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A lightweight, low cost autonomously operating terrestrial laser scanner for quantifying and monitoring ecosystem structural dynamics

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ABSTRACT

The three-dimensional (3-D) structure of ecosystems is inherently dynamic. However, this is often ignored in ecological studies because it is difficult to characterize using traditional field methods. Terrestrial laser scanning (TLS) is a rapidly maturing technique to complement and enhance traditional field methods for quantifying 3-D geometric properties of ecosystems. Two major limitations of TLS include the low temporal resolution that often exists between each data acquisition, and the relatively high cost of such systems (entry level systems cost >$40,000 USD) that puts this method out of reach for many potential users. Consequently, TLS is currently limited as a mainstream method for capturing 3-D geometric ecosystem dynamics. The objectives of this study were to (i) describe the design of a lightweight (3.85 kg), low-cost ($<12,000 USD), autonomously operating terrestrial laser scanner (ATLS) and to (ii) test its ability to provide data to quantify and monitor ecological characteristics that exhibit structural change. We tested the utility of the ATLS data to quantify plant growth by measuring plants with different heights and diameter at breast height (DBH). Specifically, we derived the canopy heights of a conifer tree (Engelmann spruce, *Picea engelmannii*), broadleaf tree (Quaking aspen, *Populus tremuloides*), graminoid (*Calamagrostis x acutiflora*), and forb (*Hemerocallis lilioasphodelus*), and the DBH of Ponderosa Pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) trees. The ATLS was also tested under varying weather conditions (including rain, snowfall and temperature ranging from −9.1 to 21.1 °C), to quantify canopy structural changes in quaking aspen during leaf drop relative to a Ponderosa Pine that retained its leaves over the same time period. We also compared canopy structural changes quantified by ATLS canopy laser returns with those quantified using a commercial TLS. Our results showed strong agreements between observed and ATLS derived conifer tree canopy height (RMSE = 0.96 cm, $r^2 = 1.00$, slope = 0.96, intercept = 1.43), broadleaf tree canopy height (RMSE = 0.08 m, $r^2 = 0.99$, slope = 1.01, intercept = −0.38), graminoid and forb canopy height (RMSE = 1.56 cm, $r^2 = 0.98$, slope = 1.04, intercept = −2.22), and DBH (RMSE = 2.24 cm, $r^2 = 0.99$, slope = 0.99, intercept = 0.45). A strong relationship ($r^2 = 0.86$) also existed between the number of TLS and ATLS canopy laser returns. Our results indicate that the ATLS is suitable for monitoring and quantifying dynamics of plant growth and potentially many other 3-D properties of ecosystems. While further research is needed to better understand the effect of scan resolution, beam divergence, and atmospheric conditions on the accuracy of ATLS derived metrics, this instrument has great promise for providing new insights into dynamic ecosystem processes that are currently difficult to monitor at high temporal and spatial resolution.

1. Introduction

Ecosystem three-dimensional (3-D) structure is inherently dynamic, often changing in complex, non-linear ways as a result of both sudden (i.e., “pulsed”) and continual (“pressed”) environmental influences (Ives and Carpenter, 2007). Methodological techniques that allow for ecosystem and geomorphological structural changes to be quantified and monitored at high temporal and spatial resolutions are therefore needed to better understand

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dynamic structural processes such as plant growth and decay, fluvial, lacustrine, and coastal geomorphology, snow/ice accumulation and melt, and other aspects of landscape evolution (e.g., Starek et al., 2011). New understanding gained from such studies could be of great practical and scientific significance, ranging in application from tracing plant growth rate response to climate change (e.g., Schurr et al., 2006), to tracking 3-D changes in wildlife habitat (e.g., Vierling et al., 2008), to untangling complexities of landform evolution (Lim et al., 2005; Roncat et al., 2011), among many others. Empirical data collected through these efforts would provide new information upon which to develop and validate mechanistic 3-D simulation models that are dynamic in time.

Although 3-D geometric dynamics of ecosystems have been studied and modeled for decades (e.g., Shugart et al., 1973; Ryu et al., 2012), relatively little quantitative 3-D data on ecosystem structural change exists. Airborne and satellite RADAR and LiDAR platforms have bolstered understanding of many critical topics relating to ecosystem and geomorphological structure at the landscape scale (e.g., Treuhaft and Cloude, 1999; Lefsky et al., 2002); however, satellite systems operate at relatively coarse spatial resolution and airborne LiDAR datasets are generally acquired at a very low temporal frequency. Therefore, both airborne and satellite RADAR and LiDAR may not be suitable to study some topics where 3-D structural change occurs rapidly, or at a fine spatial scale. At these fine spatiotemporal scales, quantification of 3-D geometric changes traditionally relies on manual field measurements (e.g., Schurr et al., 2006). Unfortunately, by their nature, manual measurements often suffer from several disadvantages: they may have poor spatial resolution and/or limited spatial extent, they may mask or influence the process of interest by altering the original study site (e.g., by removing biomass or simply accessing the study site), and they are often laborious and costly (e.g., Jester and Klik, 2005). As a consequence, our current understanding of 3-D ecosystem dynamics is limited and hinders our ability to model and predict ecosystem responses to changing environmental conditions (Arora, 2002; Scanlon et al., 2005; Schurr et al., 2006).

Terrestrial laser scanning (TLS) is a rapidly maturing technique that may complement and enhance traditional field methods for quantifying structural properties of ecosystems at the fine (cm-level) scale. For example, terrestrial laser scanners have been used to quantify the 3-D geometric properties of plants (Clawges et al., 2007; Rosell et al., 2009; Eitel et al., 2010; Keightley and Bawden, 2010; Moorthy et al., 2011; Vierling et al., 2012), soil surfaces (Haubrock et al., 2009; Eitel et al., 2011b; Sankey et al., 2011; Wenske et al., 2012; Hancock et al., 2008; Perroy et al., 2010), snow surfaces (Egli et al., 2012; Prokop, 2008; Schaffhauser et al., 2008; Gutmann et al., 2011), stream banks and stream channels (Milan et al., 2007; Williams et al., 2011), cliffs (Lim et al., 2005), and glaciers (Schwalbe et al., 2008). However, one of the major limitations of TLS is the low temporal resolution that generally exists between repeated data acquisitions which limits its use to quantify 3-D geometric changes (Milan et al., 2007; Staley et al., 2011; Egli et al., 2012). For example, Milan et al. (2007) showed that erosion and deposition volumes in a proglacial river were increasingly underestimated with a progressively coarser temporal sampling resolution. An 8-day surveying interval revealed 67% less erosion and 14% less deposition than a daily survey interval. The low temporal resolution that often exists between TLS data acquisitions is mainly due to the fact that it is expensive and labor intensive to conduct repeated surveys. Repeated measurements may also require the set-up of spatially invariable targets to tie multiple TLS surveys to a common datum, which can be time consuming and sometimes difficult, dangerous, and impractical. In addition, TLS systems are often quite expensive to purchase (e.g., an entry-level price of ∼$40,000 USD), therefore limiting their accessibility to a broad user base. Finally, many TLS systems are often too heavy to be mounted on infrastructure such as meteorological or flux towers. Because autonomous collection of ecosystem structure data would well complement such meteorological and/or flux measurements, lightweight instruments (e.g., <4 kg) would enable a suite of new applications for integration with common meteorological instrumentation.

An alternative to traditional TLS instruments is to assemble a terrestrial laser system from off-the shelf items to autonomously and continuously scan a study site. Gutmann (2010) and Gutmann et al. (2011), for example, have pioneered work in this area, using a laser rangefinder and pan-tilt unit to monitor 3-D snow accumulation and melt dynamics. To date, however, a thorough description of such a system is missing in the scientific literature.

Here, we provide detailed explanation of such a system – hereafter referred to as an autonomously operating terrestrial laser scanner (ATLS). Also, because relatively little is known about the ability of such an autonomous system to characterize structural properties of surfaces other than snow (e.g., quantifying plant dynamics), we present additional analyses in this regard. Compared to monitoring structural properties of continuous surfaces such as snow, quantifying discontinuous surfaces such as plant canopies can be complicated when using a laser rangefinder because edges of leaves and branches can split a single laser pulse so it may strike two or more objects (e.g., multiple leaf surfaces, or leaf and branch surfaces) (Hebert and Krotkov, 1992; Tuley et al., 2004). If the split laser beam returns to the laser rangefinder from the front and background object, the instrument calculates a single distance value by integrating the distances to the front and background object proportional to their signal strength (Hebert and Krotkov, 1992; Tuley et al., 2004; Rosell et al., 2009; Eitel et al., 2010; Sanz-Cortiella et al., 2011a). This then results in a mixed edge return (also known as mixed pixel, ghost return, or air return) inherent to all laser based ranging methods, where the recorded distance is neither the distance to the front and background object but rather the distance to a phantom object (i.e., fictitious point) that lays somewhere in between both objects (Hebert and Krotkov, 1992; Tuley et al., 2004). Also, the reflective properties of vegetation differ from snow which may affect the accuracy of laser derived metrics and should be considered when assembling an ATLS.

Our objective in this study was therefore first to describe the design of an autonomously and continuously operating terrestrial laser system (ATLS), and second to conduct testing on our ability to use an ATLS to quantify 3-D dynamics of plant canopies.

2. Methods

2.1. Autonomously operating terrestrial laser scanner (ATLS) instrument design

The laser system components consist of a time-of-flight laser rangefinder, circular level, electronic pan-tilt unit, tribrach, datalogger, and power supply (battery and 70 W solar panel) (Fig. 1). At air temperatures above freezing, the ATLS requires 12 V DC power and 0.5 amp of current. It is important to note that the power supply was designed to ensure a continuous operation of the ATLS for sun hours and temperatures typical for Idaho during the growing season. Hence, the power supply might need to be adjusted (e.g., increase number of solar panels and/or their nominal maximum power) for areas with different temperatures and/or sun hours to guarantee an uninterrupted power supply to the ATLS. The cost for all ATLS components as of 2013 is $11,841 USD (Table 1). Depending on the objectives of the study, proprietary software might be necessary which might add to the overall cost. However, open-source software packages are available such as LAStools (Isenburg, 2007–2012), GEON Points2Grid Utility (Kim et al.,