FUNDAMENTAL RESEARCH

For. Sci. XX(XX):1–10
doi: 10.1093/forsci/fxy065
Published by Oxford University Press on behalf of the Society of American Foresters 2019.

harvesting & operations

Evaluating Forest Biomass Recovery in South Central Alabama Pine Plantations

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Improved use of forest biomass has been presented as a viable option to satisfy a portion of the demand for sustainable alternative sources of energy. Yet, there are considerable gaps in our understanding related to the efficiencies of current state-of-the-art forest biomass recovery systems. Southern pine plantation biomass stands typically exhibit higher stand densities and smaller-diameter trees than conventional stands, which, in turn, may result in reduced recovery efficiencies. In this study, the impact of new harvest systems for biomass recovery was investigated in typical southern pine plantation biomass harvests. Specifically, spatial and temporal effects on residue distribution were examined following biomass harvest of 14- and 24-year-old loblolly pine plantations. Preharvest total standing biomass for the younger site at 90 t ac^{-1} (220 t $hectare^{-1}$) was half that of the older site at 160 t ac^{-1} (390 t $hectare^{-1}$). Although the analysis detected no significant temporal effects on residue distributions, the preharvest condition exhibited 100 percent ground cover, whereas postharvest conditions had nearly 20 percent of the area designated as bare. Two of the five residue classifications, light debris and litter-herbaceous, were found to have a significantly higher incidence of occurrence than the other residue classifications on the sites based on a multinomial regression. In general, we found recovery efficiencies for both sites of 80 percent or greater for both methods of determination, by destructive sampling and based on load tickets.

Keywords: Pinus taeda, forest biomass, residue distribution, residue quantification, recovery efficiency

Energy security has become a national focus area for the United States because of the limited availability and increasing costs, economic and environmental, of fossil-fuel energy. Significant efforts, initiatives, and mandates in recent years at the federal level emphasize the urgency and need to secure America's energy independence. These efforts aim to shift the US reliance from fossil-fuel energy to alternative energy sources. The Energy Independence and Security Act of 2007 (EISA) reinforces the national direction toward alternative energy sources by mandating the shift to alternative sources to replace 36 billion gallons per year (136 million cubic meters per year) of transportation fuels by 2022. The projection is that approximately 40 percent of the alternative fuel supply will originate from lignocellulosic feedstock (USDA FS 2010, Bailey et al. 2011). The search for sustainable alternative sources has placed a spotlight on forest biomass and sparked interest in developing improved systems for forest biomass recovery. This interest has been reinforced with strategies and action plans from federal land-management agencies to aid in development of economically feasible and environmentally sustainable lignocellulosic feedstock (i.e., Forest Service Research and Development Bioenergy and Biobased Products Strategic Direction 2009–14, National Biofuels Action Plan 2008, and US Forest Service Strategic Energy Framework).

Forests in the United States are some of the most productive in the world (Prestemon and Abt 2002). US forests cover a total of 1.2 million mi^2 (3.1 million km^2) with approximately 390,000 mi^2 (1.0 million km^2) in low-productivity forest and protected areas. These forests are expected to meet increasing demands for timber products during the next 40 years (SFRA 2002, Converse 2007). The net annual growth rate of US forests is 0.9 percent (gross annual growth – mortality – removals) for living biomass representing a net increase of nearly 220 million dry tons per year (200 million dry tonnes per year) (Converse 2007). Forestlands in the contiguous US alone are projected to have an annual biomass production

Manuscript received July 10, 2018; accepted November 27, 2018; published online March 4, 2019.

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Acknowledgments: *This work was partially funded by the Department of Energy as project DOE-EE0001036 under agreement 10-CO-11330132-088. The authors wish to acknowledge the efforts and support provided by Corley Land Services and TigerCat® in accomplishing the operations component of this investigation. The authors appreciate the administrative and logistic support of Auburn University's Biosystems Engineering Department. The authors acknowledge cooperation through laboratory support and efforts in the constructive review of this work at multiple stages by Dana Mitchell that undoubtedly improved this offering. The authors acknowledge the special contributions of Preston Steele Jr., Wes Sprinkle, Erin Huffaker, and Miles Robinson Jr. toward the completion of the project.*

of nearly 370 million dry tons (340 million dry tonnes) (Perlack et al. 2005, Langholtz et al. 2016).

Southern forests represent the largest timberland region in the United States. These forests account for a large percentage (40 percent) of the Nation's timberland (Staudhammer et al. 2011) and produce approximately 60 percent of the Nation's timber products (Prestemon and Abt 2002). In this region of the US, it is estimated that more than 40 MWh ac^{-1} (360 GJ $hectare^{-1}$) of residues (tops and slash) can remain on site following conventional harvesting operations (Scott and Dean 2006, Anderson and Mitchell 2016). These southern forests are expected to yield more than 30 million dry tons (27 million dry tonnes) of harvest residues for energy production annually (Eisenbies et al. 2009). Since the production of cellulosic ethanol is more energy-efficient than the leading agricultural biomass crops (e.g., corn) (Converse 2007), it is clear that southern forests will be a major source of biomass for bioenergy production in the United States.

Logging residues are projected to represent a significant component of future forest biomass supply based on a regional aggregate bioenergy potential analysis (Galik et al. 2009). In this analysis, logging residues accounted for a fifth of softwood and a quarter of hardwood green weight timber removals in the South, representing 530 million green tons (480 million green tonnes) total, during a period from 1995 to 2008 (Conner and Johnson 2011). During the same period, logging residues and residual inventory, which included all standing live trees ≥1 in. (2.5 cm), accounted for nearly 800 million green tons (730 million green tonnes) of biomass from harvesting activities in the South. The recovery of standing biomass ≤5 in. (12.5 cm) is not practical on a large scale, the bulk of the projected potential biomass (90 million green tons [80 million green tonnes]) for recovery from harvesting activities being derived from trees >5 in. (12.5 cm) based on the analysis. Assuming a 60 percent recovery rate, Conner and Johnson (2011) estimate that more than 55 million green tons (50 million green tonnes) of biomass is recoverable from harvesting activities in the 13 southern states. The recovery rate of 60 percent is consistent with rates previously reported by Stokes (1992) for conventional harvesting systems with total available biomass amounts ranging from 9 to 50 t ac^{-1} (20 to 110 t $hectare^{-1}$).

Previous literature does indicate that greater recovery rates can be realized with integrated harvesting systems (Stokes and Watson 1996) and whole-tree harvest (Stokes 1992). However, the percentage of available residues, taking into account the current state-of-the-art equipment and operating constraints, is relatively unknown, highly variable, and influenced by several factors (Kizha and Han 2015). Economically viable logging residue recovery hinges on quantifying the percentage of residue removal realized in typical biomass harvesting operations, evaluating removal efficiency of newly developed forest biomass harvesting systems, and improving the removal efficiencies in forest biomass harvesting operations to reduce costs of delivered feedstock. This research explores one of the primary components in reducing costs associated with biomass-harvesting operations; improving efficiency of biomass recovery.

Objectives

The investigation explores recovery efficiency in biomass-harvesting operations and effects on temporal and spatial residue distributions in southern plantation pine. The specific objectives of our work are to: (1) evaluate biomass removal (recovery) efficiency in biomass harvesting operations in plantation pine, (2) determine if biomass harvesting has an effect on the spatial distribution of residue, and (3) evaluate effects of biomass harvesting on site factors that could influence short- and long-term productivity. Study treatments in the investigation include 14- and 24-year-old loblolly pine (*Pinus taeda*) plantation harvests. This paper will focus on the biomass availability and recovery efficiency components by presenting an evaluation of recovery efficiency, residue distribution, and site assessment in two biomass harvesting operations. The information gained through this study can be used to inform biomass harvesting guidelines that are currently available or being developed as well as inform certification programs.

Methods

Study Sites

The general study area was located in south central Alabama in the Gulf Coastal Plain region. Historically, the region was characterized by fire-dependent pine communities primarily consisting of longleaf pine (*Pinus palustris*) forests and woodland. Currently, the region is dominated by loblolly pine (*Pinus taeda*) plantation stands. Two study stands, Coastal H Tract (CHT) and Gantt Tract (GT), were randomly selected from a total population of sites scheduled for treatment in a four-county region (Butler, Conecuh, Covington, and Monroe Counties) in south central Alabama (Figure 1). Site CHT was a 44-ac (18-hectare) loblolly pine plantation aged 24 years with a stand density of 770 trees per acre (1,900 trees per hectare) and basal area of 181 ft^2 ac^{-1} (41.6 m^2 $hectare^{-1}$) located at approximately 31°49′N latitude and 86°37′W longitude near Greenville, Alabama (Figure 1, Table 1). The site was bisected into two 22-ac (9-hectare) units to receive a complete (clear cut) harvest treatment. Site GT was a 37-ac (15-hectare) loblolly pine plantation aged 14 years with a stand density of 600 trees per acre

Management and Policy Implications

This study examined downed woody material quantification, forest biomass recovery efficiency, and residue distribution, which are critical in assessing watershed health, accurate carbon and nutrient accounting, and optimizing forest operation efficiencies for economic viability. The provision of a well-rounded suite of ecosystem services from forest lands requires the assessment of tradeoffs related to operational, economic, and sustainability aspects. Balancing economic viability with operational and sustainability aspects will likely require optimization of residue management (the percentage, type, and form of residue retained) in various stand types to satisfy environmental objectives. Optimization of economic outcomes and biomass recovery in harvesting often requires removal of the maximum quantities of biomass sustainably available for a particular site. Conversely, environmental objectives are satisfied by minimizing long-term effects on site productivity (nutrients, soil, and water), soil erosion (nutrients, soil, and water), carbon sequestration (nutrients and soil), biological diversity, quality wildlife habitat, and other ecosystem services. Maintaining a balance between the residue recovery for energy production in addition to the traditional suite of timber products with the need to retain residues for an increasing array of ecosystem services is critical for sustainability, and this work provides details to advance our understanding of forest biomass recovery systems.

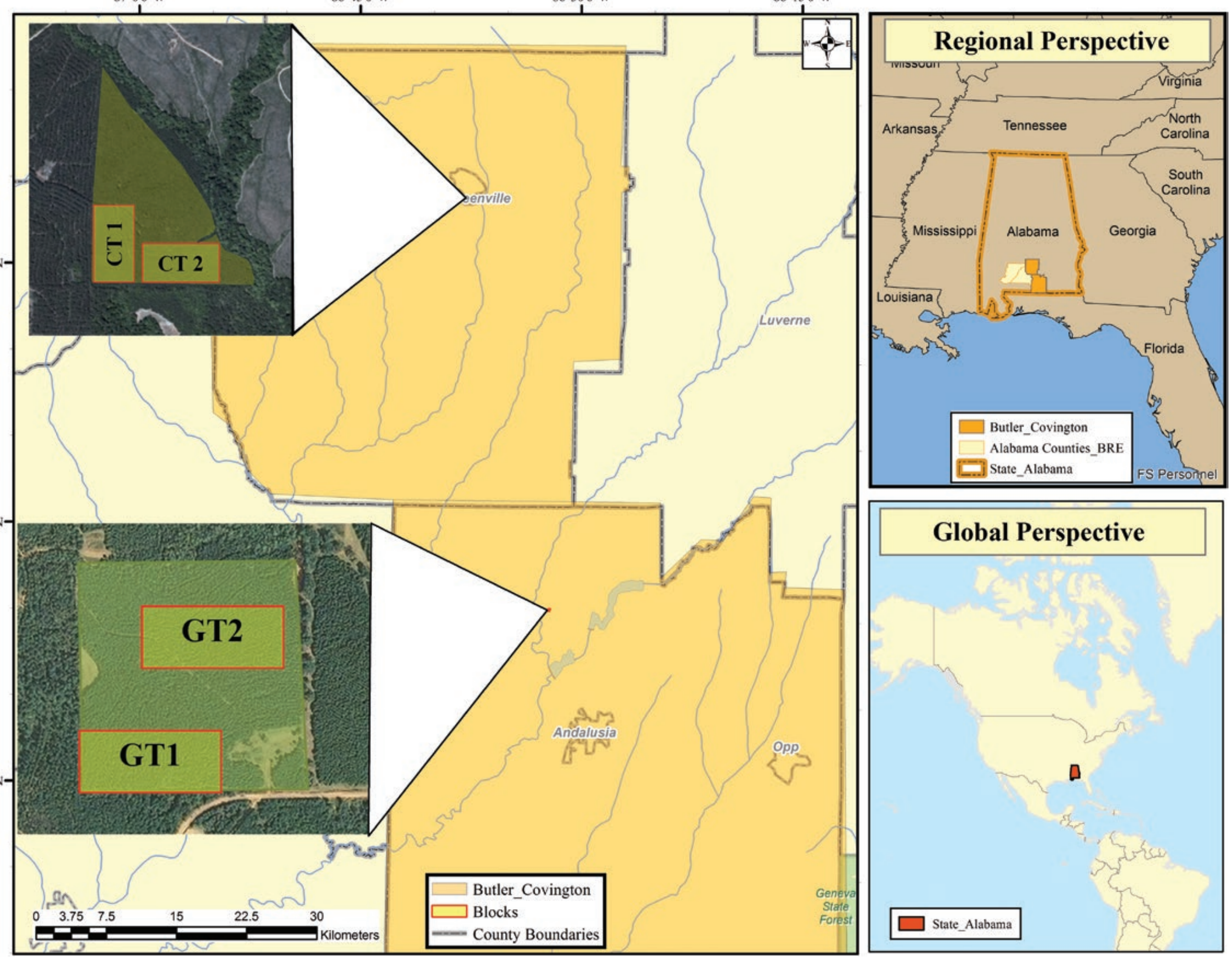

Figure 1. Global, regional, and local perspectives of the study area location in south central Alabama, USA. The four counties considered in the randomized selection of study harvest sites highlighted here are Butler, Conecuh, Covington, and Monroe Counties in Alabama (top right). Locations of study sties CHT and GT with 4-ha study blocks within each of the two study sites are highlighted (left).

Table 1. Stand density and site characteristics for study sites in the biomass recovery and distribution study.

Site	Age (years)	Area, ac (hectares)	Stand density trees per acre (trees per hectare)
Coastal H Tract	24	22 (9)	770 (1,900)
Gantt Tract	14	37 (15)	600 (1,500)

(1,500 trees per hectare) and basal area of 142 ft^2 ac^{-1} (32.7 m^2 hectare^{-1}) located at approximately 31°41′N latitude and 86°48′W longitude in Covington County near Gantt, Alabama.

Experimental Design and Analysis

Two replicates (blocks) of operational scale harvests, roughly 10 ac (4 hectares) in size, were established in each study area (Figure 1). Five randomly located 24-ft (7.3-m) fixed-radius-representing 0.04-ac (167.2-m^2) plots (α-plots) were established within each treatment block in combination with 3.3-ft (1-m) fixed-radius destructive sampling plots (β-plots) to evaluate residue distribution and biomass recovery efficiency (Figure 2). The α-plots were dimensioned consistent with the Forest Inventory and Analysis Program (FIA) Phase 2 (P2) subplots defined by Woodhall and Monleon (2007) and Woodall and Williams (2005). The β-plots were randomly located within each α-plot independently using a spreadsheet program developed to randomly generate both a β-plot center azimuth between 0° and 359° and a distance from the α-plot center ranging from 0 to 20 ft (0 to 6.1 m).

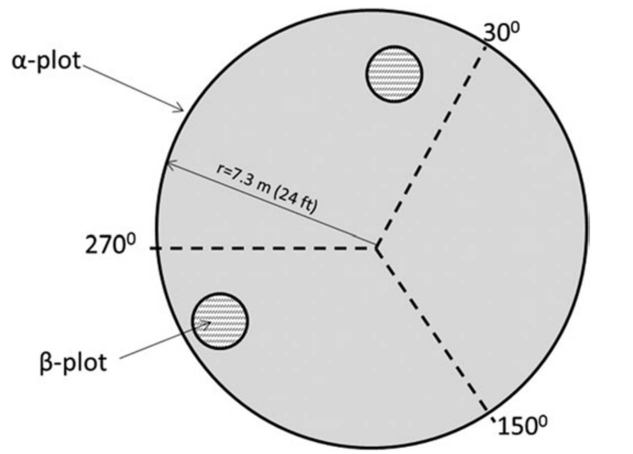

Figure 2. FIA P2 subplot sized plots used to assess available biomass, downed woody material, and biomass recovery efficiency following biomass harvests.

The experimental design for the biomass recovery and residue distribution evaluations is a completely randomized design used here to counteract limitations with operational scale harvests. That is, the number of sites was limited, and each site received a harvest distributed into two harvest blocks. The model for the single-factor study in a completely randomized design with fixed treatment effects is given by:

$$Y_{ij} = u + \tau_i + \varepsilon_{ij} \quad (1)$$

where *Y*ij is the predicted response, i.e., available, merchantable, and residual biomass; *u* is the mean; τi is treatment effect (fixed effect); and εij is experimental error associated with the particular site. Replicate samples were taken from five randomly located α-plots located within each of the sites to determine available and residual biomass, and evaluate temporal effects on residual biomass. The null hypothesis for analysis of variance (ANOVA) of each dependent variable—available, merchantable, and residual biomass—is that harvesting will have no effect on responses. The hypotheses were explored using an analysis on response variables in combination with *t*-tests to detect differences between treatments at the 0.05 level of significance (SAS 2004). The residue distribution component of the investigation collected ordinal categorical data with polytomous responses, i.e., five equally possible outcomes or classes: (1) residue piles (≥12 in. depth [30 cm]), (2) heavy residue (residue ≥3 in. [7.6 cm] diameter and length ≥3 ft [0.9 m]), (3) light residue (residue < 3 in. [7.6 cm] diameter), (4) litter-herbaceous, and (5) bare. These data were analyzed through multinomial regression analysis procedures using SAS (SAS 2004, Baker 2014). All possible pairwise comparisons were performed where logistic regression analysis indicated significant differences.

Harvesting and System Characteristics

The harvesting operation on both study sites was composed of a tracked, boom-mounted feller-buncher, a rubber-tired grapple skidder, two chippers, a flail delimber/debarker, and a tracked loader. The feller-buncher and skidder were modified with the goal of efficiency in small-diameter stands typical of southern pine energy plantations. The feller-buncher was equipped with a high-speed shear coupled with a high-capacity felling head. Trees were felled with the feller-buncher, which placed multiple accumulations of trees in a bundle to ensure a sufficient payload was available for skidding with the high-capacity skidder (Rummer et al. 2010, Taylor et al. 2014). The skidder was equipped with a 24-ft^2 (2.3-m^2) grapple and operator comfort system, which enabled the operation of the machine while facing rearward (Rummer et al. 2010). Trees on site CHT were skidded green, whereas trees on site GT were allowed to remain in bundles to dry transpirationally for approximately 7 weeks. Trees were processed at the landing for both sites through a flail delimber/debarker and chipped using a 66-in. (168-cm) disc chipper with four knives to produce clean conventional chips. Whole-tree dry microchips were also produced on site GT using a 75-in. (191-cm) disc chipper equipped with eight knives.

The harvesting treatment was completed on site CHT in January 2012, and postharvest data collection was initiated immediately following the harvest during January and February. Initial felling at site GT was completed for approximately 27 ac (11 hectares) of the 37 ac (15 hectares) stand during April 2012. Felling of the remaining 10 ac (4 hectares) was completed in late May 2012. The lapse in time between two phases of harvesting site GT to accommodate peripheral investigations was carefully timed to minimize any influences on the subsequent biomass and residue distribution analyses. The harvesting operation was completed on site GT during June 2012 and was immediately followed with postharvest data collection.

Determination of Available and Residual Biomass

Preharvest inventory measures used to estimate stand volume, stand characteristics, and aboveground biomass available for removal were a pretreatment 2 percent cruise of the study stands in combination with randomly located 0.04-ac (0.017-hectare) radial plots (α- plots) and radial 3.3-ft (1-m) destructive sampling plots (β-plots). Postharvest conditions related to residual biomass were quantified by postharvest rerandomization and sampling of α- and β-plots. Downed woody material (DWM), fine woody debris (FWD), and coarse woody debris (CWD) were determined using line intercept sampling (LIS) techniques conducted on the α-plots as defined by Woodhall and Monleon (2007). CWD is defined in this investigation, for consistency with FIA definitions, as down logs and material with a diameter ≥3 in. (7.6 cm) and length ≥3 ft (0.9 m). CWD was assessed on the 30°, 150°, and 270° transects following previously defined procedures (Figure 2). Similarly, FWD was assessed on the 150° transect consistent with FIA protocol as material having a diameter of <3 in. (7.6 cm) at the point of intersection with the transect. The FWD designation was further categorized as large fine woody debris (LFWD), medium fine woody debris (MFWD), and small fine woody debris (SFWD) representing 100, 10, and 1 fuel-hour classes, respectively (Woodall and Williams 2005, Woodhall and Monleon 2007). In addition to LIS techniques, available biomass was assessed by complete removal of aboveground biomass material from β-plots within each stand. Material within the β-plots was sheared at ground level, raked, sorted by downed residual biomass, foliage, or herbaceous designations, collected in large polyethylene bags, and transported to the G.W. Andrews Forestry Sciences Laboratory in Auburn, Alabama for analysis.

Woody Biomass

Preharvest biomass in standing inventory (living and dead) was determined through direct measurements of diameter at ground level, dbh (4.6 ft [1.4-m]), and total height of trees within α-plots. Immediately following harvesting operations, biomass of overstory, midstory, and understory woody species >2 in. (5 cm) in diameter remaining standing was determined by direct measurements of the desirable species trees for use in region-specific loblolly pine (*Pinus taeda*) prediction equations (Phillips and McNab 1982, Borders et al. 1990, Clark and Saucier 1990). Similarly, associated tree measurements for undesirable species, which included oak (*Quercus spp.*), sweetgum (*Liquidambar styraciflua*), hickory (*Carya* spp.), black cherry (*Prunus serotina*), and red maple (*Acer rubrum*), were applied in regional allometric equations (Clark et al. 1985, Vose and Swank 1993, Sah et al. 2004) for associated woody species to estimate available biomass for α-plots.

Foliage, Understory and Herbaceous

Preharvest understory biomass including both vegetative and woody species ≤2 in. (5 cm) in diameter was quantified using one to two random β-plots located within each α-plot. Biomass was severed at ground level and sorted as: (1) major woody species type; pine, cherry, maple, oak, gum, hickory, etc. or (2) herbaceous vegetation prior to weighing in the field. Subsequently, associated fractions of understory and herbaceous biomass were collected in large polypropylene bags, individually labeled, and transported to the G.W. Andrews Laboratory. Biomass was determined as a "green" weight by weighing in the field and "dry" following drying in a convection oven at 150 ± 40 °F (65 ± 5 °C) to a constant weight (ASTM E1757-01 2007).

Residue Distribution Quantification

Spatial and temporal distribution of residue was determined using three techniques: LIS transects within α-plots (Woodhall and Monleon 2007), stand-scale LIS transects and planar intersect sampling techniques (Brown 1971, 1974) and destructive sampling plots (Grace et al. 2016). The residue distribution changes associated with harvesting are considered on a temporal scale ranging from weeks to months, whereas the spatial scale considered is of ones to tens of acres (or stand level). The β-plots provided information on spatial and temporal distribution of biomass residues within the stand with the exception of deck locations. The LIS transects within α-plots following FIA protocol provided an additional estimate of biomass within stands of interest (van Wagner 1968, Woodhall and Monleon 2007). Stand-scale LIS determinations were made by overlaying 10-ac (4-hectare) treatment areas with an 80 × 80 ft (25 × 25 m) grid resulting in two to four transects on each study block. Harvesting residues of each 80 ft (25 m) grid cell point were categorized into the five residue classes. The key assumptions in the polytomous regression analysis; ordinal data with polytomous responses, i.e., equally possible outcomes, independence of outcome levels, and proportional odds of outcomes were tested and analyzed using SAS PROC LOGISTIC (SAS 2004, Baker 2014). The analysis used maximum-likelihood estimates with bare defined as the reference level to test for differences in residue distribution for each site (SAS, 2004). Additionally, DWM was inventoried using the planar intersect sampling technique on the 80-ft (25-m) grid using a 1:3 systematic grid sampling scheme (Brown 1971, 1974, Avery and Burkhart 1994). A 20 percent error was used for determination of the number of plots and length of sampling planes for each of the associated DWM diameter classes. Sampling was performed on 20 points with sampling plane lengths of 50 ft (15 m) for diameter classes ≥3 in. (7.6 cm) or CWD, 12 ft (3.7 m) for DWM ranging from 1 to 3 in. (2.5 to 7.6 cm) or LFWD, and 8 ft (2.4 m) for DWM <1 in. (2.5 cm) or MFWD and SFWD. Deck locations were considered residue piles in this assessment and analysis.

Removal Efficiency Estimation

Initial preharvest biomass was determined as standing biomass from α-plots as detailed in the available biomass section above. Similarly, postharvest biomass was defined as the unrecovered biomass as determined from α- and β-plots for each stand. The targeted biomass recovery was defined as equal to standing biomass in this assessment. Biomass recovery was the difference between preharvest biomass, or targeted recovery in this case, and postharvest biomass. Removal efficiency, based on destructive sampling, was determined as the percentage of available aboveground biomass recovered during the biomass-harvesting operations for the sites defined by the expression below:

$$R_e \ (\%) = \left[\frac{(\text{IB} \ - \text{FB})}{\text{TR}}\right] \times 100 \qquad (2)$$

where R_e is the removal efficiency expressed as a percentage, IB is the available preharvest biomass (t ac^{-1} [t hectare^{-1}]), FB is the residual biomass (t ac^{-1} [t hectare^{-1}]), and TR (t ac^{-1} [t hectare^{-1}]) is the targeted recovery. An additional stand-level determination of R_e was made based on load-scale tickets of biomass delivered to the mill. In Equation 2, accumulated delivered biomass for each stand on a per-area basis was substituted for (IB – FB) for the stand-level removal efficiency.

Results and Discussion

Residue Distribution and DWM

The ground surface cover of sites CHT and GT at 100 percent surface cover prior to treatment was characteristic of southern plantation pine stands in the Coastal Plain region (Figure 3). However, the trend observed in the residue distribution data suggests that the pretreatment conditions were not the same on the two sites. Ninety percent of site CHT area fell within class 4, which was defined as litter-herbaceous. The remaining 10 percent of site CHT was equally split between the light and heavy debris classes in the pretreatment conditions. In contrast, site GT exhibited about 75 percent of its area in the litter-herbaceous category for the pretreatment conditions. The remaining 25 percent was classified in the light litter category (Class 3).

Data and visual assessments suggest a shift in the distribution dynamics in postharvest conditions for both site CHT and site GT (Figures 3 and 4). Seven and zero percent of site CHT and site GT were covered with medium to large residue piles following the harvesting treatment, respectively. Surface cover percentage postharvest was around 80 percent for both sites as opposed to 100 percent

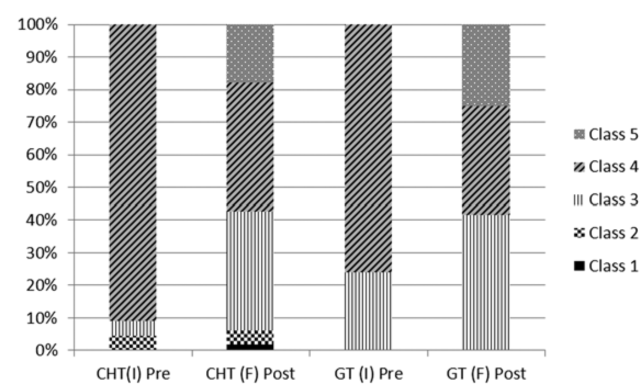

Figure 3. Residue distribution and ground cover assessment on study sites based on random azimuth transects on an 80-ft (25-m) grid with assessments at each grid point. The residue classes as presented in the figure are: Class 1 = residue piles ≥12 in. (30 cm) depth; Class 2 = heavy residue with residue ≥3 in. (7.6 cm) diameter and length ≥3 ft (0.9 m); Class 3 = light residue with residue < 3 in. (7.6 cm) diameter; Class 4 = designated as litter and herbaceous; Class 5 = designated as bare exposed soil.

Figure 4. Depiction of residue distribution and ground surface cover conditions in the investigation for: (a) preharvest site CHT, (b) postharvest site CHT, (c) preharvest site GT, and (d) postharvest site GT.

coverage prior to harvest. The observed trend indicates that residue distribution on the ground surface may decrease following harvesting operations. However, further discernment of the data through the polytomous regression analysis did not detect treatment effects in residue distribution responses ($P = .164$).

The regression analysis detected significant effects in the category responses for the sites ($P < .0001$). Analysis of maximum-likelihood estimates detected significant differences in residue distribution classes for both sites with the reference level designated as bare. There was no difference in the area attributed to debris piles, heavy debris, and bare based on maximum-likelihood estimates. Conversely, the area attributed to litter-herbaceous and light debris was significantly greater than that designated as bare, debris piles ($P = .004$) or heavy debris ($P = .003$). The area attributed to litter-herbaceous was also found to be significantly greater than the area attributed to light debris. These results suggest an ordering of the five potential categories considered in this assessment by increasing area occupied as: heavy debris < debris piles < bare < light debris and litter-herbaceous.

The downtrending tendency of surface cover or residue distribution data does not necessarily point to residue (DWM) mass decreases following harvesting operations (Grace et al. 2016). In fact, results for the postharvest effects on biomass estimation for sites CHT and GT were variable such that temporal effects were found on site CHT for FWD with $P = .014$ (Table 2), but this was not the case for site GT based on a mixed-effects ANOVA (SAS PROC MIXED). Conversely to site CHT, temporal effects were not detected for either FWD or CWD ($P > .061$) for site GT. The inability to detect CWD postharvest biomass effects on both sites may have been the result of the high variability and low replication (Table 2) exhibited by each of the tested parameters, or the influence could have been masked by the fact that the stand was younger, which presents a limitation on the CWD accumulations based on previous investigations (Radtke et al. 2004) of management influences. In general, both components of DWM trended toward an increase in postharvest condition as a result of the biomass harvest on both sites. This result was expected, considering the fact that a portion of the biomass is lost from the merchantable trees during the felling, skidding, and processing phases of forest biomass recovery. It has been shown that forest management directly influences the quantity and composition of biomass (Powers et al. 2012, Kizha and Han 2015). The quantity of residues following harvesting varies with age, harvesting method, and harvesting intensity with greater amounts for older, highly mechanized, and more intensive removals (Bradford et al. 2009, Powers et al. 2012). Older stands (mature) typically have greater CWD accumulations, whereas increased management intensity in the form of harvesting shifts stand biomass accumulations toward less CWD accumulations (Duvall and Grigal 1999, Radtke et al. 2009). The material lost during logging operations or "the recovery process" typically remains on site to be accounted for in DWM biomass estimation. It should also be noted that mechanized equipment used to perform operations may have influenced the results of this evaluation through the incorporation of residue into the surface horizon of the soil profile, redistribution and concentration of residue with decreased spatial uniformity, or a combination of these two processes.

The residue distribution results were expected to diverge for the sites, which consisted of stands at different developmental stages and stocking densities (Table 2). Site GT exhibited characteristics most closely resembling those expected of loblolly pine plantation sites at first thinning; typically a precommercial thin. For example, a typical loblolly pine plantation management scheme would involve a first thinning at around age 15 and/or a second thinning between 20 and 25 years, and a final harvest around year 25–30. Stand density has not been found to significantly impact average dbh, tree height, or mortality in stand densities between 300 and 900 trees per acre (~700 and 2,200 trees per hectare) in younger stands (before age 9) (Land et al. 2004, Carlson et al. 2009). However, density-related competition is responsible for diminishing growth increments and increased mortality because of self-thinning in stands greater than 12 years of age (MacFarlane et al. 2000, Zhao et al. 2011). In this investigation, site CHT was atypical to the aforementioned conditions for a loblolly pine plantation under a conventional management scheme in relation to the unthinned age (aged 24 years), stocking density (770 trees per acre [1,900 trees per hectare]), mortality (200 trees per hectare), and merchantable standing biomass (or volume) (160 t ac^{-1} [360 t hectare^{-1}]). An unthinned plantation of this age would be expected to show a higher mortality, greater self-pruning, and higher litter and cone production than a plantation in a traditional management pattern (Pienaar and Shiver 1993, Borders et al. 2004, Zhao et al. 2011), thereby resulting in increased residue (DWM) distributed into larger size classes.

Table 2. Biomass means and statistics as estimated in the experiment for preharvest and postharvest conditions.

Condition	N	Biomass, t ac^{-1} (t hectare^{-1})			
		Fine woody debris		Coarse woody debris	
		Mean	SD	Mean	SD
Preharvest Coastal H Tract	4	6.3 (2.8)	2.7 (1.2)	0	0
Preharvest Gantt Tract	5	3.1 (1.4)	2.6 (1.2)	0	0
Postharvest Coastal H Tract	9	44.8 (20.0)	37.8 (16.8)	10.1 (4.5)	19.9 (8.9)
Postharvest Gantt Tract	10	11.7 (5.2)	5.9 (2.6)	3.5 (1.6)	15.2 (6.8)

Table 3. Stand inventory, characteristics, and available biomass in the biomass recovery efficiency investigation.

Study site	No. of units sampled	DWM, litter and herb biomass, t ac^{-1} (t hectare^{-1})	Merchantable standing biomass[a], t ac^{-1} (t hectare^{-1})	Standing biomass[b], t ac^{-1} (t hectare^{-1})	Available biomass[c], t ac^{-1} (t hectare^{-1})
Coastal H Tract	12	10 (25)	150 (360)	160 (390)	170 (420)
Gantt Tract	15	8 (20)	80 (190)	90 (220)	100 (240)

[a] Merchantable standing biomass excludes limbs, branches, and foliage.
[b] Standing biomass—includes stem wood and bark (green weight of wood and bark [GWWB]).
[c] Total available biomass—includes downed woody material (DWM), litter and herbaceous, stem, limbs, branches, and foliage components = total tree green weight + DWM + litter + herbaceous.

Recovery Efficiency Assessments

Stand characteristics and biomass, both available and delivered, are given in Tables 3 and 4. The high stocking density on site CHT translated to a large estimated merchantable biomass of 150 t ac^{-1} (360 t hectare^{-1}) from a total standing biomass of 160 t ac^{-1} (390 t hectare^{-1}). Site GT, the younger of the two sites at 14 years of age, had a stocking density estimated at 600 trees per acre (1500 trees per hectare), a density that is typically encountered in southern loblolly pine plantations (Clutter and Lenhart 1968, Clutter et al. 1984, Zhao et al. 2011). The merchantable volume of this younger site at 80 t ac^{-1} (190 t hectare^{-1}) was around half that of the older site CHT (Table 3). Similarly, the total available biomass of 100 t ac^{-1} (240 t hectare^{-1}) for the younger stand, planted at a slightly lower stocking density, was slightly more than half that of site CHT estimated at 170 t ac^{-1} (420 t hectare^{-1}).

It follows, then, that biomass delivered as "clean" chips for site GT at 71 t ac^{-1} (176 t hectare^{-1}) was more than half that of site CHT at 110 t ac^{-1} (270 t hectare^{-1}) (Table 4). Biomass delivered as "clean" chips represented 65 and 71 percent of the total available biomass for sites CHT and GT, respectively. Site CHT delivered biomass residues were 15 percent of the available biomass, whereas delivered residues were only 3 percent of the available biomass from site GT. Site CHT was more closely aligned with the available biomass estimates than site GT, but we would expect the older site CHT to have greater quantities of residues delivered and thus total delivery agreement with available biomass estimates. That is, site CHT had stems, limbs, and tops that were larger and had less of its mass contained in limbs and tops, which would tend to translate to better estimates and less loss during the operation. The quantity of biomass delivered was slightly less than the quantity estimated by the available biomass assessments for both sites in the investigation.

The destructive sampling, R_e, the ratio of the difference between standing biomass and sampled residual biomass to standing biomass, was similar to the ratio of delivered biomass from load tickets to standing biomass. The mean recovery efficiency based on field measurements from destructive plots for sites CHT and GT was 84 and 91 percent, respectively. Similarly, the mean recovery efficiency based on load tickets was 88 and 83 percent for sites CHT and GT, respectively. In general, recovery efficiencies between 80 and 90 percent for both sites for the two methods of determination in the investigation indicate that the biomass-harvesting systems were quite efficient in these applications.

Implications

The function of CWD in forested ecosystems is multifaceted. CWD is regarded as an indicator of forest health (Woodall and Williams 2005, Woodall and Nagel 2006) and contributes to the provision of many ecosystem services provided by forested systems (McMinn and Crossley 1996). CWD is a DWM parameter that is critical in fire, carbon modeling, wildlife, and nutrient cycling sciences because of its interaction or relation with carbon pools, fuels, flora and fauna habitat, and nutrient dynamics within forested watersheds. CWD is typically highly variable in developing stands and can represent a large C pool at various stages in stand development (Powers et al. 2005). At the same time, it is recognized that forest management, particularly intensive management, can influence the extent and quantity of CWD in forest watersheds (Duvall and Grigal 1999, Wang et al. 2011, Keyser and Zarnoch 2012). Consequently, assessing watershed health, accurate carbon accounting, and effective nutrient management strategies are intricately linked to the ability to quantify DWM, particularly CWD, because the categorization of biomass can provide detail on the above-mentioned ecosystem services.

Forest biomass has gained increased acceptance as a sustainable renewable energy source in recent years. This concept has encountered some resistance because of the perceptions of overuse of the forest resource. The effect of intensive use of forests has been a concern in forest management as the demand for timber products has increased over the past half century. Biomass-harvesting operations increase the use rate of forest residue over that of whole-tree harvesting and can disproportionally remove larger fractions of nutrients (Mann et al. 1988). However, previous research reports

Table 4. Biomass component delivery and recovery efficiency for the study stands.

Study site	Total delivered biomass (clean)[a], t ac^{-1} (t $hectare^{-1}$)	Total delivered biomass residues[b], t ac^{-1} (t $hectare^{-1}$)	Total delivered biomass[c], t ac^{-1} (t $hectare^{-1}$)	Sampled residual biomass[d], t ac^{-1} (t $hectare^{-1}$)	Shortfall[e], t ac^{-1} (t $hectare^{-1}$)	R_e based on destructive sampling[f], %	R_e based on load tickets[g], %
Coastal H Tract	110 (270)	26 (64)	140 (346)	25 (62)	20 (49)	84	88
Gantt Tract	71 (176)	3 (8)	75 (184)	8 (20)	8 (21)	91	83

[a] Biomass delivered to the mill as "clean" (bole only) chips.
[b] Biomass delivered to the mill as "dirty" chips, which include deck residues (bark, limbs, and other downed woody material).
[c] Total delivered biomass = sum of "clean" and "dirty" chips delivered to mill from stands.
[d] Sampled residual biomass as determined from postharvest destructive β-plots.
[e] Shortfall = standing biomass (or targeted recovery [TR]) (t $hectare^{-1}$) – total delivered biomass (t ac^{-1} [t $hectare^{-1}$]).
[f] R_e based on destructive sampling (where IB = standing biomass; FB = sampled residual biomass) = ([{IB-FB} / IB {or TR}] x 100) (t $hectare^{-1}$).
[g] R_e = stand level based on load tickets = (total delivered biomass / standing biomass [or TR]) × 100 (t ac^{-1} [t $hectare^{-1}$]).

that productivity is controlled through management of soils, since 60–85 percent of nitrogen, phosphorus, and potassium, and as much as 95 percent of calcium and magnesium in pine plantations reside in the soil (Tew et al. 1986, Trettin et al. 1999). The conclusions from these investigations, taken collectively, indicate that increased use can have variable effects on productivity on some sites, but these effects can likely be mitigated with amendments.

The potential impacts of increased use are a focus of the USDA Forest Service's Long-Term Site Productivity network, which now includes 62 sites throughout the US and Canada. These studies were installed with the primary objective of quantifying the effects of disturbance from management activities on long-term productivity. Potential impacts and sustainability issues related to increased use of forests have been investigated relatively intensively over the past 25 years (van Lear et al. 1984, Binkley et al. 1999, Sanchez et al. 2006), and a considerable foundation of knowledge has been developed (Johnson and Curtis 2001, Laiho et al. 2003, Miller et al. 2006). However, it is critical to acknowledge that additional research is required to quantify the holistic effects of removal of understory vegetation, smaller stem diameters, and DWM on site nutrient dynamics and long-term productivity while considering the factors of change, in particular climate, land-use, and demands. Maintaining a balance between the residue recoveries for energy production in addition to the traditional suite of timber products with the need to retain residues for an increasing array of ecosystem services is critical for sustainability (Shifley 2006, Lattimore et al. 2009, Briedis et al. 2011).

Conclusions

In this study, a biomass-harvesting treatment was applied to a high density stand (age 24) and a young (age 14) moderate-density loblolly pine stand. The investigation focused on evaluating biomass recovery efficiency of operations and temporal and spatial effects on biomass residue distribution. Results indicate that the preharvest site standing biomass for the younger site at 90 t ac^{-1} (220 t $hectare^{-1}$) was approximately half that of the older site at 160 t ac^{-1} (390 t $hectare^{-1}$) which coincides with 80 t ac^{-1} and 150 t ac^{-1} (190 and 360 t $hectare^{-1}$) of merchantable biomass, respectively. The harvesting operations recovered 84 and 91 percent of standing biomass on sites CHT and GT, respectively, based on the destructive sampling estimations. Residue distributions across both sites for both pre- and postharvest conditions were significantly greater in two categories: light debris and litter-herbaceous. The analysis found that no temporal effects were discernible in residue distribution for the sites, although postharvest sites trended toward a wider range of residue distributions with nearly 20 percent of the sites designated as bare. The exploratory investigation presented here provides information critical to understanding the temporal and spatial distribution of biomass-harvesting operations, which in turn can be used in combination with nutrient analyses of residue fractions to determine on-site nutrient dynamics.

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