fluxes (Hudak et al., 2012) in both space and time. In addition to scientific inferences, lidar can be used to improve sampling designs to reduce time and analytical expenses. For example, lidar has improved insight into sampling snow measurements necessary for water management (McCreight et al., 2014). A number of challenges remain with regard to linking lidar-derived information to in situ measurements, including poor GPS information for historical datasets, constraining the observational footprint of different measurements, and comparing lidar-derived metrics to typical field measurements. Despite these challenges, opportunities exist to better integrate historical measurements into lidar-based studies and develop new in situ observations that use lidar datasets to up-scale CZ processes.

2.3.4 Linkages to satellite remote sensing

Satellite observations of surface-altimetry, reflectance, permittivity, and atmospheric profiles provide observations of CZ processes at multiple spatiotemporal scales, frequently with global coverage. The high spatial resolution offered by lidar technology compliments the regular temporal frequency of satellite observations, which could be used to co-calibrate and co-validate these types of datasets. Satellites also provide another lidar acquisition platform. There are numerous examples where lidar datasets have been used to calibrate and verify coarser estimates of vegetation, cryosphere (e.g., glaciers, permafrost, snowpacks, etc.), and geomorphic processes made via satellites. For example, Mora et al. (2013) used detailed lidar measurements of vegetation structure to quantify the spatial and temporal scalability of above ground biomass

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of continental forests measured with the very high spatial resolution (VHSR) satellite. In data limited regions of Uganda, lidar fused with Landsat datasets have improved modeled biomass predictions and understanding of phenologic processes (Avitable et al., 2012). Varhola and Coops (2013) and Ahmed et al. (2014) introduce methods for detecting changes in vegetation structure and function from disturbance by fusing Landsat and lidar measurements, and Bright et al. (2014) used similar fused datasets to investigate changes following forest mortality. Applications combining lidar and satellite measurements to change detection have also been applied to evaluate the effects of vegetation on snow disappearance (Liu et al., 2008) and compare to model and satellite-derived estimates of snow-covered area (Kirchner et al., 2014; Hedrick et al., 2015). A multifaceted approach for the prediction and monitoring of landslides was proposed by Guzzeti (2012) using measurements from satellites and lidar, however it has been difficult to detect small changes of slope in areas of dense forest cover (Khamsin et al., 2014). The Ice, Cloud, and land Elevation Satellite (ICESat) was a NASA mission from 2003 to 2009 that mapped changes in glacier mass balance using space-based lidar (Kohler et al., 2013). Scientists have used ICESat's Geoscience Laser Altimeter System (GLAS) to identify areas of forest regeneration along the Mississippi (Li et al., 2011) and has been applied in development of a global forest height map (Simard et al., 2011). A second mission (ICESat-2) is slated to launch in 2017 and while focused on ice sheet and sea ice change, it will provide complementary products to characterize terrestrial ecology. Furthermore, other current and future satellite missions will provide CZ observations that integrate with lidar, including soil moisture, groundwater storage, soil freeze/thaw, carbon flux, and primary productivity (Schimel et al., 2013). Of particular interest might be the Surface Water and Ocean Topography (SWOT) mission that provides coarse water and land topography using radar that has potential to compliment finer-scale measurements acquired with lidar. A variety of challenges exist in fusing lidar with satellite remote datasets, particularly efficient processing of large datasets that span collection platforms and spatiotempral variability while maintaining expert knowledge in data interpretation (Matmann, 2013).

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2.4 A proposed five-year vision

The fields of CZ science and lidar-based technology are both advancing rapidly. We present a vision that recognizes advances in science and technology to best position CZ researchers at the forefront of lidar hardware, processing capabilities, and linkages with complementary observations. These ideas are guided by the recognition that lidar is capable of simultaneously observing processes signatures from multiple CZ disciplines (Fig. 1). To elucidate this point, we discuss three examples of CZ research questions and suggest how they could benefit from current and future lidar technologies. We also provide specific recommendations for CZ researchers working (or considering working) with lidar datasets. Our intent is to catalyze CZ interest in the transdisciplinary possibilities of lidar datasets, while increasing the influence of CZ scientists within the broader group of lidar end-users.

Technological advances can be conceptualized as increasing data coverage, quality, and information, including new acquisition platforms or higher acquisition rates (Fig. 3). Other advances, such as full-waveform information or hyperspectral lasers, will increase the data quality and information content extractable from lidar datasets. Some examples of linked research questions (Fig. 3) that demonstrate the value of technological advances in lidar for CZ science are,

1. How does co-variation between vegetation and hydrological flowpaths control the likelihood and distribution of earth flows and landslides?

2. How is the rapidly changing cryosphere influencing hydrological connectivity, drainage network organization, nutrient and sediment fluxes, land-surface energy inputs, and vegetation structure?

3. How does above- and below-ground biomass control bedrock to soil production sediment mixing and transport and associated carbon fluxes via bioturbation and hillslope transport?

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These research questions span a wide-range of spatial and temporal scales, from smaller and faster (10^1 s and 10^{-2} min) in Question 3 to larger and long-term (10^6 s and 10^5 min) in Question 2 (see Fig. 1). Our ability to answer them benefit from several facets of improving lidar technologies, including higher acquisition rates and larger ranges, more rapid and robust deployment options, and improved processing resources for extracting information. Future lidar technologies could benefit Question 1 by identifying specific vegetation species via hyperspectral laser technologies, increasing accuracy of bare-earth estimation to improve hydrologic routing using full waveform analysis, and increasing coverage of landslide-prone areas from different physiographic regions (Fig. 3). New technology will benefit Question 2 by providing riparian vegetation productivity, measuring channel bathymetry using blue-green lidar, and with new platforms that increase sampling frequency via UASs or other low cost platforms. Lastly, new technology will benefit Question 3 with better estimates of above-ground biomass and bare-earth extraction using full waveform analysis and improving fine-scale change detection with greater processing resources. The goal of these example questions and their conceptualization (Fig. 3) is to provide the reader with concrete examples of transdisciplinary opportunities that may provide stimulus for their future CZ research.

We propose five recommendations to unite the CZ community around improved utilization and advocacy of lidar technology in important scientific contexts that synthesize the opportunities and impediments discussed previously:

- *Open lines of communication:* develop communication within and among groups, including individual CZ disciplines, remote sensing scientists, computer scientists, and funding agencies. Workshops have the potential to increase communication between "data-users" and "data-creators". Working groups within CZ communities, like the critical zone exploration network (www.czen.org) or townhall meetings at international Earth science conferences, could form sustainable communication venues.

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- *Increase information extraction:* advocate for lidar repositories that are interoperable and broaden data access, as well as open-source and community-centric processing resources. Ultimately, enhanced and streamlined data processing and analysis will enable CZ researchers to concentrate on understanding fundamental science problems instead of struggling with data access, processing, and analysis. Increasing access to lidar datasets facilitates greater information extraction in meta-analysis studies and as other, improved processing tools become available.
- *Make lidar collections more accessible:* advocate for new acquisition technologies that lower the cost of lidar collection and increase its availability, such as unmanned platforms. Institutional acquisitions of lidar systems also significantly increase accessibility to lidar systems. Community-supported lidar systems available to researchers, through agencies, such as UNAVCO and NCALM, should also be encouraged.
- *Focus on key technologies:* support the development of new lidar technologies that are useful for linking disciplinary observations. For example, our review has stressed the potential benefits that hyperspectral laser technologies for linking CZ functions to processes (Fig. 3). Other key technologies include new acquisition platforms (UASs) and improved open-source processing capabilities and open-source industry-standard data formats. The community should continue a dialogue about critical technologies in the venues mentioned previously.
- *Link alternative observations:* consider other remote sensing observations that may be complimentary to lidar (e.g., thermal, infrared, optical, and microwave). Be mindful of the synergies of collecting lidar data over areas with in situ observations. Maintain awareness of competing technologies that may prove more suitable than lidar for specific CZ applications.

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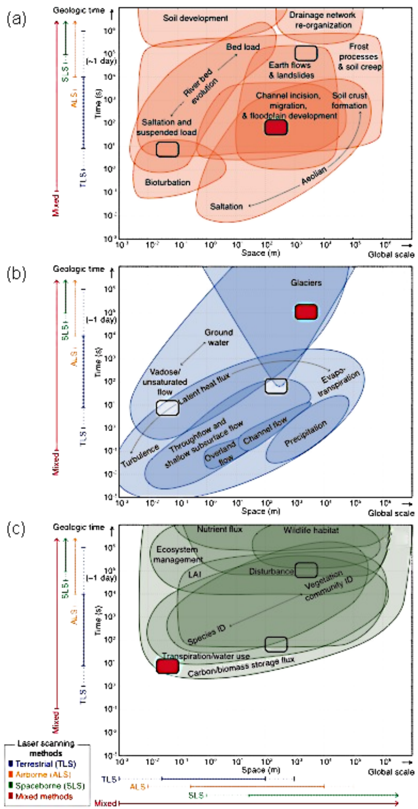

Figure 1. Important CZ processes graphed as a function of time versus space for geomorphology **(a)**, hydrology **(b)**, and ecology **(c)**. The spatial and temporal scales that lidar is currently addressing are shown as colored bars, with dotted bars indicating increasing resolutions and larger extents available in the next five years. Overlapping spatiotemporal scales that encompass the example questions in the Fig. 3 are also noted.

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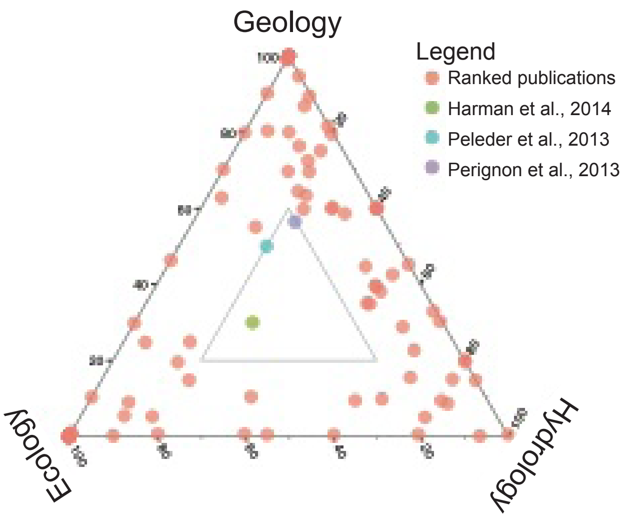

Figure 2. Depiction of the disciplinary focus of 147 journal articles using lidar. Articles were qualitatively ranked based on their applicability to geomorphological, hydrological, and/or ecological process understanding. Articles in the center (circle, triangle and square symbols) delineate example of transdisciplinary lidar applications mentioned in the text. Articles that received a 10 out of 10 in any discipline are difficult to distinguish and include 45 for ecology, 17 for geology, and 12 for hydrology.

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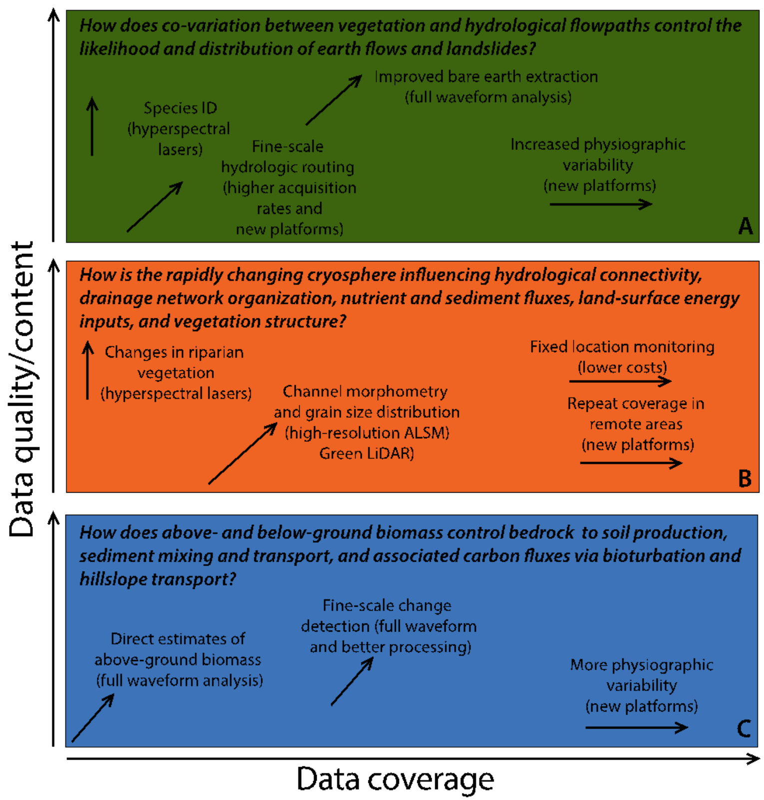

Figure 3. Example CZ research questions conceptualizing the transdisciplinary potential of lidar datasets when coupled with future technological advances. The questions encompass processes from geomorphology **(a)**, hydrology **(b)**, and ecology **(c)** that overlap spatial and temporal scales. These scales are noted in Fig. 1. The text in the panel notes specific improvements offered and the technology needed in parentheses. The arrows qualitatively represent whether the technological advance expands data coverage and/or data quality/content.

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