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Monitoring boreal forest biomass and carbon storage change by integrating airborne laser scanning, biometry and eddy covariance data

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ABSTRACT

This study presents a comparison and integration of three methods commonly used to estimate the amount of forest ecosystem carbon (C) available for storage. In particular, we examine the representation of living above- and below-ground biomass change (net accumulation) using plot-level biometry and repeat airborne laser scanning (ALS) of three dimensional forest plot structure. These are compared with cumulative net CO_2 fluxes (net ecosystem production, NEP) from eddy covariance (EC) over a six-year period within a jack pine chronosequence of four stands (~94, 30, 14 and 3 years since establishment from 2005) located in central Saskatchewan, Canada. Combining the results of the two methods yield valuable observations on the partitioning of C within ecosystems. Subtracting total living biomass C accumulation from NEP results in a residual that represents change in soil and litter C storage. When plotted against time for the stands investigated, the curve produced is analogous to the soil C dynamics described in Covington (1981). Here, ALS biomass accumulation exceeds EC-based NEP measured in young stands, with the residual declining with age as stands regenerate and litter decomposition stabilizes. During the 50–70 year age-period, NEP and live biomass accumulation come into balance, with the soil and litter pools of stands 70–100 years post-disturbance becoming a net store of C. Biomass accumulation was greater in 2008–2011 compared to 2005–2008, with the smallest increase in the 94-year-old “old jack pine” stand and greatest in the 14-year-old “harvested jack pine 1994” stand, with values of 1.4 ($\pm$3.2) tC ha^{-1} and 12.0 ($\pm$1.6) tC ha^{-1}, respectively. The efficiency with which CO_2 was stored in accumulated biomass was lowest in the youngest and oldest stands, but peaked during rapid regeneration following harvest (14-year-old stand). The analysis highlights that the primary source of uncertainty in the data integration workflow is in the calculation of biomass expansion factors, and this aspect of the workflow needs to be implemented with caution to avoid large error propagations. We suggest that the adoption of integrated ALS, in situ and atmospheric flux monitoring frameworks is needed to improve spatio-temporal partitioning of C balance components at sub-decadal scale within rapidly changing forest ecosystems and for use in national carbon accounting programs.

1. Introduction

Net ecosystem production (NEP) represents the organic carbon (C) balance of an ecosystem through the process of sequestration and loss (Randerson, Chapin, Harden, Neff, & Harmon, 2002). Specifically, this involves the processes of photosynthesis and C import, minus losses to ecosystem respiration (Re), C export and non-biological oxidation of C (Lovett, Cole, & Pace, 2006). Given linkages between atmospheric CO_2 and global climate (IPCC, 2013), monitoring of continuously changing C stocks, sources and sinks, as well as associated land management or climatic feedbacks, is required for effective greenhouse gas mitigation strategies (Canadell et al., 2007). Spatialization and partitioning of ecosystem NEP enables improved understanding of atmospheric C sequestration in biomass growth, and therefore may be linked to national C accounting programs, calibration of land surface models and diagnostic assessment of the terrestrial biosphere (Jung et al., 2011).

Reporting of C gains and losses within the terrestrial biosphere has increased in recent years as a result of these needs (Canadell et al., 2007), with national reporting guidelines set by the United Nations Framework Convention on Climate Change (UNFCCC). The need to develop and refine sophisticated C monitoring techniques are further realised through international programs like the REDD (Reducing Emissions from Deforestation and forest Degradation) and GOFC-GOLD (Global Observation of Forest and Land Cover Dynamics) programs. Examples of national agencies currently embarking on or supporting

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integrated remote sensing and in situ ecosystem-scale C monitoring and research initiatives are NEON (National Ecological Observatory Network Inc. USA, www.neonscience.org) and TERN (Terrestrial Ecosystem Research Network, Australia, www.tern.org.ca).

Several monitoring strategies are currently in place to quantify drivers of short-term C source/sink variability and longer-term changes in ecosystem C stocks. However, approaches used to understand ecosystem C differ in terms of spatial and temporal representation, as well as the physical quantities being measured (Medvigy & Moorcroft, 2011). This has the potential to create discrepancies in greenhouse gas reporting across regions and between nations. For example, eddy covariance (EC) methods routinely provide estimates of the net ecosystem exchange (NEE) of gains and losses of CO_2 between soil, vegetation and atmosphere over defined time periods and spatial extents. NEE is equivalent but opposite in sign to NEP when inorganic C fluxes balance or are negligible. Gross primary production (GPP) is NEP minus Re, though is less directly observed, as ecosystem respiration (the combination of autotrophic and heterotrophic respiration) is usually modelled (Barr, Morgenstern, Black, McCaughey, & Nesic, 2006; Griffis et al., 2003). Over periods of 2 to 10 years, changes in GPP or NEP due to factors like severe drought, fire or insect/pathogen disturbances may be monitored (Barr et al., 2007; Ciais et al., 2005). However, because EC methods provide an aggregate estimate of C exchange, there are limits to how far ecosystem process, composition changes or anthropogenic vs natural influences can be partitioned or extrapolated over broad regions. Further, large uncertainties exist with regards to within-ecosystem process interaction thereby limiting the use of data-intensive ecosystem biogeochemical models (Canadell et al., 2007).

Another C assessment option uses inventory methods to monitor above and below-ground C pools within forest plots. Plots can be revisited every few years to estimate rates of biomass accumulation and partitioning associated with age, site history, and changes to management regime. Plot measurements can include direct sampling of living biomass and other C pools including roots, detritus and litterfall. These data can be used to estimate net primary production (NPP) of cumulative biomass C stored within all above and below-ground components (Law, Thornton, Irvine, Anthoni, & Van Tuyl, 2001). (Note, NEP and NPP are parallel but distinct concepts, as NPP does not account for heterotrophic respiration C losses). Above and below-ground biomass measurements can be destructive, limited in spatial extent and temporal frequency because they are labour intensive (Curtis et al., 2002; Gower et al., 1997; Lambert et al., 2005; Peichl & Arain, 2007, Zha et al., 2013), and may not fully account for spatial variability (Kristensen, Næsset, Ohlson, Bolstad, & Kolka, 2015). Despite such limitations, in situ observations of temporal change in C stocks provide a cumulative assessment of biomass C growth and loss (Barford et al., 2001), which may allow for more direct partitioning of changes in C pool quantities associated with climatic, disturbance and land management drivers.

For long-term monitoring of plot-based C pools, measurement protocols need to be consistent to ensure accurate comparisons. A challenge associated with repetitive field sampling is the possibility that by collecting measurements and samples (e.g. invasive root measurements, trampling of understory, litter traps), the observer might alter the growth trajectory of the plot or surrounding area (Cahill, Castelli, & Casper, 2001; Semboli, Beina, Closset-Kopp, Gourlet-Fleury, & Decocq, 2014). Such concerns provide justification for refining and integrating non-invasive C assessment techniques such as eddy covariance and remote sensing (He, Chen, Pan, Birdsey, & Kattge, 2012; Kristensen et al., 2015). To this end, airborne laser scanning (ALS) provides a non-invasive spatially- and structurally-explicit scaling mechanism between field-plot data and EC-based estimates of NEP within forest ecosystems. ALS biomass models typically utilize regression relationships between ALS canopy height profile metrics and plot-level biomass derived using allometric equations. In comparison with EC and plot data, ALS provides a one-time spatial characterisation of above-ground tree biomass (Asner & Mascaro, 2014; Means et al., 1999; Næsset & Gobakken, 2008; Popescu, Wynne, & Nelson, 2003). For time intervals of three years or more, ALS has been demonstrated to accurately quantify canopy growth rates (Hopkinson, Chasmer, & Hall, 2008; Hudak et al., 2012; Næsset, Bollandsås, Gobakken, Gregoire, & Ståhl, 2013; Næsset & Gobakken, 2005) and biomass change (Økseter, Bollandsås, Gobakken, & Næsset, 2015; Skowronski, Clark, Gallagher, Birdsey, & Hom, 2014). It is feasible, therefore, to develop a framework that maps biomass C across the landscape, tracks changes through time and then reconciles these remote sensing observations with NEP.

Given the proliferation of large area, even nation-wide, ALS coverages in recent years (Wulder et al., 2012; Stoker, Cochrane, & Roy, 2013; Hopkinson et al., 2013) and new ecosystem monitoring programs like NEON and TERN in the USA and Australia, it is now logical and feasible to incorporate ALS within an integrated C flux monitoring framework. Indeed, this was a recommendation of a recent Fluxnet report (Beland et al., 2015). ALS is already a recognized method for better characterising flux tower site canopy structural variability (Chasmer et al., 2008b) within approximately 44 international Fluxnet sites, with at least 8 of these sites containing two or more temporal ALS datasets (Beland et al., 2015). Furthermore, the work of Chasmer et al. (2008a, 2008b and 2011) has provided the platform for such a framework by developing and refining methods of ALS forest canopy attribute integration with EC CO_2 flux data.

While an integrated EC and ALS ecosystem C monitoring framework is conceptually feasible, its implementation is challenged both as a result of: a) their currently being few sites around the world where long-term EC NEP records have been collected in tandem with multi-temporal ALS; and b) the subtle but critical differences in the way C pools and fluxes are quantified in EC, ALS and plot measurement methods. While plot-level monitoring can track changes in terrestrial C pools at distinct locations, this differs to ALS observations that can track above ground standing biomass changes across the landscape. And both are distinct to EC NEP, which is inferred from the NEE of C between the ecosystem and atmosphere within the footprint of a flux tower. Clearly then, each technique has distinct spatio-temporal domains of representation and each observes slightly different components of the terrestrial C cycle.

This paper addresses the disparate sampling and spatio-temporal representations of ALS, plot and EC ecosystem C observations and introduces a framework for data integration that, when combined, provides more information on ecosystem C balance than is possible using each method in isolation. The aim is to integrate all three approaches in a manner that accounts for and capitalises upon the different C pool and process representivity of each. A case study is presented to apply the integrated C assessment framework within a chronosequence of regenerating boreal forest stands over a six year period in an attempt to better partition GPP and NEP as the stands progress from adolescence to maturity.

2. Materials and methods

2.1. Study area

A chronosequence of four jack pine (*Pinus banksiana* Lamb.) stands, located approximately 100 km northeast of Prince Albert, Saskatchewan, Canada (53°54′ N, 104°39′ W, ~490 m a.s.l.) were examined in this study (Fig. 1). Jack pine is one of the most numerous boreal forest species, covering an area of ~517,000 km^2 of Canada and parts of the northern USA (Little, 1971), and therefore represents an important northern hemisphere component of global biomass. Two sites, a mature stand (91–97 year old; Old Jack Pine (OJP)) and an intermediate-aged stand harvested in 1975 (HJP75) were established during the Boreal Ecosystem Atmosphere Study (BOREAS) (Sellers et al., 1995) in 1993. Monitoring at the sites continued from 2001 to 2011 under the project name: Boreal Ecosystem Research and Monitoring Sites (BERMS) within