Using Existing Long-Term Thinning Studies To Investigate the Carbon Consequences of Thinning: Learning From the Past To Craft the Future

Coeli Hoover[1]

Abstract

Although long-term research is a critical tool for answering forest management questions, managers must often make decisions before results from such experiments are available. One way to meet those information needs is to reanalyze existing long-term data sets to address current research questions; the Forest Service Experimental Forests and Ranges (EFRs) network provides a plethora of opportunities for investigations of this nature. This study is a pilot test to assess the feasibility of using existing long-term data sets from density management studies to develop carbon sequestration estimates for forests across the United States; the objective is to generalize carbon implications of different thinning methods within and across geographic regions and forest types. Although long-term records from historic studies provide many opportunities, using these data presents many challenges, including lack of documentation and experimental design constraints. In this preliminary study, such obstacles did not permit the development of generalizations about the carbon consequences of density management treatments, although carbon stock estimates were developed for four different studies. In addition to carbon data, a discussion of the challenges inherent in working with existing long-term records is presented, as well as specific recommendations to facilitate the use of long-term experiments for retrospective and/or synthetic analyses.

Introduction

Many forestry and ecology research questions require, by their nature, a long-term research approach. This observation is especially true in forestry, where rotation lengths are often many decades long and the lifespan of individual trees may be measured in centuries. Many investigators have made compelling arguments for the need for large-scale, carefully designed, long-term research studies (Franklin et al. 1990, Powers 1999, Powers et al. 1994); a primary reason given is that short-term and long-term responses can differ (e.g., Sanchez et al. 2006, Scott et al. 2004, Zhang et al. 2005). Such long-term studies may not offer initial results until 5 to 10 years after installation, with the main results often not available for decades. Meanwhile, managers need guidelines on a much shorter timeframe. One solution to meeting these needs is to use retrospective studies, in which the researcher takes advantage of past treatments or events. Conducting a retrospective study may include remeasuring plots established for a previous study, analyzing existing long-term data, or both. The Forest Service network of EFRs (Adams et al. 2008, Lugo et al. 2006) features many preexisting long-term studies, which provide ample opportunity to seek answers to contemporary problems in a variety of forest types. There are numerous uses for existing long-term data, such as investigating the possible impacts of climate change, tracking changes in phenology and species composition, seeking patterns or changes in insect and disease outbreaks, and assessing the carbon implications of management practices.

Powers (1989) provides an excellent overview of the challenges and opportunities presented by retrospective studies. Of particular note is the list of eight critical questions to ask when planning a study. These questions address adequate replication, identification of confounding factors, and other elements of experimental design. Many, although not all, challenges encountered in this study are related to points raised by Powers (1989, 1994). Although constraints exist, the potential importance of retrospective studies is evidenced by the database of baseline information for more than 170 sites in Washington and Oregon assembled by Thomas et al. (1993) for the specific

[1] Ecologist, U.S. Department of Agriculture Forest Service, Northern Research Station, Durham, NH.

purpose of facilitating such studies. In addition to retrospective studies addressing questions that are quite different from the purpose of the original experiment, in many cases an ongoing study benefits greatly from remeasuring a study intended for a short-term purpose that was completed in the past. If the original plots can be relocated and the measurement protocols are well documented, then the opportunity exists to convert a completed short-term experiment into a long-term, and more useful, investigation. Examples of this type of work include Dolph et al. (1995) and Pitt and Lanteigne (2008).

This investigation was undertaken as an extension of a retrospective analysis of data from a long-term thinning study on the Kane Experimental Forest in northwestern Pennsylvania. Data from an experiment that was established in 1975 to examine the effects of different thinning approaches on the growth and yield of an Allegheny hardwood stand were used to assess the effects of the thinning treatments on carbon sequestration (Hoover and Stout 2007). The original intent of this current study was a set of baseline carbon sequestration estimates for various major forest types across the United States, to generalize carbon implications of different thinning methods within and across geographic regions. The focus is on carbon in aboveground live tree biomass only. Due to the challenges and constraints discussed in the following text, however, the goal of this study became an investigation into the feasibility of applying the approach of Hoover and Stout (2007) to other existing long-term data sets from areas described in Adams et al. (2008). The objectives included (1) assembling a sufficient number of data sets to have examples from several forest types, (2) presenting preliminary carbon sequestration results from four long-term thinning data sets, and (3) evaluating the use of this collection of experimental data sets and providing a series of recommendations to facilitate retrospective and/or synthetic analysis now and in the future. This paper is not intended as an indepth analysis of carbon sequestration at these few sites but rather as a trail map for maximizing the usefulness of priceless data from long-term studies.

Methods

An informal survey was developed and sent to all members of the Forest Service EFRs mailing list, which reaches the designated point of contact for all sites listed in Adams et al. (2008). The survey asked a variety of questions regarding the existence of long-term inventory records, the presence of active and closed thinning studies, the nature of the inventory design, and the state and format of the study records. Possible candidates for analysis were chosen from the replies, and requests were sent for the inventory records and any supporting materials such as study plans and establishment reports.

Because the inventory records are from different regions, the generalized biomass equations of Jenkins et al. (2003) were used to produce biomass estimates. These equations do not require height as an input variable. The minimum data required for this study are species, diameter at breast height (d.b.h.), tree status (live, dead, cut, ingrowth), thinning treatment applied, and plot size. Although many of the study designs included individually numbered stems, some tallies took the form of number of trees by species and diameter class. Either type of data can be used for biomass estimates using the generalized equations, although the individual stem records provide more precise information. The resulting biomass estimates were multiplied by 0.5 to convert to carbon. Results were summarized by experimental forest, by treatment, and average annual net carbon change was calculated and presented.

One forest included treatments that involved extensive harvesting, in which a notable amount of carbon was transferred into harvested wood products. A retrospective analysis of carbon in harvested wood products is possible in cases in which detailed harvest records were kept. Accounting for carbon in harvested wood products is a complex topic; I followed the methods described in Smith et al. (2006). To simplify the accounting, slash was not included in the estimates because detailed carbon budgets are not the focus of these case studies.

Results and Discussion

Carbon Sequestration

Of the 27 surveys received, I was able to successfully use data from four experimental forests to estimate forest carbon storage over time. The sites are the Bartlett Experimental Forest (northern hardwoods), Vinton Furnace Experimental Forest (mixed oak), Crossett Experimental Forest (loblolly/shortleaf pine), and Wind River Experimental Forest (Douglas-fir). All four forests are located in the conterminous United States; figure 1 shows the approximate location of each site. Adams et al. (2008) supplies further details on these and other sites in the Forest Service EFRs network. Issues with data that were not used are presented and discussed in the next section.

Bartlett Experimental Forest, New Hampshire—Thinning Young, Even-Aged Northern Hardwoods

This experiment was installed in 1959 in a 25-year-old, even-aged northern hardwood stand. Four thinning treatments were applied: heavy crop tree, light crop tree, weeding, and no thinning (control); each treatment was replicated five times. All stems 5 cm d.b.h. and above were tallied at each inventory. Details of the study design and early results were described by Marquis (1969). In 1972, the study was amended to add additional release and fertilization of crop trees on the plots assigned to the weeding treatment. Because of the change in treatments, data from the weeding plots were excluded from the carbon analysis. The study continues today; the plots were retreated in 2003 and the treatments were altered at that time to address slightly different questions.

Carbon stock estimates for aboveground live tree biomass in the precommercial thinning study on the Bartlett Experimental Forest are given in table 1. At the time of the last measurement, standing carbon stocks in live biomass ranged from about 80 metric tons/hectare (t C/ha) in the heavily thinned plots to about 95 t C/ha in the unthinned plots. Mean carbon increment (average annual change) for the entire analysis period differed slightly, from 1.2 t C/ha/yr in heavily thinned plots to 1.5 t C/ha/yr in unthinned control plots. Because not all data sets include pretreatment data, mean carbon increment is calculated for the entire study duration and from the first posttreatment measurement until about 15 years after treatment for each study. In the Bartlett study, mean carbon increment from 1964 through 1975 was 2.6 t C/ha in the heavily thinned plots and 1.6 t C/ha in the control plots; lightly thinned plots stored 2.4 t C/ha/yr for that period.

Figure 1.—*Approximate location of study sites.*

Vinton Furnace Experimental Forest, Ohio—Mixed Oak Stocking Study

This stocking study was initiated in 1962 in stands that were 55 to 65 years old at the time of study establishment. Six density levels were used: 40, 50, 60, 70, 80, and 100 percent of full stocking. Treatments were replicated, although each density level did not have the same number of replicates. The 80-percent level was applied to a single plot and so was excluded from the carbon analysis. The study establishment report provides details on the installation procedures as well as results from the first remeasurement and includes observations on measurement discrepancies, growing season drought, and heavy mortality in two plots. Although the report describes a pretreatment tally, these data were not available and the carbon stock estimates begin with posttreatment inventories. This situation is not uncommon; pretreatment inventories were often dot tallies of the number of stems by species and diameter class, with individual stem numbering begun after the first treatment. When data are transferred from paper to electronic formats, the initial dot tally is sometimes not included. The minimum d.b.h. for tally is 3.8 cm.

Live aboveground carbon stocks in the mixed oak stocking study are given in table 2 for four density levels and the unthinned control. Although most treatments are represented by four plots, the 70-percent density level has only two plots, and there is a single unthinned plot. Average aboveground live tree carbon stocks were similar across density levels in 2006, ranging from a maximum of 107 t C/ha in the control plot to a low of 96 t C/ha for the 50-percent density treatment. Over the entire study, the highest mean carbon increment of 1.4 t C/ha/yr occurs in the 40-percent treatment, with the lowest rates in the 70-percent density treatment (0.9 t C/ha/yr) and the control plot (0.7 t C/ha/yr). During the period from 1962 through 1976, mean carbon increment was similar in the 40-, 50-, and 60-percent treatments (1.5 to 1.7 t C/ha) and lowest in the control plot, which stored 0.1 t C/ha/yr over that period.

Table 1.—*Carbon stock in live aboveground biomass (tonnes C/ha) for the Bartlett Experimental Forest precommercial thinning trial.[a] Standard error of the mean is given in parentheses.*

Measurement year	Heavy	Light	Control
1958[b]	41.2 (1.49)	46.6 (2.05)	48.2 (3.48)
1964	40.2 (1.65)	50.2 (2.01)	61.2 (2.00)
1969	56.0 (2.39)	65.0 (3.13)	69.7 (2.22)
1975	69.4 (1.78)	76.7 (1.44)	78.5 (0.66)
1990	79.9 (0.52)	88.3 (4.24)	94.8 (5.22)
Mean C increment[c] 1964–75	2.6 (0.17)	2.4 (0.07)	1.6 (0.20)
Mean C increment 1958–90	1.2 (0.15)	1.3 (0.10)	1.5 (0.22)

C = carbon. ha = hectare.

[a] See text for study description.

[b] Data from1958 are pretreatment; 1964 is the first posttreatment measurement year.

[c] Mean C increment is average annual change (t C/ha/yr) over the time interval.

Table 2.—*Carbon stock in live aboveground biomass (tonnes C/ha) for the Vinton Furnace Experimental Forest oak stocking study.[a] Standard error of the mean is given in parentheses.*

Measurement year	40%	50%	60%	70%	100%
1962[b]	38.0 (1.47)	43.8 (1.30)	51.0 (1.13)	61.9 (2.40)	75.7(NA)
1966	40.5 (0.80)	47.3 (0.53)	55.0 (1.43)	62.4 (1.43)	76.2 (NA)
1976	58.9 (3.81)	68.0 (1.90)	71.4 (1.35)	72.7 (0.96)	77.4 (NA)
1984	72.8 (6.15)	81.6 (3.54)	85.2 (1.72)	83.6 (0.64)	90.3 (NA)
1996	83.0 (7.74)	86.4 (4.84)	88.4 (3.30)	90.1 (4.78)	91.7 (NA)
2006	98.2 (7.21)	95.9 (3.47)	99.6 (4.40)	101.0 (5.82)	107.4 (NA)
Mean C increment[c] 1962–76	1.5 (0.20)	1.7 (0.09)	1.5 (0.13)	0.8 (0.24)	0.1 (NA)
Mean C increment 1962–2006	1.4 (0.16)	1.2 (0.07)	1.1 (0.12)	0.9 (0.08)	0.7 (NA)

C = carbon. ha = hectare. NA = no data available.

[a] See text for study description.

[b] Data from 1962 are posttreatment.

[c] Mean C increment is average annual change (t C/ha/yr) over the time interval.

Crossett Experimental Forest, Arkansas—Methods of Cut Study in Natural Loblolly/Shortleaf Pine

This method of cut study began in 1943, and the following treatments were applied: merchantable clearcut, diameter limit cut, heavy seed tree cut, and selection cutting. Followup treatments were applied as scheduled according to the study design (multiple retreatments occurred), with the clearcut and seed tree cuts thinned from below, the diameter limit cut repeated, and the selection cut was managed on 5-year cutting cycles to maintain a specified volume. Each treatment was replicated three times and hardwood competition was controlled through various methods throughout the study. All pine stems 10 cm d.b.h. and above were tallied. A few instances of windthrow during the course of the study were severe enough to warrant salvage, but detailed records were not kept on the salvage operation. For this analysis, this circumstance was addressed by ending the carbon analysis in 1990, the measurement before extensive windthrow damage. Although the decision was made to stop measurements in 1957 on the clearcut plots because principal investigators had determined that those plots were successfully regenerated, measurements and thinning treatments were resumed on these plots in 1979 (Cain and Shelton 2001). This study had a notable amount of carbon transferred into the harvested wood products pool, as compared to the amount of forest carbon. For this reason, two sets of results will be presented: carbon in live aboveground biomass and carbon in live aboveground biomass plus carbon in harvested wood products.

Carbon stock estimates are given in tables 3 and 4 for the methods of cut study. Table 3 is similar to previous tables and

Table 3.—*Carbon stock in live aboveground biomass (tonnes C/ha) for the Crossett Experimental Forest methods of cut study.*[a] *Standard error of the mean is given in parentheses.*

Measurement year	Commercial clearcut	Diameter limit	Seed tree	Selection cut
1942[b]	30.7 (4.78)	27.6 (0.52)	30.3 (2.98)	33.1 (2.93)
1947	0.9 (0.25)	14.2 (0.25)	12.2 (0.71)	31.8 (1.14)
1952	8.2 (1.31)	22.8 (19.2)	20.0 (1.23)	37.4 (0.30)
1957	27.5 (3.27)	19.2 (2.30)	33.0 (1.65)	39.4 (1.92)
1962	NA	26.5 (0.96)	17.0 (0.25)	36.5 (0.61)
1967	NA	42.6 (2.31)	33.9 (2.38)	41.5 (1.88)
1979	62.7 (2.01)	39.5 (0.96)	63.8 (2.88)	50.8 (2.99)
1985	56.0 (1.72)	11.9 (0.53)	55.0 (0.99)	37.1 (3.16)
1990	54.0 (2.05)	17.3 (1.05)	53.8 (0.89)	36.7 (1.80)
Mean C increment[c] 1942–57	– 0.2 (0.44)	– 0.6 (0.02)	0.2 (0.29)	0.4 (0.29)
Mean C increment 1942–90	0.5 (0.07)	– 0.2 (0.02)	0.5 (0.07)	0.1 (0.06)

C = carbon. ha = hectare. NA = no data available.

[a] *See text for study description.*

[b] *Data from 1942 are pretreatment; 1947 is the first posttreatment measurement year.*

[c] *Mean C increment is average annual change (t C/ha/yr) over the time interval.*

Table 4.—*Carbon stock in live aboveground biomass and harvested wood (tonnes C/ha) for the Crossett Experimental Forest methods of cut study.*[a] *Standard error of the mean is given in parentheses.*

Measurement year	Commercial clearcut	Diameter limit	Seed tree	Selection cut
1942[b]	30.7 (4.78)	27.6 (0.52)	30.3 (2.98)	33.1 (2.93)
1947	11.4 (1.63)	20.5 (0.32)	18.9 (0.56)	34.3 (1.49)
1952	17.7 (1.42)	28.6 (0.20)	25.8 (0.80)	41.0 (0.76)
1957	36.3 (3.03)	29.0 (1.62)	38.3 (0.92)	45.4 (1.05)
1962	NA	37.9 (2.54)	31.1 (0.18)	45.6 (0.94)
1967	NA	53.4 (1.93)	47.0 (2.18)	51.9 (2.10)
1979	70.2 (3.28)	57.9 (0.72)	75.9 (2.65)	63.6 (3.20)
1985	70.9 (1.95)	40.8 (0.20)	73.6 (1.06)	55.8 (4.18)
1990	71.6 (3.51)	44.3 (0.93)	74.5 (1.32)	56.4 (3.56)
Mean C increment[c] 1942–57	0.4 (0.34)	0.1 (0.14)	0.5 (0.24)	0.8 (0.24)
Mean C increment 1942–90	0.9 (0.04)	0.3 (0.01)	0.9 (0.08)	0.5 (0.08)

C = carbon. ha = hectare. NA = no data available.

[a] *See text for study description.*

[b] *Data from 1942 are pretreatment; 1947 is the first posttreatment measurement year.*

[c] *Mean C increment is average annual change (t C/ha/yr) over the time interval.*

reports the carbon stock estimates for aboveground live tree biomass. Table 4 provides estimates for carbon in aboveground live tree biomass plus carbon in harvested wood products. Table 4 is presented to demonstrate that such accounting is possible in a retrospective analysis. Note that although the values for each treatment are different in tables 3 and 4, the overall outcomes are the same. Mean carbon increment over the entire study period was lowest in the diameter limit treatment and highest in the seed tree and commercial clearcuts with and without the inclusion of harvested wood products. Similarly, for the 1942 through 1957 period, mean carbon increment was highest in the selection cut and lowest in the diameter limit treatment, regardless of products. Live aboveground biomass carbon stocks in 1991 ranged from about 54 t C/ha in the commercial clearcut and seed tree treatments to 17 t C/ha in the diameter limit plots; the selection cut averaged 37 t C/ha.

Wind River Experimental Forest, Oregon—Douglas-Fir Spacing Test

This spacing test was initiated in 1925 by planting seedlings at square spacings of 1.2, 1.5, 1.8, 2.4, 3, and 3.67 m (4, 5, 6, 8, 10, and 12 ft). True replicates were not used; each spacing was applied to a single block, and measurements were taken on subplots within each block (generally three plots, although four were used in the 2.4-m spacing, and two plots were sampled in the 3.67-m spacing). In the first few years after establishment, heavy seedling mortality required the replanting of many seedlings. When the measurement plots were laid out in 1945, investigators noticed that not all plots in a block had similar soil characteristics and adjustments were made to address this observation. The 3.67-m spacing was installed on a smaller block and sampled on two small subplots; for this reason, data from this treatment were not used for the carbon analysis. Tree measurements were generally made every 5 years (stems 3.8 cm d.b.h. and above), and soil studies were begun in the 1970s. Investigators learned that soils at the southern end of the site are deeper and have greater available water-holding capacity. Although the spacing test was laid out in blocks, each block represents a single spacing treatment; treatments were not randomized within blocks. The blocks with the closest spacing are located at the northern end of the site; soil properties and spacing treatments are confounded. After careful study of the growth and soils data, however, Miller et al. (2004) concluded that, although soil properties are a factor in the growth results, tree spacing likely plays a stronger role. This careful documentation and followup work allows us to learn from the Wind River study even though design problems exist.

In the Wind River study, large differences are apparent in the live aboveground biomass carbon stocks at the last measurement (table 5). As noted previously, site differences are confounded with the spacing treatments; however, the study still provides valuable estimates of carbon stock change under different conditions. In 1991, carbon stocks were similar in the 1.5-, 1.8-, and 2.4-m spacings, ranging from 104 to 112 t C/ha; however, the average carbon stock in the 3-m (10-ft) spacing treatment was nearly double that in the 1.2-m spacing. Although this result is likely due to a combination of spacing

Table 5.—*Carbon stock in live aboveground biomass (tonnes C/ha) for the Wind River Experimental Forest spacing study.*[a] *Standard error of the mean is given in parentheses.*

Measurement year	1.2 x 1.2 m	1.5 x 1.5 m	1.8 x 1.8 m	2.4 x 2.4 m	3 x 3 m
1945[b]	38.2 (2.84)	29.4 (2.47)	27.8 (1.39)	23.4 (6.94)	24.5 (2.53)
1951	58.5 (4.67)	48.2 (3.22)	48.0 (2.13)	35.0 (3.35)	51.7 (5.05)
1957	72.2 (6.44)	62.8 (3.88)	64.1 (3.00)	58.2 (3.92)	75.5 (7.86)
1960	81.1 (7.61)	70.3 (4.30)	73.0 (4.50)	70.2 (4.58)	91.3 (8.02)
1965	81.7 (4.32)	76.3 (4.50)	77.3 (5.69)	80.4 (4.68)	105.3 (8.56)
1970	80.9 (1.90)	82.4 (5.65)	83.0 (7.40)	86.2 (4.88)	122.2 (9.32)
1975	83.1 (1.68)	88.1 (5.92)	87.8 (9.27)	93.7 (5.25)	135.8 (9.38)
1980	89.0 (1.73)	95.0 (6.27)	95.6 (11.87)	101.9 (6.26)	150.7 (8.34)
1986	92.7 (1.62)	101.9 (6.99)	102.0 (13.12)	109.3 (6.33)	163.5 (7.89)
1991	92.8 (3.46)	104.6 (6.44)	104.2 (15.68)	111.9 (6.07)	175.1 (7.79)
Mean C increment[c] 1945–60	2.9 (0.32)	2.7 (0.12)	3.0 (0.27)	3.1 (0.30)	4.5 (0.37)
Mean C increment 1945–91	1.2 (0.10)	1.6 (0.09)	1.7 (0.33)	1.9 (0.06)	3.3 (0.12)

C = carbon. ha = hectare.

[a] *See text for study description.*

[b] *Data from 1945 are posttreatment.*

[c] *Mean C increment is average annual change (t C/ha/yr) over the time interval.*

effects and moisture availability, it demonstrates the large range of carbon storage potential possible. Mean carbon increment over the entire measurement period ranged from 1.2 t C/ha/yr in the 1.2-m spacing to 1.9 t C/ha/yr in the 2.4-m treatment. Again, the 3-m spacing had a much higher mean carbon increment, storing 3.3 t C/ha/yr. Mean carbon increment for the 1945 through 1960 interval followed a similar pattern, ranging from 2.9 to 3.1 t C/ha/yr except in the 3-m treatment, which stored an average of 4.5 t C/ha/yr in that time period.

Generalizations From the Case Studies

Although there are difficulties to overcome, analysis of existing data from density management studies is a feasible way to investigate the effects of varied treatments on forest carbon storage (although considerable time is required to collect, clean, and collate records). For situations in which control plot data exist, baseline carbon accumulation estimates for various forest types can also be developed, as well as estimates of biomass in standing dead trees and the impacts of insect and disease outbreaks (in cases in which detailed mortality codes were employed). These initial results highlight the contrast between short-term and long-term results; managers wishing to consider carbon sequestration as one of several management goals need to consider whether net carbon storage or the rate of carbon uptake is the variable of concern, and over what timeframe. Of the four cases presented here, two are thinning studies (Bartlett and Vinton Furnace). In both cases, the average annual rate of carbon storage over the short term was higher in the thinned plots; long-term rates were also higher for thinned plots at Vinton Furnace (and similar among treatments at Bartlett). This observation suggests that the approach of using long-term data sets to develop generalizations about the carbon implications of management treatments is valid and that the analysis will bear fruit. In addition, these studies highlight factors worth considering when developing management strategies for carbon sequestration, such as the importance of site characteristics (Wind River) and regeneration methods (Crossett).

Challenges in Using These Data

There is a set of common problems that arise when using long-term data sets. Many of these problems have been described in detail; e.g., Burger and Powers (1991) and Curtis and Marshall (2005). Most can be avoided only during the planning stage of the experiment, although careful attention to documenting and maintaining records is necessary throughout the life of the study. Careful recordkeeping may allow a useful analysis to be conducted even if design shortcomings exist. Inadequate recordkeeping, however, can render even the most soundly designed experiment unusable to future investigators.

Challenges encountered in the course of this pilot study included many of those commonly encountered by others. The most significant challenges included the following:

- Lack of knowledge of existing data sets—the "file drawer syndrome." The survey questionnaire asked for negative and positive replies. Although some respondents indicated that the forest in question had no current or past long-term studies, a common reply was that the individual listed as the point of contact was unsure of what data existed or of the current condition or location of records. As studies are completed and closed, personnel retire or transfer, and offices move or consolidate, data files and associated documents may change hands many times. In meta-analysis, the "file drawer problem" refers to the risk of analyses that are compromised by the small number of published reports of statistically nonsignificant results. In long-term studies, there is, quite literally, a file drawer problem. Investigators and project managers inherit file cabinets full of records from closed studies; these records can provide valuable opportunities for retrospective studies and synthesis activities. In many cases, however, those records have not been cataloged and site personnel may have little idea of the contents of those file cabinets. Cataloging and documenting records requires large amounts of time, but the investment can provide large returns.
- Lack of replication. Experimental designs did not always include replication for all treatments. Early studies often incorporated multiple levels and/or combinations of intermediate treatments, sometimes resulting in just one or two plots representing a specific treatment. This scenario makes it quite difficult to draw any generalizations about the response of a stand to a particular treatment, limiting the usefulness of the retrospective approach. Since long-term studies are especially vulnerable to losses from disturbance, inadequate replication presents a significant challenge for investigators planning retrospective studies or synthesis activities.

- Absence of control plots and/or pretreatment data. Sites in the Forest Service network of EFRs have been the setting for experimental research since the 1930s. Many records exist from studies that were installed from the 1930s through the 1950s, and these studies are particularly valuable for their length of record. When these earlier studies were installed, however, experimental design and research approaches had a different focus from contemporary approaches. In many cases, the level of treatment was of interest, not the performance of treated versus untreated stands, so control plots were not installed. In addition, if the method of cutting or level of cutting was the area of interest, stand growth after harvest was the important variable and pretreatment measurements were often not taken. Resources are almost always scarce and larger scale experiments have high costs, so the decisions not to install untreated controls or take pretreatment data were made. Unfortunately, those same decisions limit the usefulness of experiments to supply baseline data or provide answers to the questions of today and tomorrow.

- Inconsistency/inadequacy of documentation. This issue is an ongoing challenge in any long-term research project. Technology, personnel, methods, study objectives, and record formats are just a few of the items that can change over time. In the case of the current study, tree status codes were a particular problem; codes were often unexplained or inconsistent with the data file, resulting in stems coded as dead that continued to increase in diameter as well as live trees with static diameter measurements. The reuse of a tree number from a dead or cut tree created difficulties in a few cases and is a common problem in long-term forestry studies. Coding of diameters also changed over time in at least one data set, with records for some years containing an implied decimal point while in other years the decimal point was explicitly recorded. In some cases, treatments were changed to address questions that had arisen since the study was installed. Although alterations of treatments were generally well documented, growth records from these plots could not be used for carbon analysis due to the change in treatment. Disturbance events also occurred; in some studies this situation was fairly well documented while in other studies only general notes were provided, making it difficult to discern the extent and impact of the disturbance on the response variables.

Lessons Learned

Although the original goals of this project were not met, this pilot test demonstrates that it is feasible to use long-term data sets from thinning trials to develop carbon estimates, although substantial time and effort are currently required to locate, acquire, clean, and understand the data files for use. Although the stated objective of this study was to glean insight into the carbon consequences of thinning treatments, the primary lessons learned are about the design and maintenance of long-term studies. Careful design can position an experiment to be useful well into the future and for purposes other than originally intended. Inadequate design and planning can greatly limit the usefulness of a study for future efforts, and the failure to properly document, maintain, and catalog records can doom even the most robustly designed experiment.

The key lessons learned in this pilot test are primarily related to documentation:

- ***Working with older data sets is like solving a puzzle.*** Many cases of insufficient documentation result because an investigator plans a study and expects to complete the study during his or her career. Often, this situation is exactly what occurs. The results are published, and the scientist moves on to the next project, not anticipating that another investigator may wish to reopen the study in the future or use the data for retrospective analysis or meta-analysis. Often, the required documentation exists but may be located in several different places and in different formats.
- ***Nothing is obvious.*** Is diameter measured in inches? What are the units for plot size? What measure of relative density is being used? Were board feet calculated using Doyle? Failure to document the obvious can require that others conduct a great deal of detective work. In some cases, this situation can render data unusable for any future analyses. Although data sets may have been transferred from paper tally sheets to electronic files, units and other key information are not always included.
- ***Formats change.*** Electronic data are extremely useful and can save a great deal of time. Data formats change rapidly, however, and money and staff time are not always available to update files to current formats. For example, Marshall and Deitschman (1976) describe a computer program written to facilitate the use of existing long-term data. They note the importance of backing up the data and keeping a copy

off site. The method chosen for data storage was tape; of course, such tapes cannot be read today. Marshall and Deitschman (1976) also report that original tally sheets and printouts of the master data files were maintained on site. Regrettably, electronic files do not render paper records unnecessary.

- ***Recollections are not always accurate.*** Many investigators inherit studies and data sets and may not be familiar with the state of the records. Before planning a study involving particular data sets, it is helpful to examine a subset of the actual data records. Data sets may not always be "as advertised."
- Although retrospective analysis is a short cut, it still requires considerable time to locate data records and supporting documentation and to clean, understand, and update the files. ***These tasks can often take more time than conducting the actual analysis.***

Recommendations and Conclusions

The following is a list of major recommendations to consider when planning, installing, and implementing experimental studies. These recommendations are intended to facilitate the use of a study for future analyses addressing issues that are currently unknown, as well as cross-site synthesis activities.

- Document the obvious; do not make assumptions. Especially as meta-analysis becomes more commonly used, it is better to provide too much detail than too little. Be sure to provide details on measurement units, plot sizes, treatment codes, mortality codes, species codes, measures of density, size cutoffs, disturbance events, etc. When in doubt, include the information.
- Keep key metadata in the main data file with the measurement. Although supplementary files such as study plans, establishment reports, and interim results are extremely useful, they can easily become separated from the main data files over time. The key metadata (see point mentioned previously) should be included in the main data file. For example, if using a spreadsheet, the first page in the workbook should include the critical metadata. Do not rely on documentation in additional files.
- Check records and formats for consistency over time. If species codes or mortality codes were changed or treatments were altered, the data records should be updated to reflect this change, or the changes must be documented in the metadata. Failure to document such changes can easily render a data set unusable. Records should be checked each time that new data are entered to detect problems such as incorrect mortality codes, reuse of tree numbers, tree diameters getting smaller, etc. Such discrepancies are much easier to clear up shortly after measurement than decades in the future.
- Think long term when considering record storage. Consider keeping paper copies of records in case formats are not updated in a timely manner.
- Apply the "bus test" to every data set for which you are responsible. If you were hit by a speeding bus tomorrow, would a colleague who is only slightly familiar with your study be able to understand and use your data? If the answer is yes, then your study is adequately documented and can be useful well into the future. If not, then add the critical metadata to the data files.
- Take time to tend data sets. If you inherit a long-term data set from another investigator, take the time to become familiar with it. Addressing any documentation problems at the time of transfer is much simpler than it will be a decade or two in the future. Be sure to update documentation as needed; in many cases, a disturbance event can provide opportunities for new studies if adequate documentation is available. In addition, data may still be usable, even if a disturbance has occurred, as long as the nature and extent of the disturbance are fully described. Again, such important information should be located in the main data file that contains the measurements.

These recommendations echo those of others and apply to the design of long-term studies as well as the maintenance of existing records. To quote Curtis and Marshall in their excellent handbook of procedures, "Long-term permanent-plot data are often analyzed by someone other than the original investigator. Analytical techniques and objectives change over time, and there can be no certainty that the computational procedures and analyses foreseen at the time the plots were established will be those judged most suitable at the time of later analyses" (2005: p. 9).

Existing long-term data sets from experiments conducted at EFRs represent a treasure trove of opportunities to address contemporary problems and lessons at the scales of landscapes and regions. This treasure is at risk, but we can preserve it by developing a central and consistent database for all long-term studies, both past and present. Many examples exist; Poage and Anderson (2007) cataloged 12 large-scale silviculture experiments in the Pacific Northwest and developed a relational database with a number of data matrices. Other models include the Long Term Ecological Research network and the Ameriflux network, both of which require that investigators input critical metadata into a central system. Such a system would not only safeguard current studies, preventing the documentation problem from continuing, but would also provide a repository for data from earlier studies that could be included as time and resources permit.

In conclusion, locating, cataloging, and documenting data sets require a great deal of commitment and effort, both of which must be sustained over time. As stated by Pitt and Lanteigne, "The long and continued efforts of a number of field and office personnel over the years have kept this study 'alive' and the data in sound form to permit our analyses." (2008: p. 607) Although not every study may be useful for future research, the time spent identifying and updating long-term studies that are good candidates for synthesis, retrospective analysis, or reopening is an investment that can provide excellent returns, both now and in the future.

Acknowledgments

Many thanks to Connie Harrington, William Leak, Mike Shelton, and Dan Yaussy for providing the data used for this study and for patiently answering my many questions. Elizabeth LaPoint provided the map used in figure 1, and Susan Stout supplied the inspiration for the study. The manuscript benefited greatly from Linda Heath's thoughtful review and comments from Susan Stout. Thanks to all who participated in the survey and to Mary Beth Adams for convening the Experimental Forests and Ranges Synthesis Workshop.

Literature Cited

Adams, M.B.; Loughry, L.; Plaugher, L., comps. 2008. Experimental forests and ranges of the USDA Forest Service. Gen. Tech. Rep. NE-321 Revised. [CD ROM] Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 178 p. http://nrs.fs.fed.us/pubs/6741. (28 January).

Burger, J.A.; Powers, R.F. 1991. Field designs for testing hypotheses in long-term site productivity studies. In: Dyck, W.W.; Mees, C.A., eds. Long-term field trials to assess environmental impacts of harvesting. Proceedings, IEA/BE T6/A6 workshop. IEA/BE T6/A6 Rep. No. 5. FRI Bulletin No. 161. Rotorua, New Zealand: Forest Research Institute: 79–105.

Cain, M.D.; Shelton, M.G. 2001. Natural loblolly and shortleaf pine productivity through 53 years of management under four reproduction cutting methods. Southern Journal of Applied Forestry. 25: 7–16.

Curtis, R.O.; Marshall, D.D. 2005. Permanent-plot procedures for silvicultural and yield research. Gen. Tech. Rep. PNW-634. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 86 p.

Dolph, K.L.; Mori, S.R.; Oliver, W.W. 1995. Long-term response of old-growth stands to varying levels of partial cutting in the eastside pine type. Western Journal of Applied Forestry. 10: 101–108.

Franklin, J.F.; Bledsoe, C.S.; Callahan, J.T. 1990. Contributions of the long-term ecological research program. BioScience. 40: 509–523.

Hoover, C.M.; Stout, S.L. 2007. The carbon consequences of thinning techniques: stand structure makes a difference. Journal of Forestry. 105: 266–270.

Jenkins, J.C.; Chojnacky, D.C.; Heath, L.S.; Birdsey, R.A. 2003. National-scale biomass estimators for United States tree species. Forest Science. 49: 12–35.

Lugo, A.E.; Swanson, F.J.; González, O.R., et al. 2006. Long-term research at the USDA Forest Service's experimental forests and ranges. BioScience. 56: 39–48.

Marquis, D.A. 1969. Thinning in young northern hardwoods: 5-year results. Res. Pap. NE-139. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 22 p.

Marshall, J.A.; Deitschman, G.H. 1976. Computerization of data handling for long-term forest research plots. Northwest Science. 50: 231–235.

Miller, R.E.; Reukema, D.L.; Anderson, H.W. 2004. Tree growth and soil relations at the 1925 Wind River spacing test in coast Douglas fir. Res. Pap. PNW-RP-558. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 41 p.

Pitt, D.; Lanteigne, L. 2008. Long-term outcome of precommercial thinning in northwestern New Brunswick: growth and yield of balsam fir and red spruce. Canadian Journal of Forest Research. 38: 592–610.

Poage, N.J.; Anderson, P.D. 2007. Large-scale silviculture experiments of western Oregon and Washington. Gen. Tech. Rep. PNW-GTR-713. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 44 p.

Powers, R.F. 1989. Retrospective studies in perspective: strengths and weaknesses. In: Dyck, W.J.; Mees, C.A., eds. Research strategies for long-term site productivity. Proceedings, IEA/BE A3 workshop. IEA/BE A3 Rep. No. 8. FRI Bulletin No.152. Rotorua, New Zealand: Forest Research Institute: 47–62.

Powers, R.F. 1999. If you build it, will they come? Survival skills for silvicultural studies. The Forestry Chronicle. 75: 367–373.

Powers, R.F.; Mean, D.J.; Burger, J.A.; Ritchie, M.W. 1994. Designing long-term site productivity experiments. In: Dyck, W.J.; Cole, D.W.; Comerford, N.B., eds. 2004. Impacts of forest harvesting on long-term site productivity. London, United Kingdom: Chapman and Hall: 247–286.

Sanchez, F.G.; Scott, D.A.; Ludovici, K.H. 2006. Negligible effects of severe organic matter removal and soil compaction on loblolly pine growth over 10 years. Forest Ecology and Management. 227: 145–154.

Scott, D.A.; Tiarks, A.E.; Sanchez, F.G., et al. 2004. Forest soil productivity on the southern long-term soil productivity sites at age 5. In: Conner, K.F., ed. Proceedings, 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS-71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 372–377.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. 2006. Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

Thomas, T.B.; Lehmkuhl, J.F.; Raphael, M.G.; DeBell, D.S. 1993. Sites for retrospective studies: opportunities for research in western Washington and Oregon. Gen. Tech. Rep. PNW-312. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 24 p.

Zhang, J.; Oliver, W.W.; Powers, R.F. 2005. Long-term effects of thinning and fertilization on growth of red fir in northeastern California. Canadian Journal of Forest Research. 35: 1285–1293.

United States Department of Agriculture

Forest Service

Gen. Tech. Report WO-84

April 2010

Meeting Current and Future Conservation Challenges Through the Synthesis of Long-Term Silviculture and Range Management Research