

Chapter 17

Landscape-Scale Carbon Sampling Strategy – Lessons Learned

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Abstract Previous chapters examined individual processes relevant to forest carbon cycling, and characterized measurement approaches for understanding those processes at landscape scales. In this final chapter, we address our overall approach to understanding forest carbon dynamics over large areas. Our objective

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is to identify any lessons that we learned in the course of measuring a wide range of carbon-related processes in a suite of forested sites. We focus on characterizing the costs and benefits of measuring individual processes and we examine the advantages and limitations to our plot layout. In addition, we draw upon the experience at individual sites to identify important lessons that may be specific to particular forest types or regions.

Keywords Terrestrial carbon cycling, carbon storage, net ecosystem carbon balance, spatial and temporal scaling

17.1 Introduction

Our objective in this chapter is to communicate some initial lessons about the practical challenges of designing and conducting landscape-scale measurements of carbon pools and fluxes. We stress that these conclusions are preliminary; much of our data is still being collected and analyzed and many of the lessons that we will learn from this project are only beginning to become clear. Nevertheless, our experiences provide insight into potential improvements for similar future efforts. Specifically, we address two topics: the cost and benefit of various measurements and the advantages and disadvantages of our plot layout strategy.

17.2 Measurement Costs and Benefits: "What We Measured"

Quantifying carbon pools and fluxes at landscape scales requires identifying the ecological processes that play an important role in the carbon cycle and developing a feasible approach to measure those processes. Individual process measurements can be evaluated by both their contribution to accurate estimates of whole ecosystem carbon dynamics versus their cost in terms of time and money. To critically examine the measurements that we conducted, we present an objective approach to assessing cost and benefit, illustrate how the measurements that we conducted fit qualitatively into that framework for one of our sites, and conclude by considering how measurements can also be valuable for comparison with alternative approaches to carbon accounting.

17.2.1 *Costs and Benefits Defined*

Developing a sampling strategy for assessing landscape-scale carbon dynamics requires objectively assessing the costs and benefits of various potential measurements. One objective approach to assessing the benefit of measuring a process is to quantify how

much the process influences either total ecosystem carbon storage or net ecosystem carbon balance. For the goal of quantifying total carbon stocks, the benefit of measuring individual pools is roughly proportional to the size of the pool. Pools with very small amounts of carbon will contribute very little to overall estimates of carbon storage, and errors in those pools will have only minor consequences. Similarly, for estimating net ecosystem carbon balance, the benefit of an individual carbon flux is equivalent to the size of the flux. Larger carbon fluxes have greater overall influence on total carbon balance and can thus be considered more beneficial to an overall carbon assessment strategy. Relating the benefit of a given measurement to the magnitude of the carbon pool or flux that it measures provides an objective quantification of importance that can be balanced against the cost of the measurement.

In general, the cost of measuring a process can be inferred from the amount of variability that the process displays both across space and time. Although some measurements are inherently more difficult than others, we found that, for long-term measurements at the landscape scale, sampling requirements for characterizing variability overshadowed differences in measurement difficulty. If a process is relatively consistent across the landscape, then only a few plots are sufficient to develop an accurate landscape-scale estimate. Likewise, if the process is consistent through time, infrequent measurements are adequate to characterize temporal patterns. Highly variable processes, on the other hand, require either many plots and/or frequent measurement to characterize spatial or temporal patterns, respectively. We found that measurements requiring multiple visits per year required substantial labor and money. For example, soil CO₂ and methane efflux and litterfall required that we visit plots multiple times per year. By contrast, the very infrequent measurements were time consuming initially, but once completed incurred essentially no additional cost. Live tree and coarse wood biomass, for example, change relatively slowly and consequently required only a single visit to characterize. Recognizing the high cost of repeated measurements is especially relevant considering the short-term nature of most research grants in which intensive work may be possible for a relatively brief period, followed by a longer period of minimal resources. In some cases, measurement of long-term processes can be designed to fit within this funding reality. For example, measuring tree growth can be achieved with either very infrequent (once in several years) measurements combined with increment coring, or with annual diameter measurements. On the other hand, if long-term monitoring resources are available, repeating detailed tree measurements may have advantages. By defining cost and benefit in terms of variability and magnitude, this conceptual framework provides an objective mechanism for evaluating the necessity of measurements, and for beginning to assess sampling design and intensity.

17.2.2 Costs vs. Benefits

Although we are still working to characterize the costs and benefits of measuring various processes, our preliminary results suggest some lessons (Fig. 17.1). Processes

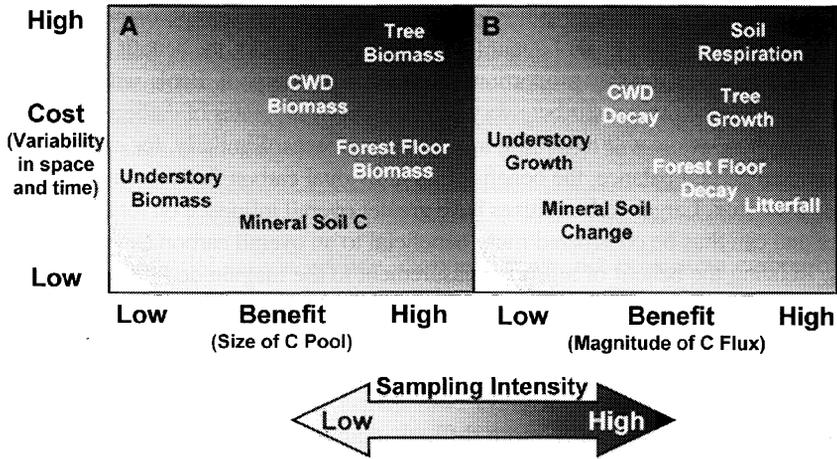


Fig. 17.1 A conceptual framework for characterizing the cost and benefit of measuring individual carbon pools (A) and fluxes (B) in an assessment of landscape-scale carbon dynamics. Benefit is defined as the size of the pool or magnitude of the flux, which is a general measure of the influence a process exerts over ecosystem carbon dynamics. Cost depends primarily on the variability of the process in space and time, with highly variable processes requiring either a large number of plots or high sampling frequency, respectively. This framework provides a mechanism of evaluating the sampling intensity necessary to accurately assess individual pools and fluxes. Processes with greater variability and benefit will require and warrant greater sampling effort, illustrated by the dark background in the upper right of both figures. Placement of individual processes within this framework is shown for subalpine Rocky Mountain forests as an example and will vary between sites. Note that benefits considered here do not include comparability to other approaches like eddy covariance or simulation models

that are low in both influence and variability, notably mineral soil carbon stocks (Chapter 10) at some locations (i.e. Rocky Mountain sites) could be adequately assessed with fewer plots than we utilized. Although mineral soil holds substantial carbon, it is very consistent across space and changes very slowly. Some processes, including understory biomass (Chapter 5) and soil respiration (Chapter 11), incurred high cost with only marginal contribution to our overall assessment of carbon storage or balance. In the forests we examined, understory biomass and productivity was modest, yet required substantial time to quantify. Likewise, soil respiration was one of the most time consuming measurements we initiated (due to instrumentation requirements and necessity of frequent measurement). Although soil respiration was not utilized in the mass balance carbon dynamics approach we adopted, the amount of carbon released via soil respiration is very substantial and provides unique and valuable insight into belowground carbon cycling and storage (Ryan and Law 2005). Tree biomass (Chapter 4) and growth, as major components of carbon cycling in forest systems, were very important for quantifying carbon pools and fluxes, although tree growth was also extremely variable in space and thus costly to measure accurately. We found that the biomass and decomposition of

coarse woody debris (Chapters 6 and 9) and forest floor material (Chapter 10) were of intermediate importance and that the cost of effectively measuring coarse woody debris was extremely large due to high spatial variability.

17.3 Comparison with Other Approaches

An important goal of our landscape-scale carbon measurements that is not considered in the above cost-benefit analysis is comparability with other approaches to assessing forest carbon dynamics, notably eddy covariance techniques (Barford et al. 2001, Curtis et al. 2002, Baldocchi 2003) and ecological simulation models that utilize remote sensing data (Turner et al. 2004, Zheng et al. 2006). We found that these comparisons can be hindered by incompatibility in the spatial scale of measurements, the temporal scale of measurements, and the specific processes that are measured. Comparison with eddy covariance data must ensure that the field plots represent the spatial extent of the flux tower footprint, that high frequency eddy covariance measurements can be synthesized to match longer-term field measurement and that the processes quantified by both approaches can be directly compared (see Chapter 16 for details). For example, preliminary comparisons of field measurements with eddy covariance data at Niwot Ridge were limited because the decomposition rate of detrital material is represented by field measurements only as a long-term mean. Consequently, although we found good agreement between NPP estimates from both eddy covariance data and our biometric data (J. Bradford unpublished data), we were unable to directly compare total carbon balance, which is the primary process that is actually measured by eddy covariance techniques (Baldocchi 2003).

Temporal integration with models based on remote sensing data is less complicated because field measurements assess carbon fluxes at the seasonal or annual scale, which is comparable to many simulation models. However, spatial compatibility with the remote sensing data remains a challenge. Although methods have been developed for assessing ground conditions to compare with remote sensing data (e.g. Turner et al. 2005) our plot layout (nested 8–10 m circular plots) was not ideally suited for compatibility with relatively high resolution remote sensing data (i.e. 30 m resolution Landsat), or more coarse resolution data (250 m or 1 km resolution). Comparison with higher resolution data would require characterizing processes over contiguous areas larger than our plots (Grunblatt 1987). Comparison with coarse resolution data requires summarizing our plot data to represent a larger area, which can be accomplished with either a simple mean (assumes the plots are representative of the landscape) or a weighted mean (which relies on outside information about cover type proportions within the landscape). Having an independent classification of the study area would help characterize how well the plots represent the landscape and provide quantification of cover type proportions.

17.4 Plot Layout: “How We Measured it”

For this project, our plots were grouped into FIA-like clusters of four subplots (Bechtold and Patterson 2005) and established in a regular grid across the landscape (Chapter 1). This design is only one of several potential approaches to orienting plots across a landscape. Alternative possibilities include one or more of the following: (a) orienting the plots along one or more transects across the landscape, possibly spanning environmental gradients, vegetation types or patch edges (e.g. Chen et al. 1992); (b) stratifying the landscape into discrete classes *a priori* and establishing plots in each class (Wagner and Fortin 2005); (c) clustering plots at varying spatial scales to facilitate characterization of spatial variability (Rossi et al. 1992); and (d) employing different plot size and/or number of plots for measurement of different processes. To examine the plot layout that we utilized, we present our initial impressions and insights in terms of advantages, limitations, and potential alternative layouts.

17.4.1 *Advantages of Our Approach*

The two primary advantages of our plot layout design are: (1) the consistency and therefore comparability it facilitates across sites and with FIA data, and (2) the completely unbiased selection of plot locations. Because we established plots very similar to the protocol employed by the FIA program, comparison of our results with FIA results will be very straightforward. Although we are only beginning to explore the possibility of merging our results with FIA data, this integration is likely to prove valuable considering our goal of generating large-area estimates of carbon pools and fluxes. In addition, because our plots are so similar to FIA plots, our work can provide insights about the FIA approach in general, including characterizing the advantages of establishing FIA plots at higher density, quantification of how well individual FIA plots represent the surrounding landscape, and estimates of the most efficient number of subplots to establish per FIA plot. Another advantage of the grid system that we utilized was its consistency across all sites. This consistency enabled direct comparison of spatial variability and patterns between sites that would be substantially more difficult if plot orientation varied between sites. In addition, because we measured all processes at each of our plots (rather than measuring some variables at only a subset of plots) we had a high sample size for comparison between variables.

Perhaps the greatest advantage of our plot layout is the systematic, unbiased process in which plot locations were selected. Whereas most efforts to characterize ecological processes at large scales involve some stratification prior to plot selection (e.g. Hansen et al. 2000), our plot locations were identified simply by a grid overlaid on the landscape. At some sites (notably the 3 Rocky Mountain landscapes), we were frequently surprised by the specific plot locations identified, initially finding some of them to be “unrepresentative” of the landscape as a whole. This suggests that

we (and perhaps other researchers) had a notion of how a given forest stand of particular species and age should appear, and locations that differ from that ideal are considered anomalous, even if those anomalies comprise a large proportion of the landscape. This completely objective approach to plot selection provides an opportunity to challenge our biases and potentially identify previously unappreciated landscape conditions that make an important contribution to large-scale carbon dynamics. Although the advantage of comparability to FIA data may not be of interest to all future studies, creating consistency across sites may be increasingly valuable as interest in national-scale carbon accounting grows, and the confrontation of unconscious bias imposed by the systematic plot selection is always useful.

17.4.2 Limitations to Our Approach

Despite these advantages, our initial experiences suggest several limitations to our plot layout. One potential limitation of our approach is that the cluster of four subplots per plot appears to not be the most efficient means of characterizing many of the processes we measured. In a nested sampling scheme like the one we employed, accuracy of the whole-landscape process estimate can be calculated from the within plot variability (variation between subplots within a plot) and the between plot variability (variation between plot means) (Cochran 1977). At all sites, the vast majority of processes were most efficiently measured by establishing independent subplots (rather than subplots clustered into plots with more than 1 subplot), suggesting that our sampling would have been more efficient if we had altered how we located our plots (Bradford et al. in review).

Another important limitation is the potential of plots to be located in areas that are genuinely un-representative of the landscape. The problem can be avoided if a sufficiently large number of plots are established. Although a very large number of plots established on a grid is probably the optimal strategy (ensures representation yet avoids bias), it is practically unfeasible in a reasonably large landscape. Evaluating how well a set of plots represents the landscape requires some type of classification and has not yet been examined for our sites. Another limitation of our gridded plot layout is the potential for plots to be either located very near or far from roads. Plots very near roads are vulnerable to vandalism, which we experienced at multiple sites, and plots extremely far from roads can be difficult to access, substantially increasing the effort required to sample those plots.

17.5 Alternative Plot Layouts

Comparing our plot layout with alternative layouts illustrates four additional limitations to our approach. First, our plots were located on a grid with 250 m between plot centers, meaning that we had no subplot pairs separated by distances between

roughly 50 and 200 m and no subplots closer than 35 m. Initial examination of the scale of spatial variability in our measurements suggests that much of the variation occurs at small scales (Bradford et al. in review), and that the 50–200 m range is crucial for geostatistical analysis (D. Hollinger and J. Bradford unpublished data). Consequently, our ability to characterize patterns in spatial variability would have been enhanced by having some subplots separated by a distance of less than 35 m and between 50 and 200 m.

Second, stratifying the landscape prior to plot establishment, a common practice in other landscape-scale carbon assessments (Noormets et al. 2006), may have increased the representation and efficiency of our measurements. Although the results of using an *a priori* stratification are heavily dependent on the assumptions made in the initial stratification, it would have allowed us to partition the landscape into classes like forested versus meadow (at GLEES), peatland versus upland (at Marcell) or young versus old (at Fraser and Bartlett) and we then could have ensured that we have sufficient plots in each class to obtain accurate within-class estimates. This would have minimized the possibility of establishing more plots than are necessary in a particular class and allowed us to efficiently utilize our sampling resources.

Third, our plot layout did not allow us to robustly characterize the importance of edges between vegetation types on carbon dynamics (although some subplots are on or near edges, they were not systematically oriented to allow us to quantify edge effects). Edges are increasingly recognized as important drivers of ecosystem processes, including productivity and carbon cycling (Euskirchen et al. 2006), and by establishing plots along a transect that crosses edges, we could have quantified this importance and potentially strengthened our landscape-scale estimates.

Fourth, we utilized the same number, and roughly same size of plots to characterize most of the processes that we examined. An alternative approach would be to vary the number and/or size of plots, depending on the process variability. For example, we found that in many of our sites, carbon stored in forest floor varied only slightly across the landscape and could have been assessed with fewer plots. Coarse woody debris biomass, by contrast, was both highly variable and non-normally distributed across our landscapes, and consequently may require larger plots and/or more plots within the landscape. By measuring all variables at all plots, we were not as efficient as possible.

17.6 Site Specific Lessons

17.6.1 *Bartlett Experimental Forest*

Heterogeneity in carbon pools and fluxes at the Bartlett Experimental Forest, a 1,052 ha secondary successional mixed northern hardwood-conifer site in the central White Mountains of New Hampshire, was observed most strongly with respect to

gradients in elevation. Though simply expressed, this relationship may not be indicative of a simple pattern. Many factors change with increasing elevation including: decreased air and soil temperatures, increased precipitation, soil type, prevalence of rock fragments and ledges, changes in vegetation composition and thus litter quality and nutrient cycling. From our results to date we cannot conclude which variables play the most important role in the observed elevational trends. We can conclude that the original 1 km² sampling frame established in 2004 was inadequate to capture the range in elevation at BEF. However, the aggregated observation of plot-based C flux within the 1 km² frame is comparable with that estimated by means of an CO₂ eddy covariance tower located at the center of the 1 km² sampling area. The sampling frame at BEF was expanded in 2005 to include 11 additional plots spanning the range in elevation at BEF (210–915 m).

Our observations of individual C pools and fluxes across the BEF are similar to those observed in previous studies in the northeastern region. Relationships among C pools and fluxes as well as to other ecosystem characteristics such as ANPP, aboveground biomass, litter quality, and N cycling, are more variable. Additional plots stratified to cover gaps in elevation, species composition, and disturbance history, as well as a longer temporal sequence of measurements, will allow better assessment of trends into the future.

17.6.2 Marcell Experimental Forest

Our implementation the landscape sampling strategy at the Marcell Experimental Forest (MEF) was hampered by heterogeneity of cover types. The MEF landscape is composed of multiple watersheds that contain upland and peatland portions. Vegetation cover in both upland and peatland portions is highly variable. While uplands are mostly aspen-dominated, there are distinct patches of mixed hardwoods and conifers. Peatlands included forested and non-forested bog and fen communities. Because of the high carbon storage known to exist in peatland soils, we elected to include them in our sampling through non-biased plot and sub-plot establishment. However, the distribution of forested and peatland cover types across the sampling plots did not represent the landscape comprehensively. For example, forested peatlands cover approximately 10% of the land area in the 1-km² sampling grid at MEF, but non-biased plot selection yielded only one forested peatland subplot out of the 64 FIA subplots established within the sampling frame. Consequently, in heterogeneous landscapes, a stratified sampling approach that guarantees inclusion of important landscape elements is desirable.

In heterogeneous landscapes, no single approach to sampling C pools and fluxes may be useful for all sample plots. The inclusion of peatlands in our analysis immediately suggested a need for different approaches to sampling C pools and fluxes within subplots, as storage and movement of carbon in peatlands can be quite different from uplands. Peatlands contain a greater depth of organic carbon than is found in upland forest, so we sampled peat deeper than we sampled mineral soil,

coring up to 5 m deep, or until contact was made with hard mineral soil. Much of NPP (net primary productivity) in peatlands can occur as *Sphagnum* moss growth, so we attempted to measure these C fluxes on peatland subplots using biometric approaches. Lastly, wetlands are the largest natural source of atmospheric methane. While methane flux represents a small fraction of the ecosystem C balance, we attempted to monitor methane because of its importance as a greenhouse gas.

Each of the additional storage and flux measurements measured on peatland subplots can be analyzed in terms of cost and benefits, as outlined previously and in Fig. 17.1. For example, the C contained in peat is substantial, and is close to 50% of the carbon stored in our 1-km² sampling area, despite the fact that peatlands represent only 18% of the subplots. The depth of peat requires a greater sampling effort than mineral soil, but repeated sampling is not required. C storage in peat is highly sensitive to variability in peat depth between subplots. Thus, assessing peat C might be considered a moderate cost, high benefit measurement. *Sphagnum* moss NPP measurements has high costs, as spatial variability imposed by microtopography requires repeated measurements in space and repeated visits. Because *Sphagnum* NPP can rival tree NPP in peatlands, there is a potentially high benefit to these measurements. Lastly, methane fluxes are notoriously variable in space and time but because peatlands are a dominant source of methane in the landscape, their measurement carries a high benefit as well as a high cost.

17.6.3 Subalpine Rocky Mountains

We examined carbon pools and fluxes at three separate small subalpine forested landscapes in the southern Rocky Mountains. Spatial heterogeneity in these forests is driven by elevation, ecosystem type and disturbance history. One of our sites was severely burned >300 years ago and was strip-logged approximately 50 years ago, one was clearcut roughly 100 year ago and contains some aspen stands in addition to the dominant coniferous forest, and one has been unmanaged but consists of a mosaic of forests and alpine meadows. At all sites, species composition varies along an elevational gradient from lower elevation lodgepole pine to higher elevation spruce-fir forests. This variability created dramatic differences in carbon storage and cycling across the landscape in patterns that were not easily predicted. Accounting for this variability was our primary challenge in assessing landscape-scale carbon dynamics. Not surprisingly, we observed substantial differences in carbon pools and fluxes between these different cover types; meadows, aspen forests, old coniferous forests and young coniferous forests were all unique in some aspects of carbon dynamics. As a consequence, an *a priori* stratification into important cover types likely would have helped us ensure that our plots accurately represented the distribution of types across the landscape and thus facilitate more accurate large-scale estimates.

Our initial experiences suggest other lessons that may be specific to these high altitude southern Rocky Mountain forests. We found that carbon stored in both

forest floor and coarse woody debris was very substantial, variable across the landscape, and not particularly well related to stand structure or forest age. This implies that accounting for these pools is both necessary and potentially challenging. Our initial impressions of cost and benefit for various measurements are illustrated in Fig. 17.1. In addition, we appreciated the grid-based plot selection because it challenged our bias about the structure and composition of “typical” forests in this region.

17.7 Conclusions

Accurately assessing landscape-scale terrestrial carbon dynamics with field measurements is a daunting, yet necessary, task. By critically evaluating our overall approach, we hope to identify potential areas for improvement and thereby strengthen future efforts. Although our project is ongoing, our initial experience establishing plots and conducting analyses suggests five primary lessons:

Standardization facilitates comparison – The consistent plot layout and sampling strategy that we employed enabled very straightforward comparisons between sites that are only beginning to be exploited.

Stratify the landscape – We found that many of our sites were diverse enough to warrant stratification prior to establishing plots, and that this stratification would likely have led to more efficient plot selection and more accurate overall carbon estimates. Ideally, this process would identify the sources of variability in carbon pools and fluxes, stratify across those sources, establish plots within each class, compare processes within and between classes to ensure the validity of the classification, and use the stratification to generate landscape-scale estimates.

Carefully consider plot layout – Plot layout must efficiently represent the landscape while minimizing bias. The FIA plot design is not efficient for characterizing short-term processes and changes – fewer subplots/plot would achieve similar accuracy with less effort.

Evaluate sampling design and intensity for each measurement – Researchers should consider how variability in space and time influences sampling intensity and frequency and balance these requirements against the impact of the process on total carbon storage and balance. A one-size fits all sampling strategy is probably not best for all sites, and certainly not most efficient for all variables at any site. Keep in mind that measuring all variables at all plots facilitates good comparison between variables, but is likely not the most efficient approach.

Anticipate compatibility with other approaches – Consider conducting measurements in a way that will provide robust ground data for imagery at smaller scales, where we have confidence in our estimates. This finer-resolution imagery can be used to scale up to the whole square kilometer. Work with models/modelers prior to conducting measurements to ensure that comparable processes are being measured.

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