EFFECT OF FOREST HARVESTING BEST MANAGEMENT PRACTICES ON COARSE WOODY DEBRIS DISTRIBUTION IN STREAM AND RIPARIAN ZONES IN THREE APPALACHIAN WATERSHEDS

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Abstract. The distribution of coarse woody debris (CWD) was analyzed in three Appalachian watersheds in eastern Kentucky, eighteen years after harvest. The three watersheds included an unharvested control (Control), a second watershed with best management practices (BMPs) applied that included a 15.2 m unharvested zone near the stream (BMP watershed), and a third watershed that was harvested without strict BMPs with harvesting occurring up to the stream edge and slash left within the stream and riparian zones (No BMP watershed). We assessed the CWD occurring both within the riparian zone and stream in the three watersheds. Within both stream and riparian zones, the BMP and No BMP watersheds contained more CWD biomass than in the Control, however, the No BMP watershed CWD was in a more advanced state of decay than in either the BMP or Control watersheds. Nitrogen content in CWD was also greater in the No BMP watershed because of the more advanced state of the decay. The CWD present in the Control is the result of natural forest processes such as death and self-pruning. The CWD in the No BMP watershed is a result of the slash left behind after the harvest since little opportunity exists for new recruitment of CWD from the surrounding area. From our decay class data, it is apparent that at least some of the CWD in the BMP watershed has occurred since harvest, and, based on our biomass data, at a much greater rate of recruitment than in the Control watershed. We hypothesize that the harvest outside of the riparian zone in the BMP watershed may have led to greater windthrow and/or slumping than in the Control watershed. As such, our data suggest that riparian zones of 15.2 m may not be effective in maintaining the short-term integrity of the CWD pool within steep gradient Appalachian systems.

Keywords: best management practices, carbon, coarse woody debris, nitrogen, riparian, stream, watershed

1. Introduction

Coarse woody debris (CWD) is widely recognized as an extremely important structural and functional component of forest communities (Harmon *et al.*, 1986; Muller and Liu, 1991; Huston, 1993; Van Lear, 1993; McCarthy and Bailey, 1994). Within undisturbed systems, CWD is composed of branches or boles formed from self-pruned, naturally damaged, or dead trees. The structural component of CWD

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also influences stream dynamics within an ecosystem by controlling sediment flux, stream turbidity, and stream orientation (Harmon *et al.*, 1986; Maser *et al.*, 1988; Dolloff, 1993; Wallace *et al.*, 1993; Hedman *et al.*, 1996; Bragg and Kershner, 1999). Ecologically, CWD provides a large reservoir of nutrients and energy essential to the detrital food chain, nutrient cycling, plant growth, and productivity (Harmon *et al.*, 1986; Muller and Liu, 1991; Huston, 1993; Goodburn and Lorimer, 1998). Combined, the physical structure and energy provided by CWD is shown to increase the biological diversity in forest ecosystems (Hansen *et al.*, 1991; Swanson and Franklin, 1992; McCarthy and Bailey, 1994). Also, the simultaneous provision of both physical structure and energy provides favorable germinating sites and establishment substrates for various plants and fungi (Sharitz, 1993), while providing important and essential microhabitat for numerous species of fauna (Muller and Liu, 1991; Carey and Johnson, 1995). Therefore, CWD is a biological legacy that has serious implications on forest health, especially within sensitive riparian zones.

Riparian areas are three-dimensional ecotones of interaction that include terrestrial and aquatic ecosystems, that extend down into the groundwater, up above the canopy, outward across the floodplain, up the near-slopes that drain to the water, laterally into the terrestrial ecosystem, and along the water course at a variable width (Ilhardt *et al.*, 2000) is the area above and below the ground surface that borders a river or stream. In as such, the vegetative condition of the riparian zone influences CWD recruitment to the stream, which in turn influences streams and the complex interactions between the terrestrial and aquatic environments (Hedman *et al.*, 1996; Bragg and Kershner, 1999; Blinn and Kilgore, 2001). The dynamics of CWD and its structural importance within riparian forest communities are little understood (MacMillan, 1988). Several studies have either characterized or modeled CWD within riparian zones (Triska and Cromack, 1980; Robinson and Beschta, 1990; Van Sickle and Gregory, 1990; Hedman *et al.*, 1996; Hairston-Strang and Adams, 1998; Bragg, 2000), but very little is known about Central Appalachian riparian communities (Hedman *et al.*, 1996). Even less is known about managed forest communities due to the past importance placed on 'old-growth' CWD surveys (MacMillan, 1988; Muller and Liu, 1991; Tyrell and Crow, 1994; Spetich *et al.*, 1999).

Deposition and distribution of CWD is a function of forest type, successional stage, pathogen activity, meteorological events, fire, decay rates, and harvest activities (Muller and Liu, 1991; Van Lear, 1993; Graham *et al.*, 1994; McCarthy and Bailey, 1994; Hagan and Grove, 1999). Harvest activities are the greatest anthropogenic factor influencing the recruitment and retention of CWD within forested riparian communities (Bragg and Kershner, 1999). Because timber harvesting removes future CWD, CWD is one of the slowest functional components to recover after harvesting (Spies *et al.*, 1988). Therefore, to curtail and limit the future losses of CWD recruitment and other ecological processes, the forestry community is ascribing to the use of Best Management Practices (BMPs) that use riparian buffer strips. All states that have developed forestry BMP guidelines or regulations use some form of riparian buffer strip for perennial streams but their proper implementation into regulated or voluntary BMPs is debated.

Riparian buffer strips are areas of the riparian zone that are either left uncut or partially cut during a harvest. The main function of buffer strips is to control non-point source pollution. Also, the strips may help maintain biological diversity and ecological functioning, including the retention of CWD and its functional properties. Huston (1993) stated 'No other manageable property of the forest environment has a greater impact on biodiversity than CWD'. However, the effectiveness of riparian buffer strips on maintaining short- and long-term CWD pools is poorly understood and lacks relevant data. The purpose of our study was to determine if differences exist in CWD biomass, decay class, nitrogen and carbon content within stream and riparian areas in three forested watersheds that varied with harvest intensity and BMP implementation both outside and inside the riparian zone. The study hopes to create an understanding of CWD dynamics for the improvement, development, and implementation of BMPs for Central Appalachian forest communities.

2. Methods

2.1. Study Site

The study site consisted of three streams and riparian zones located within Robinson Forest, the University of Kentucky's experimental research and demonstration forest (Figure 1). The forest is located within the Cumberland Plateau Physiographic Province within the southeast portion of Kentucky (37°27′ N, 83°8′ W; 245 to 475 m elevation). The area is located within the Mixed Mesophytic Forest Region, as described and defined by Braun (1950). The climate is temperate, consisting of humid, warm summers and cool winters. Soils near the streams are of the Grigsby–Rowdy complex. Grigsby soils are deep, well drained, coarse-loamy and found in alluvial valley bottoms. Rowdy soils are fine loamy and found on low terraces (Overstreet, 1984). The streams are all first order perennial streams that ultimately flow into the North Fork of the Kentucky River. The slopes of the streams range from 7% to 22%, whereas the riparian sideslopes ranged from 33% to 88%.

The three watersheds included an unharvested control (Control, 10.7 ha), a second watershed with best management practices (BMPs) applied that included a 15.2 m (50 ft.) unharvested zone near the stream (BMP watershed, 11.0 ha), and a third watershed that was harvested without strict BMPs with harvesting occurring up to the stream edge and slash left within the stream and riparian zones (No BMP watershed, 16.3 ha). The BMP and No BMP watersheds were harvested in 1983 and CWD sampling was conducted the summer of 2001, 18 years after harvest. The harvesting of the BMP and No BMP watersheds consisted of a complete silvicultural clearcut. Commercial sawtimber logs were removed from the sites and all

Figure 1. Location of Robinson Experimental Forest and a thematic of the plot design.

stems <5 cm dbh were cut and left on site (Arthur *et al.*, 1998). Prior to harvest, all watersheds were 70+ years in age and the overstory was dominated by oaks (*Quercus* spp.; 39% of overstory density), hickories (*Carya* spp.; 17% of overstory density), and yellow poplar (*Lirodendron tulipifera* L.; 15% of overstory density) (Overstreet, 1984).

2.2. CWD SAMPLING

The sample zone on each side of the stream was delineated for each watershed using the 1983 KY BMP guidelines that call for 15.2 m (50 ft.) riparian buffer strips (Figure 1). The downstream plot boundary began at H-flumes and rebar was placed every 25 m (linear, not stream distance) in the stream to identify plot corners. From each stream rebar, another rebar was installed perpendicular from stream center, uphill, 7.6 m (25 ft.) into the riparian buffer zone. This point describes the mid-point of the stream's right and left flanking riparian zone. Because of the sinuosity of the stream, plots were not identical in size. Plots were approximately 380 m^2 (15.2 m $*$ 25 m) and extended 200 meters upstream for a total of eight plots on any one side of the stream or 16 plots within a watershed (Figure 1). The true area of each riparian zone was determined by using the planimetric measurement of each zone's schematic diagram based on recorded measurements of distance and bearing between rebar. Stream plots were 25 m in length (distance between rebar points), bankfull wide and also extended 200 m upstream from the H-flumes. Within a single watershed there were eight stream plots (Figure 1). Because stream channel width varied, stream area also varied and ranged between 28.75 and 43.74 m^2.

The rebar pins were used as reference points to locate and measure all pieces of CWD present in the plots. We defined CWD to be at least 10 cm in diameter and at least 10 cm in length. Data was collected for each piece of CWD within each riparian and stream plot and for pieces that began in riparian plots but extended uphill outside of the riparian plots. For CWD that overlapped between riparian and upland and riparian and stream plot borders, we estimated a visual percentage of each piece within the plot. Each piece of CWD was assigned a distinct identification number. For pieces with branching, each continuous intact branch was given the same identification number as the parent CWD, but then given a subset letter to separate their identity. Each piece was referenced by location to the nearest pin. From the pin, horizontal distance and azimuth were measured to the nearest end of each piece of CWD. Once at the piece of CWD, diameter was measured at three locations (ends and middle) and an azimuth was taken along the length of each piece to indicate orientation. Diameter was measured with an aluminum caliper and was determined as the mean of the three measurements for each piece.

Each piece of CWD was also classified as either a ground or snag piece. A piece was considered a ground piece if it was touching the soil surface for over 50% of its length. If a piece was suspended above the ground for >50% of its length, then it was classified as a snag. Every piece of CWD measured was classified by a five-class decay ranking system (Harmon *et al.*, 1986; Muller and Liu, 1991; McCarthy and Bailey, 1994; Tyrell and Crow, 1994; Goodburn and Lorimer, 1998; Spetich *et al.*, 1999; Idol *et al.*, 2001). A class 1 piece of CWD is freshly fallen, consisting of fine branches, intact bark and sound wood. Class 2 pieces still contained bark, had larger branches and fairly sound wood. Class 3 pieces had lost most of their bark and the outer wood was somewhat decayed. Class 4 pieces had lost all branches and bark and have little sound wood but still have enough structural integrity to measure. According to the literature, class 5 pieces have lost all branches, all bark, and have no wood integrity. For this study, class 5 pieces were not measured because of the difficulty in accurately measuring diameter when CWD has no solid wood and also because of the difficulties that would have occurred when sampling for density (see below). Class 2 and 3 pieces were sometimes difficult to separate so we used a hatchet to determine the extent of sound wood to better distinguish between 2s and 3s.

Every piece of CWD was tagged with a button-capped nail. CWD was marked to keep track of measured pieces and also for future CWD recruitment studies. Eighty-two sample discs were taken from a subset of CWD to measure density. The discs represented CWD from all watersheds, decay classes and diameter classes. Discs were cut from a previously measured piece of CWD with a chainsaw, inserted into large plastic ziploc bags and taken to the University of Kentucky Department of Forestry. Prior to oven-drying, five width measurements and three diameter measurements were taken for each piece to calculate the volume. Discs were oven-dried at 65 °C for one week and weighed. Density was calculated based on the oven-dry mass and the calculated wet volume. The mean density per decay class was used, along with the length and mean diameter to determine the total biomass for each piece of CWD measured.

After density measurements, samples were taken from each piece for nutrient analysis. A 'pie-piece' section was cut from each disc using a band saw. The 'pie-

pieces' were ground with a large mill and then finely ground with a Wiley mill. The resulting powder from each sample was sent to the University of Kentucky's Regulatory Services for analysis of carbon and nitrogen. For QA/QC, twenty duplicate samples cut from the same disc were analyzed to assess variability within a disc and a second set of twenty duplicate samples were split from the original sample to assess analysis variability. Both sets of duplicate samples had <3.6% mean difference with standard errors <1.2%.

2.3. Statistical Analyses

Because the experimental unit in this study is the watershed, this is a pseudoreplicated experiment. Conclusions can only be drawn for the three watersheds and not the entire population of Central Appalachian watersheds. However, we consider the three watersheds as typical for Central Appalachian watersheds and the treatments to be typical of forest harvest operations in the region. Also, we must assume that the watersheds did not vary in CWD distribution prior to treatment installation. We are confident in this assumption because the watersheds are similar in size, elevation, slope, aspect and had similar standing timber characteristics prior to harvest.

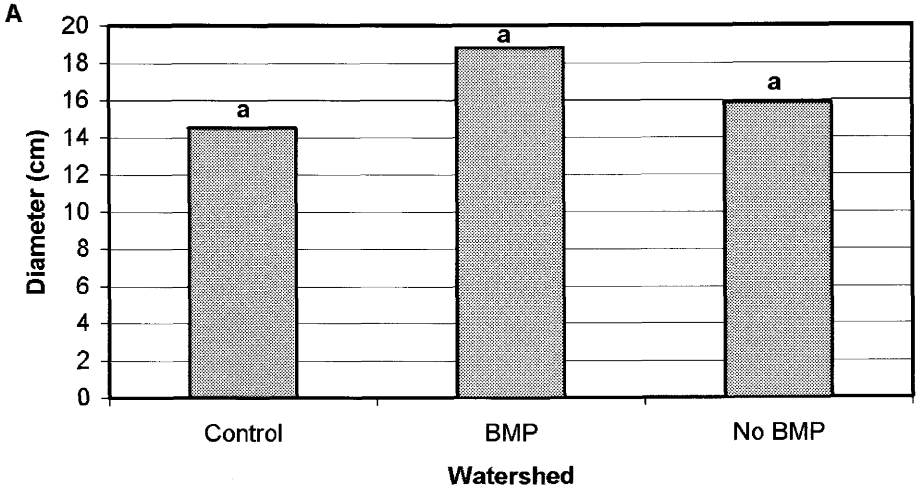
Unless otherwise indicated, single factor analysis of variance (ANOVA) and Tukey's multiple range test were used to assess all pairwise contrasts among watersheds. Tests were performed to assess differences in diameter, length, volume, decay class, biomass and nitrogen content within the riparian and stream zones among the three watersheds. Effects were considered significant when $p < 0.05$.

3. Results

A total of 1109 pieces of CWD were tallied with the No BMP (463) watershed and the BMP (384) watershed having considerably more pieces than the Control watershed (262).

3.1. CWD Diameter, Length, Volume and Decay Class

Riparian zone or stream zone CWD diameter did not vary among watersheds although CWD in the BMP watershed tended to be slightly greater in diameter than in the Control or No BMP watershed (Figure 2). Length of CWD within the riparian zone did vary by watershed with the No BMP watershed containing significantly longer pieces of CWD than the Control or BMP watersheds (Figure 3). No differences were found for length within the stream zone although the No BMP watershed tended to have longer pieces than in the Control and BMP watersheds (Figure 3). Volume is the result of diameter and length and, although there were few statistical differences in diameter and length there were differences in volume among watersheds because of the greater number of pieces of CWD present in the



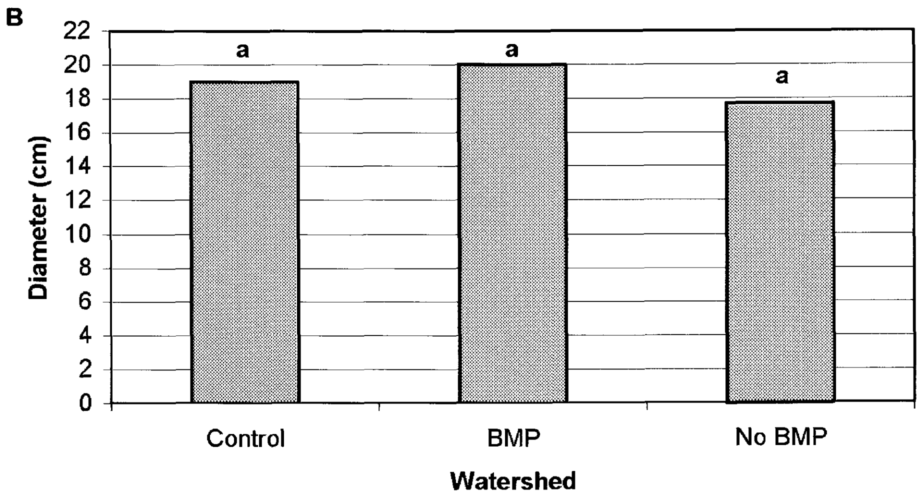


Figure 2. Watershed comparison of mean CWD diameter for riparian (A) and stream (B) plots. Different letters above the bars indicate significance at the $p < 0.05$ level.

BMP and No BMP watersheds (Figure 4). Riparian and stream zone volume was greatest in the BMP and No BMP watershed and lowest in the Control watershed. Density of CWD did differentiate among decay class although we found no statistical difference in density between 1s and 2s, and 2s and 3s (Figure 5). Decay class also varied among watersheds with the No BMP watershed having significantly higher mean decay class than the BMP and Control watersheds in both the riparian and stream zones (Figure 6).

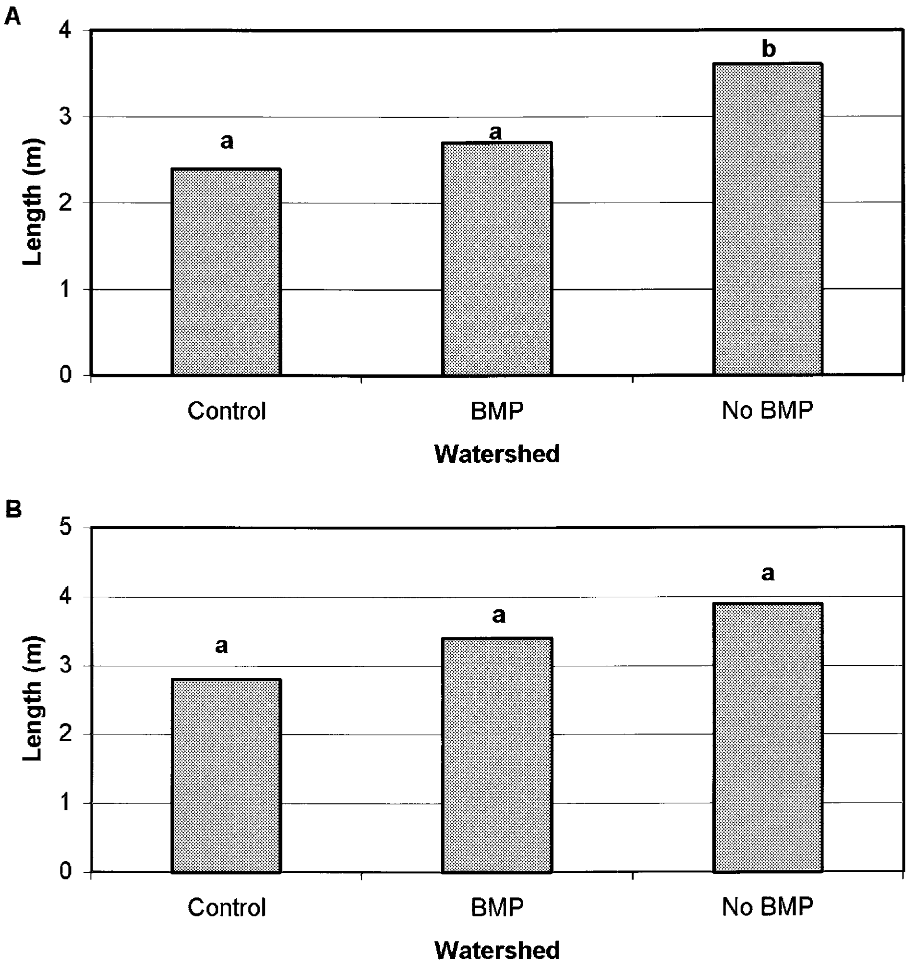
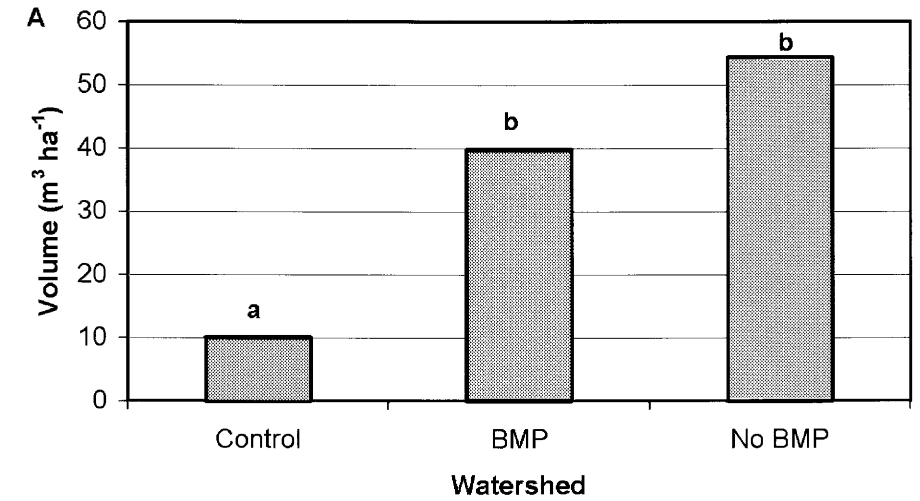


Figure 3. Watershed comparison of mean CWD length for riparian (A) and stream (B) plots. Different letters above the bars indicate significance at the $p < 0.05$ level.

3.2. CWD BIOMASSAND NITROGEN CONTENT

Density means within decay classes were used to calculate biomass of CWD. Biomass varied significantly among watersheds with the BMP and No BMP watersheds containing greater biomass in the riparian zone (Figure 7). The BMP watershed had significantly more biomass in the stream zone than the Control watershed and the No BMP watershed fell in the middle and was not different from either of the other two watersheds. As a side study, we analyzed our density samples for carbon and nitrogen. Carbon percentage did not vary among decay classes, however, nitrogen percentage was significantly greater in decay class 4 CWD than in the other decay classes (Figure 8). We used nitrogen content by



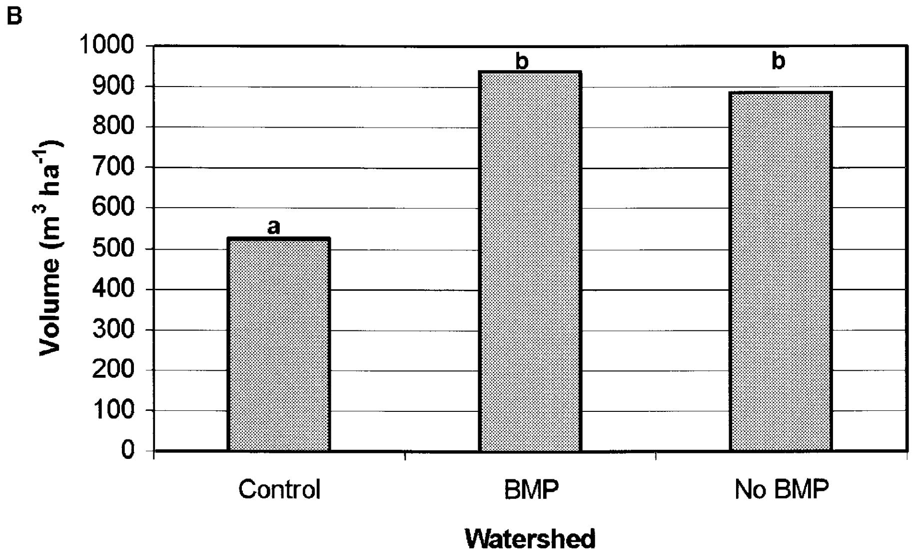


Figure 4. Watershed comparison of mean CWD volume for riparian (A) and stream (B) plots. Different letters above the bars indicate significance at the $p < 0.05$ level.

decay class to calculate the amount of nitrogen in CWD biomass. As a result of the dominance of decay class 4 CWD in the No BMP watershed, the No BMP watershed contains significantly more CWD nitrogen in the riparian zone than in the BMP and Control watersheds (Figure 9). Within the stream zone, the No BMP watershed had significantly more CWD nitrogen than the Control watershed and the BMP watershed fell in the middle and was not different from either of the other two watersheds.

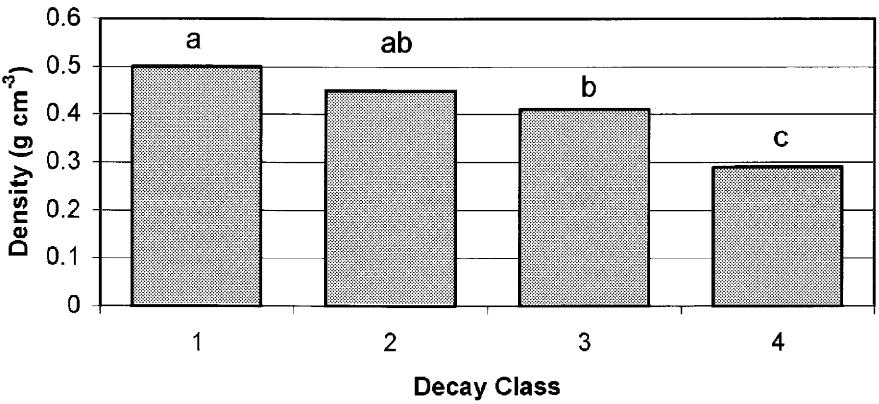


Figure 5. Distribution of density among decay classes for sampled CWD. Different letters above the bars indicate significance at the $p < 0.05$ level.

4. Discussion

It appears from our data that the treatments had a significant effect on CWD distribution within the two harvested watersheds. Although no differences were found for CWD diameter (Figure 2) among watersheds the No BMP watershed had CWD with greater length in the riparian area (Figure 3). The slash and tops left behind the harvest in the No BMP watershed likely led to the longer mean length. Because of the greater number of pieces present in the BMP and No BMP watershed, volume was greater in these watersheds than in the Control (Figure 4). Within watersheds, volume was 17–50× greater in the stream zone than in the riparian zone (Figure 4). Much greater volumes within the stream zones is not surprising considering the high slopes of the riparian zones (33–88%) and the effect of gravity transporting CWD downhill. Also, flooding within the riparian zone may have helped contribute to CWD in the stream channel.

The mean decay class was greatest in the No BMP watershed with the Control and BMP watersheds having similar decay classes (Figure 6). Most of the slash left behind the harvest 18 years ago in the No BMP watershed is now at or approaching decay class 4. Not surprisingly, no decay class 1 CWD was found in the No BMP watershed. Although decay class 4 CWD was also common in the Control and BMP watersheds, decay classes were more evenly distributed than in the No BMP watershed because of additions of new CWD over the past 18 years.

Because of the differences in volume among watersheds, riparian biomass was also greater in the BMP and No BMP watersheds than in the Control (Figure 7). Volume differences in the stream zone are also reflected in the biomass results but lower decay class CWD in the Control and BMP watersheds lessened the difference between those watersheds and the No BMP watershed (Figure 7). Biomass from other studies performed on old-growth forests of the same region compare favorably to our study. Muller and Liu (1991) found a biomass accumulation of

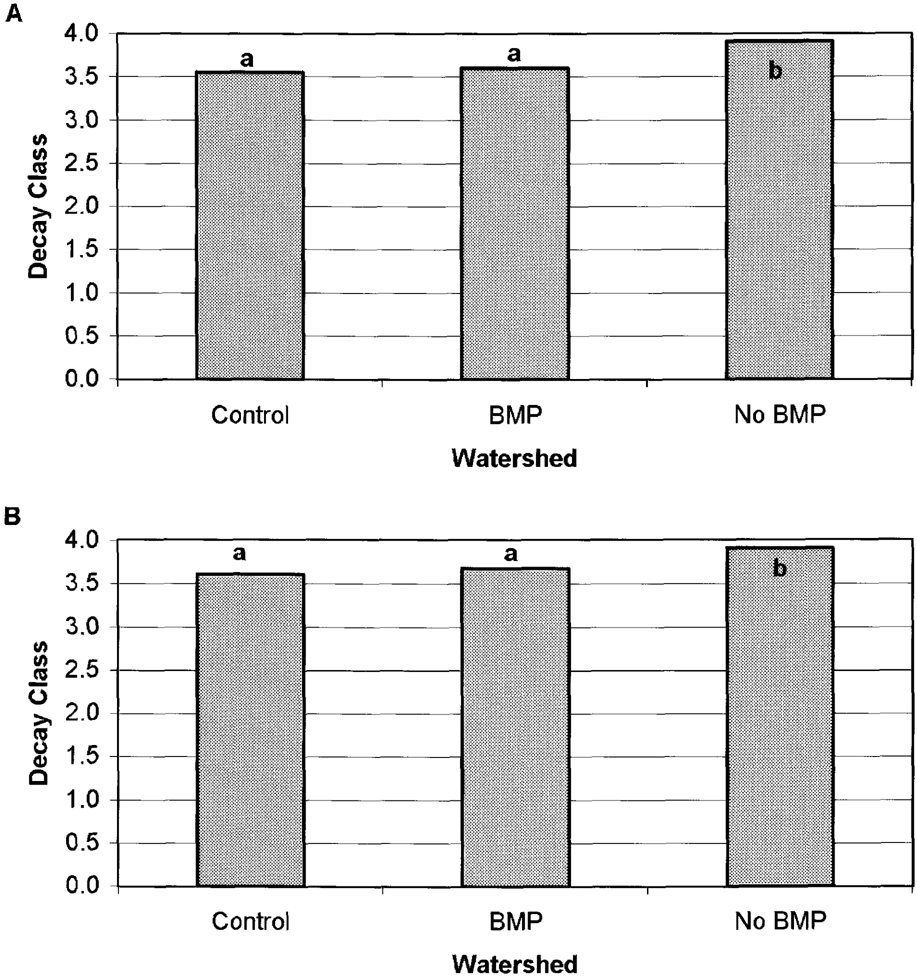


Figure 6. Watershed comparison of mean CWD decay class for riparian (A) and stream (B) plots. Different letters above the bars indicate significance at the $p < 0.05$ level.

21.6 Mg ha^{-1}, while our study varied from 3.5 to 17.1 Mg ha^{-1} in the riparian zones and from 198 to 339 Mg ha^{-1} in the stream zones. If we recalculate our results on riparian + stream basis and consider the area represented by each, our watersheds range from 10.8 Mg ha^{-1} in the Control to 27.3 Mg ha^{-1} in the No BMP watershed. McCarthy and Bailey (1994) reported an accumulation of 33 Mg ha^{-1} on their old-growth Central Appalachian plots. Others have shown that CWD accumulation is most often highest immediately following a major forest disturbance, especially after clearcut logging (Dolloff, 1993; Van Lear, 1993; Hedman *et al.*, 1996). For the Southern Appalachians, Sanders and Van Lear (1988) showed that after a clearcut CWD can accumulate as much as 90 Mg ha^{-1} across a forest survey. Also, McCarthy and Bailey (1994) showed that clearcuts produced greatly different

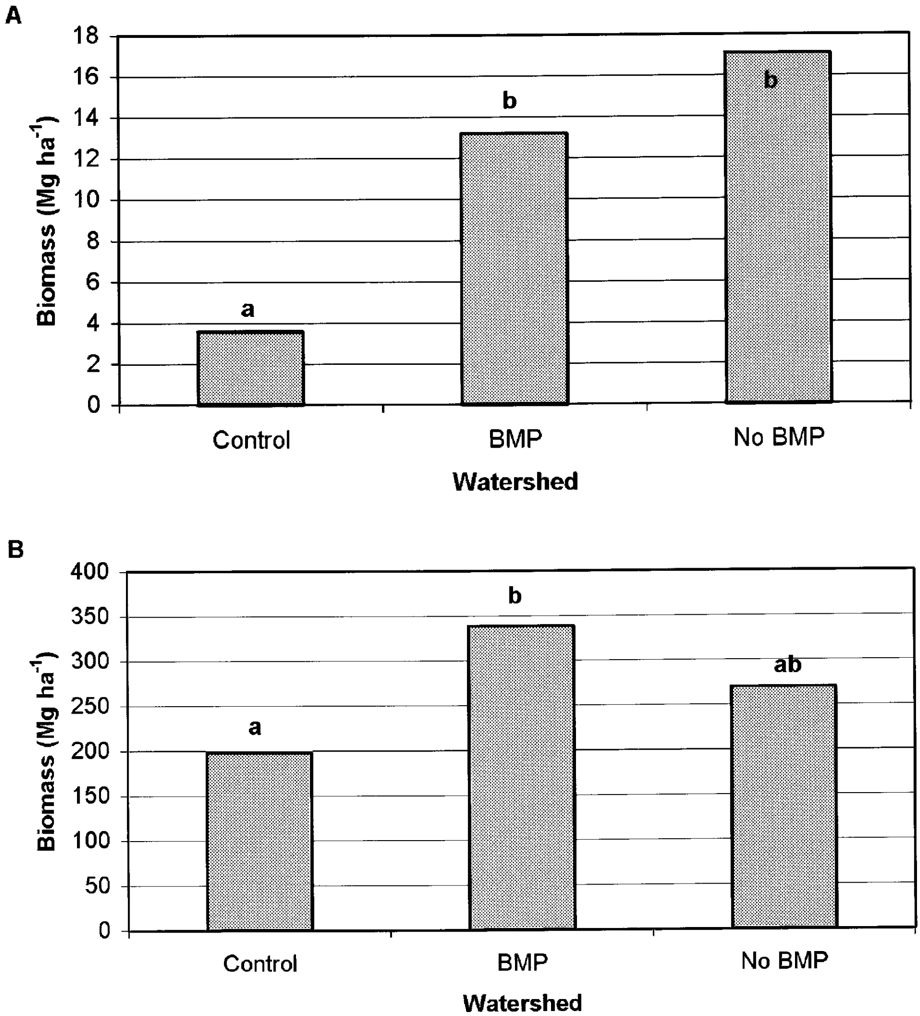


Figure 7. Watershed comparison of mean CWD biomass for riparian (A) and stream (B) plots. Different letters above the bars indicate significance at the $p < 0.05$ level.

results from old growth, mature, and selectively managed stands, where CWD accumulation averaged above 50 Mg ha^{-1}. To support these findings, predictive modeling by Waldrop (1993) estimated that CWD accumulation after clearcutting was 69 Mg ha^{-1} on mesic sites. Concurrently, there are other studies across forest types and regions that support the theory that CWD is greatest after harvest (Bretz, Guby and Dobbertin, 1996; McGee *et al.*, 1999). These results help to understand why our No BMP watershed contained statistically higher amounts of CWD than the Control, however, it does not describe the response in the BMP watershed.

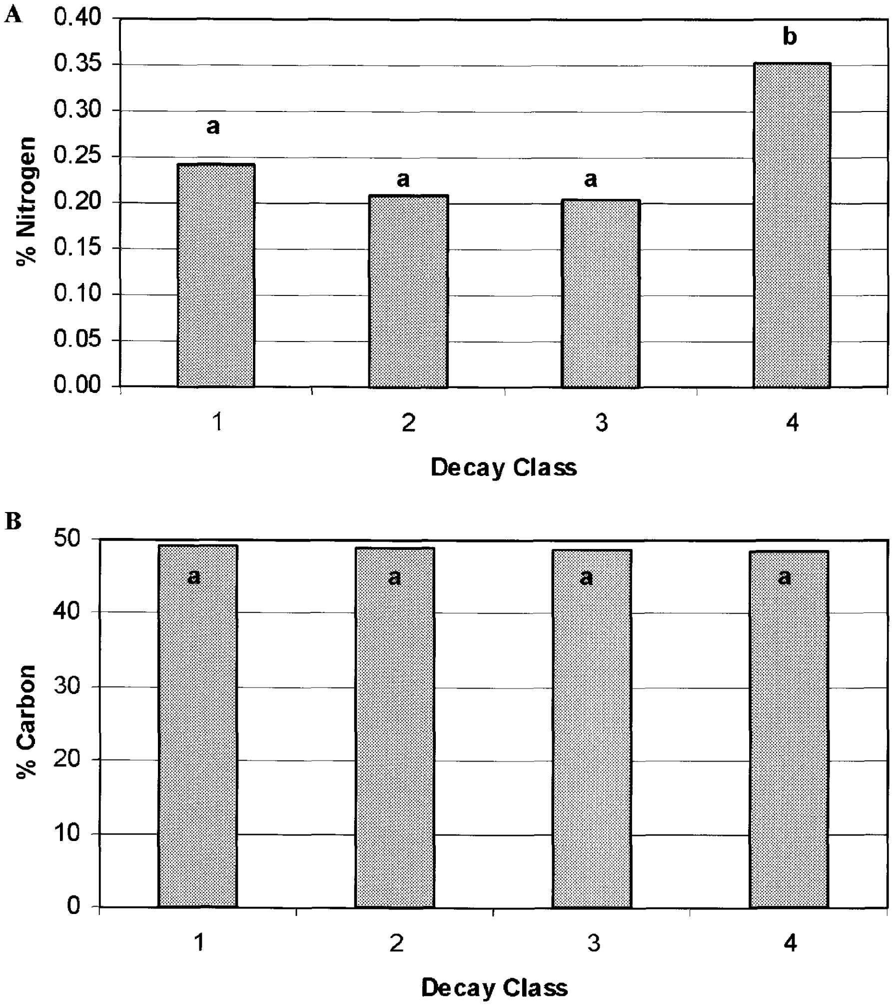


Figure 8. Distribution of nitrogen (A) and carbon (B) percent among decay classes for sampled CWD. Different letters above the bars indicate significance at the $p < 0.05$ level.

In both riparian and stream zones, the BMP watershed contained similar amounts of CWD as in the No BMP watershed (Figure 7). This was a surprising result considering that BMPs related to buffer strips are designed to protect the integrity of riparian areas and streams. It is apparent from our data that over the short-term, 15.2 m buffers do not protect the integrity of riparian areas and streams. Biomass of CWD 18 years after harvesting and leaving slash is comparable to no harvest in the riparian zone. We hypothesize that the harvest in the BMP watershed exposed those trees remaining in the riparian zone, and that windthrow and possibly slumping because of increased soil moisture led to the additional CWD recruitment. From our decay class data that indicated the presence of many decay

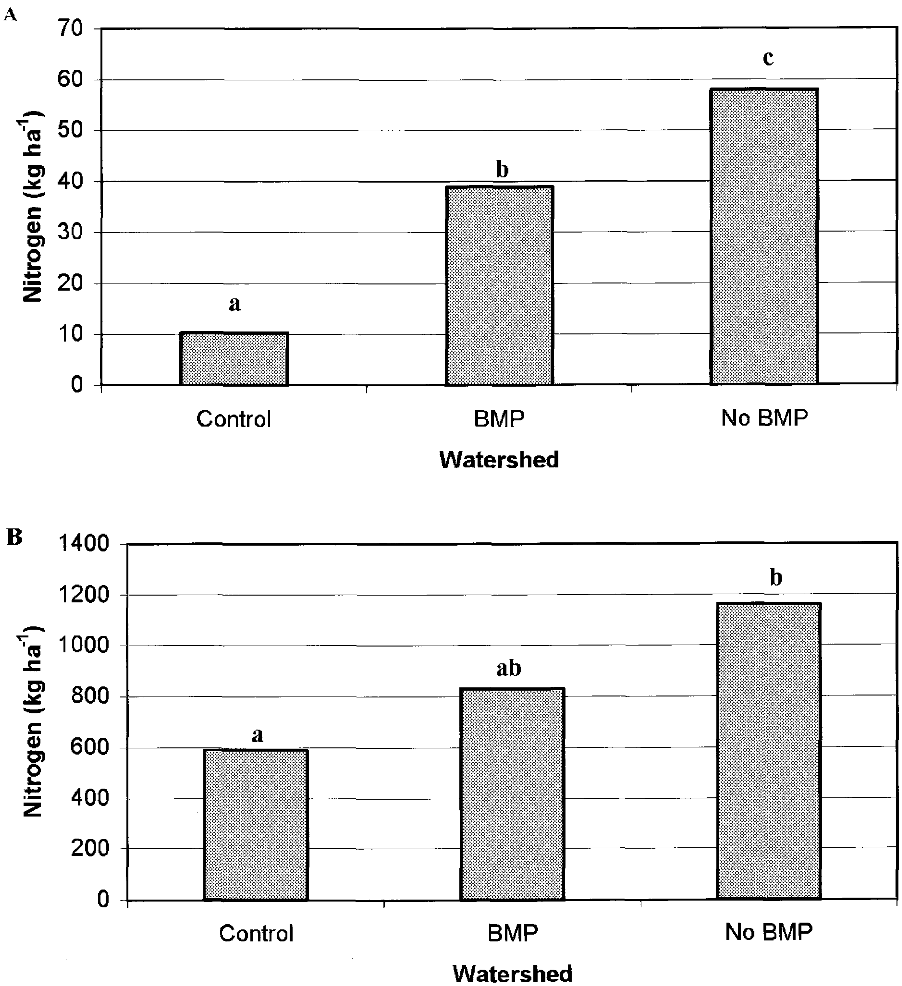


Figure 9. Watershed comparison of mean CWD nitrogen content for riparian (A) and stream (B) plots. Different letters above the bars indicate significance at the $p < 0.05$ level.

class 1 and 2 logs in the BMP watershed, it is apparent that at least some of the CWD in the BMP watershed has occurred since harvest, lending some confidence to our hypothesis.

Although carbon percent did not vary by decay class, nitrogen percent did (Figure 8). More decomposed (decay class 4) CWD had higher nitrogen than the other decay classes. This displays the importance of older decayed CWD as a site of nitrogen immobilization by microbial and fungal substrate associates. The increase in nitrogen due to immobilization is supported by other studies that showed nitrogen increases in CWD despite the decline in mass (Lambert *et al.*, 1980; Brown *et al.*, 1995).

All three watersheds were sampled weekly for water quality from 1995–1998 ($n = 160$). Nitrate (NO_3^-) was analyzed on the samples with an ion chromatograph. Concentration of NO_3^- varied among watersheds with the No BMP watershed possessing significantly higher concentration than either the Control or BMP watershed which were not different (paired t-test, $p < 0.05$ for No BMP vs. Control and No BMP vs. BMP, $p > 0.05$ for Control vs. BMP, Control = 0.25 mg L^{-1}, BMP = 0.25 mg L^{-1}, No BMP = 0.29 mg L^{-1}). Although increased concentrations of NO_3^- may be the result of other factors such as less watershed uptake because of the harvest, it may also provide some circumstantial evidence that the higher decay class CWD in the No BMP watershed is a source of NO_3^-, not a sink as would be hypothesized by the immobilization theory above. Although CWD immobilizes nitrogen with age, at some point along the decay continuum that nitrogen must again become mobile. Perhaps we are at this state in the No BMP watershed.

5. Conclusion

Our study was performed to evaluate the effects of riparian zone BMPs on the short-term distribution of CWD within riparian and stream zones. Although there are a number of benefits associated with implementing riparian buffer strips, our study found dissimilar CWD distribution in riparian and stream zones between an unharvested Control watershed and a harvested watershed with an unharvested riparian zone (BMP watershed). Our decay class data indicate at least some of the CWD in the BMP watershed has occurred since harvest, and, based on our biomass data, at a much greater rate of recruitment than in the Control watershed. Our hypothesis is that the harvest outside of the riparian zone in the BMP watershed may have led to greater windthrow and/or slumping than in the Control watershed. As such, our data suggest that riparian zones of 15.2 m may not be effective in maintaining the short-term integrity of the CWD pool within steep gradient Appalachian systems. Because of the importance of CWD to forest health and stream dynamics, we recommend either wider riparian zones or silvicultural practices other than clearcutting in the upland for steep sites such as those in this study. One approach that may be interesting to study would be to increase the width (e.g., double the width) of the riparian area and conduct some partial harvest (e.g. 50% BA reduction) within the riparian area. Potentially, the same value of forest products could result but perhaps the wider area would be a better buffer to windthrow and/or slumping, especially to those trees near the stream. It is hoped that managers will use the information gained from this study to alter or create guidelines for CWD management within forested riparian zones.