Geomorphology 200 (2013) 172–183

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

‘You are HERE’: Connecting the dots with airborne lidar for geomorphic fieldwork

Joshua J. Roering *, Benjamin H. Mackey [1], Jill A. Marshall, Kristin E. Sweeney, Natalia I. Deligne [2], Adam M. Booth [3], Alexander L. Handwerger, Corina Cerovski-Darriau

Department of Geological Sciences, University of Oregon, Eugene, OR 97403-1272, USA

ARTICLE INFO

Article history:
Received 3 February 2013
Received in revised form 7 April 2013
Accepted 8 April 2013
Available online 13 April 2013

Keywords:
Airborne lidar
Hillslopes
Channels
Landslides
Spatial Cognition

ABSTRACT

The emergence of airborne lidar data for studying landscape evolution and natural hazards has revolutionized our ability to document the topographic signature of active and ancient surface processes. Notable lidar-facilitated discoveries, however, would not have been possible without the coupling of fieldwork and lidar analysis, which contradicts the ill-considered notion that high resolution remote sensing technologies will replace geomorphic field investigations. Here, we attempt to identify the primary means by which lidar has and will continue to transform how geomorphologists study landscape form and evolution: (1) lidar serves as a detailed base map for field mapping and sample collection, (2) lidar allows for rapid and accurate description of morphologic trends and patterns across broad areas, which facilitates model testing through increased accuracy and vastly increased sample sizes, and (3) lidar enables the identification of unanticipated landforms, including those with unknown origin. Finally, because the adoption of new technologies can influence cognition and perception, we also explore the notion that the ongoing use of lidar enables geomorphologists to more effectively conceptualize landforms in the field.

1. Introduction

For early geomorphologists, field observations were central to how they investigated study sites and perceived the evolution of landscapes. Although this statement may seem obvious, upon considering the recent proliferation of maps and digital geospatial data, it invites an exploration of how technology influences how geomorphologists develop intuition about landscape development. As one of the forefathers of geomorphology, G.K. Gilbert's dependence on field observation and expedition living was so embedded in his psyche that he included a drawing entitled ‘Ways and Means’ depicting his mule, Lazarus, Duke of York, in his seminal 1877 report on the Geology of the Henry Mountains. Although whimsical at first blush (note that the illustration only appears in the first printing of the report), this drawing reflects Gilbert's reliance on and reverence for (what we now consider) ‘old-school’ technology that facilitated his protracted and far-flung field campaigns. In a related vein, Luna Leopold's contributions firmly establish the primacy of field observations, especially quantitative ones. Many of Leopold's publications begin with a simple statement about a fundamental landscape property that can be readily noted in the field, even with the untrained eye. For example, his 1966 article on river meandering begins with “Is there such thing as a straight river? Almost anyone can think of a river that is more or less straight for a certain distance, but it is unlikely that the straight portion is either very straight or very long” (Leopold and Langbein, 1966).

Decades later, digital topographic data, remote sensing imagery, and computing power afford the opportunity to readily witness many of the most captivating features on Earth not only via field observation but also from one's office. Initially, coarse-scale maps and data sets enabled geomorphologists to analyze broad landscape patterns, thus, facilitating collaboration with structural geologists and geophysicists concerned with large-scale geological problems, such as plate boundaries and fold-thrust belts. For process-scale studies of hillslope processes and valley network organization, however, the standard topographic data sets generated from aerial photos (with point densities of 1 point per 900 m^2) proved to be too coarse. Maps or imagery, such as shaded relief models generated from these early DEMs (digital elevation models), revealed landforms, but they systematically failed to portray features that are readily identifiable in the field (Fig. 1). For example, the finest scale of channels and interfluves, which defines drainage density, as well as potential shallow landslide sources in steeplands, is typically not resolved by 30-m DEMs (Montgomery et al., 2000). As a result, the most readily available and widely used topographic data sets failed to portray landforms that reflect fundamental geomorphic problems regarding the organization of the surface of Earth as well as potential natural hazards (e.g., Duffy et al., 2012). More so, contour maps derived from these data often proved intractable for successful identifying one's

* Corresponding author. Tel.: +1 541 346 5574; fax: +1 541 346 4692.
E-mail address: jroering@uoregon.edu (J.J. Roering).
[1] Now at University of Canterbury, New Zealand.
[2] Now at GNS Science, New Zealand.
[3] Now at California Institute of Technology.

0169-555X/$ – see front matter
http://dx.doi.org/10.1016/j.geomorph.2013.04.009

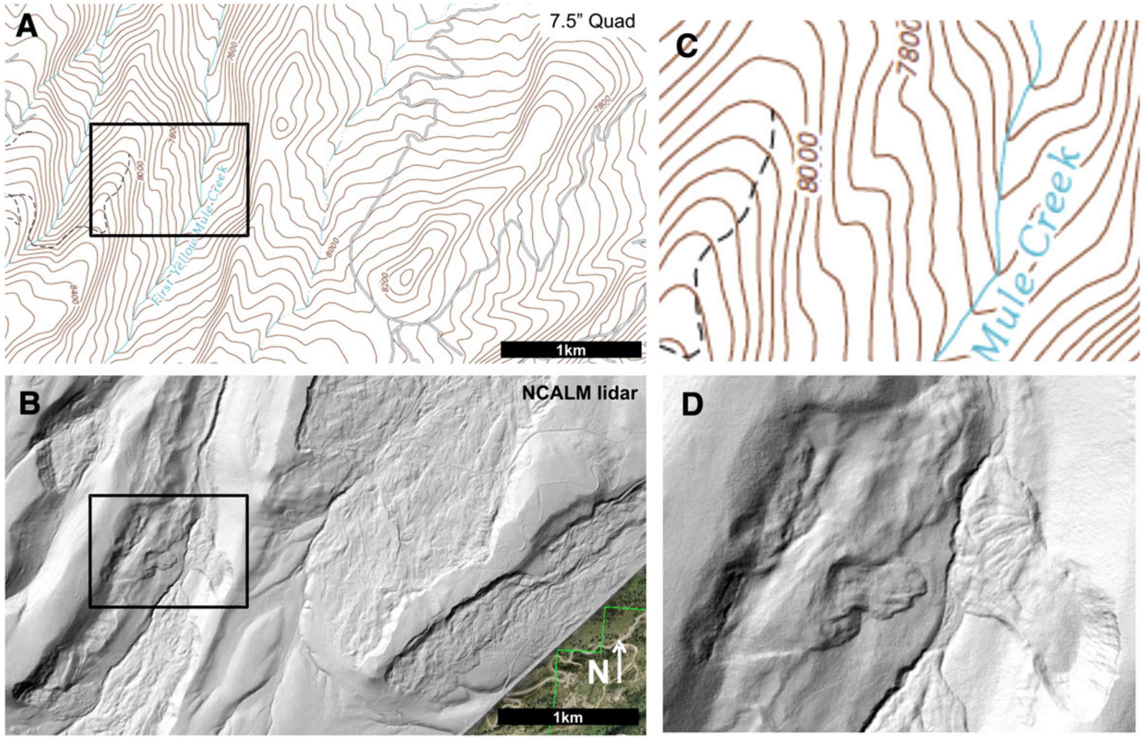

Fig. 1. Comparison of terrain near Big Sky, Montana, represented with USGS 7.5″ topographic map (A, C) and airborne lidar (B,D). The boxes in A and B correspond to the enlarged areas shown in C and D, respectively. Large landslides have shaped the vast majority of the area, including slumps and flow-like features. The topographic signature of individual landslides is clearly visible in the lidar imagery, but not apparent in the USGS contour data.

location in the field, further limiting the utility of available DEMs for process-scale geomorphic research.

Instead, investigations of process-scale geomorphology required extensive fieldwork, particularly surveying, to document and analyze spatial patterns of landscape morphology at the relevant resolution. The advent of total stations (theodolites and lasers) and global positioning system (GPS) receivers provided critical tools for topographic surveying even though acquisition rates were slow, costly, limited in scope, and challenging in remote and steep regions. Dense vegetation and steep terrain, in particular, can render total stations and GPS ineffective by blocking sight lines and satellite signals. As a result, the pressing need for high resolution topographic information guaranteed that process-oriented geomorphologists remained actively engaged with their study sites through extended field campaigns.

In the late 1990s, the increasing availability, affordability, accuracy, and point density of airborne lidar data sets constituted a monumental advance in our ability to resolve process-scale landforms. The importance of this technological innovation for geomorphic research cannot be overstated. Airborne lidar does not represent an incremental increase in data density: it enabled a more than two orders of magnitude increase in topographic information (Fig. 2). Research-grade, lidar-derived bare-earth point densities commonly exceed 1 point per square meter (Slatton et al., 2007); at this resolution, features such as gully heads, landslide scars, channel banks, and bedrock tors can be readily identified and mapped from afar. Remarkably, geomorphologists were suddenly given the ability to work with maps that portrayed an arguably complete depiction of channel networks. This technology has been used in scores of geomorphic papers, including many that tackle the same fundamental questions that challenged Gilbert, William Morris Davis, and subsequent generations of field-oriented geomorphologists.

In this contribution, our goal is not to simply highlight scientific discoveries enabled by lidar. Rather, we explore how the availability of airborne lidar has changed how geomorphologists go about their work, particularly their field investigations. In undertaking these tasks, we emphasize many of our own lidar-enabled contributions because we possess first-hand knowledge of how the availability of lidar imagery influenced our research process, including the fieldwork. The list of lidar-facilitated findings is vast and includes the identification of previously unmapped faults in metropolitan areas and the discovery of paleo-landslide dammed lakes. The complete context of these discoveries, however, would not have been realized without significant fieldwork in concert with lidar analyses. The perception that desktop, virtual geomorphic investigations fueled by lidar and an array of other remote sensing imagery will replace 'Boots on the ground' geomorphic observation simply has not come to fruition, and we contend that it will not. Instead, scientific investigation using both lidar and targeted field observation has strong potential as an efficient and effective means of geomorphic analysis (Church, 2013).

Our survey of the literature suggests that airborne lidar has influenced geomorphic research in the following ways: (1) lidar serves as a detailed base map for field mapping and sample collection, (2) lidar allows for rapid and accurate description of morphologic trends and patterns across broad areas, which facilitates model testing through increased accuracy and vastly increased samples sizes, and (3) lidar enables the identification of unanticipated and sometimes unexplained landforms. Lastly, we will explore the notion that exposure to lidar data affects how geomorphologists perceive landscapes in the field. Recognizing that lidar now enables geomorphologists to easily map subtle differences in hillslope convexity or surface roughness, has this enhanced morphologic knowledge increased our awareness of reality? In other words, does lidar stimulate new ways for us to conceptualize natural landscapes?

2. Pre-lidar technologies for documenting topography

Prior to the advent of lidar, geomorphologists relied primarily on field techniques, such as sketches, plane table/alidade surveys, inclinometers, pressure altimeters, and total stations, to quantify local landform morphology. Gilbert (1877) described the geology and surface processes of the Henry Mountains using field sketches and

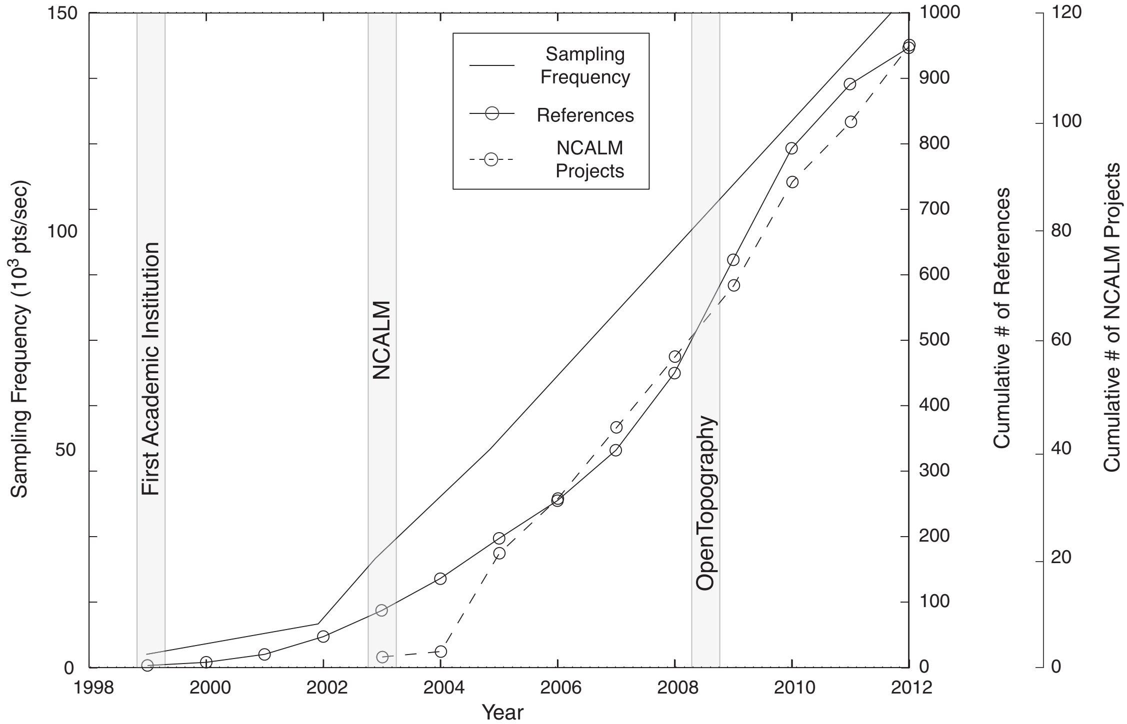

Fig. 2. Timeline showing the evolution of lidar-based geomorphological research. Solid line shows sampling frequency (proxy for bare-earth point spacing) using data from Slatton et al. (2007). Solid line with circles shows the cumulative number of references found using GeoRef to search for "lidar AND geomorphology". Dashed line with circles shows cumulative number of NCALM projects. Vertical bands mark key events in the history of lidar for geomorphic research.

observations. Because these often idealized sketches essentially served as their data, early workers devoted a great deal of time and effort on these depictions, much to the surprise and delight of modern geomorphologists (Fig. 3). Decades later, the quantitative revolution in geomorphology (e.g., Horton, 1945; see Salisbury, 1971, for a thorough review) meant that subsequent workers, such as Leopold and Maddock (1953), used survey methods to measure landscape properties and record change over annual to decadal timescales. Data collection via these methods is limited by time; for example, a team of three students can collect only 30 to 40 topographic data points per day using a plane table and alidade. Total stations, reflectorless lasers, ground-based lidar, and GPS receivers have alleviated this limitation to a certain extent, but surveying remains challenging in remote and steep landscapes (Perroy et al., 2010).

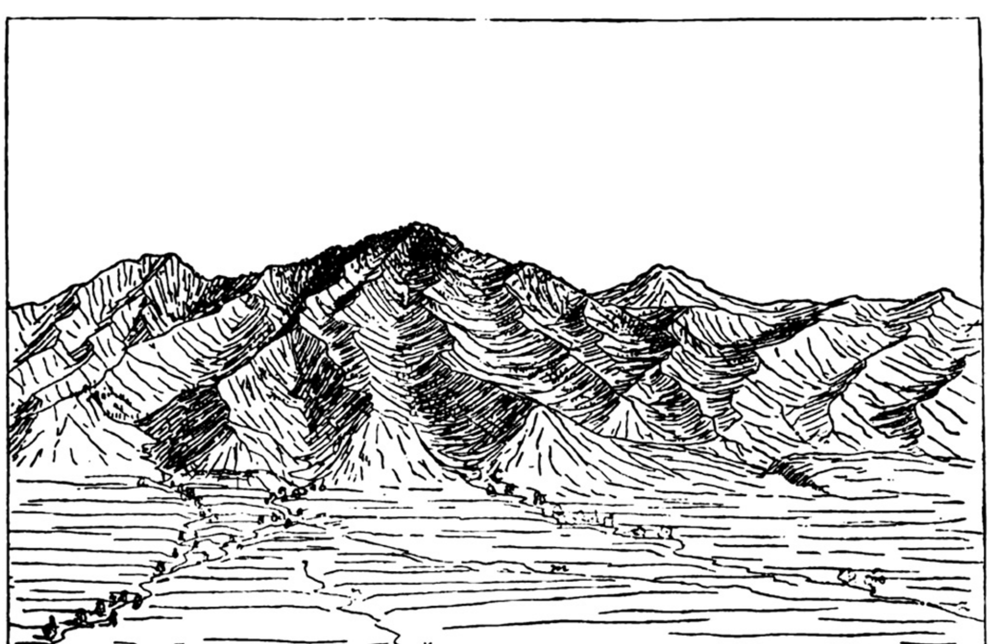

Fig. 3. Idealized sketch of a 'planation' feature from Gilbert's (1877) report, where it appears as Fig. 62. The sketch shows current stream courses across a plain subject to stream union and separation over long time periods. Modified from Gilbert (1877).

Surveying landforms requires that researchers make choices about the extent and density of topographic information they acquire. Even field sketches require deliberate thinking on the spatial field and the level of detail to be included. Certainly, the simple act of making these decisions encourages engagement with one's field area, but do drawbacks exist to using field techniques as the sole means of documenting topography? In determining appropriate survey locations, even the most savvy and intellectually rigorous geomorphologist can bias their data collection by imposing preconceived notions on the landscape. For instance, the classic Wolman and Leopold (1957) description of meandering, gravel-bed streams with fine-grained floodplains in the mid-Atlantic assumed that these streams were equilibrium landforms that had persisted from prior to European settlement. Recent work using lidar data acquired over numerous broad valleys coupled with detailed analysis of historical archives and floodplain stratigraphy, however, has shown that these streams are the product of eighteenth-century mill dams (Walter and Merritts, 2008). In this case, the scale and extent of human alteration to the valley systems made the millpond legacy challenging to decipher from local field observations. Furthermore, because our conceptualization of landscapes changes over time, project-specific field survey strategies can limit the utility of data for future investigation. By contrast, lidar provides objective, high resolution topography that functions as a topographic archive, facilitating reinterpretation of landscapes as the field of geomorphology advances.

3. Airborne lidar background

In the past 15 years, the availability, use, and quality of research-grade airborne lidar data sets have dramatically increased (Fig. 2). In the 1990s, lidar-generated data sets were sparsely available because private contractor acquisition costs were very expensive, necessitating small coverage areas. In 2000, the University of Florida and Florida International University became the first academic institutions to acquire a lidar machine for research purposes, enabling a vast expansion of lidar available to the geoscience community (Carter et al., 2001). Geomorphologists were among the first to recognize the capabilities of this technology and in 2003 the National Science Foundation sponsored the National Center for Airborne Laser Mapping (NCALM) with the primary goals of providing research-grade lidar data for scientific use, advancing the state-of-the-art in lidar mapping, and training graduate students. Since its establishment, NCALM has acquired over 100 lidar data sets, which are publically available through the NCALM Data Distribution Center (ncalm.org). Over this time period, many states embarked on lidar acquisition campaigns through cooperative agreements with local, state, and federal agencies, although the quality and point density of these data has been highly variable. In Oregon, the state geological agency, the Department of Geology and Mineral Industries (DoGAMI), spearheaded a highly successful lidar consortium that has acquired lidar data over a substantial portion of the western half of the state (Luccio, 2013). In the Puget Sound area of Washington, a similar consortium began in 1999 and has successfully acquired research-grade data over much of western Washington. Initially motivated by earthquake hazards (Haugerud et al., 2003), the consortium has expanded in scope to include a range of Earth and environmental problems.

The sampling frequency of lidar data has steadily increased since the late 1990s. Early airborne lidar systems operated at only 10^3 points per second, and over the next several years acquisition rates increased to 10^4 points per second (Slatton et al., 2007). More recently, lidar systems typically used for research-grade investigations are capable of $>1.5 \times 10^5$ points per second, which translates to bare-earth point densities of 1 to 10 per square meter depending on vegetation properties (Fig. 2). This increase has been largely facilitated by the rapid improvement of electronics in the last decade. Sampling is only one example, however, of improvements in lidar technology as other important advances have emerged, including: (1) full waveform lidar (Mallet and Bretar, 2009) that enables three-dimensional characterization of heavily vegetated or urbanized areas; (2) green wavelength lidar that enables bathymetric data in relatively shallow and non-turbid water (McKean et al., 2008); and (3) increased geo-referencing accuracy (e.g., flight paths and aircraft orientation). In addition, terrestrial laser scanning (TLS) systems have rapidly emerged, providing localized, yet dense topographic and vegetation data (Heritage and Hetherington, 2007).

The increased prevalence of airborne lidar allows for its integration with fieldwork in ways that can improve the efficiency and efficacy of field campaigns. Lidar data helps direct field tasks and allows for contextual analysis while in the field. Rather than serving as a fieldwork substitute, lidar enhances and leverages more traditional technologies and field methods in ways that benefit geomorphologists. Lidar data sets can be integrated with all stages of fieldwork, from pre-field planning to post-fieldwork analyses. Before embarking on a field campaign, areas to target for sampling, for example, can be identified clearly and precisely, and new or unanticipated features can be identified for field checking (e.g., Challis, 2006; De Pascale and Langridge, 2012). In the field, no substitute exists for having a map that enables one to clearly locate oneself amongst landforms. With hardcopy lidar maps or imagery loaded on GPS receivers, one can readily identify the spatial extent of features within view and more easily connect those observations to the larger-scale features that define landscapes. Put simply, field-based investigation with the aid of lidar provides geomorphologists with a means to rigorously explore and test process-form linkages in ways not previously possible (Dietrich et al., 2003; Perron et al., 2008).

Loading lidar imagery onto a handheld GPS unit permits accurate and rapid determination of location, and more importantly, allows geomorphologists to efficiently target desired sites for sample collection and model testing. Furthermore, lidar data derivatives, such as slope angle or drainage area, can be viewed in the field, providing geomorphologists with the means to associate field observations with quantitative topographic metrics. This context cannot be achieved by analyzing a DEM in the office or by qualitative field observations alone. In many cases, features such as subtle landslide benches or shallow channels in otherwise rubbly lava flows may not be immediately obvious in the field, but are readily revealed in lidar data sets.

Post-field lidar analyses help identify patterns in landscape texture or morphology. Such pattern recognition allows extrapolation of field data to broader areas, as well as enabling contextualization or validation of models. Precise geolocation also makes lidar ideal for repeat surveys for the purpose of mapping landscape change (Burns et al., 2010; Ventura et al., 2011; Delong et al., 2012,). High resolution DEMs have proven capable of quantifying change to the meter or sub-meter scale depending on vegetation cover, slope, and quality of lidar data (Means et al., 2000; Hodgson et al., 2005; Slatton et al., 2007). Lidar also allows for three-dimensional change calculations, eliminating the need to assume that displacement fields are composed only of vertical change (e.g., Woolard and Colby, 2002; DeLong et al., 2012). Most generally, lidar combined with field work has led to improved hazard inventory maps and planning, better short-timescale tracking of landforms, discoveries of new geomorphic features, and precise geolocation of known features.

4. Role of lidar in geomorphic research

4.1. Lidar for base maps

A driving motivation of geomorphology is to understand and explain the processes that form landscapes. The quantification of geomorphology has encouraged the development of models that establish process-form linkages. These models must be tested and validated in natural landscapes that span a range of properties (e.g., amount and intensity of rain across a region over a period of time).

Because rock properties dictate the efficacy of many geomorphic processes, geological substrate is a key parameter for landscape evolution; as such, accurate geologic maps are necessary for robust model development and testing. For most of the last century geologic maps around the world were produced using contour maps as base maps. These maps had contour intervals ranging from 10 to 100 m (or more). While they provided a skilled mapper with a reasonable representation of the landscape, these base maps did not have the capacity for meter-scale accuracy for contact locations and field measurements.

The origin and accuracy of traditional geological maps is often neglected when the geologic data are transformed into a digital format. Digitization reveals that while unit identification and geologic relations are typically correct, locations (contacts, geographic features) can be offset by hundreds of meters. In the United States, numerous state geologic surveys recognize the utility of lidar for accurate location of contacts, and have invested considerable public funds for the acquisition of lidar data sets (e.g., Oregon, Kentucky, Pennsylvania, North Carolina, South Carolina). With the recognition (internally or as a result of legislative action) that geospatial products are expected to be spatially accurate at increasingly high resolutions, several states now exclusively use lidar as basemaps for geologic and/or natural hazard mapping as well as property line definition (e.g., Oregon, Kentucky) (House, 2010; Madin and Frankel, 2010). As more agencies within the USA and internationally, follow suit, spatial products will increasingly have the accuracy that users expect (i.e., meter scale or better). Obviously, lidar-enabled improvements in accuracy also apply to landform maps used for research purposes, including maps of channels (Devauchelle et al., 2012), terraces (Fuller et al., 2009; Bowles and Cowgill, 2012), landslide scars (e.g., Mackey and Roering, 2011), and underlying structures (e.g., Martel, 2011; Pavlis and Bruhn, 2011). Also, landslide inventory maps are more readily generated for large areas, including identifying new landslides and better constrained boundaries, when using lidar—especially in conjunction with older techniques (e.g. Schulz, 2007; Van Den Eeckhaut et al., 2007; Guzzetti et al., 2012). The use of lidar-derived shaded relief maps for showing sample locations allows readers to place data (samples) in the context of the landscape and form their own interpretation.

Interestingly, because lidar enables documentation of landscape changes associated with geologic events or anthropogenic activity, agencies that employ lidar are confronting the question of how often and when to reacquire imagery for a given location. In addition, continued lidar acquisition provides more opportunities for studying surface changes associated with geomorphic processes, such as landsliding (Ventura et al., 2011; Daehne and Corsini, 2012; DeLong et al., 2012) or dune migration (Woolard and Colby, 2002; Jerolmack et al., 2012).

4.2. Lidar for rapid and accurate description of morphologic trends and patterns

The high resolution and precision of lidar-derived DEMs allows a geomorphologist to ask two classic questions with the hope of discovering robust, quantitative answers. Put simply, 'What does the surface of Earth look like?', and 'Why?' Answering the former question quantitatively requires detailed statistical analyses of surface morphology, made possible by large sample sizes of precise point measurements. For example, a typical research grade NCALM survey might collect ~10 points per square meter over a study area of ~100 km^2, yielding ~1 billion (x,y,z) data points with ~0.1 m precision. Answering the latter question requires process-based models for landscape evolution, which can now be informed by and tested against high-resolution DEMs generated from lidar point clouds. Rapid growth in the quality and availability of lidar data, as well as successful field verification, has resulted in a proliferation of studies that quantify the topographic expressions and spatial structure of a variety of geomorphic features. Importantly, in nearly all such studies, detailed fieldwork and interpretation of features observed directly by geomorphologists served as the ground truth for evaluating the performance of the lidar-based work.

The goal of many process-form studies is to identify a unique topographic signature that faithfully reflects a particular geomorphic process and then investigate how this topographic metric might change in space or in time (Dietrich et al., 2003). This venture has been especially fruitful when applied to local features defined by topographic variability, such as landslides, alluvial fans, or low order channels. For example, lidar has revealed in detail the often subtle scarps, hummocks, lateral margins, and pressure ridges of deep-seated landslides, which in many places were previously hidden under dense vegetation. McKean and Roering (2004) and Glenn et al. (2006) first documented the spatial statistics of these features and suggested that various measures of topographic roughness systematically reflect landslide deformation processes. More recently, Booth et al. (2009) showed that the roughness associated with deep-seated landsliding has a characteristic spatial scale and accurately mapped landslides in several areas of the Pacific Northwest, USA, by extracting topography with this characteristic scale (Fig. 4A, B). Similar studies have continued to improve the state-of-the-art in automated mapping of landslides (Tarolli et al., 2012; Van Den Eeckhaut et al., 2012; Berti et al., 2013), extraction of channel networks (Fig. 4C), (Lashermes et al., 2007; Snyder and Kammer, 2008; Passalacqua et al., 2010a, 2010b, 2012), identification of biotic signatures in landscape morphology (Roering et al., 2010), classification of marine terraces (Bowles and Cowgill, 2012), and characterization of alluvial fan surfaces (Staley et al., 2006; Frankel and Dolan, 2007; Volker et al., 2007). Despite the efficiency of such automated feature mapping techniques, most of these efforts still require some form of calibration or field mapping to be applied to broad areas, highlighting the complementary nature of high-resolution, remotely-sensed data and traditional geomorphic fieldwork.

The same processes documented by these relatively short length scale topographic features also drive broader scale landscape patterns, such as ridge-valley sequences, and lidar enables quantification of landscape form over the complete range of scales from <1 m to tens or even hundreds of kilometers (Hilley and Arrowsmith, 2008; Jasiewicz and Stepinski, 2013). Analysis of lidar data over this wide range of scales has already forced geomorphologists to reconsider how landscapes are organized and how water and sediment are routed through landscapes. At first glance, for example, many landscapes appear fractal such that the largest scale ridges and valleys are simply geometrically scaled versions of the smallest ridges and valleys. Analyzing the shape of the topography over a full range of scales, however, reveals that this is not always the case — in many settings distinctive characteristic spatial scales are associated with the topography (Perron et al., 2008). To differentiate landscapes, geomorphologists frequently rely on plots of local slope vs. drainage area to characterize the spatial scales (in this case drainage areas) associated with key geomorphic process transitions; lidar has contributed to the realization that trends in these plots depend on the scale of observation in addition to the particular method of calculating slope and area (Tarolli and Dalla Fontana, 2009).

Landscape evolution models, which are "mathematical theor(ies) describing how the actions of various geomorphic processes drive (and are driven by) the evolution of topography over time" (Tucker and Hancock, 2010), aim to generate the topographic signatures described in the preceding paragraphs. Pioneering multi-dimensional landscape evolution modeling produced surfaces that resembled surface of Earth at a coarse scale, but the comparison rarely went beyond a general and qualitative statement of similarity (Ahnert, 1976). Immediately prior to lidar, digital elevation models with ~10 m resolution provided a framework for more quantitative comparisons using slope-area plots, hypsometry, slope distributions, etc. (e.g., Tucker and Bras, 1998). Currently, lidar provides for a finer scale of resolution than many process models account for, which allows for accurate model calibration and evaluation (Roering et al., 2007).

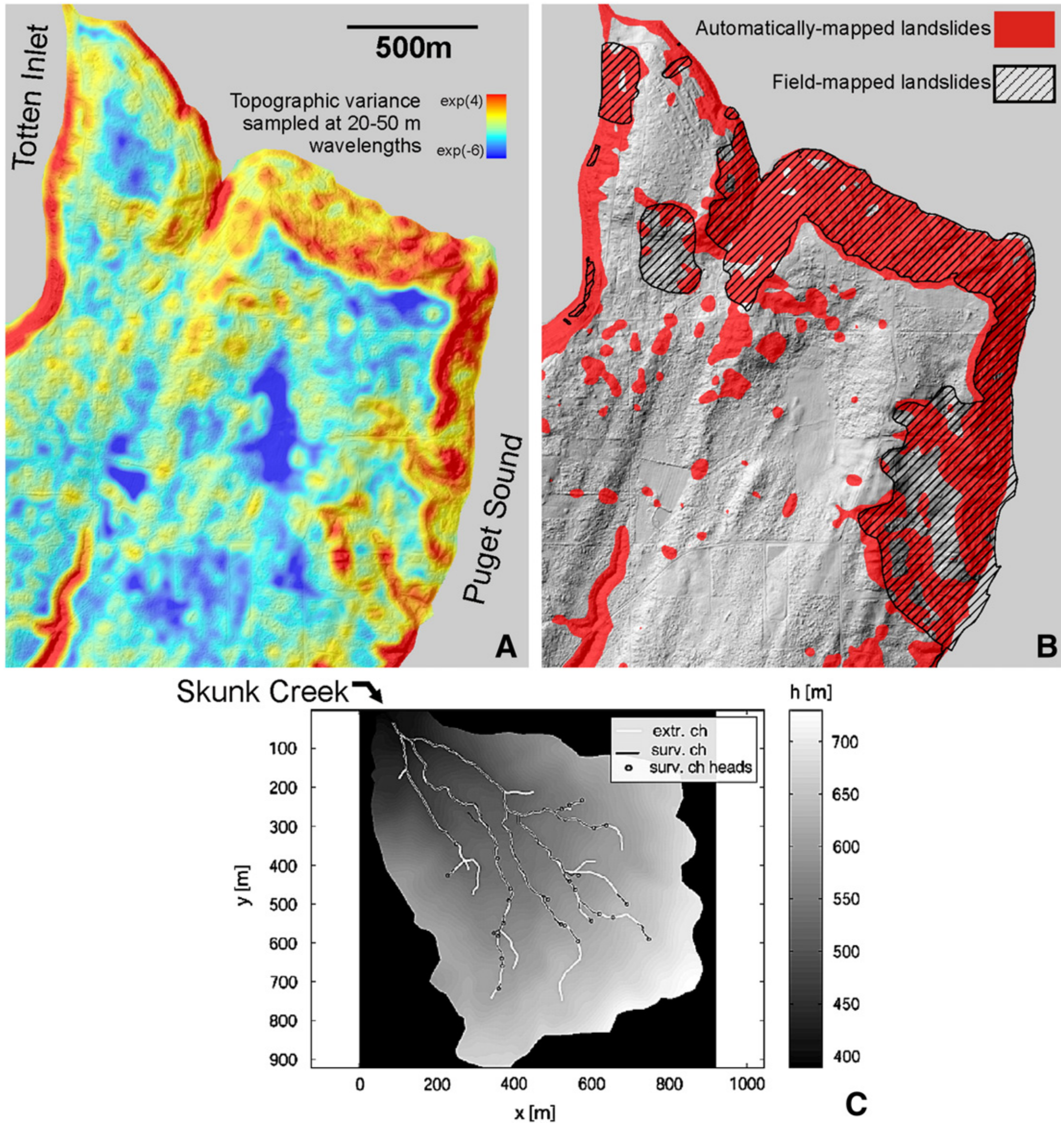

Fig. 4. Examples of semi-automated geomorphic feature mapping using lidar-derived topographic data from Booth et al. (2009) (A and B) and Passalacqua et al. (2010a) (C). A) Near Carlyon Beach, Washington, the color scale indicates the topographic roughness, measured as the variance of the topography sampled at wavelengths of ~20–50 m. B) Pixels where this variance exceeds an optimal threshold value (in red) correspond well to the independent, field-based mapping of coastal landslides (in cross hatched pattern). C) The automatically mapped channel network ("extr. ch") for a small catchment near the South Fork Eel River, California, matches the field-measured channel network ("surv. ch") well and was determined by first smoothing and enhancing edges in the lidar data, then selecting channel paths based on curvature and contributing area.

Lidar-based measurements are especially informative on hillslopes, where subtle variations of ridgetop curvature strongly influence the calibration of soil transport equations and inferred rates of erosion. Measures of topographic curvature are generally scale dependent (Heimsath et al., 1999; Lashermes et al., 2007; Roering et al., 2010), with meter-scale curvature corresponding to surface roughness in the sense of small pits and mounds associated with biological activity. Curvature measured at the ~10 m scale, which is much coarser than typical lidar data, better corresponds to process-based models and allows process rates to be estimated over vast spatial extents (Hurst et al., 2012). Lidar combined with geomorphic process modeling thereby can inform targeted fieldwork and sample collection for independently measuring process rates.

These types of subtle differences in topography allow accurate calibration of more complex landscape evolution models that involve multiple geomorphic processes, as well as differentiation among different models for the same geomorphic process. For example, Roering (2008) tested the ability of several different soil transport equations to produce realistic steady-state hillslopes at the meter scale, using lidar-derived digital elevation models to evaluate the performance. Similarly, Pelletier and Rasmussen (2009) and Pelletier et al. (2011) combined lidar data with soil depths determined in the field to determine the role soil depth plays in soil transport. Perron et al. (2009) were able to calibrate a landscape evolution model simulating hillslope and fluvial processes solely from derivatives of lidar topographic data. In slow-moving landslide-prone terrain, Booth and Roering (2011) identified subtle differences in topographic gradient with distance from the divide using lidar data and were able to determine the relative contributions of landsliding, soil creep, and fluvial incision to shaping the evolving terrain (Fig. 5).

4.3. Lidar for identification and characterization of unanticipated landforms

An immediate benefit of lidar data is revealing the form of landscapes cloaked in dense vegetation. Where features such as river terraces were previously known to exist under forests, poor visibility on

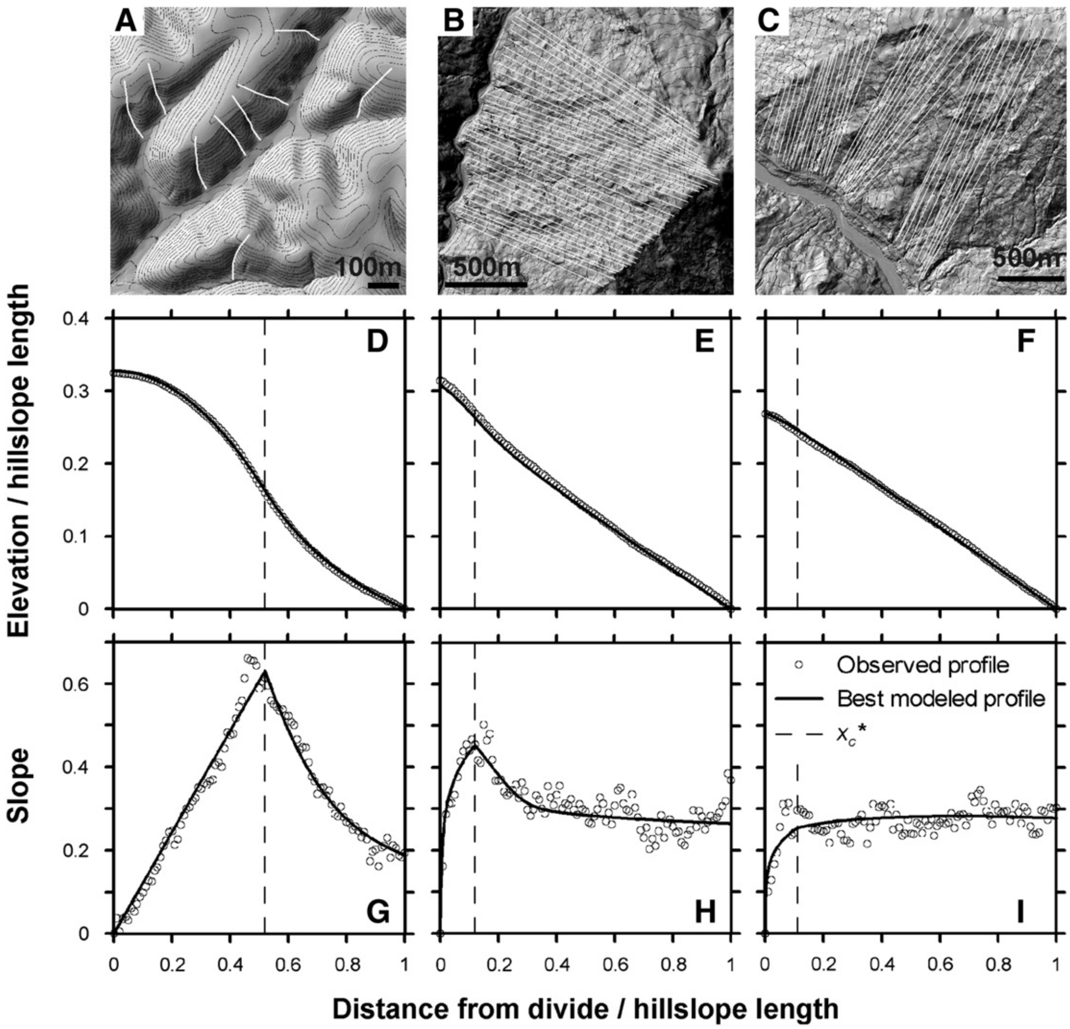

Fig. 5. Example of using lidar-derived topographic data to draw inferences from a mathematical model of landscape evolution, from Booth and Roering (2011). Panels A through C show lidar-derived hillshade maps of study sites with no landsliding (Gabilan Mesa, California), moderate landsliding (Eel River, California — sandstone lithology), and widespread landsliding (Eel — melange lithology), respectively. White lines are the observed profiles in panels D through I, which are placed below the relevant lidar map. The model included the geomorphic processes of soil creep, fluvial incision, and slow-moving landslide deformation and was able to accurately reproduce the morphology of the averaged hillslope profiles, shown as normalized elevation (D through F) and slope (G through I) vs. normalized distance from the drainage divide.

the ground, combined with surveying difficulties (poor line of sight and limited GPS coverage), rendered them difficult to study at the desired level of accuracy and spatial extent. With bare-earth lidar DEMs and derivative maps, the form of river terraces, covered by forest, could be readily observed and measured. First-order measurements, such as the longitudinal slope, areal extent, and absolute elevation of terraces, are quickly obtained from lidar-derived DEMs, but lidar can also reveal subtle smaller terraces or channel forms that may go unnoticed on foot. Precise elevation control enables researchers to link up remnants of old landforms — allowing accurate reconstruction and projection of features such as terraces and lava flows over long distances (Fuller et al., 2009; Finnegan and Dietrich, 2011; Ely et al., 2012; Foster and Kelsey, 2012).

Geomorphic features with a more complex geometry than subplanar landforms, such as terraces, can be difficult to recognize on the ground, in aerial photos, or with conventional low resolution DEMs. For example, dormant deep-seated landslides can easily go undetected, even when they are the target of a mapping campaign (Van Den Eeckhaut et al., 2007). Individual landslides can have planform areas exceeding several square kilometers. The diagnostic morphologic landforms of deep-seated landslides, such as headscarps and lateral margins, can scale according to landslide size and, thus, exceed hundreds of meters of relief. Such large-scale landforms can be difficult to attribute to deep seated landsliding from ground-based observation and this problem is amplified in forested terrain. Bare-earth lidar maps enable the geomorphologist to readily identify landslides in the context of the larger hillslope without the camouflage presented by vegetation, so that the diagnostic morphologic features of landslides can be observed in context. In this sense, lidar minimizes the ambiguity of what we see in the field: the innocuous bluff in the forest, when cross-checked on a lidar map, may emerge as the retrogressive crown scarp of a large landslide.

A recent example with broad implications highlights the utility of lidar for feature identification. Mackey et al. (2011) used lidar to map the elevation of apparent fluvial terraces along a section of the Eel River in northern California as part of a regional study of landslide processes. The patchy and poorly preserved terrace remnants (which had not been previously identified) were found to occur at a constant elevation along 30 km of the Eel River as opposed to sloping downstream, which is typical of river terraces. Terraces at a constant elevation can be diagnostic of standing water, such as lakes, although the rapidly eroding Franciscan Melange of the Eel River catchment was thought to be an unlikely environment for a large lake. Further investigations revealed a large ($>3 \times 10^6$ m^3) landslide scar in a resistant greenstone unit at the downstream extent of the terraces, suggesting that the valley had once been dammed by a large landslide deposit, backing up the Eel River to form a 50 km long lake (Fig. 6). Targeted fieldwork, aided by the lidar dataset, led to the discovery of lacustrine deposits along a tributary to the Eel River just upstream of the landslide damming site. Not only did these deposits coincide with the expected elevation rate for the reconstructed lake, but they also yielded organic material for radiometric dating of the paleo-lake age (~22 kya). Previous studies had documented evidence that the damming event had influenced offshore sedimentation as well as genetic characteristics of anadromous fish, but neither of these studies could posit a feasible mechanism for the observations. The Mackey et al. (2011) study highlights the value of lidar in the field, provided in the form of printed maps and on GPS units, which were crucial for locating and describing terrace remnants and paleo-lake stratigraphy.

By revealing unexpected landscape features, lidar can also challenge our understanding of the trajectory of landscape evolution. For example, volcanic landscapes (i.e., lava flows) are thought to change from highly permeable, undissected surfaces to erosional landscapes over ~10^5 years via the gradual reduction of permeability because of to weathering (Jefferson et al., 2010). Lidar data for Collier lava flow, a 1500 year old flow in the Oregon Cascades, however, reveals a fluvial channel (named White Branch Creek) cut into the lava (Fig. 7), despite the young morphology and presumably high permeability of the flow. In addition to two steep gorges, the channel has formed two low-relief alluvial deposits with an estimated total volume of at least 194,000 m^3, indicating significant sediment transport (Deligne et al., 2012). The channel suggests that the transformation of lava flows to dissected fluvial landscapes may occur over much shorter timescales than previously thought. Furthermore, the extensive alluvial deposits indicate that in some settings lava permeability reduction via weathering may not be as important as externally sourced sediment (Deligne et al., 2012).

In some instances, lidar surveys have revealed features of unknown origin. In the Willamette Valley, Oregon, lidar data sets exhibit ubiquitous evidence of volcanic features, including previously unmapped cinder cones buried by Missoula Flood deposits. In addition, the imagery shows hundreds of faint, subtle circular depressions with diameters of 10^1 to 10^2 m that may result from grounded icebergs during Missoula floods, tornadoes, or an alternative mechanism (Fisher, 2011). Most generally, lidar has proven powerful at identifying low-relief, long wavelength features that have gone undetected on the ground or with lower-resolution DEMs. The ability to manipulate elevation color scales or create dense contours can facilitate the identification of subtle features, which can be targeted on the ground for further analysis (Jones et al., 2007).

4.4. Lidar for enhancement of other data sets

In addition to improving our ability to characterize landscapes, lidar data sets also afford the ability to better georeference archival air photos (e.g., Liu et al., 2007). Using airborne lidar as a basemap for established ground control points and a topographic base for orthorectification, Mackey and Roering (2011) achieved 2 m or less average root mean square errors (RMSE) for the horizontal position of stable points identified in successive photos beginning in the 1940s. The historical imagery, much of which lacked camera calibration information, was more accurately rectified than when low-resolution DEMs were used for processing. The imagery was used successfully to estimate temporal and spatial variations in the velocity of slow-moving landslides by tracking the position of trees, shrubs, and large boulders in successive imagery. Another exciting future lidar-enabled enhancement involves the coupling of lidar with hyperspectral data, which records in high spectral resolution (typically 10 nm) the spectra (i.e., wavelengths emitted) of the surface (e.g., Gilvear et al., 2004; Mundt et al., 2006; Anderson et al., 2008; Elaksher, 2008; Jones et al., 2010). Because hyperspectral data has numerous applications for investigating chemical (e.g., mineral composition) and biologic (e.g., plant health) properties, its coupling with lidar provides an unprecedented opportunity to characterize the detailed form, biota, and geochemistry of the surface of Earth.

4.5. Lidar for spatial and morphologic cognition

Because emerging technologies often encourage us to observe and explore our worlds in new and different ways, it seems inevitable that technology adoption will change our perception of how Earth functions and organizes itself. For petrologists, volcanologists, and soil scientists, for example, the advent of scanning electron microscopes enabled the documentation and analysis of minerals and surface

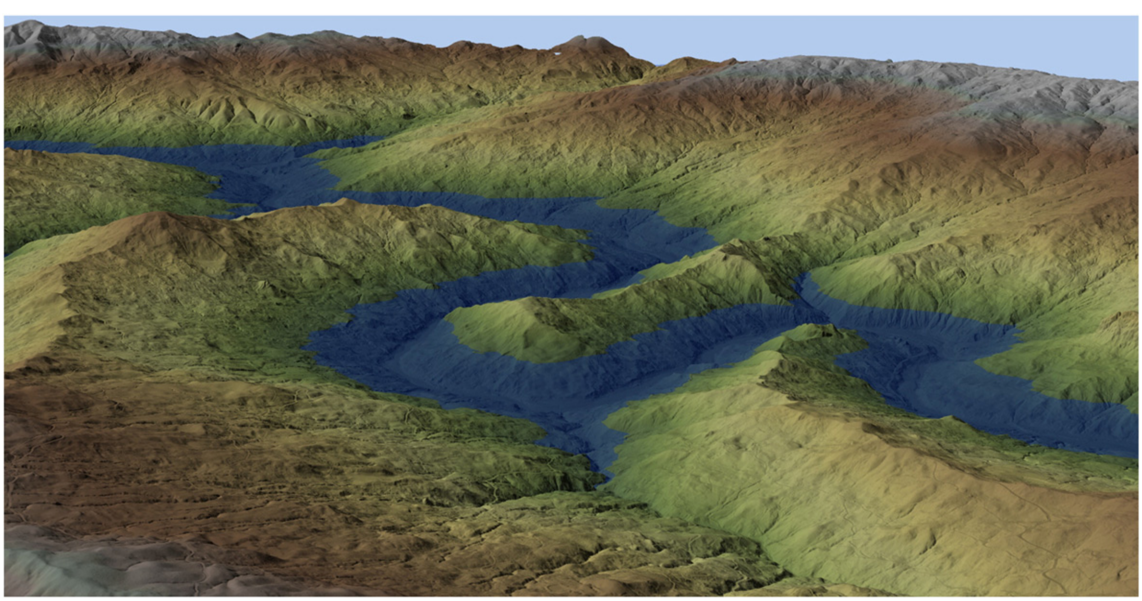

Fig. 6. Oblique view of a landslide dammed paleo-lake discovered along the Eel River, CA, reconstructed using lidar. The reconstructed lake surface at 243 m elevation is shown with blue coloring. The modern Eel River runs right to left.

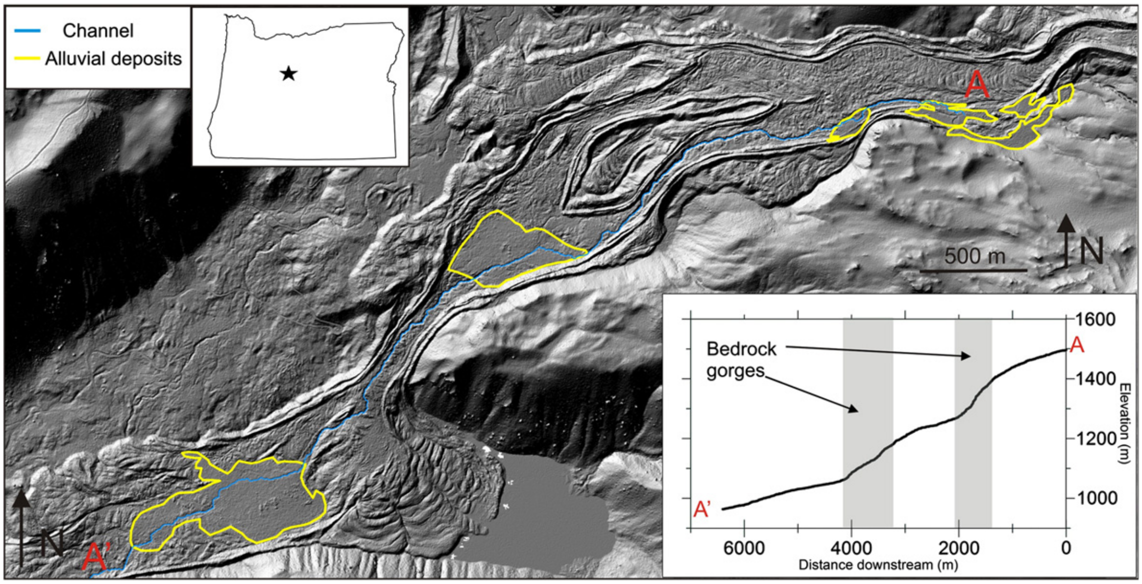

Fig. 7. Hillshade of lidar data showing fluvial channel atop the Collier Cone lava flow, Oregon Cascades. Blue line shows channel location; yellow lines outline extent of alluvial deposits mapped in the field. The longitudinal profile of the channel (which spans A–A′) is shown in the lower right inset, including the location of steep bedrock gorges demarcating up to 10 m of bedrock incision since 1500 ya.

properties that reflect geologic and pedogenic processes. This analytical capability enabled these scientists to make observations that were previously impossible and empowered them to tackle new scientific questions as well as become more thoughtful and systematic in their sample collection. By contrast, airborne lidar has provided geomorphologists with a greatly enhanced perspective on something with which they were already intimately familiar: the surface of Earth. As such, widespread lidar acquisition and application has the potential to fundamentally alter our cognitive abilities during fieldwork by encouraging us to revisit and refine how we characterize landscape morphology.

In the field of linguistics, the oft-debated concept of linguistic relativity suggests that the structure of language alters our conceptualization of reality (e.g., Boroditsky and Gaby, 2010). In essence, the tools afforded by language can activate cognitive abilities that might otherwise be lacking. One fascinating example that supports this notion also holds relevance for geomorphologists. In Western Australia, languages of the indigenous peoples of the Pormpuraaw region incorporate absolute spatial orientation. In other words, a Pormpuraaw resident uses cardinal directions (east, west, north, south) rather than a local reference frame (right, left) to convey spatial information and context. Furthermore, these indigenous languages encode spatial orientation in most daily interactions (even casual greetings), which results in superior spatial reckoning and navigation skills that have been frequently recognized (Levinson, 2003). For example, indigenous origin stories for Lake Eyre, which is a nearly 10,000 km^2 feature in central Australia, revolve around the hunting and killing of a kangaroo. The outline of the enormous lake resembles a kangaroo skin that's been laid open on the ground. Remarkably, this distinctive shape was readily apparent to indigenous peoples whom navigated the region millennia before maps or remote imagery. In the sports realm, the on-field strategic skills of indigenous rugby players has been commonly noted, including one sportswriter who opined that they played as if they could see the field from above. These examples highlight the ability of language to alter how we process information and, in this instance, demonstrate a possible connection between spatial cognition and the channels used to convey information. Put another way, Whorf (1940) states: we dissect nature along lines laid down by our native languages…the world is presented in a kaleidoscopic flux of impressions which has to be organized by our minds — and this means largely by the linguistic systems in our minds. We cut nature up, organize it into concepts, and ascribe significances as we do, largely because we are parties to an agreement to organize it in this way — an agreement that holds throughout our speech community and is codified in the patterns of our language.

By analogy, does working with high-resolution spatial data, such as those generated by airborne lidar, influence how we encounter and perceive landscapes in the field? In other words, does the 'language' of lidar shape our conceptualization of landscapes? Evidence generated by studying how children acquire and use spatial reference frames strongly suggests that language plays a significant role in structuring spatial cognition (Majid et al., 2004). In motivating this question, we are falsely equating lidar with language, but we endeavor nonetheless by conceptualizing lidar as a means to communicate the details (as well as broad patterns) of natural landscapes with an unprecedented level of resolution and accuracy.

Feedbacks between human cognition and spatial information (e.g., maps) reflect how we acquire abstract concepts of space as well as conceptualize spatial relations that have not been experienced directly (Uttal, 2001). Because lidar depicts features easily observed in the field, quantification of landforms using lidar data coupled with fieldwork may enhance our ability to decipher subtle topographic patterns in the field as a means to identify process signatures or infer landscape history. Decades ago, for example, hillslope forms were typically classified in a relatively simplistic fashion, such as convex, concave, planar, or some combination of these categories. Some studies used survey data to quantify morphology, but these efforts were usually one-dimensional hillslope profiles of limited spatial extent. As a result, geomorphologists possessed a primitive ability to reconcile their spatial data with their field-based perceptions of landscape form. Now, lidar data coupled with algorithms to calculate spatial variations in topographic derivatives, such as slope and curvature (which are functionally related to the fluxes of water and sediment), enable us to map these distributed topographic metrics broadly. Furthermore, simply being aware of the extent to which hillslope forms can vary should sharpen our capacity for distinguishing such morphologic trends in the field. In essence, the repeated coupling of lidar analysis with fieldwork may increase the richness (or gradations) that we employ for characterizing landforms while in the field. Importantly, improved landscape conceptualization facilitated by lidar likely requires active engagement during field campaigns; otherwise geomorphologists run the risk of mistaking lidar data for reality. The perils of becoming overly reliant on geospatial data and technology have been documented (Frankenstein, 2012). Witness, for example, scores of anecdotes about drivers that navigate to the same location for weeks using a GPS unit in their car. When their GPS units are lost, broken, or stolen, however, many of these drivers are unable to find their destination despite having made the trip dozens of times with the aid of geospatial technology. This is perhaps one of the most profound arguments for the primacy of field observations in geomorphology.

5. Potential future roles for lidar in geomorphology

Geomorphology is inherently interdisciplinary considering that the surface of Earth is the venue for a myriad of linked biotic, geochemical, and physical processes. For tying these fields together, lidar data may be unique in providing a common framework (or starting point) for disciplinary scientists seeking to tackle complex problems that require topographic information at different scales. For example, understanding the current status and future of an aquatic ecosystem is predicated on understanding the degree to which watershed habitat features are functionally linked at scales ranging from micro to meso (Poff, 1997; Naiman and Bilby, 1998). In other words, being able to accurately characterize the geomorphic features and processes (e.g. pool riffle habitat and sediment routing) at geomorphically and biologically relevant scales is critical for the success of such an interdisciplinary science. Innovative new models for linking geomorphic concepts with biological predictions highlight the strength of lidar data. For example, the RIPPLE model (Dietrich and Ligon, 2008) relies on geomorphic metrics, including slope and channel width, to determine the distribution of sediment size and habitat suitability for salmonid species for all stream reaches within a given watershed. More generally, lidar capability facilitates many of the grand challenges outlined in the 2010 National Research Council report 'Landscapes on the Edge', including, how do ecosystems and landscape co-evolve? Given that inadequate collaboration between ecologists and geomorphologists appears to limit our ability to develop predictions regarding landscape response to human disturbance and climate change (Reinhardt et al., 2010), lidar data sets may provide a common reference or testing ground to facilitate interdisciplinary problem solving. Linkages between land-use practices and channel habitat need to be established for ecosystem restoration and management projects and lidar is well-suited to establish these connections. For example, in Napa County, California, where road-channel crossings pose a significant impact to aquatic habitat, lidar-enabled mapping of over 400 dams and 4000 road crossings on small tributaries was used to refine and calibrate sediment production and routing calculations (Dietrich et al., 2004).

6. Conclusion

Because it is impossible to visit every locale in large study areas to form a first-hand interpretation of landforms, lidar is a critical tool for conveying landscape forms and patterns that reflect process and history. More so, because lidar enables the quantification of process-scale morphologic trends and patterns, its increasing availability has revolutionized the formulation, calibration, and testing, of geomorphic models. As lidar acquisition continues in new study areas, unanticipated features will emerge from sometimes subtle variations in landscape form. Whereas some of these features will be identified via automated feature recognition algorithms, many will be found through time-tested pattern recognition systems: the eyes and brains of geomorphologists. With frequent exposure to lidar data, geoscientists may achieve gains in their cognition of spatial and morphologic patterns in the field. Certainly, lidar data is no substitute for being in the field, but the coupled analysis of lidar data and fieldwork has spawned many of the most compelling geomorphic discoveries in the past decade.

Acknowledgments

The authors thank editors Carl Legleiter and Dick Marston for convening the 43rd Binghamton Symposium in Jackson, Wyoming. Discussions with Kathy Cashman, Jon Pelletier, Peter Almond, Mark Fonstad, and Arjun Heimsath were much appreciated and helped focus our thoughts. Comments by the editors and an anonymous reviewer were useful and improved the manuscript. JJR was supported by NSF EAR-0952186.

References

Ahnert, F., 1976. Brief description of a comprehensive three-dimensional process-response model of landform development. Zeitschrift für Geomorphologie 25, 29–49.

Anderson, J., Plourde, L., Martin, M., Braswell, B., Smith, M., Dubayah, R., Hofton, M., Blair, J., 2008. Integrating waveform lidar with hyperspectral imagery for inventory of a northern temperate forest. Remote Sensing of Environment 112, 1856–1870.

Berti, M., Corsini, A., Daehne, A., 2013. Comparative analysis of surface roughness algorithms for the identification of active landslides. Geomorphology 182, 1–18.

Booth, A.M., Roering, J.J., 2011. A 1-D mechanistic model for the evolution of earthflow-prone hillslopes. Journal of Geophysical Research 116, 1–20.

Booth, A.M., Roering, J.J., Perron, J.T., 2009. Automated landslide mapping using spectral analysis and high-resolution topographic data: Puget Sound lowlands, Washington, and Portland Hills, Oregon. Geomorphology 109, 132–147.

Boroditsky, L., Gaby, A., 2010. Remembrances of times East: absolute spatial representations of time in an Australian aboriginal community. Psychological Science 21, 1635–1639.

Bowles, C., Cowgill, E., 2012. Discovering marine terraces using airborne LiDAR along the Mendocino-Sonoma coast, northern California. Geosphere 8, 386–402.

Burns, W.J., Coe, J.A., Kaya, B.S., Ma, L., 2010. Analysis of elevation changes detected from multi-temporal LiDAR surveys in forested landslide terrain in western Oregon. Environmental and Engineering Geology 16, 315–341.

Carter, W., Shrestha, R., Tuell, G., Bloomquist, D., Sartori, M., 2001. Airborne laser swath mapping shines new light on Earth's topography. Eos, Transactions American Geophysical Union 82, 549–555.

Challis, K., 2006. Airborne laser altimetry in alluviated landscapes. Archaeological Prospection 13, 103–127.

Church, M., 2013. Refocusing geomorphology: field work in four acts. Geomorphology 1–9. http://dx.doi.org/10.1016/j.geomorph.2013.01.014.

Daehne, A., Corsini, A., 2012. Kinematics of active earthflows revealed by digital image correlation and DEM subtraction techniques applied to multi-temporal LiDAR data. Earth Surface Processes and Landforms. http://dx.doi.org/10.1002/esp.3351.

De Pascale, G.P., Langridge, R.M., 2012. New on-fault evidence for a great earthquake in A.D. 1717, central Alpine fault, New Zealand. Geology 40, 791–794.

Deligne, N.I., Cashman, K.V., Roering, J.J., 2012. After the lava flow: the importance of external soil sources for plant colonization of recent lava flows in the central Oregon Cascades, USA. Geomorphology. http://dx.doi.org/10.1016/j.geomorph.2012.12.009.

DeLong, S.B., Prentice, C.S., Hilley, G.E., Ebert, Y., 2012. Multitemporal ALSM change detection, sediment delivery, and process mapping at an active earthflow. Earth Surface Processes and Landforms 37, 262–272.

Devauchelle, O., Petroff, A.P., Seybold, H.F., Rothman, D.H., 2012. Ramification of stream networks. Proceedings of the National Academy of Sciences of the United States of America 109, 20832–20836.

Dietrich, W.E., Ligon, F., 2008. RIPPLE — A Digital Terrain-Based Model for Linking Salmon Population Dynamics to Channel Networks. Prepared by Stillwater Sciences Berkeley, California, p28.

Dietrich, W.E., Bellugi, D.G., Sklar, L.S., Stock, J.D., Heimsath, A.M., Roering, J.J., 2003. Geomorphic transport laws for predicting landscape form and dynamics. Geophysical Monograph-American Geophysical Union 135, 103–132.

Dietrich, W.E., Bellugi, D., Real de Asua, R., Iordache, I., Allen, D., Napolitano, M., Trso, M., 2004. The use of airborne laser swath mapping data in watershed analysis to guide restoration priorities: the Napa River Watershed Study. AGU Fall Meeting.

Duffy, B., Quigley, M., Barrell, D.J.A., Van Dissen, R., Stahl, T., Leprince, S., McInnes, C., Bilderback, E., 2012. Fault kinematics and surface deformation across a releasing bend during the 2010 MW 7.1 Darfield, New Zealand, earthquake revealed by differential LiDAR and cadastral surveying. Geological Society of America Bulletin 125, 420–431.

Elaksher, A.F., 2008. Fusion of hyperspectral images and lidar-based DEMS for coastal mapping. Optics and Lasers in Engineering 46, 493–498.

Ely, L.L., Brossy, C.C., House, P.K., Safran, E.B., O'Connor, J.E., Champion, D.E., Fenton, C.R., Bondre, N.R., Orem, C.A., Grant, G.E., Henry, C.D., Turrin, B.D., 2012. Owyhee River intracanyon lava flows: does the river give a dam? Geological Society of America Bulletin 124, 1667–1687.

Finnegan, N.J., Dietrich, W.E., 2011. Episodic bedrock strath terrace formation due to meander migration and cutoff. Geology 39, 143–146.

Fisher, N., 2011. LIDAR — Pits of Mystery, Oregon Field Guide (OPB). Oregon Public Broadcasting, USA (http://www.opb.org/programs/ofg/segments/view/1775).

Foster, M.A., Kelsey, H.M., 2012. Knickpoint and knickzone formation and propagation, South Fork Eel River, northern California. Geosphere 8, 403–416.

Frankel, K.L., Dolan, J.F., 2007. Characterizing arid region alluvial fan surface roughness with airborne laser swath mapping digital topographic data. Journal of Geophysical Research 112 F02025.

Frankenstein, J., 2012. Is GPS All in Our Heads. New York Times.

Fuller, T.K., Perg, L.A., Willenbring, J.K., Lepper, K., 2009. Field evidence for climate-driven changes in sediment supply leading to strath terrace formation. Geology 37, 467–470.

Gilbert, G.K., 1877. Report on the Geology of the Henry Mountains. Dept. of the Interior, U.S. Geographical and Geological Survey of the Rocky Mountain Region, Reston, VA.

Gilvear, D., Tyler, A., Davids, C., 2004. Detection of estuarine and tidal river hydromorphology using hyper-spectral and LiDAR data: Forth estuary, Scotland. Estuarine, Coastal and Shelf Science 61, 379–392.

Glenn, N.F., Streutker, D.R., Chadwick, D.J., Thackray, G.D., Dorsch, S.J., 2006. Analysis of LiDAR-derived topographic information for characterizing and differentiating landslide morphology and activity. Geomorphology 73, 131–148.

Guzzetti, F., Mondini, A.C., Cardinali, M., Fiorucci, F., Santangelo, M., Chang, K.-T., 2012. Landslide inventory maps: new tools for an old problem. Earth-Science Reviews 112, 42–66.

Haugerud, R.A., Harding, D.J., Johnson, S.Y., Harless, J.L., Weaver, C.S., 2003. High-resolution lidar topography of the Puget lowland, Washington — a bonanza for earth science. GSA Today 13, 4–10.

Heimsath, A.M., Dietrich, W.E., Nishiizumi, K., Finkel, R.C., 1999. Cosmogenic nuclides, topography, and the spatial variation of soil depth. Geomorphology 27, 151–172.

Heritage, G., Hetherington, D., 2007. Towards a protocol for laser scanning in fluvial geomorphology. Earth Surface Processes and Landforms 32 (1), 66–74.

Hilley, G.E., Arrowsmith, J.R., 2008. Geomorphic response to uplift along the Dragon's Back pressure ridge, Carrizo Plain, California. Geology 36, 367–370.

Hodgson, M., Jensen, J., Raber, G., 2005. An evaluation of lidar-derived elevation and terrain slope in leaf-off conditions. Photogrammetric Engineering and Remote Sensing 71, 817–823.

Horton, R., 1945. Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. Geological Society of America Bulletin 56, 275–370.

House, P.K., 2010. My love affair with lidar: confessions of an inveterate surficial mapper. Geological Society of America Abstracts with Programs 42, 39.

Hurst, M.D., Mudd, S.M., Walcott, R., Attal, M., Yoo, K., 2012. Using hilltop curvature to derive the spatial distribution of erosion rates. Journal of Geophysical Research 117, 1–19.

Jasiewicz, J., Stepinski, T.F., 2013. Geomorphons — a pattern recognition approach to classification and mapping of landforms. Geomorphology 182, 147–156.

Jefferson, A., Grant, G.E., Lewis, S.L., Lancaster, S.T., 2010. Coevolution of hydrology and topography on a basalt landscape in the Oregon Cascade Range, USA. Earth Surface Processes and Landforms 35, 803–816.

Jerolmack, D.J., Ewing, R.C., Falcini, F., Martin, R.L., Masteller, C., Phillips, C., Reitz, M., Buynevich, I., 2012. Internal boundary layer model for the evolution of desert dune fields. Nature Geoscience 5 (3), 206–209.

Jones, A.F., Brewer, P.A., Johnstone, E., Macklin, M.G., 2007. High-resolution interpretative geomorphological mapping of river valley environments using airborne LiDAR data. Earth Surface Processes and Landforms 32 (10), 1574–1592.

Jones, T.G., Coops, N.C., Sharma, T., 2010. Assessing the utility of airborne hyperspectral and LiDAR data for species distribution mapping in the coastal Pacific Northwest, Canada. Remote Sensing of Environment 114, 2841–2852.

Lashermes, B., Foufoula-Georgiou, E., Dietrich, W.E., 2007. Channel network extraction from high resolution topography using wavelets. Geophysical Research Letters 34, L23S04.

Leopold, Luna B., Langbein, W.B., 1966. River Meanders. Scientific American, pp. 60–70 (June).

Leopold, L.B., Maddock Jr., T., 1953. The Hydraulic Geometry of Stream Channels and Some Physiographic Implications. US Geological Survey Professional Paper 252 United States Government Printing Office, Washington, D.C.

Levinson, S.C., 2003. Space in Language and Cognition: Explorations in Cognitive Diversity. Cambridge University Press, New York.

Liu, X., Zhang, Z., Peterson, J., Chandra, S., 2007. LiDAR-derived high quality ground control information and DEM for image orthorectification. GeoInformatica 11, 37–53.

Luccio, M., 2013. The Oregon Lidar Consortium. The Professional Surveyor 10 (January).

Mackey, B.H., Roering, J.J., 2011. Sediment yield, spatial characteristics, and the long-term evolution of active earthflows determined from airborne LiDAR and historical aerial photographs, Eel River, California. Geological Society of America Bulletin 123 (7–8), 1560–1576.

Mackey, B.H., Roering, J.J., Lamb, M.P., 2011. Landslide-dammed paleolake perturbs marine sedimentation and drives genetic change in anadromous fish. Proceedings of the National Academy of Sciences 108 (47), 18905–18909.

Madin, I., Frankel, K., 2010. Seeing the True Shape of Earth: Quantitative and Qualitative Applications of Airborne Lidar. (conveners) Geological Society of America, Pardee Keynote Symposium, Denver, Colorado.

Majid, A., Bowerman, M., Kita, S., Haun, D., Levinson, S.C., 2004. Can language restructure cognition? The case for space. Trends in Cognitive Sciences 8 (3), 108–114.

Mallet, C., Bretar, F., 2009. Full-waveform topographic lidar: state-of-the-art. ISPRS Journal of Photogrammetry and Remote Sensing 64 (1), 1–16.

Martel, S.J., 2011. Mechanics of curved surfaces, with application to surface-parallel cracks. Geophysical Research Letters 38 (20) L20303.

McKean, J., Roering, J., 2004. Objective landslide detection and surface morphology mapping using high-resolution airborne laser altimetry. Geomorphology 57 (3), 331–351.

McKean, J.A., Isaak, D.J., Wright, C.W., 2008. Geomorphic controls on salmon nesting patterns described by a new, narrow-beam terrestrial-aquatic lidar. Frontiers in Ecology and the Environment 6 (3), 125–130.

Means, J.E., Acker, S.A., Fitt, B.J., Renslow, M., Emerson, L., Hendrix, C.J., 2000. Predicting forest stand characteristics with airborne scanning lidar. Photogrammetric Engineering and Remote Sensing 66 (11), 1367–1371.

Montgomery, D.R., Schmidt, K.M., Greenberg, H.M., Dietrich, W.E., 2000. Forest clearing and regional landsliding. Geology 28 (4), 311–314.

Mundt, J.T., Streutker, D.R., Glenn, N.F., 2006. Mapping sagebrush distribution using fusion of hyperspectral and lidar classifications. Photogrammetric Engineering and Remote Sensing 72 (1), 47.

Naiman, R.J., Bilby, R.E., Kantor, E. (Eds.), 1998. River Ecology and Management: Lessons from the Pacific Coastal Ecoregion. Springer.

Passalacqua, P., Do Trung, T., Foufoula-Georgiou, E., Sapiro, G., Dietrich, W.E., 2010a. A geometric framework for channel network extraction from lidar: Nonlinear diffusion and geodesic paths. Journal of Geophysical Research 115 (F1). http://dx.doi.org/10.1029/2009JF001254 F01002.

Passalacqua, P., Tarolli, P., Foufoula-Georgiou, E., 2010b. Testing space-scale methodologies for automatic geomorphic feature extraction from lidar in a complex mountainous landscape. Water Resources Research 46. http://dx.doi.org/10.1029/2009WR008812 W11535.

Passalacqua, P., Belmont, P., Foufoula-Georgiou, E., 2012. Automatic geomorphic feature extraction from lidar in flat and engineered landscapes. Water Resources Research 48 (3) W03528.

Pavlis, T.L., Bruhn, R.L., 2011. Application of LIDAR to resolving bedrock structure in areas of poor exposure: an example from the STEEP study area, southern Alaska. Geological Society of America Bulletin 123 (1–2), 206–217.

Pelletier, J.D., Rasmussen, C., 2009. Geomorphically based predictive mapping of soil thickness in upland watersheds. Water Resources Research 45 (9) W09417.

Pelletier, J.D., McGuire, L.A., Ash, J.L., Engelder, T.M., Hill, L.E., Leroy, K.W., Orem, C.A., Rosenthal, W.S., Trees, M.A., Rasmussen, C., 2011. Calibration and testing of upland hillslope evolution models in a dated landscape: Banco Bonito, New Mexico. Journal of Geophysical Research 116. http://dx.doi.org/10.1029/2011JF001976 F04004.

Perron, J.T., Kirchner, J.W., Dietrich, W.E., 2008. Spectral signatures of characteristic spatial scales and nonfractal structure in landscapes. Journal of Geophysical Research 113 (F4) F04003.

Perron, J.T., Kirchner, J.W., Dietrich, W.E., 2009. Formation of evenly spaced ridges and valleys. Nature 460 (7254), 502–505.

Perroy, R.L., Bookhagen, B., Asner, G.P., Chadwick, O.A., 2010. Comparison of gully erosion estimates using airborne and ground-based LiDAR on Santa Cruz Island, California. Geomorphology 118 (3), 288–300.

Poff, N.L.R., 1997. Landscape filters and species traits: towards mechanistic understanding and prediction in stream ecology. Journal of the North American Benthological Society 391–409.

Reinhardt, L., Jerolmack, D., Cardinale, B.J., Vanacker, V., Wright, J., 2010. Dynamic interactions of life and its landscape: feedbacks at the interface of geomorphology and ecology. Earth Surface Processes and Landforms 35 (1), 78–101.

Roering, J.J., 2008. How well can hillslope evolution models explain topography? Simulating soil production and transport using high-resolution topographic data. Geological Society of America Bulletin 120, 1248–1262.

Roering, J.J., Perron, J.T., Kirchner, J.W., 2007. Functional relationships between denudation and hillslope form and relief. Earth and Planetary Science Letters 264 (1–2), 245–258.

Roering, J.J., Marshall, J., Booth, A.M., Mort, M., Jin, Q., 2010. Evidence for biotic controls on topography and soil production. Earth and Planetary Science Letters 298 (1–2), 183–190.

Salisbury, N., 1971. Threads of inquiry in quantitative geomorphology. In: Morisawa, M. (Ed.), Quantitative geomorphology, some aspects and applications, Binghamton Symposium Proceedings, Binghamton, NY.

Schulz, W.H., 2007. Landslide susceptibility revealed by LIDAR imagery and historical records, Seattle, Washington. Engineering Geology 89 (1), 67–87.

Slatton, K.C., Carter, W.E., Shrestha, R.L., Dietrich, W., 2007. Airborne laser swath mapping: achieving the resolution and accuracy required for geosurficial research. Geophysical Research Letters 34 (23), L23S10.

Snyder, N.P., Kammer, L.L., 2008. Dynamic adjustments in channel width in response to a forced diversion: Gower Gulch, Death Valley National Park, California. Geology 36 (2), 187–190.

Staley, D.M., Wasklewicz, T.A., Blaszczynski, J.S., 2006. Surficial patterns of debris flow deposition on alluvial fans in Death Valley, CA using airborne laser swath mapping data. Geomorphology 74 (1), 152–163.

Tarolli, P., Dalla Fontana, G., 2009. Hillslope-to-valley transition morphology: new opportunities from high resolution DTMs. Geomorphology 113 (1), 47–56.

Tarolli, P., Sofia, G., Dalla Fontana, G., 2012. Geomorphic features extraction from high-resolution topography: landslide crowns and bank erosion. Natural Hazards 1–19.

Tucker, G.E., Bras, R.L., 1998. Hillslope processes, drainage density, and landscape morphology. Water Resources Research 34 (10), 2751–2764.

Tucker, G.E., Hancock, G.R., 2010. Modelling landscape evolution. Earth Surface Processes and Landforms 35 (1), 28–50.

Uttal, D.H., 2001. Seeing the big picture: map use and the development of spatial cognition. Developmental Science 3 (3), 247–264.

Van Den Eeckhaut, M., Poesen, J., Verstraeten, G., Vanacker, V., Nyssen, J., Moeyersons, J., Beek, L.P.H.V., Vandekerckhove, L., 2007. Use of LIDAR-derived images for mapping old landslides under forest. Earth Surface Processes and Landforms 32 (5), 754–769.

Van Den Eeckhaut, M., Kerle, N., Poesen, J., Hervás, J., 2012. Object-oriented identification of forested landslides with derivatives of single pulse LiDAR data. Geomorphology 173–174, 30–42.
Ventura, G., Vilardo, G., Terranova, C., Sessa, E.B., 2011. Tracking and evolution of complex active landslides by multi-temporal airborne LiDAR data: the Montaguto landslide (Southern Italy). Remote Sensing of Environment 115 (12), 3237–3248.
Volker, H., Wasklewicz, T., Ellis, M., 2007. A topographic fingerprint to distinguish alluvial fan formative processes. Geomorphology 88 (1), 34–45.
Walter, R.C., Merritts, D.J., 2008. Natural streams and the legacy of water-powered mills. Science 319 (5861), 299–304.
Whorf, B.L., 1940. Science and linguistics. MIT Technology Review 42, 229–231.
Wolman, M.G., Leopold, L.B., 1957. River flood plains: some observations on their formation. USGS Professional Paper 282-C. U.S. Government Printing Office, Washington, DC, pp. 87–107.
Woolard, J.W., Colby, J.D., 2002. Spatial characterization, resolution, and volumetric change of coastal dunes using airborne LIDAR: Cape Hatteras, North Carolina. Geomorphology 48 (1), 269–287.