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Carbon pools and fluxes in small temperate forest landscapes: Variability and implications for sampling design

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ABSTRACT

Assessing forest carbon storage and cycling over large areas is a growing challenge that is complicated by the inherent heterogeneity of forest systems. Field measurements must be conducted and analyzed appropriately to generate precise estimates at scales large enough for mapping or comparison with remote sensing data. In this study we examined spatial variability in three small temperate forest landscapes. Our objectives were (1) to quantify the magnitude and scale of variability in stand structure, carbon pools and carbon fluxes and (2) to assess how this variability influences both optimal sampling strategy and required sampling intensity. Stand structure was consistently less variable than carbon pools or fluxes, suggesting that measuring carbon dynamics may require more intense sampling than traditional forestry inventories. Likewise, the magnitude of variability differed substantially among response variables, implying that sampling efficiency can be enhanced by adopting a flexible sampling strategy that is optimized for each carbon pool. Our results indicate that plots dispersed across the study area are generally more effective than clustered plots for characterizing carbon dynamics.

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1. Introduction

Terrestrial ecosystems contain substantial carbon pools whose dynamics may impact and interact with atmospheric CO_2 concentrations (Schimel, 1995; Steffen et al., 1998), potentially influencing climatic conditions (IPCC, 2007). Consequently, quantifying forest carbon dynamics over areas substantially larger than measurement plots or relatively homogeneous forest stands is a central goal for ecosystem ecologists (Sellers et al., 1997). Furthermore, forest ecosystems are notoriously heterogeneous in space (Townsend et al., 1996; Wilson and Meyers, 2001), and accounting for that heterogeneity is a substantial obstacle to scaling carbon estimates from plots and stands to landscapes and regions (Botkin et al., 1993; Jarvis, 1995; Enquist et al., 2007).

Approaches to assessing spatial heterogeneity generally fall into three complimentary categories: measurement of carbon pools and/or fluxes using biometric methods at the plot-level (Botkin et al., 1993; Brown and Schroeder, 1999; Burrows et al., 2003; Zheng et al., 2003), continuous monitoring of whole ecosystem carbon balance with micrometeorological towers (Baldocchi et al., 2001; Hollinger et al., 2004; Kim et al., 2006), and analysis of remotely sensed imagery (Schimel, 1995; Turner et al., 2000; Ollinger et al., 2002; Turner et al., 2003). Biometric measurements provide direct quantification of carbon pools as well as annual or multi-year carbon accumulation and decomposition at individual locations (Curtis et al., 2002; Ohtsuka et al., 2005). By comparison, continuous flux tower data generate insight into the impact of environmental conditions on net ecosystem carbon balance (Baldocchi, 2003; Monson et al., 2005; Desai et al., 2008). Remotely sensed imagery facilitates the scaling of these insights to regional and global areas by measuring light absorption and relating it to vegetation composition and structure as well photosynthetic rates (Roughgarden et al., 1991; Running et al., 2004). Each approach has advantages and limitations, and the most robust insights into forest carbon dynamics over large areas rely on insights from multiple approaches integrated into ecological simulation models (Reich et al., 1999; Running et al., 1999; Turner et al., 2004b; Kennedy et al., 2006). These approaches compliment

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each other because they measure the same response variable over very different spatial and temporal scales, providing validation of each other (Cohen and Justice, 1999; Canadell et al., 2000; Cook et al., 2004; Ollinger and Smith, 2005; Turner et al., 2006a,b).

However, these differences in scale also present an obstacle to comparison between methods. One of the most confounding differences is the variability in spatial scale between biometric field plots and both flux tower measurements and remotely sensed imagery. Individual field plots often cover between 200 and 500 m^2 (8–12 m radius circles), although very large, labor intensive plots may sample areas as large as 900 m^2 (30 m by 30 m; Ollinger and Smith, 2005; Turner et al., 2005), and even larger plots have been installed in some studies (Leigh et al., 2004). By contrast, flux tower footprints, while more difficult to define, can extend several hundred meters from the tower, potentially covering >50,000 m^2 (Baldocchi, 1997) and can be much larger during periods of high wind and in areas with variable topography (Finnigan, 2004). Although pixels for commonly available remotely sensed imagery can be as small as ~900 m^2 (Landsat ETM), complications of image registration and blurring mean that relating specific pixels to field measurements requires sampling an area 4 times the pixel size, or roughly 3600 m^2 (Curran and Williamson, 1986). In addition, remotely sensed imagery currently used for regional and global vegetation studies has much larger minimum pixel sizes (i.e. 250 m minimum pixel size on MODIS; Hook et al., 2001). The obstacle to reconciling these data sources is that plots measure carbon dynamics over hundreds of m^2 whereas both flux towers and remote sensing measure carbon dynamics over thousands of m^2.

The challenge in bridging this gap in spatial scales involves determining how to collect and analyze field measurements to precisely estimate carbon pools and fluxes over areas that can be directly compared to flux tower footprints and remote sensing pixels (Wessman, 1992; Turner and Chapin, 2005). For assessment of large-scale forest carbon pools and fluxes, important unanswered questions include: How much does the magnitude of spatial variability differ between various carbon pools and fluxes, and how many plots are necessary to precisely characterize pools or fluxes within small landscapes? To address these questions we measured stand structure, carbon pools and carbon fluxes in nested forest plots distributed across small landscapes in three temperate forest ecosystems. Our objectives were (1) to quantify the magnitude and spatial scale of variability in stand structure, carbon pools and carbon fluxes and (2) to assess how this variability influences both optimal sampling strategy and required sampling intensity. Few studies have directly addressed spatial variability and sampling design, but with increasing interest in quantifying forest carbon dynamics at landscape and larger scales, such an examination can help ecologists move beyond using somewhat arbitrary guidelines (Kloeppel et al., 2007) to guide sampling design.

2. Methods

2.1. Site description

We examined variability of aboveground carbon pools and fluxes in small landscapes of three temperate forest ecosystems (Fig. 1): northern hardwoods in central NH (Bartlett Experimental Forest), mixed forests of northern MN (Marcell Experimental Forest), and subalpine Rocky Mountain forests in CO and WY (3 sites).

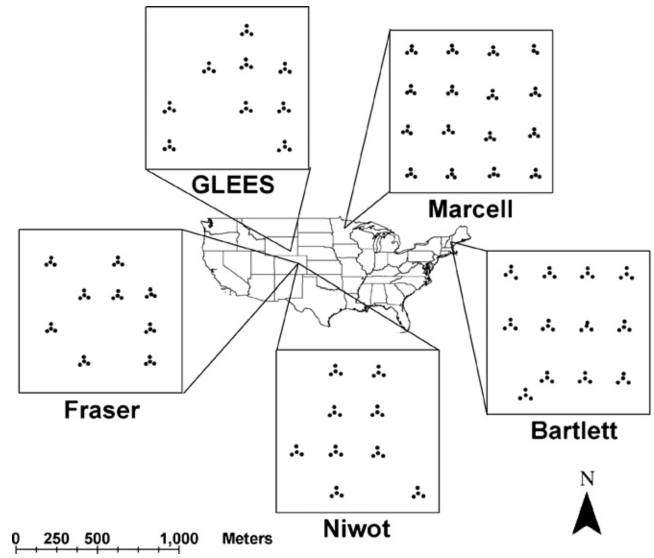

Fig. 1. Site locations and plot layouts for sampling of stand structure, carbon pools and carbon fluxes in 3 forest types. Plots are organized into 4-plot clusters (similar to FIA protocol) within small landscapes of 1 km by 1 km (scale bar refers to square zoomed views of study areas). Forest types include Northern Hardwoods (Bartlett), northern mixed forests (Marcell) and subalpine Rocky Mountains (GLEES, Niwot and Fraser).

Bartlett Experimental Forest. Bartlett consists primarily of second-growth northern hardwoods dominated by *Fagus grandifolia*, *Betula alleghaniensis*, *Acer saccharum*, and *Tsuga canadensis* with scattered stands of *Acer rubrum*, *Betula papyrifera*, *Populus tremuloides*, *Picea rubens* and *Pinus strobus*. Summer air temperature highs often top 32 °C and winter lows reach −34 °C while average annual precipitation is 127 cm, well distributed throughout the year (Table 1). Bartlett soils are moist but generally well drained spodosols. In the late 19th century, the lower third of Bartlett was logged while upper portions were less impacted. Natural disturbances at Bartlett include hurricanes (1938) and ice storms (1998) and occasional small scale wind storms (Anderson et al., 2006). Variation in stand characteristics and annual net primary production across the Bartlett landscape have been reported by Ollinger and Smith (2005).

Marcell Experimental Forest. Marcell includes both upland forests and peatlands. Uplands forests are generally dominated by *P. tremuloides* and *grandidentata*, but contain substantial components of *B. papyrifera*, *Pinus resinosa*, *P. strobus*, and *Pinus banksiana*. Lowland tree species include *Larix laricina*, *Picea mariana*, *Fraxinus nigra*, and *Thuja occidentalis*. Climate at Marcell is subhumid continental, with air temperature extremes of −46 °C and 38 °C (Table 1). Upland soils at Marcell are mainly loamy sands or fine loams sandy whereas the fen or bog soils contain substantial peat ranging from highly to moderately decomposed (Nichols and

Table 1
Climatic conditions, sample size and general stand structure for forested landscapes in NH, MN, CO and WY.

Site	Latitude, longitude	Mean annual temperature (°C)	Mean annual precipitation (mm)	Elevation (m)	Plots	Maximum age (years)
Bartlett	44°2′39″N, 71°9′56″W	6	1270	275	48	120
Marcell	47°30′N, 93°28′W	3	785	425	63	69
Fraser	39°4′N, 105°52′W	0	737	3100	36	246
Glees	41°22′N, 106°15′W	−2	1000	3180	36	247
Niwot	40°2′N, 105°33′W	4	800	3050	36	137