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Integrating Landsat pixel composites and change metrics with lidar plots to predictively map forest structure and aboveground biomass in Saskatchewan, Canada

Harold S.J. Zald [a,*], Michael A. Wulder [b], Joanne C. White [b], Thomas Hilker [a], Txomin Hermosilla [c], Geordie W. Hobart [b], Nicholas C. Coops [c]

[a] *Department of Forest Engineering Resources and Management, College of Forestry, Oregon State University, Corvallis, OR 97331, USA*
[b] *Pacific Forestry Centre, Canadian Forest Service, Natural Resources Canada, Victoria, British Columbia V8Z 1M5, Canada*
[c] *Integrated Remote Sensing Studio, Department of Forest Resources Management, University of British Columbia, Vancouver, British Columbia V6T 1Z4, Canada*

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ABSTRACT

Forest inventory and monitoring programs are needed to provide timely, spatially complete (i.e. mapped), and verifiable information to support forest management, policy formulation, and reporting obligations. Satellite images, in particular data from the Landsat Thematic Mapper and Enhanced Thematic Mapper (TM/ETM+) sensors, are often integrated with field plots from forest inventory programs, leveraging the complete spatial coverage of imagery with detailed ecological information from a sample of plots to spatially model forest conditions and resources. However, in remote and unmanaged areas such as Canada's northern forests, financial and logistic constraints can severely limit the availability of inventory plot data. Additionally, Landsat spectral information has known limitations for characterizing vertical vegetation structure and biomass; while clouds, snow, and short growing seasons can limit development of large area image mosaics that are spectrally and phenologically consistent across space and time. In this study we predict and map forest structure and aboveground biomass over 37 million ha of forestland in Saskatchewan, Canada. We utilize lidar plots—observations of forest structure collected from airborne discrete-return lidar transects acquired in 2010—as a surrogate for traditional field and photo plots. Mapped explanatory data included Tasseled Cap indices and multi-temporal change metrics derived from Landsat TM/ETM+ pixel-based image composites. Maps of forest structure and total aboveground biomass were created using a Random Forest (RF) implementation of Nearest Neighbor (NN) imputation. The imputation model had moderate to high plot-level accuracy across all forest attributes (R^2 values of 0.42–0.69), as well as reasonable attribute predictions and error estimates (for example, canopy cover above 2 m on validation plots averaged 35.77%, with an RMSE of 13.45%, while unsystematic and systematic agreement coefficients (AC_{uns} and AC_{sys}) had values of 0.63 and 0.97 respectively). Additionally, forest attributes displayed consistent trends in relation to the time since and magnitude of wildfires, indicating model predictions captured the dominant ecological patterns and processes in these forests. Acknowledging methodological and conceptual challenges based upon the use of lidar plots from transects, this study demonstrates that using lidar plots and pixel compositing in imputation mapping can provide forest inventory and monitoring information for regions lacking ongoing or up-to-date field data collection programs.

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1. Introduction

Forests cover approximately 31% of global land surface area (FAO, 2010), providing critical ecosystem services such as wood products, wildlife habitat, biodiversity, and regulation of the earth's biogeochemical cycles (Daily, 1997; Millennium Ecosystem Assessment, 2005). In Canada, forests cover over 400 million ha, representing more than 53% of Canada's land area and accounting for approximately 10% of global forest cover (Natural Resources Canada, 2014). Canada's forests make significant contributions to global bio-geochemical cycles and provide

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* Corresponding author at: 280 Peavy Hall, Oregon State University, Corvallis, OR 97331, USA.
E-mail addresses: harold.zald@oregonstate.edu (H.S.J. Zald), mike.wulder@canada.ca (M.A. Wulder), joanne.white@canada.ca (J.C. White), thomas.hilker@oregonstate.edu (T. Hilker), txomin.hermosilla@live.forestry.ubc.ca (T. Hermosilla), geordie.hobart@canada.ca (G.W. Hobart), nicholas.coops@ubc.ca (N.C. Coops).

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a wide array of other ecosystem services (Natural Resources Canada, 2014). Sustainable management and conservation of forests to maintain these services requires consideration of a wide array of ecological, economic, and societal values. To inform these needs, comprehensive inventory and monitoring systems are required to provide timely, spatially complete (i.e. mapped), and verifiable information on forest structure (i.e. canopy cover, stand height, and stem volume), biomass, and carbon pools.

Inventory and monitoring of forest conditions (i.e. structure, composition, biomass, and carbon) are often conducted by National Forest Inventory programs that rely upon plot-based field sampling (Tomppo et al., 2010). Measurements from field inventory plots include highly detailed information about forest vegetation composition and structure, from which sample-based estimates of forest conditions can be calculated. Information from inventory plots and other long-term plot networks can be used to develop and calibrate growth and yield equations (Smith, Bell, Herman, & See, 1984; Lessard, McRoberts, & Holdaway, 2001; Lacerte, Larocque, Woods, Parton, & Penner, 2006), and facilitate the calibration and validation of remotely sensed estimates of forest inventory attributes (Smith, 2002; Wulder, Kurz, & Gillis, 2004). The re-measurement of permanent sample plots in a forest inventory cycle can also provide critical information for change monitoring (Poso, 2006; Woodbury, Smith, & Heath, 2007; Herold et al., 2011; Moeur et al., 2011). Despite their widespread use, lack of spatial coverage and lengthy re-measurement intervals can limit the effectiveness of field plots in quantifying forest change, especially in remote and/or unmanaged forests that often have greatly reduced or non-existent field inventory data (Wulder et al., 2004). To accommodate the difficulty and expense in collecting ground plots, photo plots are often used as a substitute for field plots, as well as for stratification purposes in multi-phase plot-based inventory programs (Bechtold & Patterson, 2005; Gillis, Omule, & Brierley, 2005). Photo plots provide an opportunity for implementation of a sample-based inventory upon similar statistical underpinnings as plot-based programs. Large area representation is possible with photo plots (Nielsen, Aldred, & MacLeod, 1979; Magnussen & Russo, 2012); however complete spatial coverage is lacking. Furthermore, establishing and measuring photo plots typically requires purpose collected imagery, which in combination with expert interpretation and the need for some level of supporting field plot data, can substantially increase costs in remote and unmanaged forests.

As a complementary approach to field and photo-based inventories, satellite imagery can provide spatially complete information about forests across large areas. Regional and global maps of forest cover and change over time have long been derived from multispectral satellite imagery (Woodcock et al., 1994; Cohen, Maiersperger, Spies, & Oetter, 2001; Hansen et al., 2003, 2013. Hermosilla, Wulder, White, Coops, & Hobart, 2015a). In particular, Landsat TM/ETM + imagery is widely used for forest mapping because of its free and open data policy, global coverage, long temporal record, large scene-sizes, and spectral and spatial resolutions compatible with characterizing vegetation conditions and dynamics (Cohen & Goward, 2004; Woodcock et al., 2008; Wulder, Masek, Cohen, Loveland, & Woodcock, 2012a; Kennedy et al., 2014). Regional and national forest inventory programs increasingly integrate satellite imagery with inventory plots, leveraging the detailed forest conditions provided by sampled field or photo plots with complete spatial coverage provided by satellite imagery to generate spatial predictions (e.g. maps) of forest conditions (Ohmann & Gregory, 2002; Tomppo et al., 2008; Wilson, Woodall, & Griffith, 2013; Beaudoin et al., 2014). As one possible approach, nearest neighbor (NN) imputation methods are widely used in plot/imagery integration. Imputation methods fill in observations that are missing for some records (Y-variables), using related variables that are available for all records (X-variables). In forest mapping applications, Y-variables are usually measures of forest composition or structure derived from a sample of field or photo plots, while mapped X-variables can include multispectral satellite imagery and other spatially complete datasets (i.e. climate, topography). Regression approaches predict new Y-variables when they are missing, but can distort marginal distributions and covariation between Y-variables. In contrast, imputation is a method for filling in missing data by substituting values from donor observations with the underlying assumption that two locations with similar values of X-variables should be similar with respect to Y-variables. A major strength of imputation approaches is these donor-based methods are multivariate, non-parametric, and distribution-free (Eskelson et al., 2009).

Common across large scale imputation mapping projects is the use of satellite imagery as explanatory variables (X-variables). The recent availability of cost-free Landsat images in a consistent, analysis-ready, and easy-to-use format has facilitated a conceptual shift in how Landsat imagery is used in ecosystem inventory, mapping, monitoring (Wulder et al., 2012a; Kennedy et al., 2014). Advances in pixel-based image composting and change detection using the Landsat time series (LTS) can be especially important for improving the accuracy of forest maps and partially overcoming passive optical imagery limitations. Pixel-based image compositing methods are applied to the Landsat archive to generate cloud-free, radiometrically and phenologically consistent image composites that are spatially contiguous over large areas (Roy et al., 2010; Hansen & Loveland, 2012; Griffiths, van der Linden, Kuemmerle, & Hostert, 2013; White et al., 2014). LTS change detection methods provide pixel-level characterization of forest disturbance, recovery, and other trends (Masek et al., 2008; Huang et al., 2010; Kennedy, Yang, & Cohen, 2010; Hermosilla et al., 2015a). Pixel-based image composites are invaluable for image/plot integration when minimization of year-to-year spectral variability and seamless multi-scene image mosaics are needed to relate to plot data collected across large spatial extents or multiple years (Ohmann et al., 2012). By quantifying disturbance, recovery, and trends, LTS change metrics can improve and partially overcome Landsat limitations in predicting forest vegetation structure (Lu, 2006), because they characterize temporal changes associated with forest processes of mortality, succession, and growth (Pflugmacher, Cohen, & Kennedy, 2012; Zald et al., 2014), and facilitate predictions of forest biomass dynamics over time (Powell et al., 2010; Main-Knorn et al., 2013; Pflugmacher, Cohen, Kennedy, & Yang, 2014).

A more practical approach for large scale inventory in remote areas may be to improve maps of forest attributes using remotely sensed information on vegetation structure. Airborne light detection and ranging (lidar) can provide detailed three-dimensional structure of forest canopies, and has been widely used to characterize forest cover and structure (see reviews by Dubayah & Drake, 2000; Lefsky, Cohen, Parker, & Harding, 2002; Reutebuch, Andersen, & McGaughey, 2005), been integrated with plot-based samples of forest conditions to accurately map forest structure (Hudak, Crookston, Evans, Hall, & Falkowski, 2008; Falkowski et al., 2010; Zald et al., 2014), and used to update forest inventory data (Hilker, Wulder, & Coops, 2008). Declining costs have made lidar acquisitions possible for increasingly large areas; yet complete, single-year wall-to-wall lidar coverage for large areas is still costly and logistically prohibitive for many regional and national forest inventory programs. As a result, the use of lidar in mapping forest conditions is often constrained to sub regional extents (Hudak et al., 2008; Falkowski et al., 2010; Zald et al., 2014), or as a component of multi-phase sampling procedures in larger landscapes (Andersen, Strunk, Temesgen, Atwood, & Winterberger, 2012; Strunk, Temesgen, Andersen, & Packalen, 2014). Alternatively, sample based "lidar plots" may provide detailed, spatially discrete information about vegetation structure, similar to field plots in areas without sufficient field inventory data (Wulder et al., 2012b).

In this paper, we build upon the potential synergies of the Landsat times series and lidar observations to predictively map forest structure (i.e. canopy cover, stand height, basal area, etc.) and aboveground

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