GUIDELINES FOR SAMPLING ABOVEGROUND BIOMASS AND CARBON IN MATURE CENTRAL HARDWOOD FORESTS

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Abstract.—As impacts of climate change expand, determining accurate measures of forest biomass and associated carbon storage in forests is critical. We present sampling guidance for 12 combinations of percent error, plot size, and alpha levels by disturbance regime to help determine the optimal size of plots to estimate aboveground biomass and carbon in an old-growth Central Hardwood forest. The analyses are based on five 100-percent inventories covering a 66-year time period. Disturbance regimes during that time included periods of grazing, low tree mortality, and high tree mortality. The size and number of plots recommended for estimating biomass and carbon changed with the type of disturbance. This information can be used to help design inventories of biomass and carbon in older forests.

INTRODUCTION

Millions of acres of forest in the northern United States are expected to grow into age classes older than 100 years over the next two decades (Shifley et al. 2014), and most of those old forests will have experienced some degree of prior partial disturbance. Determining the current and future significance of these forests in biomass and carbon storage is important to resource managers, climate scientists, resource scientists, and policy makers. With limited forest monitoring resources, managers need efficient inventory methods to estimate biomass and carbon in old forests. Efficient inventory taking and biomass and carbon monitoring will improve understanding of the role of old forests in carbon sequestration and bioenergy production, both of which are relevant to managing climate change.

Spetich and Parker (1998b) published plot size recommendations for biomass estimation in old-growth hardwood forests; however, the tabular data presented in that publication were not sufficient to meet the current need for a wide range of inventory options. Accurate estimates of biomass and associated carbon estimates in hardwood forests have become increasingly important in climate-change-related policy and management decisions. Our objective in this paper is to provide information that is complete enough to support inventory designs for monitoring biomass and carbon in old midwestern hardwood forests. Analyses improve guidance on the interaction of plot size, sample size, and precision to support well-informed decisions about designing inventories for maturing upland hardwood forests.

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Table 1.—Physical characteristics of the 7.92-ha core area of the Davis Research Forest, Randolph County, Indiana

Year	Basal area (m^2/ha)	Density (number of trees/ha)	Average d.b.h. (cm)	Total biomass (Mg/ha)
1926	24	165	38	154
1976	31	320	27	207
1981	34	338	27	220
1986	33	329	27	216
1992	33	312	28	211

METHODS

Study Site

The study site is Davis Research Forest, a 21 ha old-growth deciduous forest in Randolph County, IN. Physiographically, the site is mainly mesic with inclusions of wet-mesic to hydric areas (Spetich et al. 1999). In 1926 a 100 percent census was done in which every tree 10.2 cm or larger was measured and tagged with a unique identification number. To facilitate the inventory, the forest was divided into a mapped grid of 55 contiguous plots. After field measurements were completed, all trees were plotted on a large-scale map.[2] These trees continued to be measured throughout their lives including inventories in 1976, 1981, 1986, and 1992. This paper focuses on the core 7.92 ha of the Davis Research Forest where data are most consistent across all inventories and influences of edge effects are minimized. Parker et al. (1985) and Spetich and Parker (1998a) report additional study details.

The forest overstory is dominated by oak-hickory (*Quercus-Carya*) species, and the understory is dominated by maple (*Acer*) and elm (*Ulmus*) species. Between 1926 and 1992 the average diameter at breast height (d.b.h.) decreased while density increased because of a developing understory. Tree density was greater in 1992 than in 1926 because of the ingrowth of small diameter trees, which resulted in a lower arithmetic average d.b.h. (Table 1). Biomass of all trees in the core area of the forest larger than 10 cm d.b.h. was 154 Mg/ha in 1926 and increased to 211 Mg/ha by 1992. The biomass of trees in forest understory (trees from 10 to 25 cm d.b.h.) more than quadrupled during that time, however, increasing from 4 Mg/ha in 1926 to 17 Mg/ha by 1992 (Spetich and Parker 1998a). Previous disturbances on this site included livestock grazing between the mid-1800s and 1917 that likely created the sparse understory observed during the 1926 inventory.

Analysis

Biomass dry weight of each tree was calculated for each of the five inventory periods: 1926, 1976, 1981, 1986, and 1992. Tree bole biomass was calculated using Hahn and Hansen (1991) equations; tree-top and branch biomass was determined using Smith (1985) equations. Species-specific site index values for use with these equations were determined from Neely (1987), Carmean (1979), and the Natural Resources Conservation Service (data from the Soil Conservation Service integrated resource information system, based on a statewide inventory for site index). For further details, see Spetich and Parker (1998a).

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[2] Bur M. Prentice. 1927. Forest survey No. 1 Herbert Davis Forestry Farm unpublished report to the Department of Forestry and Conservation, Purdue University, West Lafayette, IN.

Table 2.—The 16 plot sizes used within the 7.92-ha core area of the Davis Research Forest for comparisons of sample size

Plot dimensions (m)	Number of plots in core area	Plot area (ha)	Total area of plots (ha)
10 × 10	792	0.01	7.92
20 × 20	198	0.04	7.92
30 × 30	84	0.09	7.56
40 × 40	44	0.16	7.04
50 × 50	24	0.25	6.00
60 × 60	21	0.36	7.56
70 × 70	12	0.49	5.88
80 × 80	10	0.64	6.40
90 × 90	8	0.81	6.48
50 × 180	8	0.90	7.20
60 × 180	7	1.08	7.56
70 × 180	6	1.26	7.56
80 × 180	5	1.44	7.20
90 × 180	4	1.62	6.48
100 × 180	4	1.80	7.20
110 × 180	4	1.98	7.92

Sixteen plot sizes were used to estimate biomass based on sample size comparisons (Table 2). The mean and standard deviations of biomass were calculated for each plot size. These results were used to estimate sample sizes required to estimate biomass within 5, 10, and 20 percent of the mean. Specifically (Freese 1962)

$$n = \frac{1}{\frac{E^2}{t^2C^2} + \frac{1}{N}}$$

Where

n = the number of units in the sample,

N = the total number of sample units in the entire population,

E = allowable error (percent),

t = student’s statistic for a specified α and n −1 degrees of freedom, and

C = the coefficient of variation for a particular plot size.

The sample size, n, was determined for all 16 plot sizes at allowable error levels of 5, 10, and 20 percent. For each error level, n was determined at α levels of 0.01, 0.05, 0.10, and 0.20. Sample size values were computed for each of the five inventory dates to develop recommendations for sampling biomass under the various disturbance regimes.

In each case, the most efficient plot size and sample size combination was designated as that which required measuring the least total area (plot size × n) at a specified allowable error and α. To simplify comparison of alternatives, we assumed that sampling efficiency was directly related to total area sampled to achieve a given allowable error (e.g., travel costs and plot establishment costs were zero).

Table 3.—Size and number of plots necessary to inventory total biomass while measuring the least total area for each percent error and α level combination (based on data from Davis Research Forest, Randolph County, Indiana)

		Disturbance regime														
		Grazing			Low mortality [a]						High mortality [b]					
		Year of Measurement														
		1926 [c]			1976			1981			1986			1992		
% error	Alpha	Plot size (ha)	Number of plots [d]	Total area (size x number)	Plot size (ha)	Number of plots	Total area (size x number)	Plot size (ha)	Number of plots	Total area (size x number)	Plot size (ha)	Number of plots	Total area (size x number)	Plot size (ha)	Number of plots	Total area (size x number)
5	0.01	0.01	642	6.42	0.09	62	5.58	0.09	62	5.58	0.09	58	5.22	0.64	8	5.12
5	0.05	0.01	564	5.64	0.09	50	4.50	0.09	50	4.50	0.09	47	4.23	0.64	6	3.84
5	0.10	0.01	504	5.04	0.09	43	3.87	0.09	42	3.78	0.09	39	3.51	0.64	5	3.20
5	0.20	0.01	408	4.08	0.09	32	2.88	0.09	32	2.88	0.09	29	2.61	0.64	4	2.56
10	0.01	0.01	410	4.10	0.09	34	3.06	0.09	34	3.06	0.09	30	2.70	0.09	33	2.97
10	0.05	0.01	303	3.03	0.09	23	2.07	0.09	23	2.07	0.09	21	1.89	0.09	22	1.98
10	0.10	0.01	241	2.41	0.09	18	1.62	0.09	18	1.62	0.09	16	1.44	0.09	17	1.53
10	0.20	0.01	166	1.66	0.09	12	1.08	0.09	12	1.08	0.09	11	0.99	0.09	12	1.08
20	0.01	0.01	167	1.67	0.09	14	1.26	0.09	14	1.26	0.09	13	1.17	0.09	14	1.26
20	0.05	0.01	109	1.09	0.09	9	0.81	0.09	9	0.81	0.09	8	0.72	0.09	9	0.81
20	0.10	0.01	80	0.80	0.09	7	0.63	0.09	7	0.63	0.09	6	0.54	0.09	7	0.63
20	0.20	0.01	51	0.51	0.04	10	0.40	0.04	10	0.40	0.09	4	0.36	0.04	11	0.44

[a] Low mortality = 1,299 kg/ha/year from 1977 to 1981.

[b] High mortality = 3,534 kg/ha/year from 1982 to 1992.

[c] Note: In 1926 even a small difference in cost of travel between plots would favor the 0.04-ha plot size. The 0.04-ha plots required measuring no more than 0.09 ha greater total area than the 0.01-ha plot size (see Table 4).

[d] Number of plots of a given size required to estimate mean biomass (or carbon) for live trees >10 cm d.b.h. within the indicated percent error (5, 10, or 20 percent) while accepting a probability of 1 – α that the error associated with the sample mean will be greater than the indicated percent error.

RESULTS

Recommended plot sizes for biomass estimation range from 0.04 to 0.64 ha and differ by disturbance regime (Tables 3 and 4). The smallest plot size was the most efficient in 1926 shortly after the grazing disturbance and the largest size was the most efficient for the 1992 measurement when the acceptable error was 5 percent.

Grazing during decades before 1926 reduced the biomass of small diameter trees. The 0.01-ha plot size (Table 3) was the most efficient in 1926, but it required only slightly less total area than the 0.04-ha plot size (Table 4). For the 1926 data set, samples based on the 0.04-ha plot size required measuring only slightly more total area than the 0.01-ha plot size. Estimated differences in the total area that needed to be measured when using the 0.01 versus the 0.04-ha plot sizes were small: 0.08 ha for the 5 percent error with an α of 0.20, 0.06 ha for the 10-percent error with an α of 0.20, and 0.05 ha for the 20 percent error with an α of 0.20. Conversely, using the 0.01-ha plot size required 3.6 to 4.0 times more plots (depending on E and α level) than the 0.04-ha size. Even a small difference in cost of travel between plots would favor the 0.04-ha plot size over the 0.01-ha plot size in this case (Tables 3 and 4).

For inventory years 1976, 1981, and 1986, the most efficient plot size for aboveground tree biomass estimation was usually 0.09 ha (Table 3). The only two exceptions were for 1976 and 1981 when the most efficient plot size was 0.04 ha at 20-percent error with α of 0.2. In those two cases, however, the total area to be sampled differed by only 0.05 ha between the 0.04-ha and 0.09-ha plot sizes.

Table 4.—Size and number of plots necessary to inventory 1926 total biomass while measuring the least total area for a 0.04 ha plot

		1926		
% error	Alpha	Plot size (ha)	Number of plots	Total area (size × number)
5	0.01	0.04	161	6.44
5	0.05	0.04	142	5.68
5	0.10	0.04	127	5.08
5	0.20	0.04	104	4.16
10	0.01	0.04	105	4.20
10	0.05	0.04	78	3.12
10	0.10	0.04	62	2.48
10	0.20	0.04	43	1.72
20	0.01	0.04	46	1.84
20	0.05	0.04	29	1.16
20	0.10	0.04	22	0.88
20	0.20	0.04	14	0.56

Tree mortality was relatively high between 1986 and 1992. Consequently, for some situations, the most efficient plot size increased to 0.64 ha. The 0.64-ha plot, however, was most efficient only at an allowable error rate of 5 percent. At 10- and 20-percent allowable error rates the 0.09-ha plot size was still the recommended size. At the 20-percent error and 0.2 α level, the 0.04-ha plot size was recommended (Table 3), but the difference in total area sampled for the 0.04-ha plots versus the 0.09 ha plots was only 0.01 ha.

For practical purposes, efficient strategies for measuring live tree biomass apply equally to measurement of carbon in live trees. The quantity of carbon in hardwoods is approximately half the biomass dry weight (Lamlom and Savidge 2003), and converting biomass estimates to carbon estimates by a constant multiplier of 0.5 has no influence on sample size estimates. When comparing estimates of carbon sequestered in trees with estimates of atmospheric carbon emissions, it is important to remember that by convention atmospheric carbon emissions are typically reported in terms of equivalent carbon dioxide (CO_2; i.e., two oxygen atoms joined with each carbon atom) rather than as carbon per se. Given that the atomic weight of a CO_2 molecule is 44 (two oxygen atoms at 16 each and one carbon atom at 12), 1 ton of carbon sequestered in biomass corresponds to 3.67 tons of atmospheric CO_2.

DISCUSSION

In this analysis we simplified the comparison of alternatives by assuming that efficiency was directly related to total area sampled to achieve a given allowable error. In real-world applications, however, we must consider numerous other factors, including travel costs to sites and between plots, plot establishment costs, plot perimeter versus borderline trees, and topography. All factors can vary between locations. The tables we provide can be used as a starting point to incorporate the considerations that are unique to particular circumstances into the decision-making process (e.g., see Husch et al. 2003). The plot size and number in Table 3 can assist in developing a biomass sampling scheme for aging upland hardwood forests. Table 3 also gives insight into how various types of disturbances may influence sample design (Cochran 1963, 1977; Freese 1962; Johnson 2000).

In 1926, it would have been necessary to inventory a greater area at each α level and percent error combination than in later measurement years. Grazing that ended by 1917 had reduced much of the understory biomass, resulting in high coefficient of variation values for biomass. This also resulted in a much patchier distribution of understory biomass (Ward et al. 1996). In 1926, sampling with the 0.01-ha plot size would have required up to four times more plots than the 0.04-ha plot size, which would have considerably increased the plot perimeter when these sampling options were compared at a 5-percent error and an α of 0.05. Other factors being equal, larger plots are more desirable because they have a smaller total perimeter for a given cumulative sampled area. Smaller plot sizes result in more borderline trees along plot perimeters. When dealing with borderline trees, determining whether they are in or out of the plot boundary is time consuming, and imprecise determinations can introduce a considerable source of error to sample estimates (Loetsch et al. 1973). For instance, the perimeter of 564 0.01-ha plots is nearly twice that of the perimeter for 142 0.04-ha plots.

In most cases a plot size of 0.01, 0.04, or 0.09 ha was appropriate for sampling aboveground biomass in this population. Plot sizes of 0.01 or 0.04 were the best options soon after understory disturbance, such as the grazing in the Davis Research Forest just before the 1926 inventory. A plot size of 0.09 ha was appropriate in most other inventories from 1976 to 1992. The most significant exception was after high mortality with a 5-percent error for the 1992 inventory where the most efficient plot size was 0.64 ha when the allowable error was 5 percent.

In practice the plot size and number of plots may need to be adjusted when live-tree biomass is inventoried simultaneously with other attributes of old forests such as tree density, dead trees, or coarse woody debris. Other studies that have investigated sampling for old-growth midwestern forests (e.g., Shifley and Schlesinger 1994) have shown that estimates of tree density are efficient with small plots sizes (e.g., 0.01 ha). Larger plot sizes (e.g., 0.1 ha) are more efficient for taking inventory of basal area and presumably for biomass and carbon estimates that are typically highly correlated with basal area. For a given plot size, forest attributes such as downed wood or density of standing dead trees generally have higher coefficients of variation than biomass, basal area, or volume and thus require larger plot sizes or larger sample sizes to estimate mean values with comparable levels of precision (Lombardi et al. 2014, Shifley and Schlesinger 1994).

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