

ABSTRACT

OSBORNE, NATHANIEL LEE. Forest Harvest Residuals: A Composite Report of Five Years of Research in the Southern United States and Sweden. (Under the direction of Dennis Hazel, Robert Bardon, James McCarter, Bronson Bullock).

Increasing fossil fuel prices, concerns about domestic energy security and demand for environmentally friendly, carbon mitigating energy sources are renewing interest to use wood for energy. State and federal governments have responded to increased interest with legislation that promotes renewable energy. Logging residues important role as an energy feedstock and environmental component has been a central topic of discussion for the growing forest energy sector. Over the last five years, I have studied forest harvest residues in the Southern United States and abroad. My principle research focus has been the rapid inventory of residues, determination of their stocking and the identification of factors influencing that stocking. This thesis provides a detailed account of two studies based on five years of data in North Carolina and Southern Sweden. Provided in the thesis is an adapted method to inventory scattered and piled forest harvest residues and a report about the relationship of harvest residues and several covariates. The goal of providing these studies is to contribute observations towards the ongoing discussion about forest harvest residues and to provide a sampling framework others can employ for similar studies.

Forest Harvest Residuals: A Composite Report of Five Years of
Research in the Southern United States and Sweden

by
Nathaniel Lee Osborne

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Forestry and Environmental Resources

Raleigh, North Carolina

2012

APPROVED BY:

Dr. Dennis Hazel
Co-Chair

Dr. Robert Bardon
Co-Chair

Dr. Bronson Bullock

Dr. James McCarter

BIOGRAPHY

Nathaniel Lee Osborne was born on July 24, 1986 in Winston-Salem, North Carolina. As a young man, Nathaniel developed a passion for the outdoors, guided by his family and the Boy Scouts of America. His passion for the outdoors was transformed into practice after he enrolled as a freshman in forestry at North Carolina State University. While at North Carolina State University, Nathaniel developed several relationships with researchers. He worked mostly with the North Carolina State University Extension-Forestry. Under the mentorship of the extension team, Nathaniel developed a strong interest in forestry research and outreach. In May of 2010, Nathaniel earned a B.S. in forest management. In August 2010, fueled by his research and outreach interests, Nathaniel pursued an M.S. in forestry at North Carolina State University and an MSc in forest ecology and business at the University of Helsinki in Finland. Nathaniel spent 2011 living in Lomma, Sweden and Helsinki, Finland. It was over that year he wrote this thesis.

ACKNOWLEDGMENTS

Completion of this thesis is owed to several individuals and organizations. As an undergraduate student and graduate student, I have grown in a garden of exceptional professors and mentors. My committee and friends Dennis Hazel, Robert Bardon, James McCarter, Bronson Bullock, Bo Dahlin and Eric Agestam have tirelessly guided me towards academic success and rewarding works. Under their mentorship, I have grown as a forester, scientist and person. My most sincere thanks are also extended to the North Carolina Biofuels Center, the USDA AFRI project, the University of Helsinki, the Swedish University of Agriculture Sciences and the Atlantis Transatlantic Master's Degree Programme. This thesis would not have been made possible without their structure and generous financial support. It is difficult to do a field study without a field. I'd like to acknowledge Plum Creek, Georgia Pacific, Weyerhaeuser and all the private landowners and consulting foresters we worked with in North Carolina, Georgia and Sweden. Without the efforts of these companies and individuals, we would have ideas in the absence of application. Over the last five years, I have had the chance to collaborate with many excellent land managers. Two of the finest have been Rob Hicks of Plum Creek and Matts Karlsson of Skogsförvaltare. I can say, without reservation, that these forest managers are artists in their field and they deserve the highest respect. My family deserves the greatest acknowledgement. They have become very knowledgeable about downed woody material over the last few years and I thank them for their support and patience.

TABLE OF CONTENTS

List of Tables	v
List of Figures	vi
Chapter 1 How to Rapidly Inventory Scattered and Piled Forest Harvest Residue.....	1
1.1 What is Prism Sweep Sampling?	1
1.2 Efficiency and Precision of Prism Sweep Sampling	3
1.3 Prepare for the Inventory	4
1.4 Conduct the Inventory	7
1.5 Calculate FHR Volume Estimate	9
1.6 Conclusions.....	13
Chapter 2 Downed Woody Material Associated With and Without In-Woods Chipping and Whole Tree Utilization in North Carolina and Southern Sweden.....	13
2.1 Abstract	13
2.2 Introduction.....	14
2.3 Methods.....	16
2.3.1 Analysis Variables and Site Selection	16
2.3.2 Inventory of Downed Woody Material.....	17
2.3.3 Analysis Procedure	19
2.4 Results.....	19
2.5 Discussion	21
2.6 Conclusions.....	23
Literature Cited	25

LIST OF TABLES

Table 1.	
Descriptive statistics of forest harvest residue (tons/acre) using line-intersect sampling, prism-sweep sampling, and 0.1-acre fixed radius plots.....	3
Table 2.	
Descriptive statistics of efficiencies (minutes per sample location) for line-intersect sampling and prism-sweep sampling using a two-person field sampling team.....	4
Table 3.	
Equations for determining net volume of piles based on shape code.....	11
Table 4.	
Number of samples taken and estimated harvest area by study site in North Carolina and Southern Sweden.....	18
Table 5.	
Covariates included in ANOVA and Tukey's honestly significant difference test.....	16
Table 6.	
Estimated volume of downed woody material by study location and covariate.....	20
Table 7.	
ANOVA table for comparisons of volume of downed woody material.....	20
Table 8.	
Tukey's HSD table for comparison of means among North Carolina species types.....	21

LIST OF FIGURES

Figure 1. Sighting through a prism at the midpoint of a forest harvest residue piece to determine if it is “in” and should be sampled.	2
Figure 2. A typical layout of a sampling scheme.	6
Figure 3. Packing density for three different piles.	8
Figure 4. Shape codes and required dimensional measurements for piled FHR.....	9
Figure 5. Number of study sites within counties in North Carolina and Southern Sweden.....	16
Figure 6. Average volume of downed woody material and associated error (95% confidence interval) for North Carolina (A) regions, (B) species types, (C) harvest types and (D) harvest types in Southern Sweden	22

CHAPTER 1

How to Rapidly Inventory Scattered and Piled Forest Harvest Residue

Forest harvest residue (FHR) is an important environmental component, but how do you measure it? The recent surge in interest in renewable energy in the U.S., including wood energy, has brought growing concern about the impact of biomass removal and its impact on biodiversity, water quality, and long-term site productivity (Björheden, 2010).

Forest harvest residue can be scattered or piled. FHR usually consists primarily of material from live trees added during harvesting, such as limbs, tops, and small diameter stems and, to a lesser extent, some dead material that existed prior to harvest. In some states, biomass harvesting guidelines (BHG) have been developed or proposed to encourage retention of forest harvest residue. Thus, assessing success of BHGs or other measures intended to mitigate environmental impacts will require sampling to determine stocking of forest harvest residue. Unlike a timber cruise, where the expense may be carried by a timber sale or management agreement, measurement of forest harvest residue is likely to be part of environmental monitoring and needs to be done quickly and inexpensively, while obtaining an acceptable level of accuracy.

Depending on the size, forest harvest residue may be referred to as coarse woody debris (CWD) or fine woody debris (FWD). For this discussion, we will refer to forest harvest residue that encompass both CWD and FWD as defined by the USDA Forest Service. FHR also includes slash piles that are conglomerations of CWD created by human activity or natural events (Woodall and Monleon, 2007). This document will describe how to rapidly inventory scattered and piled FHR.

1.1 What is Prism Sweep Sampling?

The prism sweep sampling (PSS) method is an accurate and efficient way to sample scattered FHR (Bebber and Thomas, 2003). This method is used to obtain volume estimates over a site when the spatial distribution and estimation of multiple FHR attributes is not needed.

Understanding the spatial arrangement and attributes of individual FHR pieces like size and decay classification is commonly of interest in ecological assessments. If you are interested in the spatial distribution and multiple attributes of FHR over a site, it is best to use line-intercept sampling (LIS), a well-known and frequently used method employed by the USDA Forest Service Forest Inventory and Analysis Unit (Woodall and Monleon, 2007). PSS is a probability-proportional-to-size method that uses the same principles as point relascope sampling with inexpensive, readily available equipment. Woody biomass to be measured must be subtending by a prism angle where the midpoint diameter viewed from the point center is greater than the critical prism angle (Figure 1). The piece that is determined as “in” would then have its length measured. Often, woody biomass will be viewed from a nearly vertical position at the point center. Although woody biomass can still be sighted, the smallest pieces may be underestimated. To minimize this underestimation, you may sight woody biomass closer to the ground or take direct measurements of diameter and horizontal distance to the piece of interest (Bebber and Thomas, 2003).

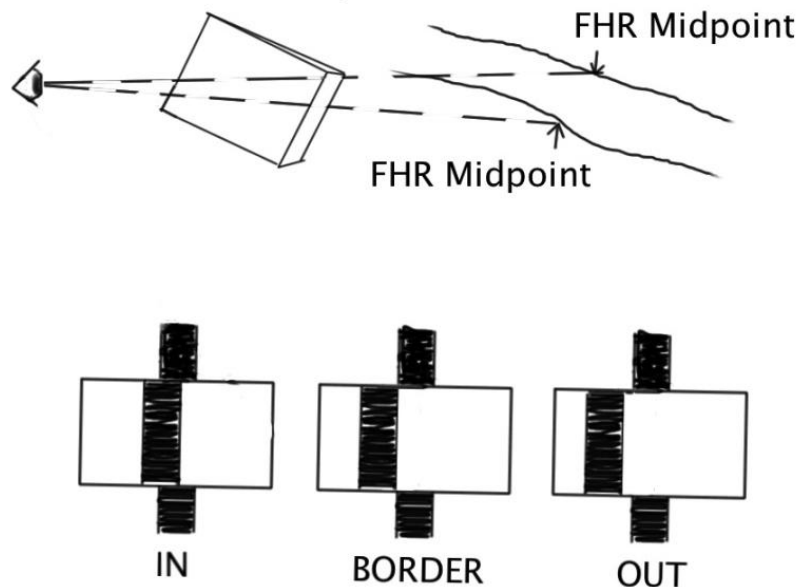


Figure 1. Sighting through a prism at the midpoint of a forest harvest residue piece to determine if it is “in” and should be sampled

PSS requires a clear line of sight from the point center to any potential piece of FHR. Sites with advanced herbaceous regeneration, multiple layers of FHR, or other situations where piece centers cannot be seen may require use of another method.

1.2 Efficiency and Precision of Prism Sweep Sampling

Prism-sweep and line-intercept-sampling methods were used to measure forest harvest residue within a recently harvested site in Johnston County, North Carolina, and compared with 0.1-acre plots to investigate efficiency and precision. Fifty plots were situated on a grid and of these, twenty were randomly selected for sampling. Of those twenty plots, thirteen were in a clearcut hardwood forest and seven within a clearcut pine forest. At each plot location, line-intersect, prism-sweep and 0.1-acre fixed radius plot sampling methods were applied using a two-person crew (tables 1 and 2).

Table 1. Descriptive statistics of forest harvest residue (tons/acre) using line-intersect sampling, prism-sweep sampling, and 0.1-acre fixed radius plots

Statistic	Estimated Biomass (tons per acre)		
	Line Intersect	Prism Sweep	Fixed Radius Plot
Mean	25.97	21.04	22.32
Median	21.78	19.2	21.06
Standard Deviation	13.86	11.22	7.17
Range	47.66	45.15	26.11
Confidence Limit (95%)	6.49	5.25	3.36

Table 2. Descriptive statistics of efficiencies (minutes per sample location) for line-intersect sampling and prism-sweep sampling using a two-person field sampling team

Statistic	Sampling Efficiency (minutes per sample)	
	Line Intersect	Prism Sweep
Mean	17.2	3.2
Standard Deviation	5.4	1.3
Range	15	5
Confidence Limit (95%)	2.5	0.6

For this field comparison, the prism sweep provided an accurate estimate when compared to the 0.1 acre fixed-radius plots (Table 1) at a fraction of the time required for the line-intersect sampling method (Table 2).

1.3 Prepare for the Inventory

Proper planning helps facilitate a successful inventory of a property. Preparation will minimize time spent in the field and increase the accuracy of the estimates determined from the inventory data. To begin planning, you will need:

- Map or aerial photograph of the area to be sampled
- Estimate of the number of acres to be sampled
- Calculator

Before conducting the inventory, determine the number of sample points to measure and decide where they will be installed in the field. The number of points to be sampled is based on the degree of confidence desired and variation in the amount of the FHR to be measured. You can estimate the variation in the amount of FHR from previous inventories on similar sites or by using information on the range of observations from a small sample of the area to be measured. The following calculation is used to determine the approximate number of points to sample.

$$n = \frac{S \cdot t^2}{E}$$

Where, n is number of sampling points that will be installed,

t is dependent on the degree of confidence required for the confidence interval.

Use the following approximations for t ; $t = 1.7$ for a 90% confidence interval,

$t = 2$ for a 95% confidence interval and $t = 2.6$ for a 99% confidence interval.

S is the standard deviation in the amount of the FHR to be measured. A good estimate of the standard deviation in the amount of the FHR can be determined by the range of observations from a small sample of the site to be inventoried or from a previous inventory of a similar site. To determine the standard deviation, divide the range of the observations by 4.

E is the error of tolerance, and the person who requests the inventory specifies it.

E is in the same units as S .

For example: You are asked to sample a 50-acre forest tract, with an error of tolerance specified at ± 3 tons/acre and a desired confidence level set at 95 percent. A small sample of the forest tract indicates a range of 32 tons/acre of FHR. The number of sample points needed to conduct the inventory is calculated as follows.

$$S = \frac{32 \text{ tons/ac}}{4} = 8 \text{ tons/acre}$$

$t = 2$, for a 95% confidence interval

$E = \pm 3$ tons/acre

$$n = \frac{S \cdot t^2}{E} = \frac{8 \cdot 2^2}{3} = \frac{16 \cdot 2}{3} = 28.4 \approx 29$$

Once the number of sample points has been determined, plot their location in the field (Figure 2). On a map or aerial photo of the area to be inventoried, draw parallel lines that reasonably cover the tract. The lines represent the approximate path to follow in sampling.

The spacing of the lines and the distance between points will be based on the sampling intensity you are trying to achieve. Draw the lines perpendicular to drainage patterns or other environmental gradients to pick up changes in vegetation caused by changes in soil moisture and elevation. Locate sample points at regular intervals, which will produce approximately the target number of sample points.

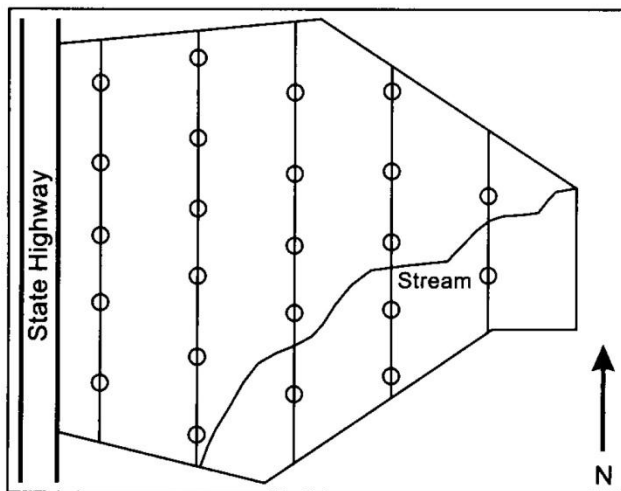


Figure 2. A typical layout of a sampling scheme

It is important to understand how to navigate in the field using a compass and pacing before beginning the inventory. To learn more, read: *Woodland Owner Note 39, Using a Compass and Pacing*, available online at <http://www.ces.ncsu.edu/forestry/pdf/WON/won39.pdf>.

Once the number of sample points is determined and a sampling scheme identified, you are ready to begin the inventory. The following procedure is based on a two-person team, but it can be accomplished by a single person. As with prism cruising of standing trees, a single person must return to the point center periodically between measuring lengths of “in” FHR pieces.

1.4 Conduct the Inventory

To begin an inventory, you will need to gather a few pieces of equipment and locate the first sampling point center. The equipment needed for the inventory includes the following.

- BAF 10 wedge prism or angle gauge
- Measuring tape (25- or 50-foot length)
- Compass
- Pin flag
- Data sheets

Once you have located the first sampling point, use the following guidelines to conduct the sampling of scattered FHR.

1. Place a pin flag marking the sampling point.
2. With the compass, determine the direction you are facing. This will be the starting and ending point as you rotate 360° around the sampling point as marked with the pin flag.
3. Stand with the prism over the sampling point. Hold the prism approximately 10 inches from your eye and at a right angle to the axis of the length of the residue (Figure 1). With one eye closed, begin sighting FHR, counting only pieces whose midpoint is “offset” by the prism and considered “in” (Figure 1). Measure the total length of “in” pieces to the nearest inch and record the measurements on the data sheet. As you rotate 360° around the prism, make sure to hold the prism over the sampling point.
4. After assessing scattered FHR, observe whether there is any piled FHR that has a midpoint within 24 feet of the sampling point, as marked by the pin flag. If there is a pile with a midpoint within 24 feet of the sampling point, then complete the following steps.

- a) Estimate the proportion of each pile that falls within 24 feet of the sampling point. The proportion is between 0 and 1 and is recorded as a decimal to the nearest tenth (0.1, 0.2, 0.3, etc.). Record this on a data sheet under the column labeled “MP.”
- b) Next, estimate the packing density of each pile that falls within 24 feet of the sampling point. The proportion is between 0 and 1 and is recorded as a decimal to the nearest tenth (0.1, 0.2, 0.3, etc.). Record this on a data sheet under the column labeled “Packing Density.” Packing Density is a measure of how dense a pile of FHR is considering the amount of wood and airspace in the pile. Some examples of packing density for three different piles are shown in Figure 3.



Figure 3. Packing density for three different piles

- c) After determining packing density for each pile, determine the shape code that best represents the pile. Use figure four to determine which shape code to use. Based on the code you select, measure the indicated dimensions. Record the dimensions and shape code under the respective columns on the data sheet.

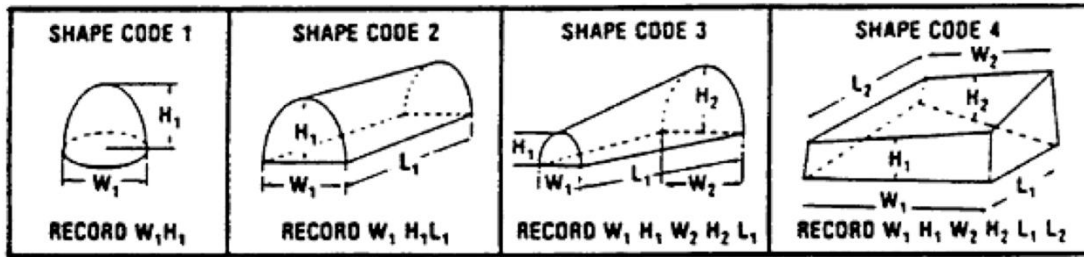


Figure 4. Shape codes and required dimensional measurements for piled FHR

Figure from Woodall and Monleon (2007)

5. Move to the next sampling point and repeat the above steps. Do this for all sampling points.

1.5 Calculate FHR Volume Estimate

After conducting the inventory and collecting the data, estimate the volume of scattered and piled FHR on the site using the following equations.

I. Scattered FHR Volume Estimates

The mean cubic-foot volume per acre of scattered FHR is calculated using the following equation based on the sum of measured lengths of tallied FHR pieces for each plot, the prism basal area factor, and number of sample points taken.

$$\bar{x}_{volume} = \frac{\sum L * BAF}{n}$$

Where, \bar{x}_{volume} is the mean cubic-foot volume per acre of scattered FHR,
 $\sum L$ is the sum of lengths of tallied pieces over all points,
 BAF is the basal area factor of the prism used in sampling,
 n is the number of sample points

After mean cubic foot volume per acre is calculated for the scattered FHR, it is multiplied by a wood density value (WD) to estimate scattered FHR volume in tons per acre.

The equation for this calculation is:

$$\bar{x}_{biomass} = \bar{x}_{volume} \times WD$$

Where, $\bar{x}_{biomass}$ is the mean biomass in tons per acre of scattered FHR,
 \bar{x}_{volume} is the mean cubic-foot volume per acre of scattered FHR
and, WD is constant at 0.03 based on the assumption that scattered FHR weighs 60 lbs per cubic foot.

For example, assume that the length of 89 “in” FHR pieces over 28 sample points were measured. To determine which pieces were “in”, a 10 basal area factor prism was used. The sum of “in” pieces measured lengths is 763 feet. With this information, the estimated cubic-foot volume per acre of scattered FHR is:

$$\bar{x}_{volume} = \frac{\sum L * BAF}{n} = \frac{763 \times 10}{28} = \frac{7630}{28} = 272.5 \frac{ft^3}{acre}$$

The estimated biomass of scattered FHR in tons per acre is:

$$\bar{x}_{biomass} = 272.5 \times 0.03 = 8.18 \frac{tons}{acre}$$

II. FHR Pile Volume Estimates

Net cubic-foot volume estimates for individual FHR piles are calculated using shape-specific formulas that incorporate height, width, and/or length measurements (adapted from Woodall and Monleon, 2007). Choose the formula in table three based on the shape code in figure four of the pile for which you are calculating volume estimates.

Table 3. Equations for determining net volume of piles based on shape code

Shape code	net volume equation
1	$(\pi HW^2 / 8)(PD)$
2	$(\pi HWL/4)(PD)$
3	$(\pi L[(H_1 W_1) + \overline{H_1 W_1 H_2 W_2} + (H_2 W_2)]/12)(PD)$
4	$[(L_1 + L_2)(W_1 + W_2)(H_1 + H_2) / 8](PD)$

H, W, L refer to pile dimensions (in feet) according to shape code and PD is packing density

Once the net cubic foot volume is estimated for individual piles, calculate volume per acre on a cubic-foot basis for individual sample points. This calculation is based on the sum of individual pile volume within a sample point, the sample point's expansion factor, and the mean observed proportion of piles falling within the sample point's plot boundary.

The equation for this calculation is:

$$\sum p_{acre} = \sum p_{plot} \times 24 \times MP$$

Where, $\sum p_{acre}$ is the cubic-foot volume per acre of piled FHR for a plot,
 $\sum p_{plot}$ is the sum of cubic-foot volume for all measured FHR piles
falling within 24 feet of the sampling plot center,
24 is the fixed-radius plot expansion factor and,
MP is the observed mean proportion of piles falling within 24 feet of
the sampling plot center

The next step is to compute the mean volume per acre of FHR piles over all sample plots. This calculation is based on the sum of volume per acre for individual sample plots and the number of sample plots installed.

The equation for this calculation is:

$$\bar{x}_{pile\ volume} = \sum p_{overall} / n$$

Where, $\bar{x}_{pile\ volume}$ is the mean cubic-foot volume of piles over all samples,
 $\sum p_{overall}$ is the sum of cubic-foot volume per acre of FHR piles over
all sample plots and,
 n is the number of sample plots installed

After mean volume on cubic-foot-per-acre basis for piled FHR is calculated, it is multiplied by a wood density value (WD) to estimate mean volume in tons per acre for piled FHR.

The equation for this calculation is:

$$\bar{x}_{pile\ biomass} = \bar{x}_{pile\ volume} \times WD$$

Where, $\bar{x}_{pile\ biomass}$ is the mean biomass in tons per acre over all samples,
WD is constant at 0.03 based on the assumption that scattered FHR
weighs 60 lbs per cubic foot.

For example, assume you sampled two piles on one point over a total of 28 sample points. The shape of these piles best matches shape code 2, so you measured height, length, and width of the piles. Pile one measured 7.5 feet in height, 10 feet in length, and 5 feet in width. Pile two measured 3 feet in height, 10 feet in length, and 4 feet in width. The packing density for piles one and two is estimated at 0.6 and 0.45, respectively. The observed mean proportion of piles falling within the sample plot was 0.75.

With this information, the estimated volume on a net-cubic-foot basis is:

$$pile\ 1 = (\pi HWL/4)(PD) = (\pi \times 7.5 \times 5 \times 10)/4(0.6) = (294.52)(0.6) = 176.71\ ft^3$$

$$pile\ 2 = (\pi HWL/4)(PD) = (\pi \times 3 \times 4 \times 10)/4(0.45) = (94.24)(0.45) = 42.41\ ft^3$$

The cubic-foot volume for piled FHR per acre for the individual sample plot is:

$$\sum p_{acre} = \sum p_{plot} \times 24 \times MP = pile\ 1 + pile\ 2 \times 24 \times 0.75$$

$$\bar{\Sigma}p_{acre} = (176.71 + 42.41) \times 24 \times 0.75$$

$$\bar{\Sigma}p_{acre} = 3944.16 \frac{ft^3}{acre}$$

The mean cubic-foot volume per acre over all sample points is:

$$\bar{x}_{pile\ volume} = \bar{\Sigma}p_{overall} / n = 3944.16 / 28 = 140.86 \frac{ft^3}{acre}$$

The mean biomass for piled FHR in tons per acre over all sample points is:

$$\bar{x}_{pile\ biomass} = \bar{x}_{pile\ volume} \times 0.03 = 140.86 \times 0.03 = 4.22 \frac{tons}{acre}$$

1.6 Conclusions

Conducting inventories using prism-sweep sampling and fixed-radius sampling for scattered and piled FHR requires planning and several steps. Relative to other sampling methods, however, these techniques provide an excellent way to quickly conduct accurate and rapid inventories of recently harvested forests. Estimates of FHR on harvest areas can help landowners, natural-resource professionals, and others assess the success of BHGs or other measures intended to mitigate environmental impacts.

CHAPTER 2

Downed Woody Material Associated With and Without In-Woods Chipping and Whole Tree Utilization in North Carolina and Southern Sweden

2.1 Abstract

There is a renewed interest in the use of wood for energy. It is forecasted that the demand for woody biomass will increase over the coming years. Increased demand is expected to intensify harvests by promoting practices like in-woods chipping and whole tree utilization. This is concerning because downed woody material is an important environmental component and increased removal of this material could be environmentally and

economically unsustainable. Twenty-six study sites were installed in North Carolina and ten study sites installed in Southern Sweden to measure the amount of downed woody material left after forest harvesting. The stocking of downed woody material in North Carolina with in-woods chipping ($18.5 \pm 4.8 \text{ m}^3/\text{ha}$) was not significantly different from sites without in-woods chipping ($17.1 \pm 4.8 \text{ m}^3/\text{ha}$). Similarly sites in Sweden with whole-tree utilization ($8.8 \pm 5.7 \text{ m}^3/\text{ha}$) were not significantly different from sites without whole-tree utilization ($13 \pm 2.5 \text{ m}^3/\text{ha}$). There was an interaction between volume of downed woody material and forest types in North Carolina. There was also evidence of differences between forest types in North Carolina and Norway Spruce (*Picea abies* (L.) Karst)) forests in Southern Sweden. Study results indicated that, when a forest is harvested, several covariates influence the stocking of downed woody material. Using a single covariate, to explain the decreased or increased stocking of downed woody material after harvest is unwise. The stocking of downed woody material after harvesting is the consequence of several covariates interacting spatially and temporally at different levels, given difference circumstances. These results also indicate that in most cases, a significant amount of downed woody material is left after harvesting. If biomass harvest guidelines are followed, an abundant biomass source can be harvested to produce energy while meeting sustainable forest management goals.

2.2 Introduction

Wood has been and continues to be an important resource for the production of energy. After European settlement and throughout the 1800's wood was used to make charcoal and as an essential home heating fuel (Abrams, 1992; Doggett, 1987). During the late 19th century, the use of wood and wood products for energy was greater than contemporary usage (Janowiak and Webster, 2010). Today, public demands for energy independence, reduced carbon emissions and fuel prices have renewed interest to use wood for the production of energy, especially for large-scale production such as biofuels and biopower.

Increased demand for woody biomass is considered to generally have potentially positive silvicultural, environmental and economic benefits (Manley and Richardson, 1995). One of the most notable benefits from increased demand for woody biomass is more effective forest-

fire risk management. In the White Mountains of Arizona, a market for wood fuels to homes, businesses, cogeneration plants and coal-fired power stations was instrumental in a US Forest Service effort to reduce catastrophic wildfire risk (Neary and Zieroth, 2007). Forest energy markets also provide opportunities to reduce salvage costs in areas affected by wildfires (Gautam et al., 2010), insects or disease. Reducing fire risk and salvage costs is instrumental in adapting forests to a global climate with an altered frequency, severity, duration and timing of fire (Dale et al., 2001). There are also potential environmental and economic costs associated with increased demand for woody biomass. One of the most notable perceived negative impacts is the increased removal of nutrients during harvests. Helmisaari et al. (2011) found increased removal of foliage during wood energy harvests reduced forest yield on twenty-two Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies* (L.) Karst) forests in Sweden and Finland. Similarly, Smolander et al. (2010) found whole-tree harvesting for wood energy decreased nitrogen availability relative to stemwood only harvests on two of four sites in Central and Southern Finland. In the United States, a meta-analysis by Eisenbies et al. (2009) suggested that a 45-60% increase in mid-rotation fertilization could be required to fully replace nutrients from biomass harvesting. Reduced forest yield and the necessity for mid-rotation fertilization could carry significant economic cost. Removals during harvesting could also impact carbon cycling. This is an important consideration as downed deadwood is an important pool of carbon that ranges from about 0.8 to 4 tons per hectare of biomass in the United States (Evans and Ducey, 2010). There are also concerns that increased demand for woody biomass will decrease profitability of existing forest industries. A survey by Conrad et al. (2011) indicated, that while the wood supply chain could profit from increased woody biomass harvesting, there are concerns about how existing forest products industries will coexist. Some speculate that increased demand for woody biomass will encourage non-industrial private forest landowners to harvest more pulpwood and will have a minimal impact on sawtimber harvests (Snider and Cabbage, 2006). Fundamentally, the central concern regarding wood energy harvesting is best stated by Hess and Zimmerman (2001) who reported that chip mills decrease downed woody material and “more woody debris is almost always better than less”.

The first objective of this study was to empirically assess how much downed woody material is left after harvesting in North Carolina and Southern Sweden. The second objective was to assess if there is an interaction between the volume of downed woody material and harvest practices, regions and forest types.

2.3 Methods

2.3.1 Analysis Variables and Site Selection

In North Carolina, twenty-six forests were sampled (Figure 5). Of the twenty-six forests, there were two harvest types ($N_{\text{with}} = 12$, $N_{\text{without}} = 14$), two region types ($N_{\text{piedmont}} = 13$, $N_{\text{coast}} = 13$) and three forest types ($N_{\text{hardwood}} = 3$, $N_{\text{mixed}} = 8$, $N_{\text{pine}} = 15$). Harvest type was defined as a final felling with or without the addition of an in-woods whole-tree chipper. With in-woods chipping in much of the Southeast, all trees are cut at the base, skidded to a logging deck and dependent on several factors, some trees are fed into the chipper while other trees are merchandized as traditional forest products. Similarly, without in-woods chipping, all trees are cut at the base, skidded to a logging deck, and are merchandized only as traditional forest products. Region type was defined by the physiographic region that a given study site was located in (eg., Piedmont or Coastal Plain).

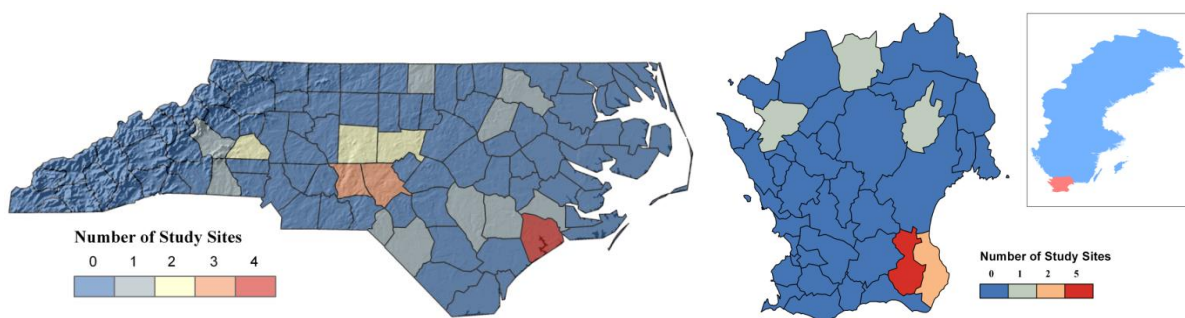


Figure 5. Number of study sites within counties in North Carolina and Southern Sweden

Forest type was defined by the estimated proportion of dominate pine or hardwood in the standing stock before harvest ($P_{\text{hardwood}} = >80\%$ hardwood, $P_{\text{mixed}} = >50\%$ pine or $>50\%$ hardwood, $P_{\text{pine}} = >80\%$ pine). The proportion of standing stock before the harvest was reported in an informal interview with the local or state forester who was responsible for a given study forest. In Southern Sweden, ten Norway spruce (*Picea abies* (L.) Karst) forests were sampled (Figure 5). Of the ten forests, there were two harvest types ($N_{\text{with}} = 6$, $N_{\text{without}} = 4$). In Sweden, harvest type was defined as a roundwood harvest or whole-tree harvest. During a roundwood harvest, all trees are cut at the base and only roundwood is forwarded to the staging area. During a whole-tree harvest, all trees are cut at the base and both roundwood and limbs and tops are forwarded to the staging area. In Sweden, limbs and tops are usually comminuted several months after the harvest when staged limbs and tops have dried at the staging area.

Sites were identified in North Carolina and Sweden through the aid of local and state foresters. Selection was based on availability and if the site was a final harvest, with no treatments applied since the harvest, and the time since the harvest ended was no more than three months in North Carolina and one year in Sweden.

2.3.2 Inventory of Downed Woody Material

Sampling points and transects were randomly established on all study sites to inventory downed woody material (Table 4). Randomly selected sampling locations were at least 20 meters from the edge of the harvested area and were separated by equal distances proportional to the area to be sampled (eg., greater distances for larger sampling areas, lesser distances for smaller sampling areas). Downed woody material is both coarse and fine woody debris disconnected from the rootstock, located at least 12.7 centimeters above the duff layer (Woodall and Monleon, 2007). Coarse woody debris is deadwood that is greater than or equal to 7.62 centimeters in diameter for at least 0.91 meters. Fine woody debris is deadwood that is less than 7.62 centimeters in diameter and has no length requirement or minimum diameter.

Table 4. Number of samples taken and estimated harvest area by study site in North Carolina and Southern Sweden

Study Location	Study Site	Number of Samples	Harvest Area (ha)	Study Site	Number of Samples	Harvest Area (ha)
North Carolina	1	40	12.1	11	30	24.3
	2	20	39.7	12	20	12.1
	3	30	10.9	13	30	32.0
	4	30	54.6	14	30	33.5
	5	40	16.2	15	30	46.2
	6	30	36.4	16	25	27.1
	7	30	19.2	17	30	38.4
	8	30	33.2	18	30	14.2
	9	30	42.1	19	40	93.9
	10	30	35.2	20	30	40.5
	21	30	20.2	24	30	17.8
	22	25	40.1	25	30	22.3
	23	30	20.2	26	25	71.6
Southern Sweden	1	10	-	6	6	0.9
	2	6	-	7	8	2.8
	3	11	-	8	8	3.2
	4	10	4.7	9	4	1.0
	5	5	0.8	10	5	2.9

In North Carolina, prism sweep sampling was used to inventory downed woody material on study sites. Prism sweep sampling is a probability-proportional-to-size method that uses the same principles as point relascope sampling (Bebber and Thomas, 2003). In total, 775 prism sweep sampling points were installed in North Carolina. In Sweden, line intersect sampling was used to inventory both coarse and fine downed woody material on study sites. Line intersect sampling is a probability-proportional-to-size method, used to estimate multiple attributes of downed woody material which intersect a sampling plane (Van Wagner, 1968; Woodall and Monleon, 2007; Woodall and Williams, 2007). A total of 73 transects were installed in Sweden. In North Carolina and Sweden, the major limitation of sampling intensity was time and the harvest area size.

2.3.3 Analysis Procedure

In North Carolina, volume of downed woody material per hectare was estimated using the equations in Bebber and Thomas (2003). In Sweden, volume of coarse and fine woody material per hectare was estimated using the equations in Woodall and Monleon (2007). ANOVA was used to compare the mean stocking of downed woody material among covariates in North Carolina and Sweden (Table 5). Tukey's honestly significant difference test was used to identify means that were significantly different within covariates in North Carolina and Sweden. Both statistical tests were performed using the {stats} package in R GUI 2.14.2.

Table 5. Covariates included in ANOVA and Tukey's honestly significant difference test

Covariate Name	Description
Volume	Volume of downed woody material (m ³ /ha)
Harvest	Whether the final harvest was traditional or utilized in-woods chipping or whole tree utilization
Region	Piedmont or Coastal Plain
Species	Dominate forest composition prior to the harvest

2.4 Results

Results indicate that 17.7 m³/ha and 10.5 m³/ha of downed woody material was left after harvesting in North Carolina and Sweden, respectively (Table 6). In North Carolina and Sweden volume estimates of downed woody material did not differ significantly by region or harvest type (all $P > 0.05$; Table 7). There was an interaction in North Carolina between estimated volume and species type ($P < 0.001$). Tukey's honestly significant difference test indicated that the pine-mixed species type differed significantly, while mixed-hardwood and pine-hardwood types did not differ significantly ($P_{\text{pine-mixed}} = <0.001$, $P_{\text{mixed-hardwood}} = 0.12$, $P_{\text{pine-hardwood}} = 0.56$; Table 8).

Table 6. Estimated volume of downed woody material by study location and covariate

Study Location	Covariate	n	Volume	
			Mean	stdev
			--- m ³ /ha ---	
North Carolina	Region Type			
	<i>Coastal Plain</i>	13	17.2	10
	<i>Piedmont</i>	13	18.4	7.4
	Species Type			
	<i>Hardwood</i>	3	17.5	5.3
	<i>Mixed</i>	8	26.4	9.4
	<i>Pine</i>	15	13.2	4.6
	Harvest Type			
	<i>Chipped</i>	12	18.5	8.4
<i>Not Chipped</i>	14	17.1	9.1	
	Overall	26	17.8	8.7
Southern Sweden	Harvest Type			
	<i>Wholetree</i>	6	8.8	7.1
	<i>Roundwood</i>	4	13	2.6
	Overall	10	10.5	5.9

There is evidence that the relationship between volume and species type could explain why there is less downed woody material on average in Norway Spruce (*Picea abies* (L.) Karst) forests in Southern Sweden ($V_{\text{spruce}} = 10.4 \text{ m}^3/\text{ha}$) than hardwood, mixed and pine forest types in North Carolina ($V_{\text{mixed}} = 26.4 \text{ m}^3/\text{ha}$, $V_{\text{hardwood}} = 17.5 \text{ m}^3/\text{ha}$, $V_{\text{pine}} = 13.2 \text{ m}^3/\text{ha}$; Figure 6).

Table 7. ANOVA table for comparisons of volume of downed woody material

Study Location	Response Variable	Source of Variation	df	F value	P value
North Carolina	Volume	Region	1	0.22	0.63
		Species	2	10.45	<0.001
		Harvest	1	0.60	0.44
		Statistical Residuals	21		
Southern Sweden	Volume	Harvest	1	1.21	0.30
		Statistical Residuals	8		

Table 8. Tukey's HSD table for comparison of means among North Carolina species types

Response Variable	Comparison Group	Difference	P value
Volume	Mixed-Hardwood	8.96	0.12
	Pine-Hardwood	-4.22	0.56
	Pine-Mixed	-13.19	<0.001

2.5 Discussion

The findings in this study should be evaluated within the context of challenges inherent to sampling downed woody material after harvesting. In both North Carolina and Sweden, there was considerable variability in estimated volume of downed woody material among sites and between countries ($\text{Range}_{\text{Carolina}} = 32.2 \text{ m}^3/\text{ha}$, $\text{Range}_{\text{Sweden}} = 19.7 \text{ m}^3/\text{ha}$). There is evidence that some of the variability among sites and countries could be related to an interaction between volume and species type (Figure 6). Part of this interaction could be explained by differences in tree physiology. Jenkins et al. indicated that branch biomass is allocated differently between softwood and hardwood trees in North America (ie. of the above ground biomass, 7-20% is allocated to limbs of softwoods and 15-96% is allocated to limbs of hardwoods) (2003). Additionally, Marklund found that between 25-65% of a Norway Spruce (*Picea abies* (L.) Karst)) stem could be held within limb biomass in Sweden (1987). The allocation of limb biomass can be a proxy for greater physiological differences and varies both over time and between species types. Limbs are often an essential component of downed woody material left after harvesting. It is possible that differences in the allocation of limb biomass could partly account for differences in the stocking of downed woody material. Results of downed woody material surveys among different forest types have potentially indicated this difference. For instance, one study in Wisconsin found roundwood harvests of Aspen stands ($125.7 \pm 20.8 \text{ m}^3/\text{ha}$) left more downed woody material than with whole-tree harvesting ($75.5 \pm 23.7 \text{ m}^3/\text{ha}$) (Rittenhouse et al., 2012). In Wisconsin, both sites with and without whole-tree harvesting had more downed woody material than sites in North Carolina and Sweden. Additional variability in the amount of downed woody material left after harvesting could be related to the amount of conglomerated coarse woody debris found on each site. In North Carolina, conglomerated coarse woody debris piles

ranged from small to large and piles were located both on sites with and without in-woods chipping. These piles were not measured, so their relative contribution towards the stocking of scattered downed woody material is unknown. There were no instances of conglomerated coarse woody debris on harvest sites in Southern Sweden.

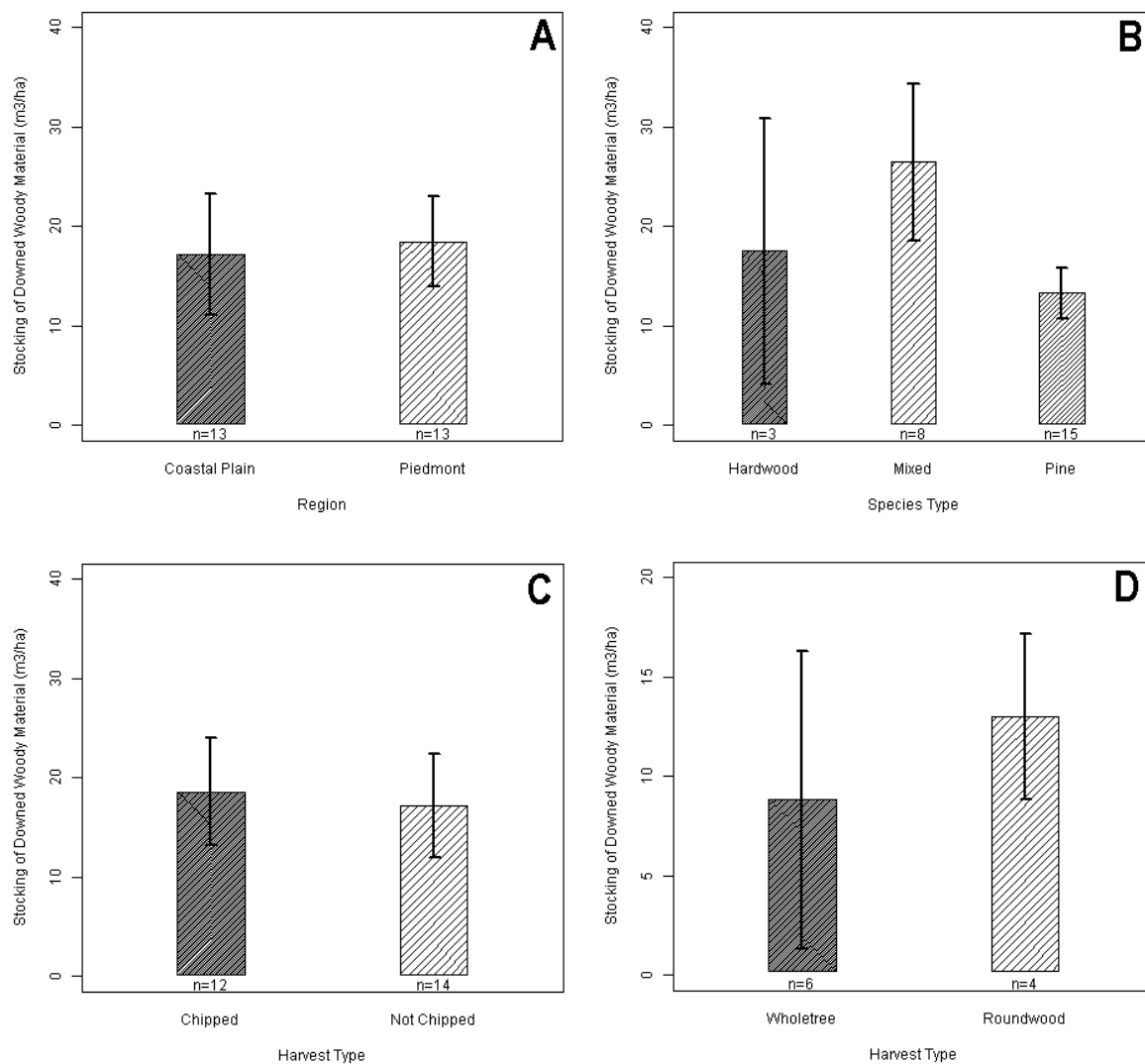


Figure 6. Average volume of downed woody material and associated error (95% confidence interval) for North Carolina (A) regions, (B) species types, (C) harvest types and (D) harvest types in Southern Sweden

The interaction between logging capacity and daily quota from biomass consumers also contributes to variability within and among sites. Greene et al. found that quota is the most cited reason for lost production during harvests (2004). The decision of what is merchandized during chipping or whole-tree utilization is subject to daily circumstances of production (i.e., like quota levels), not a fixed classification of what is considered woody biomass. The complex decisions of how products will be merchandized and the influence of quota systems contribute to variability between sites; further blurring the distinction between sites with and without in-woods chipping or whole-tree utilization. Variability of downed woody material within and among sites, the potential underestimation of conglomerated coarse woody debris and influence of quota systems are just a few of the factors contributing to the error terms of volume estimates in this study. When a forest is harvested, several covariates influence the stocking of downed woody material. Using a single covariate to explain the decreased or increased stocking of downed woody material after harvest is unwise. The stocking of downed woody material after harvesting is the consequence of several covariates interacting spatially and temporally at different levels, given difference circumstances.

2.6 Conclusions

The central concern regarding increased demand for woody biomass regards the intensification of forest harvesting. In principle, harvests with in-woods chipping or whole-tree utilization are expected to be significantly more intensive than those without. Results from this study indicates that the amount of downed woody material left after harvesting on sites in North Carolina with in-woods chipping ($18.5 \pm 4.8 \text{ m}^3/\text{ha}$) is not significantly different than sites without in-woods chipping ($17.1 \pm 4.8 \text{ m}^3/\text{ha}$). Similarly, sites in Sweden with whole-tree utilization ($8.8 \pm 5.7 \text{ m}^3/\text{ha}$) are not significantly different in the amount of downed woody material than harvest sites without whole-tree utilization ($13 \pm 2.5 \text{ m}^3/\text{ha}$). Yet, as discussed, there is potential for significant error terms in volume estimates of downed woody material. Additionally, results of this study represent only a sample of the population of all harvests. This means it is possible to observe harvest sites with exceptionally abundant or deficient stocking of downed woody material. To ensure the sustainability of wood energy harvesting using in-woods chipping, biomass harvesting guidelines could be

employed during harvests incorporating in-woods chipping or whole-tree utilization. Biomass harvesting guidelines have been established for the Northern United States, Southern United States, Finland and United Kingdom (Evans et al., 2010; Perschel et al. 2012; Äijälä et al., 2010; Nisbet et al., 2009). When carefully applied, biomass harvesting guidelines can ensure sustainable forest management while accessing an abundant woody biomass resource.

LITERATURE CITED

Abrams, Marc. "Fire and the Development of Oak Forests." *Bioscience* 42, no. 5 (May 1992): 346–353.

Äijälä, Olli, Martti Kuusinen, and Arto Koistinen. "Hyvän Metsanhoidon Suositukset Energiapuun Korjuuseen Jakasvatukseen." *Tapio* (2010).

Bebber, Daniel, and Thomas, Sean. "Prism Sweeps for Coarse Woody Debris." *Canadian Journal of Forest Research* 33, no. 9 (2003): 1737–1743.

Björheden, Rolf. "Efficient Forest Fuel Supply Systems: Composite Report from a Four Year R & D Programme 2007-2010." *Skogsforsk Research and Development* (2010).

Conrad, Joseph, Bolding, Chad, Smith, Robert, and Aust, Michael. "Wood-energy Market Impact on Competition, Procurement Practices, and Profitability of Landowners and Forest Products Industry in the U.S. South." *Biomass and Bioenergy* 35 (2011): 280–287.

Dale, Virginia, Joyce, Linda, McNulty, Steve, Neilson, Ronald, and Ayres, Matthew. "Climate Change and Forest Disturbance." *Bioscience* 51, no. 9 (September 2001): 723–734.

Doggett, Coleman. "The Moravian Foresters." *Journal of Forest History* 31, no. 1 (1987): 19–24.

Eisenbies, M. H., E. D. Vance, W. M. Aust, and J. R. Seiler. "Intensive Utilization of Harvest Residues in Southern Pine Plantations: Quantities Available and Implications for Nutrient Budgets and Sustainable Site Productivity." *BioEnergy Research* 2 (July 29, 2009): 90–98.

Evans, Alexander, and Ducey, Mark. "Carbon Accounting and Management of Lying Dead Wood." *The Forest Guild* (November 2010).

Evans, Alexander, Perschel, Robert, and Kittler, Brian. "Revised Assessment of Biomass Harvesting and Retention Guidelines." *The Forest Guild* (April 2010).

Gautam, Shuva, Pulkki, Reino, Chander, Shahi,, and Leitch, Mathew. "Economic and Energy Efficiency of Salvaging Biomass from Wildfire Burnt Areas for Bioenergy Production in Northwestern Ontario: A Case Study." *Biomass and Bioenergy*, no. 34 (2010): 1562–1572.

Greene, Dale, Jefferson Mayo, Cornelis deHoop, and Andy Egan. "Causes and Costs of Unused Logging Production Capacity in the Southern United States and Maine." *Forest Products Journal* 54, no. 5 (2004): 29–37.

- Helmisaari, Heljä-Sisko, Hanssen, Kjersti Holt, Jacobson, Staffan, Kukkola, Mikko, Luro, Jukka, Saarsalmi, Anna, Tamminen, Pekka, and Tveite, Bjørn. “Logging Residue Removal After Thinning in Nordic Boreal Forests: Long-term Impact on Tree Growth.” *Forest Ecology and Management* 261, no. 11 (June 2011): 1919–1927.
- Hess, George, and Zimmerman, Dale. “Woody Debris Volume on Clearcuts With and Without Satellite Chip Mills” *Southern Journal of Applied Forestry* 25, no. 4 (2001): 173–177.
- Janowiak, Maria, and Christopher Webster. “Promoting Ecological Sustainability in Woody Biomass Harvesting.” *Journal of Forestry*, no. January (2010): 16–23.
- Jenkins, Jennifer, David Chojnacky, Linda Heath, and Richard Birdsey. “National-Scale Biomass Estimators for United States Tree Species.” *Forest Science* 49, no. 1 (2003): 12–35.
- Manley, A., and J. Richardson. “Silviculture and Economic Benefits of Producing Wood Energy from Conventional Forestry Systems and Measures to Mitigate Negative Impacts.” *Biomass and Bioenergy* 9, no. 1–5 (1995): 89–105.
- Marklund, Lars Gunnar. “Biomass Functions for Norway Spruce (*Picea Abies* (L.) Karst.) in Sweden.” *Sveriges Lantbruksuniversitet*, no. Department of Forest Survey Report 43 (1987).
- Neary, Daniel, and Zieroth, Elaine. “Forest Bioenergy System to Reduce the Hazard of Wildfires: White Mountains, Arizona.” *Biomass and Bioenergy* 31 (2007): 638–645.
- Nisbet, T., B. Nicoll, and M. Perks. “Stump Harvesting: Interim Guidance on Site Selection and Good Practice.” *Forest Research, UK* (April 2009).
- Perschel,, Robert, Alexander Evans, and Mike DeBonis. “Forest Biomass Retention and Harvesting Guidelines for the Southeast.” *Forest Guild* (February 2012).
- Rittenhouse, Tracy, David MacFarland, Karl Martin, and Timothy Van Deelen. “Downed Wood Associated with Roundwood Harvest, Whole-tree Harvest, and Unharvested Stands of Aspen in Wisconsin.” *Forest Ecology and Management* 266 (2012): 239–245.
- Smolander, A, Kitunen, V, Tamminen, P, and Kukkola, M. “Removal of Logging Residue in Norway Spruce Thinning Stands: Long-term Changes in Organic Layer Properties.” *Soil Biology & Biochemistry* 42 (2010): 1222–1228.
- Snider, A.G., and F.W. Cabbage. “Economic Analyses of Wood Chip Mill Expansion in North Carolina: Implications for Nonindustrial Private Forest (NIPF) Management.” *Southern Journal of Applied Forestry* 30, no. 2 (2006): 102–108.

Van Wagner, C.E. "The Line Intersect Method In Forest Fuel Sampling." *Forest Science* 14, no. 1 (1968): 20–26.

Woodall, Christopher, and Monleon, Vicente. "Sampling Protocol, Estimation, and Analysis Procedures for the Down Woody Materials Indicator of the FIA Program." *United States Department of Agriculture Forest Service General Technical Report NRS-22* (August 2007).

Woodall, Christopher, and Williams, Michael. "Sampling Protocol, Estimation, and Analysis Procedures for the Down Woody Materials Indicator of the FIA Program." *United States Department of Agriculture Forest Service General Technical Report NC-256* (February 2007).