Biomass Harvesting Effects on Soil Physical Properties in the Coastal Plain of North Carolina

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Abstract

Biomass harvesting offers opportunities to produce portions of US energy demands from renewable resources, yet there are concerns that biomass harvesting could deplete nutrient reserves, increase potential for soil erosion, or lead to problems associated with increased forest trafficking. On intensively managed loblolly pine (*Pinus taeda*) plantations on relatively flat coastal plain terrain, nutrient demands may be met with fertilization and soil erosion is of lower concern. However, soil disturbance associated specifically with coastal plain biomass harvests for renewable energy production have not been widely documented. Soil disturbance classes and physical properties were examined on three intensities of biomass harvesting on a 52 ha loblolly pine plantation in the North Carolina coastal plain. Study objectives were to determine if biomass harvesting intensity and associated traffic were correlated with changes in soil physical properties or visual soil disturbance classifications. Harvesting intensities included in the designed operational study were: 1) roundwood removal only, 2) integrated harvest including roundwood removal and biomass production, and 3) chip only harvest where all trees were removed and chipped for biomass. Harvesting treatments were replicated 3 times each (9 experimental units) using a randomized complete block design. Soil properties were evaluated pre- and post-harvest to determine harvesting related impacts. Results indicate that most soil physical properties were not significantly altered due to harvest level with the exception of small deck areas. These data indicate that biomass harvesting did not result in visual or physical changes to soil properties as compared to traditional harvests and indicate that standard best management practices may be adequate to address biomass harvesting issues for similar sites.

Keywords: Bulk density, soil disturbance, forest operations, porosity, conductivity

Introduction

Increasing energy costs, changing domestic policies, and desires for energy independence have increased interest in biomass energy production from numerous sources, including wood (US Senate 2006, Demchik et al. 2009, Galik et al. 2009). Although woody biomass utilization has potential benefits, biomass harvesting must meet common environmental criteria for sustainability. Environmental criteria of concern typically include excessive woody debris and litter removal, soil disturbance/compaction/erosion, nutrient drains, plant diversity and sustainability, and wildlife habitat (Reijnders 2006, Evans and Finkral 2009).

Currently, southern pine plantations are major areas of focus for potential bioenergy feedstocks due to their productivity and intensity of plantation management (Fox 2000, Munsell and Fox 2010). Southern pine plantations are some of the most intensively managed forests in the United States (Allen and Campbell 1988, Conner and Hartsell 2002, Eisenbies et al. 2005). Current management practices include planting genetically improved seedlings, mechanical and chemical site preparation, fertilization, and thinning (Fox 2000). Research indicates that these practices can be sustainable (Kelting et al. 1999, Stanturf et al. 2003), but some concerns exist regarding the long-term sustainability of biomass harvesting where typically non-merchantable stems are removed. Following the oil shortages of the 1970's, biomass harvests received considerable research attention. Much of this research focused on nutrient depletion and indicated that whole tree harvesting can remove a disproportionate quantity of nutrients (Hewett et al. 1981), but these losses can be offset by atmospheric deposition or fertilization (Fox 2000, Reijnders 2006, Munsell and Fox 2010).

Accelerated soil erosion from biomass harvesting is another area of concern. The concept is that biomass harvesting will expose additional bare soil and increase the potential for soil erosion. The literature for soil erosion following conventional harvesting indicates that erosion typically increases 3-8 Mg/ha/year following disturbance, but returns to pre-harvest levels within 2-5 years (Aust and Blinn 2004). Shepard (2006) reviewed best management practices (BMPs) used for conventional harvesting operations and concluded that existing BMPs should be sufficient for erosion control and water quality protection for biomass harvests. However, several states have recently developed or are considering establishing biomass harvesting related BMPs (Briedis et al. 2011).

Biomass harvesting, due to the more complete removal of standing trees and harvesting residues, is also believed to increase the potential for site trafficking and disturbance of soil physical properties (Evans and Finkral 2009, Page-Dumroese et al. 2010). Trafficking associated with intensively managed forests has received considerable research attention due to issues such as reduced seedling survival and reduced height and diameter growth of crop trees early in rotations (Miwa et al. 2004, Eisenbies et al. 2005). Numerous studies indicate that forest management practices, such as harvesting, can negatively impact soil physical properties (Eisenbies et al. 2005). Common properties found to be affected by harvest trafficking include soil strength, bulk density, saturated hydraulic conductivity, micro porosity, macro porosity, and total porosity (Greacan and Sands 1980, Gent et al. 1983, Aust et al. 1995, Miwa et al. 2004). Greacan and Sands (1980) developed a model to explain potential effects of trafficking on soil physical properties. Major modifiers that may influence the degree of soil compaction with traffic include soil moisture, soil texture, soil structure, soil organic matter, roots, litter, slash, equipment weight and pressure, and number of passes. Numerous studies have found that coastal plain sites are subject to compaction following harvests (Gent et al. 1983, Aust et al.

1998, Eisenbies et al. 2005) which can negatively affect soil physical properties and reduce overall site productivity (Kozlowski 1999, Eisenbies et al. 2004).

Overall, previous research indicates that problems associated with biomass harvesting may include nutrient depletions, erosion increases, and traffic disturbances. However, there is limited research that specifically examines the effect of biomass harvesting intensity on soil physical properties in the coastal plain. The objective of this study was to determine whether biomass harvesting created a higher degree of alteration on soil physical properties, as compared to conventional roundwood harvesting techniques. The alternative hypothesis was that harvesting woody biomass would contribute to a greater degree of soil disturbance because of the increased passes that the feller-buncher would require to sever conventionally non-merchantable stems as well as the increased number of cycles required to skid smaller stems to decking areas.

The study was also designed to determine if a visual soil disturbance scale (e.g. Aust et al. 1993, Aust et al. 1998) could be used to correlate impacts on soil physical properties in a harvested area. Visual disturbance classes have been used in many cases to assess the amount of change to desired soil properties that has occurred due to harvesting and can provide a method to efficiently and consistently collect data about soil disturbance within an area (Craig and Howes 2007, Page et al. 2009). Many studies have focused on using visual soil disturbance classes in the western part of the U.S. (e.g., Curran 2005, Curran 2007, Craig and Howes 2007, Bolding et al. 2009) while fewer studies have been done in the eastern U.S. (e.g., Aust et al. 1998). The purpose for using visual disturbance classes in this study was to determine if a scale could be used to accurately determine changes in physical properties on a site that had already been disturbed by previous management regimes.

Methods

Study Site

This study was conducted in the upper Atlantic Coastal Plain physiographic province in Bertie County, North Carolina (Figure 1). Bertie County is characterized as having low, flat plains with slight ridges and shallow stream valleys. Elevations range from sea level at the county's eastern boundary to 30 m at its highest point. The county is drained by the Cashie, Chowan, and Roanoke Rivers and features fertile and productive soils. The climate is mild with the average temperature in January being 7.2^{o} C and an average temperature of 26.1^{o} C in July (Bertie County, NC 2009).

The 52 ha site consisted of two stands of loblolly pine (*Pinus taeda)* plantations on a wet flat. One stand was bedded and was approximately 24 years in age, while the other stand had been wind-rowed and bedded and was approximately 30 years in age. The dominant soil type found on this site was leaf loam, fine, mixed, active, thermic Typic Albaquults. Surface textures are silt loam while lower argillic horizons (Btgs) are silty clay. This series is formed in clayey alluvial and fluvial sediments, and is characterized as being very deep and poorly drained (NRCS 2010). The slope for the study site ranged from 1-2%. Although the stand was dominated by planted loblolly pine, other common overstory and midstory species included sweetgum (*Liquidambar styraciflua*) and red maple (*Acer rubrum*).

Treatments

The study site was divided into three blocks based on deck location and access, stand conditions, and soil drainage class. Three harvesting treatments were replicated in each of the three blocks for a total of 9 experimental units and all treatment boundaries were flagged to ensure logging contractor compliance with treatments. The harvesting treatments (Figure 2) consisted of a conventional roundwood harvest (Roundwood Only), a biomass harvest (Chip Only), and an integrated treatment where both typically non-merchantable biomass trees and merchantable roundwood were harvested simultaneously (Integrated).

The roundwood only treatment (Roundwood Only) consisted of conventional tree-length harvesting in a commercial clearcut. A tracked feller-buncher (Tigercat M822C) felled merchantable stems throughout the stand. Pine was merchandized into sawtimber or pulpwood and hardwood stems were processed for pulpwood. Non-merchantable stems were not felled. Two rubber-tired grapple skidders were used to skid felled stems to the landing areas (Tigercat 625C operating with 12-wheels and a Tigercat E620C operating with 8-wheels). After processing roundwood, skidders returned limbs and tops back into the treatment area en route to attain another turn of felled stems. Two loaders (Tigercat 240B) equipped with buck saws at the landing bucked and loaded the roundwood for delivery to appropriate mills. The same felling and skidding equipment were used for all treatments. Each skidder operator was instructed not to cross flagged treatment lines.

The chip only treatment (Chip Only) chipped whole trees to produce dirty chips for boiler fuel. The feller-buncher operator was instructed to harvest as many stems from the site as possible, whether they were merchantable or non-merchantable. All stems were then skidded to the landing and chipped using a Conehead Model 585 in-woods chipper. The chipper was fed using a tracked Tigercat 240B mobile loader. The dirty chips were loaded into chip vans and delivered to a local pulp and paper facility.

The Integrated treatment (Integrated) was a combination of the Roundwood Only and Chip Only treatments. The feller-buncher performed a silvicultural clearcut where all stems in the treatment area were felled. The feller-buncher sorted stems into merchantable and non-merchantable piles which were skidded to landing areas. Stems large enough to be processed for sawtimber or pulpwood were processed and loaded as roundwood. In this harvesting treatment, non-merchantable stems were skidded separately to the deck and were processed by the in-woods chipper. Limbs and tops that would normally be returned to the site were also processed by the chipper. Loaders bucked and loaded roundwood for delivery to appropriate mills.

Field Methods

Soil disturbance was assessed for pre- and post-harvest conditions. For the pre-harvest samples, five sample locations were randomly established across each of the nine experimental units (45 locations). Visual assessments were conducted and all points were found to be non-trafficked. Soil bulk density cores (5 cm diameter) were collected with a double cylinder, hammer driven soil corer (Blake and Hartage 1986) at each assessment point in the surface Ap horizon (0-10 cm) and subsurface Btg horizon (30-40 cm). The 45 locations and two soil depths equated to 90 pre-harvest soil core samples. The first core sample was taken after removing O horizons until mineral soil was exposed. The second core sample was obtained after auguring to a depth of approximately 30 cm. Samples were subsequently transported to the soils laboratory to determine average bulk density (Blake and Hartage 1986), porosity (macro porosity, micro porosity, and total porosity) (Danielson and Sutherland 1986), and saturated hydraulic conductivity (Klute and Dirksen 1986).

After harvest treatments were completed, a 20 m x 20 m grid was established across the study site. The grid was used to map major skid trails (Figure 3) and locate measurement points for visual soil disturbance classifications (Figure 4). At each grid point, visual soil disturbance classes were recorded using five soil disturbance classes adapted from Aust et al. (1993). Disturbance classes were: Class 5 - undisturbed, Class 4 - evidence of traffic with no rutting, Class 3 - traffic ruts < 15 cm deep, Class 2 - traffic ruts > 15 cm deep, and Class 1 - traffic induced churning or puddling.

Due to favorable weather conditions and gentle terrain, the majority of the site was in Classes 4 and 5 (Table 1), and Classes 1 and 2 were not found at any sampling point. A weighted average of area within each class was used to determine the number of bulk density samples that would be collected within each visual disturbance class. A total of 270 post-harvest bulk density samples were taken across the site, which is approximately one bulk density sample location per 0.4 ha with each point consisting of two depths.

Lab Analyses

Soil core samples were analyzed to determine bulk density, micro porosity, macro porosity, total porosity, and saturated hydraulic conductivity. Soil cores were first re-labeled and saturated for at least 24 hours in a plastic container. Saturated cores were placed inside PVC KSat silos, which allowed for the determination of saturated hydraulic conductivity (Klute and Dirksen 1986). Samples with saturated hydraulic conductivity values over 100 cm/hr were assumed to have pipe flow (Uchida et al. 1999) and were not included in conductivity calculations. After saturated hydraulic conductivity measures were completed, cores were weighed and placed on a 50 cm tension table for 24 hours to remove water from macropores. Cores were reweighed and differences in saturated and post-tension table weights were used to calculate water mass and soil macro porosity volumes (Danielson and Sutherland 1986). Cores were oven dried at 105º C for 24 hours and weighed. Oven dried weights were used to calculate micro porosity (Danielson and Sutherland 1986) and bulk density (Blake and Haratge 1986). Total porosity was obtained by simply combining micro porosity and macro porosity.

Statistical Analysis

The study was arranged as a randomized complete block design with an incomplete split, as disturbance classes were nested within treatments (Steele and Torrie 1980). The design consisted of three blocks and three treatments per block. Soil physical properties and disturbance classes were the variables of interest. For pre-harvest conditions, a soil visual disturbance Class of 5 (undisturbed) provided a control. Analyses of variance was performed with JMP version 9 (SAS Institute 2010) at an alpha level of 0.10. Tukey HSD tests were used for mean separations when p-values indicated significant differences.

Results and Discussion

Studies have indicated that saturated hydraulic conductivity is often more responsive to disturbance than bulk density or porosity (e.g. Aust et al. 1995) which corresponds to findings in this study. Saturated hydraulic conductivity values for pre-harvest soil samples averaged 0.60 cm/hr for the Ap horizon (Table 2). Post-harvest, saturated hydraulic conductivity averages for the Ap horizon were significantly reduced ($p<0.0001$) to 0.19, 0.14, and 0.16 cm/hr for the Roundwood Only, Integrated, and Chip Only treatments, respectively. This can be caused by compaction of the soil due to machine trafficking during harvest. When examining the Btg horizon, no significant differences were detected between pre- and post-harvest values. These findings are similar to findings reported by (Aust et al. 1995, 1998), in that previous site preparation and harvesting regimes caused disturbance and made detection of disturbance related change hard to detect.

Bulk density rates were reduced in all treatments following harvesting (Table 2). The reductions were not at a high enough level in the Ap horizon to be significant. In the Ap horizon this can possibly be explained by an increase in the amount of organic matter following harvest.

These findings can also be attributed to a relatively small number of samples pre-harvest compared to the number of post-harvest samples collected. Often harvesting causes compaction and rutting on sites and increases bulk density due to reductions in pore space. The lack of significant harvesting effects can be related to the fact that the study occurred on a wet flat. These areas are often already disturbed due to natural stand conditions and previous management and are often more resistant to further harvesting related impacts than sites on better drained soils. High bulk density ranges as found on site are approaching levels that may impede root growth and reduce productivity of future rotations (Gent et al. 1983, Fox 2000, Page-Dumroese 2006). In the Btg horizon however, significant differences were detected ($p<0.0001$). Average bulk density reductions were found for all treatments following harvest, with the Roundwood Only treatment having the lowest values. A larger sample size following harvesting could have resulted in these findings. Also, there was a large amount of variation found within the bulk density samples taken in the Btg horizon, which can lead to the detection of more significant differences.

Porosity refers to the amount of space found within soil samples available for air and water to be held. Macropores are responsible for the rapid drainage of water through soils by gravity. Micropores bind to water using capillary forces making the water in these pores more difficult to be accessed by penetrating roots. Total porosity is the sum of the two values represented as a percentage of the volume. Macro porosity is a more commonly studied variable, as water and air found in the macropores are more easily accessed by penetrating roots. There were fluctuations in the macropores between treatments but they were variable and not found to be significantly different (Table 2). Micro porosity was found to increase in both the Ap and Btg horizons following harvest, possibly due to compaction of macropores into micropores. In the

Ap horizon the changes in micro porosity were not found to be significant, however in the Btg horizon changes were found to be significant (p=0.0010). These findings can be related to an increased amount of macropores being compacted into micropores, but it would be expected to find this same trend in the Ap horizon. Large variation within samples is more likely the reason for this finding. Total porosity followed the same trend as micro porosity; no significant difference were found in the Ap horizon, however significant differences were detected within the Btg horizon (p=0.0060). The similar findings of significance found within the Btg horizon for micro and total porosity can likely be explained by the same reasons.

Tests were next used to evaluate whether visual soil disturbance classes, nested within the treatments were valuable in determining the amount of change that had occurred to soil physical properties. Average values for each disturbance class was determined (Table 3) and used in order to evaluate whether or not significant differences could be found based on visual soil disturbance. When examining the classes for the Ap horizon, no significant differences could be determined between soil visual disturbance classes and any of the soil physical properties examined (Table 3). When examining bulk density, a majority of lower classes (more disturbed) had higher bulk density values, but this was not the case in every instance. The same is true with regard to hydraulic conductivity and macro porosity, with increases in conductivity and macro porosity being found in higher (less disturbed) classes. These variables are interrelated and therefore follow similar patterns. Micro and total porosity values varied so much that no distinctive trends could be found. In the Btg horizon, significant differences between disturbance classes were found when studying macro porosity, total porosity, and bulk density. Macro porosity had a p-value of 0.0003, total porosity a p-value of 0.0720, and bulk density had a p-value of 0.0711. Macro porosity changed in unexpected patterns as did total porosity, with lower disturbance classes (more disturbed) having higher macropore space, it would be expected that higher classes which are less disturbed would have more macropore space due to less mechanical disturbance. Bulk density varied across disturbance classes and the finding of significant differences here can possibly be explained by the variation and number of samples taken from each class. These findings suggest that soil disturbance classifications; although fast, simple and inexpensive to perform, have negligible value as an indicator of the amount of change to soil physical properties.

Summary and Conclusions

Based upon statistical tests, biomass harvesting intensity did not affect the degree to which soil physical properties were altered. Tests showed that all physical properties differed slightly after harvesting, some at significant levels. Conductivity is an important soil physical property in that it determines how fast water permeates the soil and becomes available to roots as well as how lateral flows through sub-soils will occur. Conductivity within the Ap horizon was found to be reduced at a significant level, meaning that best management practices (BMPs) and future site preparation may be needed to impede further site and stand damage. No significant differences were found within the Btg horizon. This is usually expected, especially within an environment such as the one this study was performed on where a thick clay horizon is found beneath the Ap horizon. Studies on similar coastal plain sites (Aust et al. 1993, 1995, and 1998) also reported decreases in hydraulic conductivity following harvest likely due to its relationship to macro porosity.

The variability of changes to bulk density can be attributed to the amount of residual woody debris found on site, the spatial variability in soil moisture, and block differences. When sites have low soil moisture values, such is the case on a majority of wet flats; the possibility of increasing soil bulk density due to trafficking is reduced as compared to sites that have higher soil moisture regimes (Greacen and Sands 1980). Ranges in values could also be attributed to differences across blocks, as the northwestern sites were slightly lower in elevation and had and increased amount of above-ground moisture as compared to the blocks located further southeast. It was evident as well that an increasing amount of residual woody debris was being left on site as the study progressed. After removing all stems in the Integrated and Chip Only units of the first block, the feller-buncher operator continuously removed fewer of the non-merchantable stems increasing the residual trafficking mat that equipment could operate on. Studies have found that leaving increased residual debris can help reduce compaction due to a more even distribution of machine weight (Han et al. 2009). The significant differences that were detected in the Btg horizon can be attributed to small sample size and spatial variability. The fact that these differences were only found in the Btg horizon and cannot be correlated to changes in other physical properties does not warrant extra BMPs.

Macro porosity varied depending on harvesting treatment, but the variations were not found to be significant in either horizon. Since macro porosity plays a large role in the availability of water to tree roots, it is often a more studied variable. Micro porosity was found to increase significantly only in the Btg horizon and these increases were related to the significant differences detected within the Btg horizon for total porosity. Often BMPs and site preparation are intended to reduce harvesting related disturbance in the upper soil horizons, so further BMP regulations may not be warranted, but may be installed depending on landowner objectives. The changes found on this wet flat are similar to findings by Aust et al. (1998) when total pore and micro pore space increased randomly across the study site.

Visual disturbance classifications are simple for trained professionals to perform, they are easy to determine and inexpensive. Significant differences were found when examining macro porosity, total porosity and bulk density, but only in the Btg horizon. The findings can possibly be explained by variation within samples and sample size. Based upon the number of statistically significant differences found, visual soil disturbance classes may not be the most accurate assessment used to determine a numerical value for the amount of change that has occurred to soil physical properties. The amount of change that is occurring in subsurface horizons may not be accurately assessed using visual soil disturbance due to residual debris found on site. As shown in Table 1, a majority of the study site remained classified as undisturbed (Class 5) following harvest. Within the Integrated and Chip Only treatments, typically non-merchantable stems were removed, however there were still broken branches and litter remaining on the surface layer, causing the litter layer on site to look similar to the litter layer of the conventional roundwood harvest. This would cause the sampler to identify the sample area as undisturbed although many passes may have been made over the area. Visual soil disturbance may also vary depending upon the sample location. Figure 3 shows a layout of major skid trails found on site. Visual disturbance classes (Figure 4) were determined by traversing the site using a 20 meter by 20 meter grid following harvest. Plots that were sampled in skid trails typically were more disturbed as compared to sample locations not located in skid trails due to stems removing the litter layer as they were skidded to the decking area. Findings similar to these, with respect to lack of accuracy of visual disturbance classes, have been documented in alternate studies conducted on visual soil disturbance (Aust et al. 1998, Bolding et al. 2009).

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Figure 1. Map showing the state of North Carolina, with Bertie County highlighted in black.

Figure 2. Study design layout consisted of 3 treatments replicated 3 times, for a total of 9 units located on site. Block 1 is the southeastern most block, followed by blocks 2 and 3 to the northwest.

Figure 3. Detail map showing where major skid trails where located throughout all treatments on site.

Figure 4. Visual soil disturbance as determined by using a 2 chain by 2 chain grid to traverse the study site.

Table 1. Distribution of area by percentage of total hectares that were covered by each visual soil disturbance class across the entire study site.

Table 2. Mean values of soil physical properties for pre- and post-harvest conditions following study implementation. Different letters within columns indicate significant difference using the Tukey HSD test with alpha = 0.10.

Table 3. Mean values of soil physical properties for the pre- and post-harvest conditions. Mean values are show by disturbance class for each condition. Different letters within columns indicate significant differences using the Tukey HSD test with alpha = 0.10.

Table 1. Distribution of area by percentage of total hectares that were covered by each visual soil disturbance class across the entire study site.

Treatment	Area (ha)	% Area in Class 5	% Area in Class 4	% Area in Classes 1-3
Preharvest	52	100	0	0
Roundwood Only	19	67	31	2
Integrated	20	59	33	8
Chip Only	13	56	41	3

Table 2. Mean values of soil physical properties for pre- and post-harvest conditions following study implementation. Different letters within columns indicate significant difference using the Tukey HSD test with alpha = 0.10.

	Treatment	**Bulk Density (g/cm^3)**	**Saturated Hydraulic Conductivity (cm/hr)**	**Macro porosity (%)**	**Micro porosity (%)**	**Total Porosity (%)**
Ap						
	Preharvest	1.38A	0.60A	6.04A	39.56A	45.60A
	Roundwood Only	1.26A	0.19B	6.77A	42.16A	48.93A
	Integrated	1.26A	0.14B	5.91A	42.77A	48.69A
	Chip Only	1.25A	0.16B	6.37A	42.93A	49.30A
Btg						
	Preharvest	1.56A	0.16AB	4.35A	37.14A	41.49A
	Roundwood Only	1.51AB	0.01A	2.84A	39.23AB	42.07AB
	Integrated	1.43C	0.07A	3.42A	40.36B	43.79B
	Chip Only	1.43BC	0.05A	3.88A	41.22B	45.09B

Table 3. Mean values of soil physical properties for the pre- and post-harvest conditions. Mean values are show by disturbance class for each condition. Different letters within columns indicate significant differences using the Tukey HSD test with alpha = 0.10.

Soil Horizon	Treatment	Soil Disturbance Class	Bulk Density (g/cm^3)	Saturated Hydraulic Conductivity (cm/hr)	Macro porosity (%)	Micro porosity (%)	Total Porosity (%)
A							
	Preharvest	5	1.38A	0.60A	6.04A	39.56A	45.60A
	Roundwood Only	3	1.44A	0.01A	1.07A	46.39A	47.46A
		4	1.31A	0.13A	6.25A	39.52A	45.77A
		5	1.21A	0.24A	7.46A	43.84A	51.30A
	Integrated	3	1.28A	0.01A	3.97A	44.66A	48.63A
		4	1.36A	0.13A	5.73A	40.31A	46.04A
		5	1.20A	0.17A	6.31A	44.14A	50.46A
	Chip Only	4	1.30A	0.06A	6.42A	41.90A	48.32A
		5	1.21A	0.25A	6.54A	43.73A	50.27A
B							
	Preharvest	5	1.56A	0.16A	4.35AB	37.14A	41.49B
	Roundwood Only	3	1.55ABC	0.01A	1.07C	43.17A	44.25AB
		4	1.54AB	0.01A	3.07A	38.61A	41.67AB
		5	1.50AB	0.02A	2.79C	39.41A	42.19AB
	Integrated	3	1.19C	0.23A	3.95ABC	46.84A	50.80A
		4	1.41BC	0.16A	3.67BC	41.63A	45.30AB
		5	1.47AB	0.01A	3.25BC	39.08A	42.33AB
	Chip Only	4	1.42ABC	0.04A	5.99A	40.58A	46.56A
		5	1.43BC	0.05A	2.39C	41.76A	44.16AB

Figure 1. Map showing the state of North Carolina, with Bertie County highlighted in black.

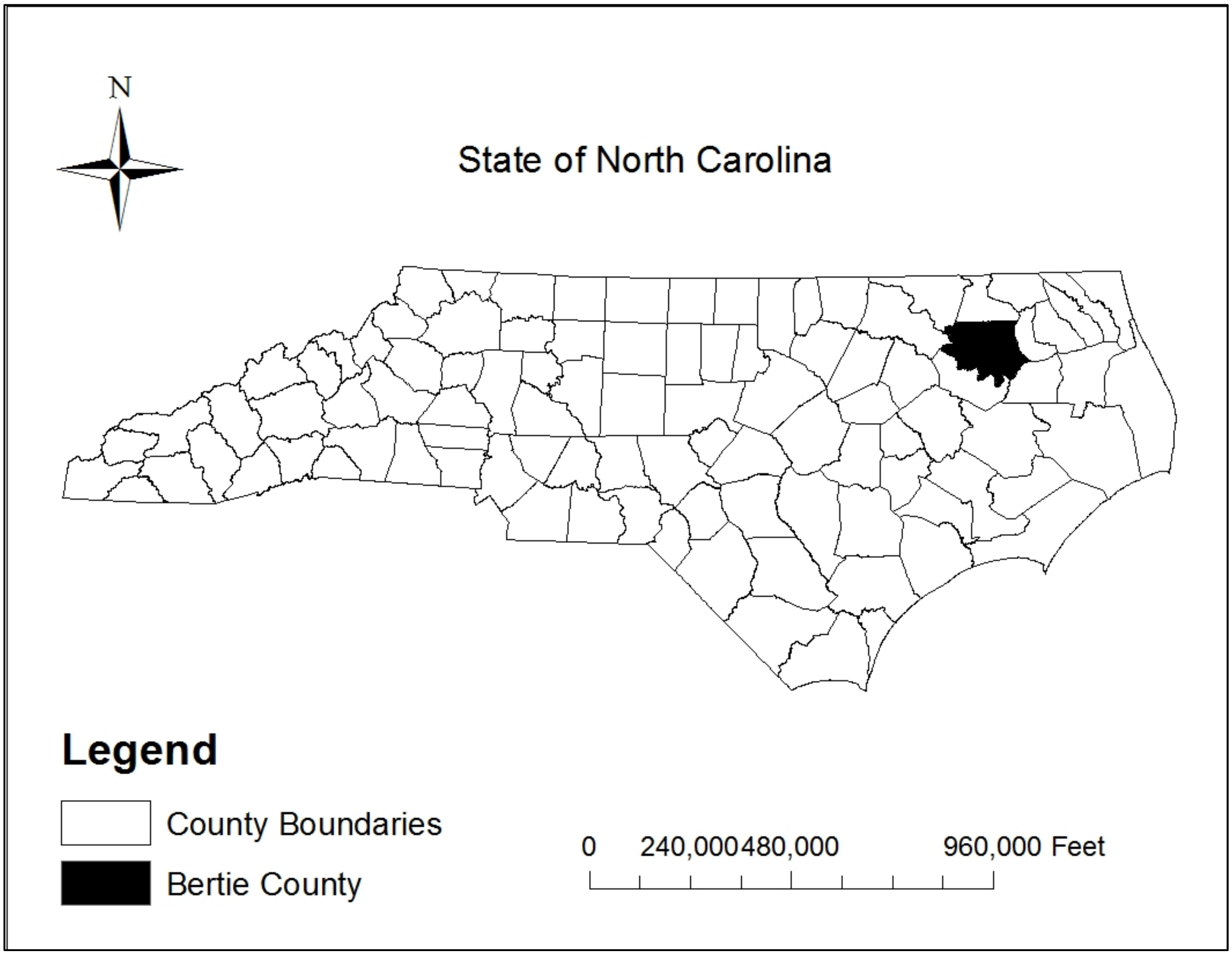

Figure 2. Study design layout consisted of 3 treatments replicated 3 times, for a total of 9 experimental units. Block 1 is the southeastern most block, followed by blocks 2 and 3 to the northwest.

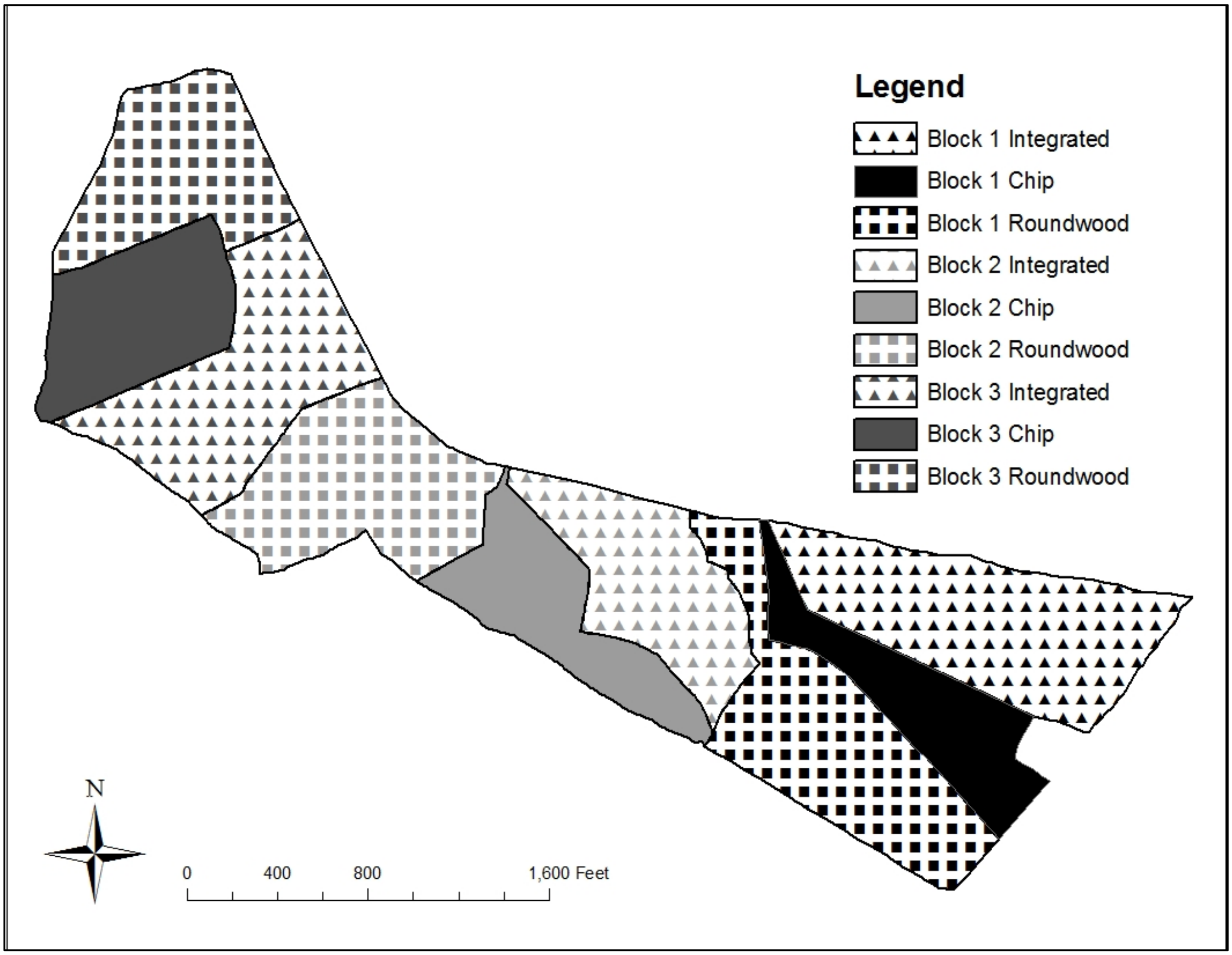

Figure 3. Detail map showing where major skid trails where located throughout all treatments on site.

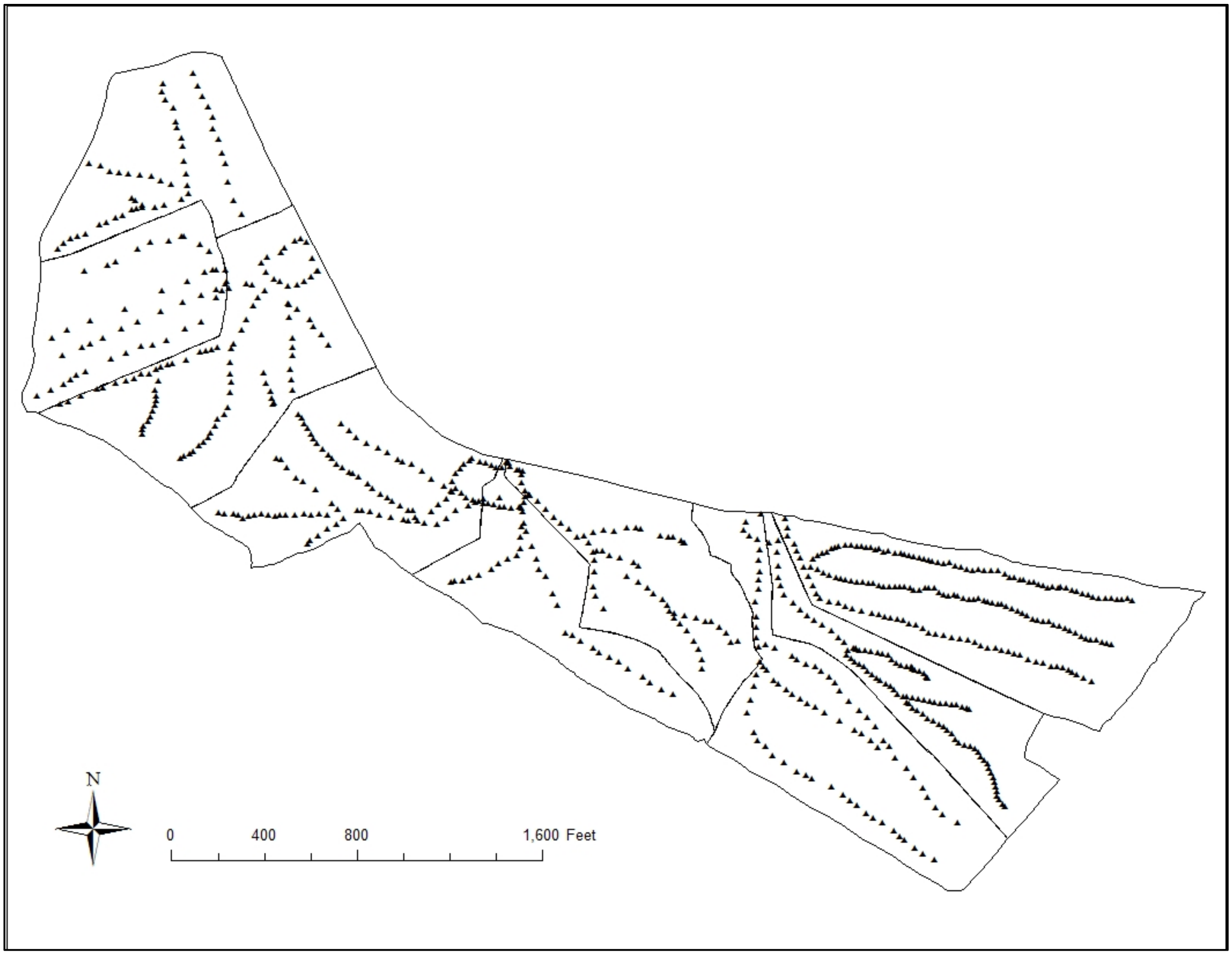

Figure 4. Visual soil disturbance results by classes (3-5) as determined by using a 2 chain by 2 chain grid to traverse the study site.