ALS monitoring of changes in forest biomass carbon storage

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Abstract

Multi-temporal ALS and field plot data are used to model changes in carbon storage over several years at jack pine and eucalyptus forest stands in Canada and Australia, respectively. Results are compared with continuous eddy covariance estimates of net ecosystem exchange and gross ecosystem production. Combined, these carbon monitoring techniques can yield improved partitioning of forest carbon storages and pathways through time.

1. Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) is an international agreement requiring countries to report on forest carbon stocks and changes (IPCC 2006). Flux towers employing eddy covariance (EC) techniques (Baldocchi and Meyers, 1998) provide localised estimates of the carbon balance and require continuous operation to provide long term estimates. These data can be used to calibrate remote sensing data products (Heinsch et al., 2006) so that above ground carbon (AGC) changes can be reported over large scales. Airborne laser scanning (ALS) has been used to map above ground biomass (e.g. van Aardt et al., 2006; Hopkinson et al., 2011) and since data availability is increasing while costs are dropping, better understanding the capacity for ALS to monitor biomass and growth is of great interest (e.g. Hopkinson et al., 2008). Furthermore, CO_2 flux monitoring stations require continuous operation and frequent maintenance, creating uncertainty over long term data availability and a need for complementary monitoring methods.

We report on efforts to evaluate multi-year biomass monitoring at two sites: i) the Boreal Ecosystem Research and Monitoring Sites (BERMS) in Saskatchewan Canada, and ii) a Eucalyptus forest at Tumbarumba in New South Wales, Australia. We report on the ability to model changes in forest carbon storage at stands ranging in maturity (BERMS) and management (Tumbarumba), while comparing long term ALS biomass change estimates with flux tower records of gross ecosystem production (GEP) and net ecosystem exchange (-NEE) (-ve sign as atmosphere is sink).

2. Methods

2.1 Study areas

The BERMS area is located in the southern boreal forest of central Saskatchewan, Canada, experiences ~500 mm annual precipitation and a mean temperature of ~0.4 ^{o}C. The sites were established, in part, by the Boreal Ecosystems Atmosphere Study (BOREAS) in 1993 and continued from 2001 to 2011 as part of an effort to better understand the impacts of climate change and disturbance on the carbon cycle of terrestrial ecosystems (Fluxnet-Canada, Canadian Carbon Program) (Margolis et al., 2006). The BERMS sites include mature trembling aspen (*Populus tremuloides*) and black spruce (*Picea mariana*), a jack pine (*Pinus banksiana*) chronosequence, peatland and forest fire sites. In this paper, four jack pine sites have been studied, due to the availability of multiple ALS datasets. The old jack pine (OJP) stand was cleared in 1914, whilst the other three stands were clear cut harvested in 1975 (HJP75), 1994 (HJP94) and 2002 (HJP02). These four stands are spread across an area of 5 km x 8 km, ranging in elevation from 500 m to 520 m with stem heights for the oldest stand reaching ~ 20 m (Figure 1A, 1B).

The Tumbarumba study site is in the Bago State Forest of the southern tablelands of New South Wales, Australia. It has a moist temperate climate with annual precipitation ~ 1500 mm and a mean annual temperature of 8.0 ^{o}C (Leuning et al., 2005). The wet sclerophyll forest site ranges in elevation from 1175 m to 1325 m, is dominated by mature alpine ash (*Eucalyptus delegatensis*) with stem heights up to 50 m, drains a small headwater catchment and has undergone significant forest management in recent years (Figure 1C, 1D). The focus of the study is the area immediately surrounding a flux tower, which lies at the boundary of two stands that were operationally thinned in 1984 and 1985. Surrounding these stands (>500 m from the tower), commercial thinning operations have occurred prior to and following the installation of the EC flux tower in 2000.

2.2 Data collection

Summertime ALS data were captured over BERMS each August for 2005, 2008 and 2011 using a small-footprint multiple-discrete-return airborne laser terrain mapper (ALTM) 3100C (Optech Inc. Toronto) operated with comparable flight and sensor settings, resulting in an aerial sampling density >2 pts/m^2. Coincident with the 2005 ALS mission, species, height and diameter at breast height (DBH) were measured at 22 x 11.3 m (0.04 ha) radius permanent sample plots (PSPs) (8 for OJP and HJP75, 6 for HJP94). The plots were located in a radial pattern at 100 m and 500 m out from a flux tower located near the centre of each stand (Figure 1A). All stems down to 2 cm diameter were measured and all plot centres were surveyed with a dual frequency differential global position system (DGPS) to within 10 cm. Flux monitoring towers were operational at the sites from ~2000 to 2008 (more recent data were collected but are unavailable at present).

At Tumbarumba, summertime ALS data were captured in December 2001 (Optech ALTM 2050), November 2009 (Riegl LMS-Q560) and January 2011 (Leica ALS60) (January 2011 is assumed to represent conditions at end of 2010). Unlike BERMS, the ALS data were not collected using equivalent acquisition configurations. Based on scan geometry, discrete return properties and sampling density (>2pts/m^2), the Optech ALTM and Leica ALS datasets collected nine years apart at ends of 2001 and 2010 were the most comparable. Within approximately 1 km of the flux tower, there are 30 x 17.8m radius (0.1 ha) PSP. In December 2009 (~ one year prior to the 2010 ALS survey), 20 of the PSP centres were surveyed with a single frequency DGPS to within 2 m, and DBH values for all stems were recorded. NEE and GEP data are available for the entire period.

2.3 Analysis

Field data were used to estimate stem- and plot-level above ground biomass (AGB) using established species-specific allometric equations. For the jack pine stands, stem height and DBH data were used (Lambert et al., 2005), while for the eucalyptus stands DBH data alone were applied to a native sclerophyll forest equation (Keith et al., 2000). No plot data were collected at HJP02 for this study but biometric data were collected in 2004 by Theede (2007) and are available on the Fluxnet-Canada Data Information System (DIS) (http://fluxnet.ccrp.ec.gc.ca/e_DataAccess.htm). Consequently, AGB at HJP02 was estimated from data collected in 2004. Plot-level biomass data were used to test ALS models of biomass by extracting coincident point cloud data and running regression models against many commonly used point cloud metrics. All ALS points within a plot were normalised by computing elevation residuals relative to a ground-classified digital elevation model (DEM) so that heights were reported relative to ground. The following metrics were tested for all returns and all returns above 0.2 m (to remove ground influence): mean, maximum, standard deviation, inter-quartile range (IQR), percentiles [P25, P50, P75, P90, P95, P99] and the following ratios: i) all returns / all returns above 1.5m, ii) all returns / all returns above average height and iii) all returns / all first returns above 1.5m. Single variable linear, power, log and exponential models were tested.

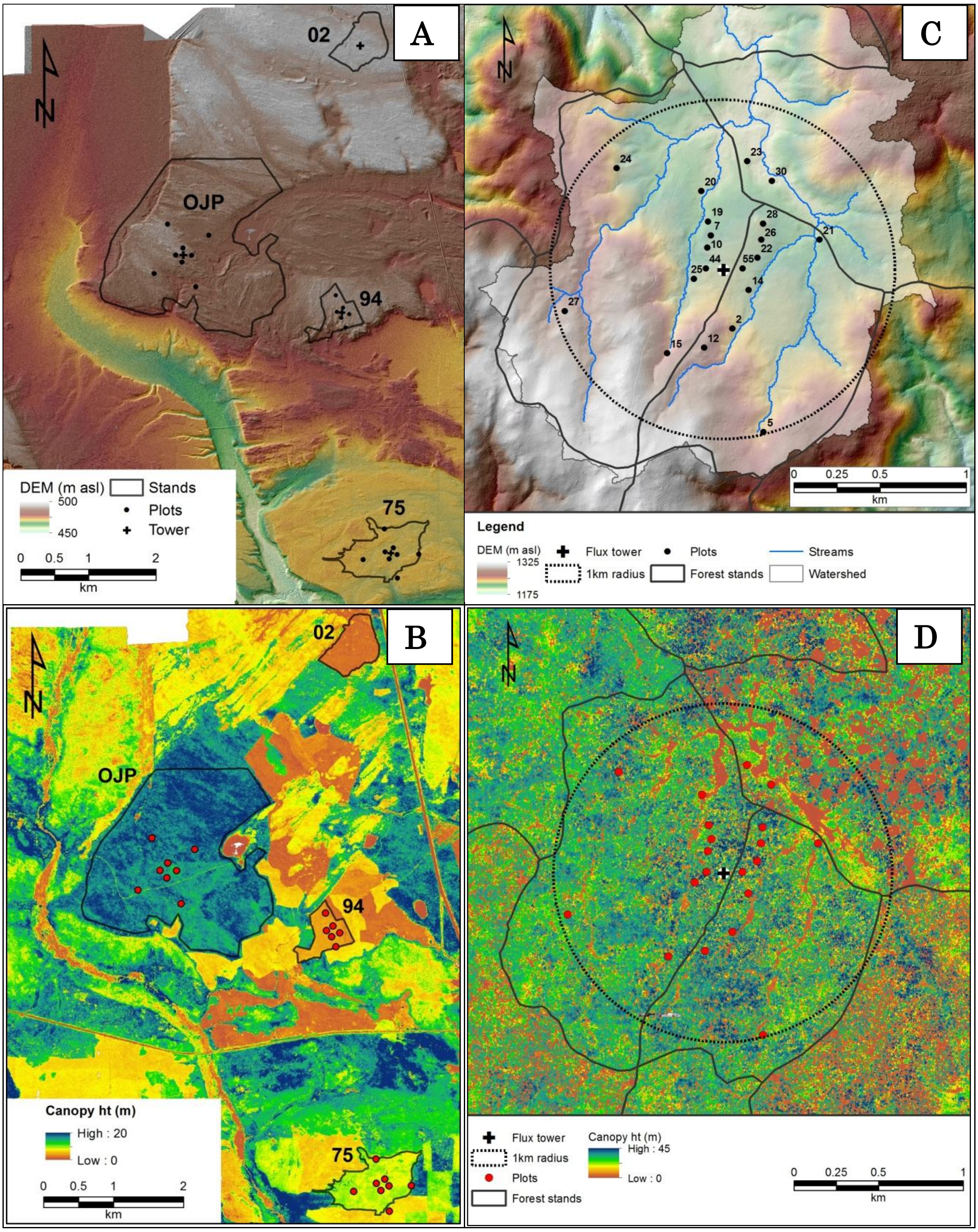

Figure 1: A) DEM, forest stands and plot locations for BERMS; B) Canopy height model (CHM) for BERMS illustrating jack pine stand heights in 2011; C) Tumbarumba DEM, forest stands, and plots with 1 km radius around tower to illustrate proximity to stands and headwater catchment; D) Tumbarumba CHM in 2010 illustrating variations in canopy openness associated with different stand management practices.

An optimal ALS model was chosen, based on predictive capability and consistency of its application to different datasets; i.e. a model could theoretically reproduce plot-level biomass estimates for the year of coincident plot and ALS sampling yet when applied to other years produce unrealistic or incomparable biomass estimates across the same landscape. Aside from differences in canopy sampling due to variations in laser pulse strength or geometry (Hopkinson, 2007), differences in understory, ground cover, leaf area index or surface moisture could potentially alter the point cloud frequency distribution shape and therefore the efficacy of the chosen model. Temporal plot data were not available for this test of comparability, so judgement was exercised based on years of field observations and knowledge of canopy conditions and management treatments at each site. For these reasons, a simple univariate model was preferred over a more sophisticated model adopting multiple variables or curve fitting techniques that could easily be trained to a dataset that itself might contain significant uncertainty. The assumption is that a simpler technique might not produce the highest accuracy model but it should be more robust for comparative analyses across a range of canopy heights and densities (e.g. Hopkinson et al., 2004).

Once an ALS AGB model was calibrated for BERMS and Tumbarumba, it was applied to the ALS point clouds surrounding each site. ALS model data were gridded to 20 m x 20 m cell arrays due to the BERMS training data that were extracted from 400 m^2 areas and a decision by AusCover to develop national ALS variable datasets at this raster resolution. This resolution was also convenient in that it ensured there were sufficient ALS points in each cell to generate a complete frequency distribution, while mitigating slight positional uncertainties in any of the datasets compared. AGB was converted to AGC_{ALS} (above ground carbon estimated from ALS) by assuming 50% of dry biomass is C and thus applying a multiplier of 0.5 (Atjay et al. 1977) to the model grids.

An expansion factor *e* (i.e. a multiplier greater than 1) was applied to AGC_{ALS} grids to derive $eAGC_{ALS}$ and add in a below ground biomass (BGB) component, so that tower-based productivity estimates would be more directly comparable with the biometric estimates derived from ALS. Dead biomass and other carbon pools were not included in this biomass expansion, as the intent was to map long-term productivity (growth). At BERMS, BGB *e* factors were derived from the biometric database on the Fluxnet DIS and ranged from 30% at the mature OJP site to 100% (or a doubling of AGC) at the HJP02 site. No data were available to derive an accurate expansion factor for the mature eucalyptus stands, so a generic *e* factor of 20% was applied (Greenhouse Challenge, 1998).

At BERMS and Tumbarumba, stand- and plot-level estimates of $eAGC_{ALS}$ were estimated for each year of ALS data. By summarising the plot-level estimates, it was possible to infer whether or not the plots accurately captured the spatial variability of biomass within the stands. The total change in above ground carbon ($\Delta eAGC_{ALS}$) was calculated by differencing the grid arrays and summarising by stand, plot and, in the case of Tumbarumba, the 1 km radius area surrounding the flux tower. These results were then compared with available GEP records (BERMS), and -NEE and GEP (Tumbarumba) to assess the relative magnitudes of biometric ALS estimates of forest carbon storage change with those obtained from atmospheric flux measurements.

3. Results and discussion

3.1 AGC_{ALS} model

Plot-level AGC derived from allometric equations ranged from a minimum of 0.8 t C/ha at HJP94 to a maximum of 50.9 t C/ha at OJP, and 30.8 t C/ha to 305 t C/ha over Tumbarumba stands. At BERMS, the field mensuration and allometric equations contained more information and resulted in reduced uncertainty in the biomass training data than at Tumbarumba. Consequently, iterative model testing was performed on the BERMS 2005 data first and when suitable metrics identified, testing was then carried out on the Tumbarumba 2010 data. Plot-level model results for BERMS are presented in Table 1. The best fit regression model using a single independent variable at BERMS was a power function of the average height (Avg_{all}) of the ‘all return’ point cloud distribution ($r^2 = 0.98$, RMSE = 2.4 t C/ha, n = 22). However, this model was considered unsuitable for four reasons: i) it did not pass through the origin and it is expected that at zero AGC, there should be no point cloud data (apart from noise) overlying the ground surface; ii) outside the height range of the training dataset, biomass estimates increased unrealistically for small increases in Avg_{all}; iii) when applied to 2008 and 2011 datasets, the grid comparisons demonstrated unrealistic gains and losses in biomass at locations where it is known biomass was accumulating at a relatively steady state; iv) Avg_{all} was sensitive to outliers associated with scan artefacts in swath overlap regions. From Table 1, it is also clear that simple linear models with a more physically realistic zero origin produced model results that were not appreciably inferior to non-linear models. Avg_{all} still produced the best fit model to the training data (i.e., $r^2 = 0.97$) but still suffered from artefacts and unrealistic comparison results when applied to subsequent datasets.

Table 1: Plot-level AGC_{ALS} model test results at the BERMS jack pine stands.

Point cloud	R^2 (all returns)		R^2 (all returns > 0.2m)	
metric	linear model through origin	non-linear model	linear model through origin	non-linear model
P25	0.41	0.53	0.45	0.79
P50	0.09	0.43	0.92	0.96
P75	0.96	0.97	0.94	0.94
P90	0.95	0.97	0.93	0.93
P95	0.94	0.96	0.92	0.93
P99	0.92	0.92	0.91	0.91
Max	0.9	0.91	0.9	0.91
Avg_{all}	0.97	0.98	0.9	0.93
SD	0.95	0.96	0.91	0.91
IQR_{all}	0.96	0.97	0.56	0.87
All/1.5	0.62	0.91	0.6	0.88
All/avg	0.34	0.75	0.24	0.81

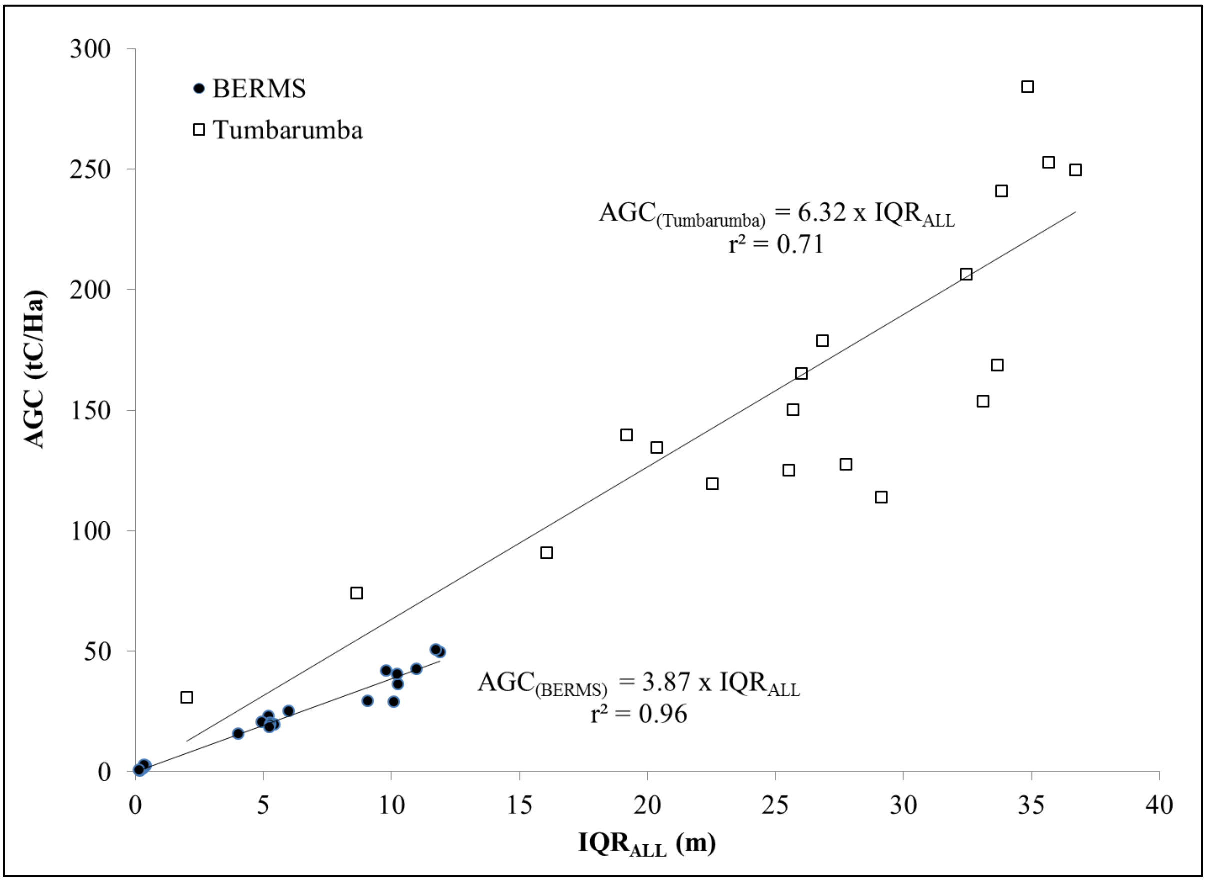

Figure 2: Linear best fit models of AGC_{ALS} from IQR_{all} at BERMS and Tumbarumba.

Interquartile range (IQR_{all}) was found to produce the best compromise between accurate model results (r^2 0.96, RMSE = 3.2 t C/ha, n = 22), and realistic temporal comparisons. IQR_{all} was thought to provide a superior variable for biomass prediction because it represents a surrogate measure of overall point cloud height and density without being over-sensitive to the tails of the distribution. IQR_{all} was also found to provide the best fit model at Tumbarumba ($r^2 = 0.71$, RMSE = 37.6 t C/ha, n = 20)

(Figure 2). That Tumbarumba's r^2 was lower than at BERMS is likely due to plot biomass estimates being generated from DBH only and the adoption of a more generic allometric equation. Nonetheless, it is encouraging that at two sites with very different canopy structure and ALS point cloud attributes, biomass could be reasonably accurately predicted using a simple linear function of the point cloud IQR. The multiplier was lower at the jack pine sites and this is likely because of the shorter trees, higher stem densities and more clumped canopy biomass characteristic of the boreal forest.

3.2 Stand-level $\Delta eAGC_{ALS}$

Stand- and plot-level estimates of $eAGC_{ALS}$ and $\Delta eAGC_{ALS}$ (Figure 3A) at BERMS were similar and within the range of observed standard deviations (Table 2). However, stand-level biomass estimates for OJP were almost 10% greater than those calculated from the modeled results at the plot locations alone. This discrepancy is because the plots were located around the flux tower, which is in an area of relatively short canopy (Figure 1B) (and therefore low biomass) when compared to the rest of the stand. Consequently, while the plots provide a reasonable estimate of biomass in the area around the tower, the estimate aggregated from the raster cells within the stand is probably a more reliable indicator of more widespread jack pine conditions for a stand of this age and in this region.

Table 2: BERMS stand- and plot-level $eAGC_{ALS}$ estimates and the associated change between years surveyed. Also shown is the ratio of $\Delta eAGC_{ALS}$ to mean GEP for the study period (GEP periods vary due to availability)

Stand-level	Mean $eAGC_{ALS}$ (t C/ha) (SD)			$\Delta eAGC_{ALS}$ (t C/ha)			$\Delta eAGC_{ALS}$ / GEP 2005-2011
	2005	2008	2011	2005 - 08	2008 - 11	2005 - 11	%GEP (estimated.)
HJP02	0.29 (0.20)	0.37 (0.51)	1.1 (0.78)	0.1	0.7	0.8	1%
HJP94	1.9 (0.70)	7.5 (2.8)	14.7 (3.2)	5.6	7.3	12.8	36%
HJP75	31.1 (2.1)	33.2 (2.1)	37.1 (2.3)	2.1	3.9	6.0	11%
OJP	59.1 (7.6)	59.7 (6.8)	60.7 (7.4)	0.5	1.0	1.5	4%
Plot-level							
HJP94	1.8 (0.70)	5.9 (3.9)	12.6 (5.2)	4.2	6.7	10.8	30%
HJP75	30.2 (3.0)	32.4 (2.7)	36.2 (2.7)	2.2	3.9	6.1	11%
OJP	53.7 (4.6)	54.7 (4.4)	55.4 (4.9)	1.0	0.7	1.7	5%

NEE and GEP were not available for all of 2005 to 2011 at all the BERMS jack pine sites. Mean annual $\Delta eAGC_{ALS}$ was therefore compared to mean annual GEP for the years of data availability at each site to derive an estimate of 'GEP efficiency'; i.e. an estimate of the proportion of GEP (photosynthesis) that has been utilized within each stand to increase its total living biomass (Table 2). From this we infer that GEP efficiency at the jack pine stands is smallest at the youngest and oldest sites (HJP02 and OJP, respectively) and is highest at the immature HJP94. These estimates suggest annual woody biomass increases are small relative to seasonal biomass production and biomass replacement at young sites where there is high mortality and in mature sites where a high proportion of GEP goes into maintaining already high levels of biomass.

Table 3: Tumbarumba $eAGC_{ALS}$ estimates and the associated change.

		Mean $eAGC_{ALS}$ (t C/ha)				$\Delta eAGC_{ALS}$ (t C/ha)
		2001		2010		2001-10
Location	Area (ha)	Avg	SD	Avg	SD	
Tower stands	341	184	79	207	61	23
1 km radius around tower	314	179	86	193	77	14
Field plots	2	168	53	176	35	8

At Tumbarumba, stand, 1 km tower radius and aggregated field plot $eAGC_{ALS}$ estimates varied by 16 t C/ha or < 10% (2001) and 31 t C/ha or <18% (2010) and these differences were within the range of observed standard deviations (Table 3). In both years, plot estimates were the lowest, with stand estimates being the highest and the 1 km tower radius area being intermediate. The implication of these relatively small differences in biomass estimate is clear in the $\Delta eAGC_{ALS}$ estimates, where the plot-based estimate is 57% that of the tower radius and 35% that of the stands surrounding the tower. These observations illustrate large spatial variability in biomass change across this eucalyptus forest ecosystem (Figure 3B) and an inherent challenge in identifying the ideal spatial domain for ecosystem characterization. This is particularly important when relating biometric estimates of biomass change to tower-based estimates of ecosystem productivity and thus highlights the need to integrate spatial ALS and point-based EC data using flux footprint models (Kljun et al., 2004; Chasmer et al., 2008).

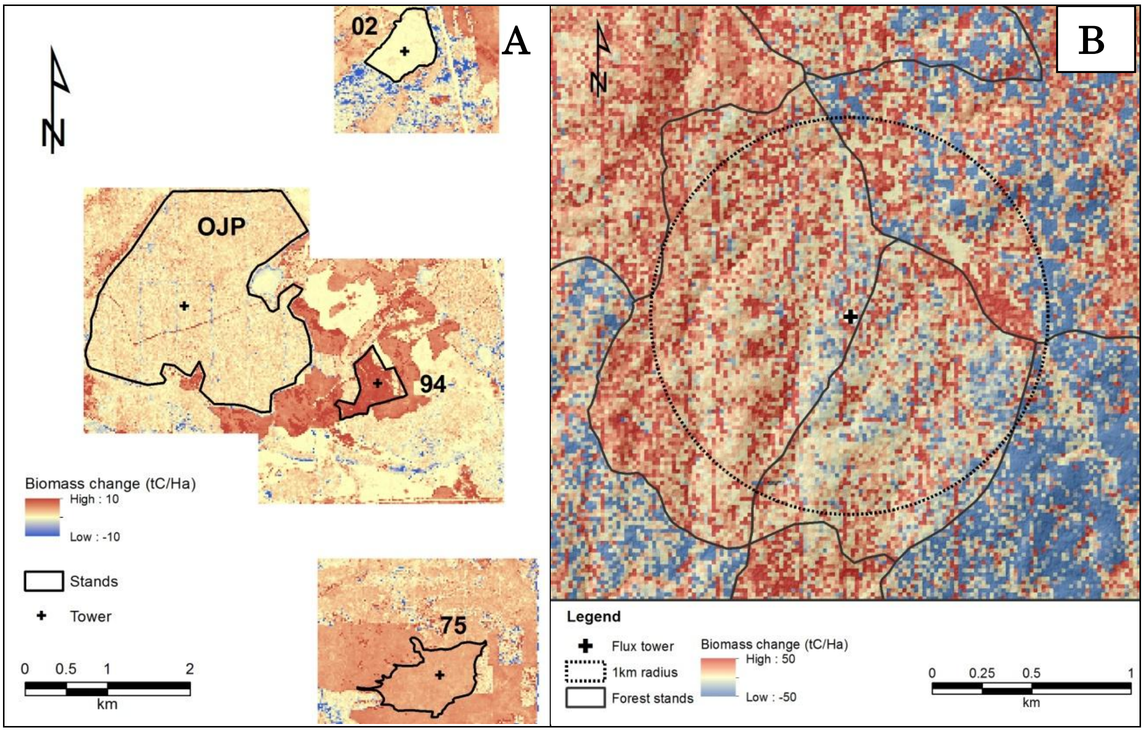

Figure 3: $\Delta eAGC_{ALS}$ at BERMS (6 yrs) and Tumbarumba (9 yrs). Biomass losses at both sites are primarily due to commercial thinning operations, while gains are due to natural stem growth.

In the undisturbed stand area where the EC flux tower is situated, $\Delta eAGC_{ALS}$ indicates there has been ~23 t C/ha net biomass accumulation over nine years. This represents ~46% of cumulative -NEE (50 t C/ha) and ~10% of the cumulative annual GEP (232 t C/ha). Similar to the BERMS OJP and HJP75 stands, this suggests that ~90% of the CO_2 uptake is used to support seasonal growth that subsequently dies and in replacing biomass lost from mature trees. Over the longer term, the -NEE (net CO_2 uptake) does not balance the ALS-modeled change in biomass. Some of this imbalance is likely due to spatial uncertainty in the tower footprint, e factor assumption-errors, plot-level allometric biomass estimates or due to inconsistency in the two ALS datasets. (Some imbalance is expected due to soil organic matter decomposition and heterotrophic respiration but this loss of CO_2 from the ecosystem would act to close the gap we see not widen it). More effort is required to understand and mitigate these measurement uncertainties. If indeed, however, there is a large difference between ALS-modeled biomass accumulation and tower-based estimates of -NEE, this suggests either a large and growing storage of CO_2 in the ecosystem or export out of the ecosystem via a pathway that is unaccounted for.

4. Conclusions

A straightforward ALS-based approach to monitoring the carbon in living tree biomass in managed forests has been presented. By comparing these data with EC flux-based estimates of -NEE and GEP, it is possible to partition ecosystem production into growth components associated with: i) sustained biomass accumulation (of interest from a commercial growth and yield perspective); and ii) seasonal biomass cycling and replacement. More research is needed to understand long term CO_2 storages and pathways within the boreal jack pine and temperate eucalyptus ecosystems studied, and the uncertainties propagated during the ALS biomass modelling stages adopted in this study.

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