Evaluation of Coarse Woody Debris and Forest Litter Based on Harvest Treatment in a Tupelo-Cypress Wetland

by

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Abstract

Nutrient cycling in forested wetlands can be temporarily disrupted following timber harvesting, primarily through the removal of woody biomass from the area. Impacts to the carbon (C) cycle are especially pronounced. An important component of the C cycle in wetland systems is the detrital biomass deposited onto the wetland floor. The objective of this study was to evaluate the impacts of harvest treatments to detrital biomass, which consists of coarse woody debris (CWD) and forest litter. In 1986, a tupelo-cypress wetland was logged to investigate the long-term impacts of three timber harvest treatments. The three treatments were helicopter harvest (HELI), helicopter harvest followed by simulated skidder removal (SKID), and helicopter harvest followed by glyphosate herbicide application (GLYP). Adjacent to the treatment plots was an undisturbed reference area (REF). The volume of CWD and the CWD C mass for each treatment was determined along with the mass of C from the forest litter. Combining the C masses of the CWD and the litter revealed the SKID treatment contained the most detrital C on the forest floor with 6.53 megagrams of C per hectare (Mg-C/ha) followed by the HELI (5.94 Mg-C/ha) and the GLYP (1.74 Mg-C/ha). The REF plots contained 4.15 Mg-C/ha. The results show that the initial impact to detrital production following harvest in the SKID and HELI treatments were only temporary and the two harvest treatments are currently depositing more C onto the wetland floor than the REF, largely due to increased CWD deposits. The percentage of detrital C to aboveground C in all three treatments was shown to be higher than the REF treatment. The accelerated rates of nutrient cycling indicate that harvest treatments are rapidly recovering 24 years after harvest.

1.0 Introduction

Forested wetlands have long been valued by society as sources of hardwood timber and have been managed for centuries employing a wide range of logging techniques (Loehle et al., 2009; Willingham, 1990). Past concerns that logging forested wetlands would have long-term effects on site productivity (Aust and Blinn, 2004) resulted in several studies being conducted investigating the effects of various silvicultural practices (Aust et al., 2006; Lockaby et al., 1997a; Lockaby et al., 1997b; Shepard, 1994). In general, these studies demonstrated that clearcutting with natural regeneration resulted in an alteration of nutrient cycling in the initial years following harvest. One obvious alteration was in the C cycle as a result of the removal of large quantities of timber.

Carbon is utilized within wetlands by microbes and other fauna as an energy source. As the organic material is broken down and the C is utilized for energy, the nutrients once associated with the organic C are released (Mitsch and Gosselink, 2007). It is this association with energy production and nutrient cycling that has led some to label C as the hub of all biogeochemical process within wetlands (Reddy and DeLaune, 2008). Any change in the C cycle could have negative implications for other wetland processes.

Inputs from macrophyte and tree detritus represent the largest source of organic matter inputs into wetlands (Reddy and DeLaune, 2008). Tree detritus then represents an important component in the C cycle within forested wetlands. This detrital material could be in the form of woody debris (dead and downed trees and limbs) or forest litter (leaves, twigs, seeds, etc.) (USDA Forest Service, 2007; Woodall and Williams, 2005).

Within the few long-term studies that exist on harvesting forested wetlands, there is a paucity of data that quantifies the response of forest debris to harvesting events. Changes in production and accumulation of woody debris and forest litter can be detrimental to the wetland system. Therefore, it is important to monitor woody debris and forest litter to ensure the wetland processes are maintained in response to management practices.

2.0 Literature Review

Forested wetlands make up almost one-half of all remaining wetlands in the conterminous United States (Dahl, 2006). In the southeastern United States, the estimated area of forested wetlands exceeds 14 million ha (Messina and Conner, 1998). Southeastern forested wetlands are generally dominated by hardwood species and located along streams or in riverine floodplains. Forests with long hydroperiods, dominated by water tupelo (*Nyssa aquatic* L.) and bald cypress (*Taxodium distichum* (L.) Rich.), are often referred to as tupelo-cypress wetlands, deepwater swamps, or muck swamp (Hodges, 1997; Kellison and Young, 1997). These forests regulate a wide range of hydrological and biogeochemical functions through storage, transformation, and exportation processes (Walbridge, 1993).

Forested wetlands in the southern United States have been valued as a source of timber for hundreds of years. European settlers quickly discovered these areas provided fertile farmland once the wetlands were drained (Loehle et al., 2009). The trees cut during these land conversions were valued for shipbuilding and other uses. Federal regulations such as the Swamp Act of 1849 further encouraged the draining and filling of forested wetlands (Stine, 2008). Harvesting timber as a byproduct of land conversion continued until the middle of the 20th century when wetlands received stronger protection. Today, what is typically practiced is harvesting followed by natural regeneration of the site (Kellison and Young, 1997).

Several logging techniques were used throughout the centuries to remove timber from wetlands. Early harvesters relied on "float logging" to remove timber from these wetter areas (Willingham, 1990). Under this method, trees were felled and left on the forest floor prior to seasonal flooding. As the site flooded, the timber was floated to a nearby stream where they were bunched and floated to a nearby mill. In the dryer areas, animals were used to drag the timber from the forest and were delivered to the mills via railroad (Walker, 1991). By the late 1800s, pull-boat logging became popular, especially in forested wetlands adjacent to waterways (Willingham, 1990). With this technique, the timber was typically bunched and dragged out of the forest by steam-powered winches and cables. The repeated dragging of timber down the same path, or run, would carve out canals through the landscape ranging from 6 to 10-feet deep. Pull-boat operations created lasting effects in the landscape, with many pull boat runs still visible almost a century after being created (Lockaby et al., 1997c; Willingham, 1990). The advanced equipment available by the second half of the 20th century allowed for a type of harvesting in wetland areas that was more efficient with less environmental impact (Willingham, 1990). Today, ground-based harvesting using wide-tired skidders is the most common and cost-effective means of wood extraction for wet sites (Stokes and Schilling, 1997). The wide tires, which range in width from 700 mm to more than 1000 mm, increase the tire's surface area and reduce the pressure exerted on the forest soils. Timber removal by helicopter is also used under wet conditions but to a much lesser extent than skidder removal (Stokes and Schilling, 1997). Helicopter removal is thought to reduce soil disturbances caused by road construction and skidder trails, especially in wetter sites (Rummer, 2002). This method is only applicable in limited circumstances due to costs and implementation issues.

Relatively little information exists regarding the impacts of timber harvesting in deepwater swamps. It is only in recent decades that studies have investigated the effects of silvicultural practices in these systems, and even then most studies are limited to short-term results (Messina and Conner, 1998). The main impacts of harvesting timber in deepwater swamps are soil disturbance, changes in water quality, and changes in biogeochemical cycling.

Soil disturbances result from road and trail construction, equipment traffic, and the dragging of material across the soft forest floor. (Rummer, 2002). Such activities can cause physical displacement and loosening of soil, compaction, or puddling, all of which can be directly related to harvest intensity. Sheppard (1994) reported that soil disturbances can lead to increased sediment export from the forest site into surrounding water bodies, thereby decreasing water quality. He also found that silvicultural operations led to other measurable effects on water quality; however, the author concluded that these effects were typically small and relatively short-lived. The most common hydrological change seen after timber harvesting is an increase in elevation of soil water tables as a result of a reduction in transpiration (Lockaby et al., 1997c). Water levels typically return to normal after aboveground vegetation is re-established. Road design and trails are shown to have a greater impact on hydrology compared to the minor effects of tree removal.

Lockaby et al. (1997a) investigated the impacts to the biogeochemical processes of forested wetlands in response to partial and clearcut harvesting. The results of the study showed that one year after harvest there was statistically significant changes to total dissolved solids, nitrate, total phosphorus, and potassium in the waters leaving the harvested plots. The harvest treatments also showed a decrease in depth of soil oxidation and decrease in sedimentation compared to the unharvested control. A similar study reported that such changes in water quality and nutrient cycles were minimal in response to minor harvesting impacts (Lockaby et al., 1997b).

While changes in most biogeochemical processes and nutrient cycles are relatively minor, impacts to the C cycle are greatly affected by timber removal. Timber harvesting removes a significant amount of biomass from the forest C pool (Turner et al., 1995). Half of forest C is present in the aboveground biomass, which includes trees, woody debris, forest litter, and understory. Harvesting operations initially will result in an increase in woody debris, but the amounts are small compared to the large reductions in the other three components. Harvesting also can lead to changes in the below ground C pools as well. Loss of soil organic C results from decreased litter inputs, changes in root systems, increased soil temperature, and decrease in net primary productivity (Lal, 2005).

Carbon primarily enters the forest via the process of photosynthesis, the conversion of atmospheric carbon dioxide into plant biomass, and potentially from external sources based on landscape position. The C can be removed from the tree by annual leaf litterfall and woody debris deposition as the tree senesces. Under aerobic conditions, as the biomass lands on the forest floor, the process of decomposition is accelerated by microfauna and microbial communities found in the forest soil (Sylvia et al., 2005). The microfauna help break down the complex biomass structures into smaller, simpler forms, which are then utilized by the microbes as an energy source. The C in the biomass is oxidized by the microbes, eventually returning to the atmosphere. The C is released primarily in the form of CO_2, thus completing the nutrient cycle. Several other important nutrients are associated with the organic C in the plant biomass (eg. nitrogen, phosphorus, and sulfur). During the redox reactions carried out by the microbes, these other elements can be transformed and released as bioavailable nutrients (Schlesinger, 1997).

A critical part of the C cycle is the transfer of biomass from the plant to the forest floor. Forest debris, in the form of woody debris and forest litter, only makes up a small percentage (16 percent) of the total C pool in U.S. forests (Turner et al., 1995). This is partially the reason why forest debris historically has been overlooked in forest management. It was not until recent decades that scientists and forest managers came to realize the role that forest debris plays as a source and sink of C, nutrient regulator, wildlife habitat, fire fuel, and indicator of forest ecosystem health.

Woody debris includes all the forms of aboveground dead woody material and is generally divided into two broad categories: downed coarse woody debris (CWD) and snags (Harmon and Sexton, 1996). The USDA Forest Service (2007) defines CWD as downed, dead tree or shrub boles, large limbs, and other woody pieces that are severed from their original source of growth. This would include naturally occurring debris, as well as debris produced during timber harvesting. Coarse woody debris can influence hydrology and increase sedimentation by increasing surface roughness, thereby slowing flow velocity (Swanson and Lienkaemper, 1978; Hagan and Grove, 1999). Coarse woody debris also plays an important role in biogeochemical cycling of C and soil organic matter formation (Bradford et al., 2009). Furthermore, CWD has been shown to be a useful indicator of site productivity and management effects (Huston, 1996; NCASI, 2008). Changes in the volume of CWD could indicate a shift in species composition or biomass production.

Forest litter is defined as loose plant material found atop the mineral soil surface (USDA Forest Service, 2007). The forest litter is a significant part of the biogeochemical cycling within a forested wetland (Baker III et al., 2001). An estimated 43% of the total aboveground net primary productivity is represented by leaf material that returns to the forest floor each year (Conner, 1994). Therefore, forest litter can be a large source of C and nutrients within a forested wetland.

In response to concerns that timber harvesting in forested wetlands could potentially have lasting effects on water quality and site productivity, a long-term study was initiated to investigate the impact of various harvesting techniques (Aust and Blinn, 2004; Aust et al., 1997). Within the 25 ha study area, three major treatments were arranged in three 60 m x 60 m plots in a 3x3 Latin Squares design with an adjacent 3 x 3 reference area (Fig. 1). In the fall of 1986, the entire treatment area was clearcut with chainsaws and timber was removed using a Bell 205 helicopter (Bell Helicopter, Hurst, TX). This represents the treatment for plots designated as helicopter harvest (HELI). A Franklin 105 skidder (Franklin Treefarmer, Franklin, VA) with 86 cm wide tires was used to simulate ground-based harvesting in plots designated as skidder harvest (SKID). The skidder treatment resulted in tire ruts covering approximately 50% of the plot with an average depth of 30 cm. The third treatment (GLYP) consisted of glyphosate herbicide (The Monsanto Company, Creve Coeur, MO) being applied during the first two growing seasons to remove coppice and seed regeneration. The GLYP treatment was not meant to represent typical harvest techniques, but rather to investigate coppice and seed regeneration and to represent a severe site disturbance. This treatment resulted in plots converting into herbaceous-dominated marshes, which is not an effect of typical clearcutting practices. The adjacent reference area (REF) remained undisturbed without harvesting or glyphosate treatment. The REF plots could not be integrated within the treatment Latin Square design due to helicopter safety concerns during harvesting. Pre-harvest measurements showed no statistical difference between the reference and treatment areas. Detailed information about the site can be found in Aust et al. (2006).

Aust et al. (1997) evaluated site properties and stand growth seven years after harvest. The authors found that the HELI and SKID treatments contained equivalent amounts of biomass and species present, but the distribution of tree species in the two treatments were not the same. The HELI plots contained more Carolina ash while the SKID contained almost twice as many water tupelo stems. The authors suggest that the soil disturbance caused by the skidder in the SKID plots produced a wetter site that was more favorable to the water-tolerant water tupelo, while suppressing the growth of competing species such as Carolina ash. Both treatments contained large amounts of black willow (*Salix nigra* Marsh.), which were not present in the REF plots. The GLYP plots were converted into an herbaceous-dominated marsh with approximately 20 times less stems/ha than the other two harvest treatments. Sixteen years after harvest, the HELI and SKID plots contained approximately 20% of the REF plot biomass, which was deemed satisfactory (Aust et al., 2006). The authors did not measure biomass content of the GLYP plots at the time.

3.0 Objectives

The literature shows that timber harvesting in wetland systems can initially impact wetland indices by decreasing water quality, disrupting nutrient cycles, and decreasing habitat quality for wildlife (Clawson et al., 1997; Lockaby et al., 1997a; Lockaby et al., 1997b; Sheppard, 1994). Studies indicate that some of the impacts, such as those on water quality, are only short-lived (Sheppard, 1994). However, it remains unclear what long-term impacts harvesting has on the C cycle and, more specifically, the detrital portion of the cycle. Because of the large importance of detrital material for nutrient cycling and biodiversity in wetland systems, this study was designed to evaluate the amount of forest debris generated in response to harvest treatments in a bottomland hardwood forest 24 years after harvest. The study site used was the same as described by Aust et al. (2006). The sampling was conducted in plots that were subjected to three separate harvesting treatments and to plots located in an undisturbed reference area (see Section 2.0). The objectives of this study were: 1) to determine the influence of treatment on the volume (m^3/ha) and C weight (Mg-C/ha) of woody debris and, 2) to determine the influence of treatment on forest litter weight, C and N content.

4.0 Hypothesis

The following hypotheses were based on the site data provided by Aust et al. (2006) and on the general knowledge related to woody debris and forest litter.

- The GLYP treatment resulted in plots dominated by herbaceous plants; therefore, the volume of woody debris in the GLYP should be lower than from the HELI and SKID.
- The HELI and SKID treatments resulted in plots with equivalent biomass production; therefore, the volume of woody debris should not be significantly different between the HELI and SKID treatments.
- Mature plots should produce larger volumes of woody debris due to an increased rate of natural mortality; therefore the REF plots should have the largest volume of woody debris.
- Each harvest treatment resulted in a different species composition. The GLYP plots are mostly herbaceous, the SKIDs are dominated by tupelo, and the HELIs produced a larger percentage of cypress; therefore, the differences in species composition should result in

differences within the forest litter properties (total biomass, mass of C, mass of nitrogen) across all treatment types.

- The differences in the amounts of CWD volume and forest litter across treatments will correspond to a difference in total debris C; therefore, there should be statistical differences in the total debris mass C between treatments.

5.0 Study Site

The study site for this project is located approximately 35 km northeast of Mobile, AL along the western bank of the Tensaw River within the Mobile-Tensaw River Delta (30°53’21”N and 87°53’21”W). The Tensaw River is freshwater at the study site, but the flow is tidally influenced due to the close proximity to Mobile Bay (approximately 30 km). The climate at the site is classified as subtropical with an average yearly temperature of 20 °C and average rainfall of 1600 mm/year (Aust et al. 2006). Soil series of the area is classified as a Levy silty clay loam (Fine, mixed, superactive, acid, thermic, Typic Hydraquents). The entire study site was previously harvested in 1915 using a pull-boat operation followed by natural regrowth. The regrowth forest was a mixture of water tupelo (85%) and baldcypress (10%), along with Carolina ash (*Fraxinus caroliniana* Mill.), pumpkin ash (*Fraxinus profunda* (Bush) Bush), red maple (*Acer rubrum* L.), and water elm (*Planera aquatic* J.F. Gmel.) (5%).

6.0 Methods

6.1 Field Sampling

The study site has a slight elevation drop as distances upstream and away from the river increase. The second and third row of treatment plots remain flooded throughout a majority of the year, while the water table in the first row is typically lower. Due to the difficulty of taking ground measurements in flooded conditions, only the first row of treatment and reference plots were used for this study.

Initial sampling of CWD volume was conducted in the fall of 2009, 23 years after harvesting. A second sampling event to measure CWD was conducted in the fall of 2010. The two separate sampling events were used to evaluate the effects of annual flooding on CWD stocking. Litterfall also was collected in the fall of 2010.

Coarse woody debris was measured using a strip plot method (Harmon and Sexton, 1996). Four strip plots at 45, 135, 225, and 315 degrees extended from the center of the treatment plot. Strips were 15 m long by 2.75 m wide (41.25 m^2). Starting at the center of the treatment plot and walking towards the end of the strip plot, all CWD with a small-end diameter greater than or equal to 10 cm and that fell within the strip plot were counted. Large- and small-end diameters and length from large- to small-end diameter were measured. Portions of debris that fell outside the strip plot were not sampled. Each piece was rated on its degree of decomposition ranging from 1 (sound, intact, no rot) to 5 (no structural integrity, soft, powdery) (Table 1) (Woodall and Williams, 2005). The species of CWD was noted if it could be positively identified. Medium woody debris was measured in a sub-plot of each strip plot. Sub-plots were 5 m long and 1.375 m wide, and located in first portion of each strip plot. Medium woody debris was defined as having a diameter less than 10 cm, but greater than 2.5 cm. Medium woody debris volume is typically an insignificant amount compared to CWD; therefore, it was not quantified, but total count was noted (USDA Forest Service, 2007; Bate et al., 2004; Harmon and Sexton, 1996).

Litter samples were collected from three randomly chosen subplots within each treatment and reference plot, resulting in nine samples per treatment. The three samples from each whole treatment plot were composited for analysis. A PVC clip plot (0.125 m^2) was used for collection. Clip plots are a form of quadrant sampling in which the shape and size of the sample area remains constant, and materials within the sample quadrant are removed from the study area (Harmon and Sexton, 1996). Only samples that fell within the clip plot and to a maximum depth of 2 cm were collected.

6.2 Analysis

The volume (V) of CWD was quantified using the conic-paraboloid formula introduced by Fraver et al. (2007):

$$V = \frac{L}{12}(5A_b + 5A_u + 2\sqrt{A_bA_u})$$

where L is the length of transect, A_b is the diameter of the cross-sectional area at the larger end, and A_u is the diameter of cross-sectional area at the smaller end. The biomass weight (BW) of each piece was calculated by using the following formula:

$$BW = V * G * DC$$

where G is the species specific gravity and DC is the wood specific decay constant (Table 2) (Woodall and Williams, 2005). Specific gravity values were obtained from the USDA Forest Products Laboratory (2011) and are expressed on a dry weight basis. If the species of the debris could not be determined, an estimated specific gravity was used based on the proportions of species present in each treatment plot seven years after harvest (Aust et al. 1997). The decay constant used is based on the decay rating given to the piece of debris in the field and whether the species of wood is classified as a hardwood or softwood. The only softwood species present in the sample site was cypress. All other species and the unidentifiable pieces were designated as hardwoods. The C mass (CM) of each piece of debris was calculated by the following:

$$CM = BW * CF$$

where CF is the C conversion factor (Softwood = 0.521, Hardwood = 0.491) (Woodall and Williams, 2005).

The total volume and C mass of CWD that fell within the strip plot was determined. The average for the four strip plots were calculated and results for each treatment plot are reported as m^3/ha and Mg-C/ha for volume and C mass, respectively (Section 8.0). T-tests were used to compare the 2009 and 2010 CWD results for each treatment ($\alpha = 0.05$). No statistical difference was seen for the two sampling events; therefore, the 2009 and 2010 results were averaged to give a single reported value.

The forest litter samples from each treatment were washed with deionized water using a 1 mm screen to remove the silt and clay associated with the debris. A small amount of clay was still visible on the debris surface after washing. The samples then were placed in tared aluminum pans and dried for a minimum of three days at 70 °C. Once oven dried, the samples were weighed to obtain a dry biomass weight. Samples then were ground in a Thomas-Wiley Laboratory Mill Model 4 (Thomas Scientific, Swedesboro, NJ) and screened through a 0.5 mm screen. The samples were analyzed for percent C and N using a PE2400 Series II CHNS/O analyzer (PerkinElmer, Waltham, MA) along with percent ash by loss on ignition analysis (Nelson and Sommers, 1996). The ash free dry mass of each sample plot was calculated along with the mass of C and N.

The total C and N masses for each treatment plot are reported as Mg-C/ha and Mg-N/ha, respectively. The amount of C from litter was added to the woody debris C, which gives the total amount of detrital C for each treatment plot.

7.0 Statistical Procedure

The first row of the study site contained three plots for each of the three harvest treatments (HELI, SKID, GLYP) along with three reference plots for a total of 12 plots. The average volume of CWD and mass of C from all debris for each of the three treatments and references were analyzed using a one-way ANOVA to determine if there is a statistical difference between any of the four treatments, at $\alpha = 0.05$. If the ANOVA test indicated the means were not equal then a Tukey Honestly Significant Difference (HSD) test was performed to determine which of the treatments were significantly different from each other. Statistical analysis was performed in Microsoft Office Excel 2007 using the Analysis ToolPak.

8.0 Results

The HELI treatment contained the highest average amount of total CWD volume, with 37.84 m^3/ha. The average volume for the SKID, REF, and GLYP treatments contained 35.58, 16.80, and 5.98 m^3/ha, respectively. CWD volume in the GLYP plots were statistically different from the HELI and SKID means (p-value = 0.048).

The REF plots contained the highest number of medium woody debris pieces with 8,242 pieces/ha. The HELI, SKID, and GLYP contained 7,818, 5,878, and 2,060 pieces/ha, respectively. The medium woody debris count in the GLYP plots were statistically different from the REF and HELI means (p-value = 0.042).

The C mass of the CWD for the four treatments followed a similar trend as the volume results. The HELI contained 4.93 Mg-C/ha of woody debris C, followed by the SKID (4.83 Mg-C/ha), REF (2.57 Mg-C/ha), and then the GLYP treatment (0.89 Mg-C/ha). Unlike the volume results, the ANOVA test for C mass revealed that there was no statistical difference in the means of the four treatments, likely due to the large variance in treatment means. For the C mass from the forest litter, the SKID treatment contained 1.70 Mg-C/ha, followed by the REF (1.58 Mg-C/ha), the HELI (1.01 Mg-C/ha), and then the GLYP treatment (0.85 Mg-C/ha). There was no statistical difference between the treatment means.

The total amount of detrital C located on the plot floor was calculated by combining the C mass of the two debris components. The SKID treatment contained 6.53 Mg-C/ha of C mass, followed by HELI (5.94 Mg-C/ha), the REF (4.15 Mg-C/ha), and the GLYP (1.74 Mg-C/ha). There was no statistical difference between the treatment means.

The results show that the REF contained 0.056 Mg-N/ha of N mass present in the litter debris, followed by the SKID (0.051 Mg-N/ha), the HELI (0.036 Mg-N/ha), and the GLYP (0.030 Mg-N/ha). There was no statistical difference between treatment means. The resulting C:N ratios based on weight were 33 for the SKID, 29 for the GLYP, and 28 for the HELI and REF.

9.0 Discussion

As noted earlier the GLYP treatment is in a transition from herbaceous marsh to scrub-shrub wetland. The first hypothesis proposed that because of the abundant herbaceous groundcover, the GLYP treatment would have less CWD than the other harvest treatments. The results showed that the GLYP was indeed statistically different than the HELI and SKID. The

GLYP treatment represented a severely impacted harvest site where seed and coppice growth were initially inhibited. These results demonstrated that such treatment clearly had an impact on stand recovery and on woody debris stockings.

The second hypothesis of this study stated that volume of CWD in the SKID and HELI were not expected to be statistically different. This hypothesis was based on the finding of Aust et al. (2006) that 16 years after harvest both treatments contained equivalent amounts of overstory biomass. The authors did state there was a shift in species composition with the SKID providing more favorable growth condition for water tupelo than the HELI. The results of this study confirmed that this change in species composition had no statistical impact on CWD volume.

The volume of CWD in the HELI and SKID plots was more than twice the volume found in the REF treatment. The third hypothesis stated that the REF should have a larger volume due to the presence of larger, more mature trees that naturally drop woody debris as the trees age (Giese et al., 2003). One explanation for the increased volume in the harvested plots is the presence of black willow. Black willow is an early succession species, thriving in sunlight and moist soils, such as those found in harvested wetlands (Pitcher and McKnight, 1990). The wood of this species is considered weak and prone to breakage. The black willow is a short-lived forest species with a shallow root system. Aust et al. (1997) found an abundant amount of black willow seven years after harvest, second only to water tupelo. During this study, an overwhelming majority of the species of CWD that could be identified were black willow. Therefore, the increase in woody debris volume found in the HELI and SKID plots can partly be attributed to black willows' naturally falling out and severing limbs.

An alternative explanation involved the loss of stump sprouts as water tupelo trees mature. Sixteen years after harvest, Aust et al. (2006) noted that 75% of the tupelo stocking was due to stump sprouts. The authors also noted that the average amount of sprouts per stump had decreased from ten to five, a trend predicted to continue. The natural fall out of water tupelo sprouts would increase coarse woody debris volumes in the younger, harvested treatments, while the loss of sprouts in the REF plots is much slower, if it continued to occur at all.

The amount of medium debris in the REF treatment was higher than the three harvest treatments. The amount of medium debris produced is often directly proportional to the amount of medium woody material present in the live biomass (Harmon and Sexton, 1996). The amount of small branches is positively correlated with stand age, so this type of debris would be expected to be produced in greater quantities in a mature stand.

The C mass of the forest litter across the four treatments was hypothesized to be different based on the varying density and composition in the aboveground biomass. The results showed no significant difference in the treatment means. The harvest treatments were similar to the REF average, suggesting the high amounts of net primary productivity was occurring in the young HELI and SKID plots and the disturbed GLYP plots. The amount of N entering the forest floor via litter deposits also was comparable across all four treatments. The resulting C:N ratios of the forest litter were tightly grouped ranging from 28 to 33. The C:N ratios found are very close to the optimum range for microbial mineralization of N. Once mineralized, the N would be available for re-uptake by the forest plant community, supporting further growth and recovery.

It was predicted that the volume of CWD and amount of forest litter would be statistically different across treatments. Therefore, the final hypothesis stated that the total detrital C mass should be different as well. The results, however, showed no statistical difference. The SKID and

HELI total C mass was quite comparable. Both treatments had large amounts of detrital C, mainly due to the increased volume of CWD.

A recent study investigated above and belowground C pools at the study site (McKee, 2011). The aboveground C pool consisted of overstory, lower story, and herbaceous measurements but not aboveground detrital C. The results of that study showed that the REF contained the highest aboveground C pool with 209.7 Mg-C/ha. The SKID and HELI followed with 77.1 Mg-C/ha and 55.7 Mg-C/ha, respectively. The GLYP contained the lowest amount with 28.3 Mg-C/ha. The author concluded that overstory biomass had the greatest influence on aboveground C pools, which explains the large C storage in the mature REF treatment. Detrital C masses measured in this study were compared against the aboveground C pool results reported by McKee. The HELI contained the highest detrital C to aboveground C percentage with 10.7 percent. The SKID and the GLYP followed closely with 8.5 and 6.1 percent, respectively. The REF contained the lowest percentage with 2.0 percent.

The results show that detrital C masses are indeed a small portion of the aboveground C pools. This, however, does not imply that the detrital C is insignificant. The HELI and SKID contained both greater amounts of detrital C and higher percentages of detrital to aboveground C than the REF, which was both surprising and promising. This early pulse of debris onto the wetland floor provided a much needed energy and nutrient source, as well as valuable habitat as the harvested sites recovered. Even the small amount of detrital C found in the GLYP treatment resulted in a higher detrital C to aboveground C percentage than the REF. This demonstrated that even thought the C cycle was severely impacted in the GLYP plots, recovery and C cycling still occurred, although at a much slower pace.

10.0 Conclusions

The results of this study showed the HELI and SKID treatments contained approximately twice as much CWD volume and C mass as the REF treatment, and both contained equivalent amount of forest litter C as the REF. In all cases, the HELI and SKID resulted in nearly equivalent values, indicating that neither harvest treatment resulted in different effects on CWD or C mass. When compared to the REF treatment, the results of this study show that the HELI and SKID harvest had no negative lasting impact on CWD and forest litter production 24 years after harvest. This finding coincides with other studies that concluded that the HELI and SKID treatments resulted in adequate biomass growth rates, and both are on an acceptable trajectory for recovery (Aust et al., 2006; McKee, 2011).

The GLYP treatment resulted in less CWD volume and forest litter mass than the other three treatments. This is due to the glyphosate application for two years after harvest, inhibiting seed growth and coppice regeneration and resulting in a high disturbance treatment. This study found that while the GLYP plots contained low amount of detrital C and aboveground C, the ratio of the two was higher than those found in the REF treatment. This suggested that nutrient cycling was very active in the GLYP plots and that they were recovering, just at a slow pace. This conclusion was supported by McKee (2011) who stated the GLYP plots were transitioning into a bottomland hardwood wetland after starting as an herbaceous marsh. The active cycling is likely due to the faster rates of biomass turnover inherent to the herbaceous plant species which continue to have a large presence in these treatment plots.

The findings of this and other studies at the site revealed that helicopter and skidder harvest techniques resulted in minimal impacts to above-ground detrital C dynamics. Therefore, it's evident that clearcutting followed by helicopter harvesting and clearcutting followed by skidder harvesting are both acceptable silvicultural treatments for this type of wetland. Aust et al. (2006) concluded that site specific properties, such as large annual sediment inputs and shrink-swell clays, contributed to the recovery of the harvested sites. Results from this study may not apply to all wetland types. Therefore, there is a need for more long-term studies on the effects of harvesting in other types of forested wetlands. Specifically, there is a need for more CWD and forest litter research from forested wetlands in all stages of development following timber harvesting.

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Figures and Tables

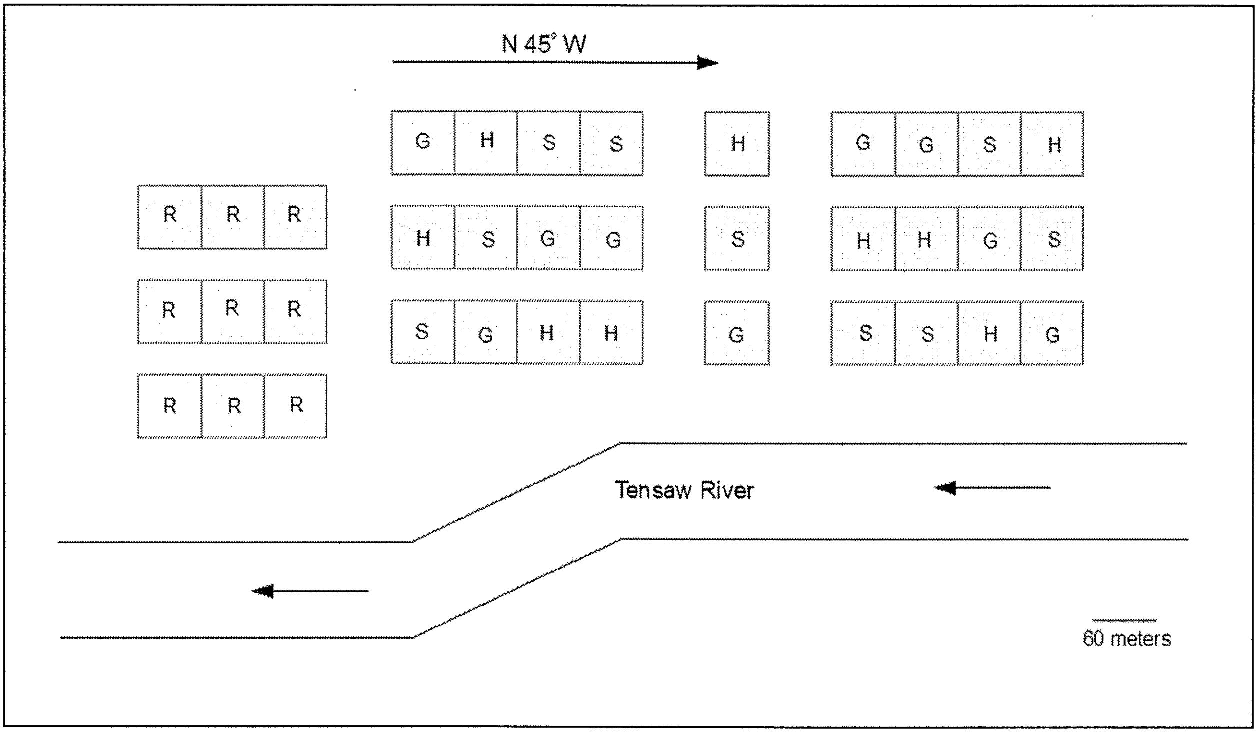

Figure 1 Study site treatment arrangement. R = undisturbed reference area (REF); H = helicopter harvested (HELI); S = skidder simulated harvest (SKID); G = glyphosate treatment (GLYP). Plots are 60 x 60 meters. Adapted from Aust and Lea (1991).

Table 1 Coarse woody debris decomposition classification

Decay class	Structural Integrity	Texture of Rotten Portion	Color of Wood	Invading Roots	Branches and Twigs
1	Sound, freshly fallen, intact logs	Intact, no rot; conks of stem decay absent	Original color	Absent	If branches are present, fine twigs are still attached and have tight bark
2	Sound	Mostly intact; sapwood partly soft (starting to decay) but can't be pulled apart by hand	Original color	Absent	If branches are present, many fine twigs are gone and remaining fine twigs have peeling bark
3	Heartwood sound; piece supports its own weight	Hard, large pieces; sapwood can be pulled apart by hand or sapwood absent	Reddish-brown or original color	Sapwood only	Branch stubs will not pull out
4	Heartwood rotten; piece does not support its own weight, but maintains its shape	Soft, small blocky pieces; a metal pin can be pushed into heartwood	Reddish or light brown	Through-out	Branch stubs pull out
5	None; piece no longer maintains its shape, it spreads out on ground	Soft; powdery when dry	Red-brown to dark brown	Through-out	Branch stubs and pitch pockets have usually rotted down

Table 2 Wood specific decay constant

Decay Class	**Softwood**	**Hardwood**
1	1	1
2	0.84	0.78
3	0.71	0.45
4	0.45	0.42
5	0.45	0.42

Table 3 Coarse woody debris volume, m^3/ha

HELI		SKID		GLYP		REF	
Plot 2	37.111	Plot 3	23.776	Plot 1	5.429	Plot 28	9.790
Plot 6	31.405	Plot 4	26.187	Plot 5	5.648	Plot 29	4.334
Plot 7	45.002	Plot 9	56.785	Plot 8	6.874	Plot 30	36.273
Average	37.84(a)	Average	35.58(a)	Average	5.98(b)	Average	16.80(ab)

Values with different letters are significantly different (alpha = 0.05)

Table 4 Medium woody debris count, number of pieces/ha

HELI		SKID		GLYP		REF	
Plot 2	7636	Plot 3	2545	Plot 1	2727	Plot 28	7455
Plot 6	6364	Plot 4	7818	Plot 5	1455	Plot 29	5455
Plot 7	9455	Plot 9	7273	Plot 8	2000	Plot 30	11818
Average	7818(a)	Average	5879(a)	Average	2061(b)	Average	8242(a)

Values with different letters are significantly different (alpha = 0.05)

Table 5 Coarse woody debris C mass, Mg-C/ha

HELI		SKID		GLYP		REF	
Plot 2	5.6	Plot 3	2.5	Plot 1	0.971	Plot 28	1.6
Plot 6	3.8	Plot 4	3.6	Plot 5	0.557	Plot 29	0.8
Plot 7	5.4	Plot 9	8.4	Plot 8	1.138	Plot 30	5.3
Average	4.93(a)	Average	4.83(a)	Average	0.89(a)	Average	2.57(a)

Values with different letters are significantly different (alpha = 0.05)

Table 6 Forest litter C mass, Mg-C/ha

HELI		SKID		GLYP		REF	
Plot 2	1.27	Plot 3	0.97	Plot 1	1.21	Plot 28	0.84
Plot 6	0.95	Plot 4	1.89	Plot 5	0.92	Plot 29	2.26
Plot 7	0.82	Plot 9	2.24	Plot 8	0.44	Plot 30	1.63
Average	1.01(a)	Average	1.70(a)	Average	0.85(a)	Average	1.58(a)

Values with different letters are significantly different (alpha = 0.05)

Table 7 Total detrital C mass, Mg-C/ha

HELI		SKID		GLYP		REF	
Plot 2	6.85	Plot 3	3.51	Plot 1	2.18	Plot 28	2.46
Plot 6	4.74	Plot 4	5.46	Plot 5	1.48	Plot 29	3.05
Plot 7	6.24	Plot 9	10.62	Plot 8	1.57	Plot 30	6.94
Average	5.94(a)	Average	6.53(a)	Average	1.74(a)	Average	4.15(a)

Values with different letters are significantly different (alpha = 0.05)

Table 8 Litter nitrogen mass, Mg-N/ha

HELI		SKID		GLYP		REF	
Plot 2	0.041	Plot 3	0.035	Plot 1	0.044	Plot 28	0.034
Plot 6	0.038	Plot 4	0.056	Plot 5	0.030	Plot 29	0.079
Plot 7	0.030	Plot 9	0.060	Plot 8	0.016	Plot 30	0.056
Average	0.036(a)	Average	0.051(a)	Average	0.030(a)	Average	0.056(a)

Values with different letters are significantly different (alpha = 0.05)