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Residue distribution and biomass recovery following biomass harvest of plantation pine

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ABSTRACT. *Forest biomass is anticipated to play a significant role in addressing an alternative energy supply. However, the efficiencies of current state-of-the-art recovery systems operating in forest biomass harvests are still relatively unknown. Forest biomass harvest stands typically have higher stand densities and smaller diameter trees than conventional stands which may result in reduced recovery efficiencies. In this study, we explore the spatial and temporal effects on residue distribution as a result of biomass harvest of 14-year- and 24-year-old loblolly pine (Pinus taeda) plantations at stand densities of 1500 and 1900 trees per hectare, respectively. Additionally, we explore biomass recovery efficiency by a harvesting system that was specifically designed for southern pine plantation biomass harvests. Pre-harvest aboveground biomass for the younger site was half that of the older site (240 vs. 420 t ha^{-1}) with approximately 79% and 86% being merchantable biomass, respectively. The pre-harvest condition exhibited 100 percent ground cover; whereas, post-harvest conditions had nearly 20 percent of the area designated as bare based on the residue distribution assessments. The assessments found increased incidence of ground cover in the finer biomass classes in comparison to the larger debris and bare classifications. The harvesting operations recovered 85 percent of standing biomass in a 24-year old stand and 90 percent of the standing biomass in a 14-year old stand. In general, harvesting the plantations increased downed woody material on site and these unrecovered residues are expected to satisfy objectives related to maintaining site productivity, minimizing erosion, and preserving ecological values.*

Keywords. *forest biomass, spatial variability, residue distribution, residue quantification, efficiency, site assessment*

Introduction

Global energy demands have been steadily increasing over the past several decades (Kiran et al., 2014) despite technological advances and energy efficiency regulations and practices. The escalating demand is attributed to a myriad of factors with population growth and industrialization as the primary factors (EIA, 2005). The trends in global energy demands in combination with the recognition that alternative energy sources are the prudent path forward in terms of environmental sustainability has catalyzed efforts towards development of a suite of holistically sustainable alternative energy sources (renewable, nuclear, hydropower, geothermal). These efforts are fueled by national initiatives aimed at stimulating the scientific and technology development sectors through economic and research incentives. In the US for example, the Energy Independence and Security Act (EISA) of 2007 calls for a significant portion of the US fossil fuel demand to be substituted with bioenergy by 2022 with as much as 3.8 million cubic meters of this supply composed of liquid lignocellulosic biofuel (Morrison et al., 2014). As another example, the European Union (EU)'s Renewable Energy Directive requires fulfilling 20 percent of EU total energy needs as well as each EU country to supply 10 percent of its transportation fuels with renewable energy by 2020.

Renewable energy sources in the form of solar, wind, hydropower, and geothermal are critical to addressing the energy demands while minimizing the environmental footprint. Biomass energy, a derivative of solar energy which serves as the energy source for photosynthesis processes in plant for growth increments, is a relatively inexpensive form of renewable alternative energy (Timmons, 2013). Biomass energy from lignocellulosic feedstocks is presented as a clean and environmentally sustainable alternative renewable energy source (Dincer et al., 2008) in terms of greenhouse gas (GHG) emissions and pollution in comparison to fossil fuel energy. Forest biomass is just one of the leading forms of lignocellulosic feedstock which also include dedicated energy crops, agricultural crop residues, and household waste. In fact, as much as 30 percent of the targeted reduction of 136 million cubic meters/year in transportation fuels by 2022 is expected to be supplied by lignocellulosic feedstock in the US (Bailey et al, 2011; Perlack et al., 2005; USDA FS, 2010).

Forest biomass has potential to represent a significant portion of the bioenergy supply (Galik et al., 2009) due to the vast extent of land area devoted to forests, high productivity of forest lands, and recoverable materials from harvesting operations (residues). Forest residues from harvest operations in the form of tops, limbs, damaged or defective wood, bark, and stumps are lower-value materials typically left on site but could represent 30 million dry tonnes for energy production in the southern US alone (Eisenbies et al., 2009; Scott and Dean, 2006). However, the economic viability of forest residues as a biomass source is challenged by complications with available biomass estimation and inefficiencies related to collection, site processing, and transport (Grace et al. in review; Long and Boston, 2014). In recent years, the focus on alternative energy sources has resulted in an intensification of research and development to improve the efficiencies in harvesting systems and operations which hinge on accurate quantification of available biomass and subsequently forest residues.

The previous work related to the effect of utilization on forests and the ecosystem services they provide over the past quarter-century indicate that increased utilization has variable effects on productivity on some sites but these effects are likely mitigated with amendments or prudent residue management (Brinkley et al., 1999; Johnson et al., 2002; Laiho et al., 2003; Mann et al., 1988; McBroom et al., 2008; Miller et al., 2006; Powers et al., 2005; Sanchez et al., 2006). Further, it is recognized that improved residue management and removal efficiency can increase profitability, decrease the carbon intensity of biofuels, enhance nutrient dynamics and reduce soil losses (Conner and Johnson, 2011; Eisenbies et al. 2009; Morrison et al, 2016). Balancing the economic viability with operational and sustainability aspects requires progress in quantifying residues and defining optimal residue management (the percentage, type, and form of residue retained) in various stand types. Additional research is required on the relative effects of removal of smaller stem diameters, understory vegetation, and downed woody material on site nutrient dynamics and subsequent long-term productivity.

Optimizing economic outcomes, recovery efficiencies, and environmental sustainability in forest biomass harvesting operations often predicates efficiently removing available biomass in a holistically sustainable manner for a particular site. This paper aims to explore forest residue distribution and the biomass recovery efficiencies achievable in southern energy plantations using state-of-the-art harvesting systems proposed for biomass recovery in small diameter stands. The objectives presented here are to: (1) determine the spatial and temporal effects on residue distribution as a result of biomass harvest of 14-year- and 24-year-old loblolly pine (*Pinus taeda* L.) plantations and (2) evaluate biomass recovery efficiency by a harvesting system designed for operations in small diameter southern pine plantations.

Methods

The study area is within Southeastern Plains Ecoregion of the Gulf Coastal Plains and is characterized by warm and humid climate with a long-term average annual precipitation of 1500 mm. Historically, the area consisted of fire dominated longleaf pine (*Pinus palustris* Mill.) forests and woodlands but have subsequently been replaced with managed timberland consisting of high density loblolly pine (*Pinus tadea* L.) plantations. Topography is gentle with surface soils consisting of deposited unconsolidated sands, silts, and clays from higher elevations that are generally well drained.

Two study sites, Coastal (CT) and Gantt (GT), were randomly selected from a total of 17 sites available for harvesting in Butler, Conecuh, Covington, and Monroe counties in south central Alabama (Figure 1). The CT site was located in Butler County at approximately 31º49'N latitude and 86º37'W longitude near Greenville, Alabama and the GT site was located in Covington County at approximately 31º41'N latitude and 86º48'W longitude near Gantt, Alabama. The CT site featured a 24 year-old, 18-ha loblolly pine plantation with a stand density of 1900 trees ha^{-1} and a basal area (BA) of 41.6 m^2 ha^{-1} (Table 1). Similarly, the GT site was a loblolly pine plantation 15-ha in area and aged only 14 years. Stand density at GT was 1500 trees ha^{-1} with a BA of 32.7 m^2 ha^{-1}.

Experimental Design & Analysis

The residue distribution and biomass recovery components were designed as completely randomized design experiments. In both components, the design used two levels of evaluation time, pre-harvest and post-harvest, in two randomly located operational scale 4-ha experimental blocks on each study site. Five randomly located 7.3-m fixed radius plots in combination with 1-m fixed radius plots were established within each harvest block to evaluate spatial and temporal effects on residue distribution and biomass removal efficiency. The single factor model in each completely randomized design is given by:

$$Y_{ij} = u. + \tau_i + \varepsilon_{ij}$$

Where Y_{ij} is the response; u. represents the overall mean; τ_i is the treatment effect (fixed effect); and ε_{ij} is the experimental error associated with a given site. The null hypothesis (H_o) is that harvest would have no effect on either the residue distribution or biomass recovery efficiency response. The hypotheses were tested through a regression analysis (SAS PROC LOGISTIC) on residue distribution and an analysis of variance (ANOVA) in combination with t-tests (SAS PROC TTEST) on biomass recovery response variables (SAS, 2004).

Table 1. Stand characteristics, biomass, and recovery for the study stands.

Study Site	Age	Area (ha)	Stand Density (trees ha^{-1})	Aboveground Biomass* (t ha^{-1})	Total Delivered Biomass† (t ha^{-1})	Sampled Residual Biomass‡ (t ha^{-1})	Destructive Sampling R_e[a] (%)
CT	24	9	1900	420	340	60 (30)	85%
GT	14	15	1500	240	190	20 (10)	90%

* Aboveground biomass which includes (DWM, litter & herbaceous, stem, limbs, and branches & foliage components).

† Biomass delivered to the mill which includes (bole, bark, limbs, and other DWM).

‡ Sampled residual biomass as determined from post-harvest destructive plots.

[a] R_e - recovery efficiency based on destructive sampling.

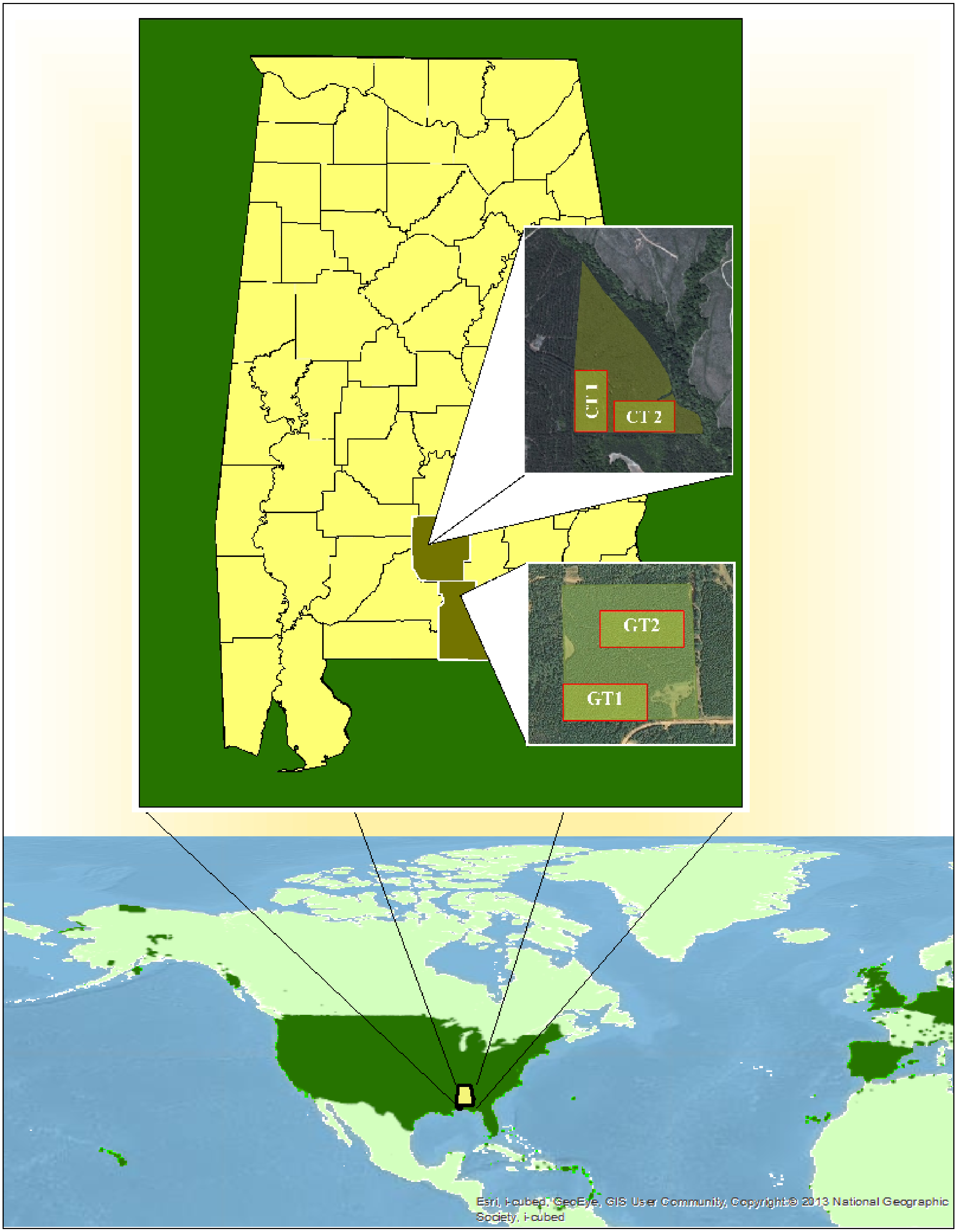

Figure 1. Location of study sites in Butler and Covington Counties in south central Alabama USA. Aerial imagery depicts biomass harvest sites CT and GT overlain with locations of treatment blocks.

Harvesting

Harvests and post-harvest data collection occurred Jan–Feb 2012 (CT site) and Apr–May 2012 (GT site). Both sites were harvested using a tracked, boom-mounted feller-buncher, a rubber-tired grapple skidder, a flail delimber/debarker, two disc chippers and a tracked loader. The feller-buncher and skidder were modified for efficiency, including a high capacity felling head accumulator to allow for larger load accumulations and a high-capacity grapple and an enhanced seating configuration that allowed either forward- or rear-facing operation (Rummer and others, 2010). The two disc chippers in the systems featured either a 168-cm or 191-cm diameter disc. The 191-cm diameter disk chipper could be mounted with either four knives for conventional size chips or eight knives for microchips.

Felled trees on the CT site were skidded green to the landing for processing while felled trees on the GT site remained in bundles following felling to allow drying for approximately seven weeks. Trees from both sites were passed through a flail delimber/debarker and chipped with the 191-cm disc chipper (CT) or a 168-cm disc chipper (GT); thereby, producing green clean conventional chips (CT site) or dry clean conventional chips for transport. In addition to conventional chips, whole-tree dry microchips were produced on the GT site using the 191-cm disc chipper equipped with eight knives.

Study Measurements

Foliage, woody material, and understory vegetation, was determined through direct measurements during the pre-harvest and post-harvest conditions on each site. Overstory biomass was estimated allometrically from cruise data and growth and yield equations (Borders et al., 1990; Clark and Saucier, 1990; Clark et al. 1985; Phillips et al., 1982; USDA FS, 1982; 2013) in combination with site specific green weights for volume estimation. Three methods for assessing residue volumes, downed woody material (DWM), and available biomass were utilized including: (1) line intercept sampling (LIS) within 7.3-m fixed radius plots, (2) stand scale plane intercept sampling (PIS), and (3) small plot destructive sampling within 1-m fixed radius plots. Previous work found that all three methods estimated residue, DWM, and biomass consistently from the sites (Grace et al. in review); therefore this paper will focus on the small plot destructive sampling data.

We destructively sampled to quantify effects of harvest on biomass and DWM. Standing understory woody and vegetative biomass with a diameter ≤ 5 cm was quantified using 7.3-m fixed radius plots in combination with 1-m fixed radius destructive sampling plots. Biomass was collected from destructive sampling plots by severing material at ground level, sorting into woody or herbaceous fractions, collecting into large labeled polypropylene bags, weighing to determine 'green' field weight and transporting to the laboratory for drying in a convection oven at 65 ± 5 ºC to a constant weight for subsequent laboratory analyses (ASTM, 2007). Biomass collected from the destructive sampling plots were further processed by hand sorting into DWM categories that were defined consistent with existing protocols (Woodhall and Monleon, 2007; Woodhall and Williams, 2005) where:

Small Fine Woody Debris (SFWD): woody material with diameter < 0.61 cm (0.24 in.). Debris with a length < 2.54 cm (1.00 in.) considered as litter in this category.
Medium Fine Woody Debris (MFWD): woody material with diameter ≥0.64 cm (0.25 in.) and ≤ 2.51 cm (0.99 in.). Debris with a length < 0.64 cm (0.25 in.) considered as litter in this category.
Large Fine Woody Debris (LFWD): woody material with diameter ≥ 2.54 cm (1.00 in.) and ≤ 7.59 cm (2.99 in.)
Coarse Woody Debris (CWD): woody material with diameter ≥ 7.62 cm (3.00 in.).

Spatial and temporal patterns in residue distribution were quantified through pre- and post-harvest sampling of the CT and GT sites. We explored the hypothesis that harvesting would have no effect on residue patterns and distribution through a mixed effects analysis of variance (SAS PROC MIXED) on biomass estimation response variables; DWM, CWD and Fine Woody Debris (FWD) (SAS, 2004). Individual means for response variables were tested for differences using Tukey means separation tests when the main factors indicated significant differences at the 0.10 significance level. Further, stand scale LIS determinations were made by overlaying the replicate 4-ha operational scale treatment blocks with a 25 x 25 m grid for point evaluations of residue distribution. The grid resulted in two to four randomly located transects on each block within study sites to provide detail into the relative distribution of residue over the sites. The cover and residues of each 25-m grid cell point were categorized into five residue classes: 1) residue pile (≥ 30 cm depth), 2) heavy residue - residue ≥ 7.6 cm diameter and length ≥ 0.9 m, 3) light residue - residue < 7.6 cm diameter, 4) litter and/or herbaceous, and 5) bare exposed soil. The recorded responses represent ordinal categorical data with five equally possible outcomes or classes, i.e. polytomous responses. We analyzed this data through multinomial regression analysis procedures using SAS PROC LOGISTIC [Baker, 2014; SAS, 2004] using maximum likelihood estimates with a designated reference level of bare to test for significant differences in residue distribution classes for both sites. Pairwise comparisons were performed where logistic regression analysis indicated significant differences.

Results and Discussion

Initial stand conditions on the two sites were generally similar in terms of species composition since both sites were plantation pine with a high planting density typical of energy wood sites. CT trees were larger and taller than those at GT (19 vs. 15 cm DBH and 20.5 vs. 12.8 m height), as they were 10 years older. As a result, CT had nearly twice the aboveground biomass as GT (Table 1).

The harvesting system was relatively efficient, with 85 and 90 percent biomass recovered for CT and GT, respectively. These are well within the range of values previously reported for conventional systems in plantation stands. Residual biomass for the older CT site was 60 t ha^{-1}, which was greater than the biomass remaining on GT at 20 t ha^{-1}. The older CT site had larger trees which coincides with larger limbs and tops which could account for the increased residual biomass. That is, a greater proportion of the biomass was lost to breakage during the felling and skidding (transport to the landing) resulting in more biomass remaining on the site and not available for recovery and delivery to the mill. The residual biomass on CT and GT represents 100 and 40 percent of the pre-inventoried non-merchantable biomass, taken as the difference between aboveground biomass and merchantable biomass, of 60 and 50 t ha^{-1} for the sites, respectively. The residual biomass volumes on both sites is expected to satisfy objectives of maintaining site productivity and nutrient dynamics, minimizing site degradation from erosion, and preserving ecological values (Forest Guild, 2012). However, satisfying the biomass retention needs not only requires that sufficient quantities are retained but also that these quantities are adequately distributed over the harvested sites to maintain some uniformity of site conditions.

Previous work on forest plantations, and forests in general, has shown that forested conditions are optimal for providing high levels of ground cover (Croke and Hairsine, 2006). Our results indicate that pre-harvest plantation conditions afford maximum ground cover and optimal residue retention. Residue distribution was primarily in the light litter and litter/herbaceous classifications (>95 percent). Heavy debris (CWD) represented 5 percent of the area on CT in the pre-harvest but was not found on the pre-harvest GT site (Figure 2) (Table 2), consistent with the age of these stands.

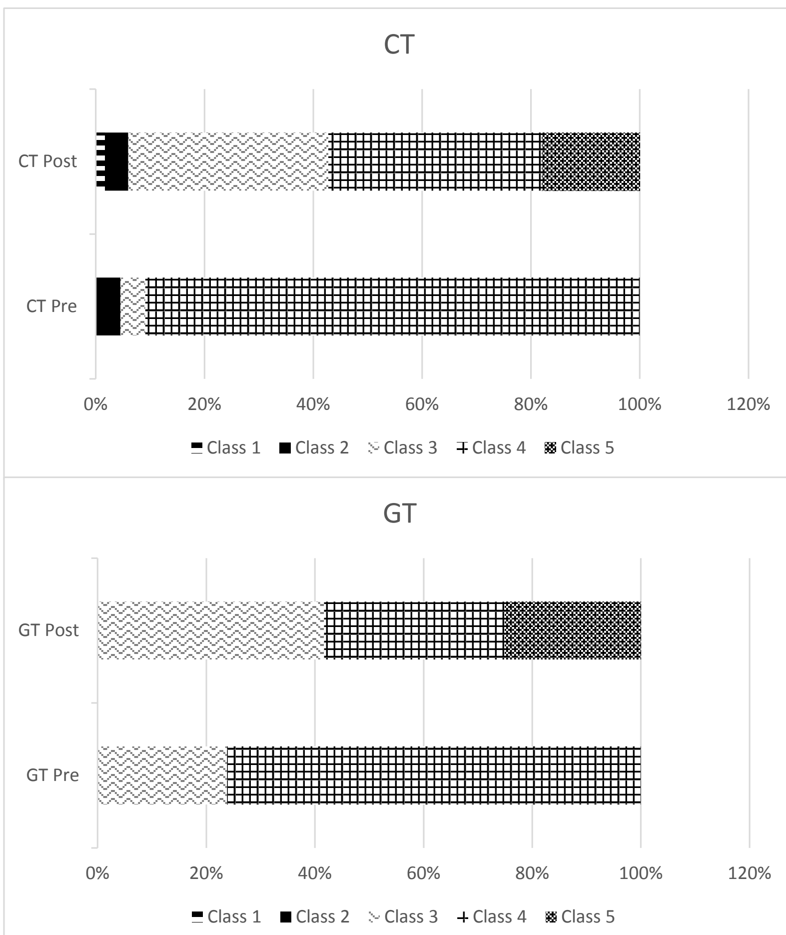

Figure 2. Residue distribution for study sites based on 25 x 25-m grid point assessments. Residue classes defined as: Class 1) residue pile (≥ 30 cm depth), Class 2) heavy residue - residue ≥ 7.6 cm diameter and length ≥ 0.9 m, Class 3) light residue - residue < 7.6 cm diameter, Class 4) litter and/or herbaceous, and Class 5) bare exposed soil.

Table 2. Means and statistics for FWD, CWD, and total DWM at study sites as determined by destructive sampling plots during pre-harvest and post-harvest conditions. Standard deviations are presented as values in parentheses immediately following the mean values for each biomass component.

			Biomass Component ($t\ ha^{-1}$)		
Condition	Site	N	FWD	CWD	DWM
Pre-harvest					
	CT	4	6.3 (2.7)	0 (0)	6.3 (2.7)
	GT	5	3.1 (2.6)	0 (0)	3.1 (2.6)
Post-harvest					
	CT	9	44.8 (37.8)	10.1 (19.9)	54.9 (53.6)
	GT	10	11.7 (5.9)	3.5 (10.0)	15.2 (15.2)

The post-harvest conditions had a wider range of responses than the pre-harvest condition. In fact, all five residue classes were represented on the CT site and 3 classes were represented on GT (Figure 2). The post-harvest condition provided a greater quantity of FWD (P=0.014), CWD ($P=0.074$), and DWM ($P=0.063$) on the CT site and DWM ($P=0.061$) on the GT site in comparison to the pre-harvest conditions (Table 2). The assessment revealed that bare conditions represented 25 percent of the CT post-harvest area and 18 percent on the GT post-harvest area. The regression analysis detected differences in the categorical responses for the site ($P<0.0001$). Further, greater litter-herbaceous was greater than all other categories (P=0.004, bare, debris piles, and heavy debris).

Conclusions

In this study, residue distribution and biomass recovery was explored in biomass harvest operations on two different age loblolly pine plantations. The study revealed that aboveground biomass for the CT site aged 24 years was nearly twice that of the GT site aged 14 years. The harvesting operation recovered 85 and 90 percent of the standing biomass for the older CT and younger GT site, respectively. The residual biomass at the sites was 100 percent and 40 percent of the inventoried pre-harvest non-merchantable biomass indicating that the residue retained on site was consistent with the pre-harvested residue conditions.

In addition to the removal of the standing biomass from the sites as a result of the harvest operations, we found that the residual biomass composition shifted as a result of the harvest operations. Harvesting resulting in greater quantities of DWM than hypothesized. The residue on the CT site following the harvest was distributed more heavily in the FWD and CWD components in comparison to pre-harvest conditions. These results provide information that will help managers understand efficiency in biomass harvesting operations and the effects on residual biomass composition.

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