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harvesting & operations

Woody Debris and Nutrient Retention following Alternative Biomass Harvesting Guidelines

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Concern about excessive woody debris removals during biomass harvests has led to the development of biomass harvesting guidelines (BHGs) for retaining woody debris for habitat and nutrient cycling. However, the efficacy of BHGs has not been experimentally examined. Two BHG treatments applied during clearcutting and thinning operations were examined in a replicated complete-block experiment. The first BHG treatment included the retention of one-third of tops of trees ≥8 in. dbh and one-third of trees <8-in. dbh. The second included the retention of all tops of trees ≥8-in. dbh and no restriction on the removal of smaller trees. In clearcuts, the two BHGs each increased the biomass of woody debris retained by 1.7 times compared to where no BHG was applied. However, in thinned units, there were no differences in retained woody debris regardless of BHG application. Nutrient retention trends followed those of biomass. Nutrients retained in woody debris generally exceeded nutrient removals in harvested wood except for calcium, for which removals equaled retention where BHGs were applied and exceeded retention in the absence of BHGs. Findings suggest that applying BHGs for retaining woody debris becomes more important as harvest intensity increases.

Keywords: biomass harvesting, biofuel, woody debris retention, nutrient retention, harvesting guidelines

The growing demand for renewable energy sources has increased interest in using low-quality or nonmerchantable woody material for bioenergy feedstock including saplings, small trees, and the branches and tops of sawlog-sized trees ordinarily comprising logging slash (Goerndt et al. 2014). This woody material can be cut into fuelwood lengths or chipped on site and hauled to facilities capable of burning or pyrolyzing it for energy (Aguilar and Mabee 2014). Thus, "biomass harvesting" for wood energy potentially entails removing large quantities of biomass from the forest that otherwise would be retained as woody debris during a traditional roundwood harvest. This has caused concern that forest harvesting for bioenergy may dramatically reduce the quantity of woody debris and nutrients retained within the forest compared to traditional roundwood harvesting (Janowiak and Webster 2010).

In forested stands harvested for sawlogs or other kinds of roundwood such as pulpwood, typically only the merchantable bole wood is removed from the site. Much of the felled, nonmerchantable trees and logs and logging slash is left behind to provide large quantities of woody debris for habitat and nutrients. On a mass basis, merchantable roundwood comprises 70% to 80% of the total above-ground woody biomass, but it contains lower nutrient concentrations than foliage, branches, and the residues of nonmerchantable trees left behind (Johnson and Todd 1987, Kabrick et al. 2013). Because foliage, branches, and nonmerchantable trees are retained as slash, there is considerably less concern about excessive woody debris or nutrient removal associated with merchantable roundwood harvesting, particularly where long (100-year) rotations are used (Vance et al. 2014).

Woody debris in forests serves many important functions. Decaying logs and branches on the forest floor provide important habitat for a variety of small mammals, reptiles, amphibians, and invertebrates (Riffell et al. 2011). Fungi and some bacteria derive food or energy directly through the decomposition of woody debris, while fungivores, bacterivores, and invertebrates derive food

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and energy indirectly from decomposition processes (Graham et al. 1994, Fukasawa et al. 2015). As woody debris decomposes, nutrients are released where they are stored in the soil or taken up and utilized in plant biomass. Thus, retaining woody debris in harvested stands is considered important for sustaining both short-and long-term nutrient availability (Abbas et al. 2011, Thiffault et al. 2011, Tamminen et al. 2012).

Concern about excessive removals of woody residues during harvesting operations began several decades ago when whole-tree harvests became common. With whole-tree harvest, limbing, topping, and bucking of harvested trees into roundwood products were completed at log landings, leaving little slash in the harvested stand for habitat and nutrient cycling (Boyle et al. 1973, Freedman et al. 1981, Johnson and Todd 1987, Johnson and Todd 1998). This concern led to the development of recommendations for either retaining woody residues or returning woody residues to harvested stands, particularly where soils have an inherently low capacity to supply nutrients (NEFA 2012). However, with biomass harvests, much of this woody residue is a forest product to be removed and utilized rather than a byproduct to be dispersed during harvest operations.

Recently, concerns about excessive woody debris removals during biomass harvests has led to the development of many biomass harvesting guidelines (BHGs) designed to retain woody debris for habitat and nutrient capital (NEFA 2012). Several states in the eastern United States have developed guidelines recommending the retention of the tops and limbs and other residues from a fraction (usually one-sixth to one-third) of the trees or residues (Evans et al. 2013). While recommendations for retaining tree biomass are based on expert opinion or on findings reported in the scientific literature for other kinds of harvesting such as whole-tree harvesting versus sawlog-only harvesting (Johnson and Todd 1987), few studies have operationally evaluated the efficacy of biomass BHGs. The objective of this study was to determine the quantity of woody debris and nutrients retained by BHGs alternatives during biomass harvests compared to biomass harvests in the absence of BHGs or with roundwood-only harvests in oak forests of low to moderate site quality.

Methods

Study Area

The study was conducted at Indian Trail Conservation Area in northeastern Dent County, Missouri, USA (Lat 37.68776°, Long -91.36846°) about 11 miles northeast of the city of Salem and 17 miles south of the city of Steelville. The study area is owned and has been managed by the Missouri Department of Conservation (MDC) since about 1924. Prior to MDC ownership, trees from the study area were harvested frequently until 1906 for the production of charcoal used in a nearby iron smelter. Between 1906 and 1924, the land was privately owned, used for livestock grazing, and burned frequently to reduce woody sprouts and to promote grass cover. After the land was purchased by the MDC, grazing and burning practices were stopped and the forests were allowed to naturally reestablish.

The study sites are on the border of the West Meramec River Oak Woodland/Forest Hills Landtype Association and the Huzzah-Courtois Oak Woodland Dissected Plain Landtype Association within the Ozark Highlands (Nigh and Schroeder 2002). Data from a weather station located at the US Forest Service Sinkin Experimental Forest located 15 miles south of Indian Trail Conservation Area indicated that during the last decade the average annual precipitation was 51 in., with about 60% falling between April and September. The average temperature was 57°F annually, 75°F during the summer (June, July, and August), and 36°F during winter (December, January, and February).

The landscape is a deeply dissected upland comprising rounded ridges with steep short slopes. Elevations in the study area range from 1,100 to 1,300 ft and slopes range from 5% to 30%. The underlying bedrock includes coarsely-crystalline cherty dolomite from the Gasconade Formation (Ordovician Age) and cherty dolomite from the Eminence Formation (Cambrian Age). The soils within the study site are mapped as Clarksville very gravelly silt loams (loamy-skeletal, siliceous, semiactive, mesic, Typic Paleudults) formed in gravelly hillslope sediments and cherty residuum from dolomite. They are very deep (>60 in.), well drained, and have a low pH and subsoil base cation saturation (<35% by sum of cations method). Coarse fragments comprising gravel- and cobble-sized chert range

Management and Policy Implications

During harvests for bioenergy, there is the potential to remove saplings, small trees, and the branches and tops of sawlog-sized trees that ordinarily would remain on site as logging slash during conventional roundwood harvests. Biomass Harvesting Guidelines (BHGs) have recently been developed by several states to address concerns about excessive woody debris removal during harvesting for bioenergy. They are similar to Best Management Practices for protecting soil and water during and after harvesting, but BHGs include provisions for retaining woody debris for many reasons, including wildlife habitat and nutrient capital retention for future forest growth. Biomass Harvesting Guidelines are intended to provide practical guidance during harvesting operations. The retention recommendations typically are based on findings reported in the scientific literature for other kinds of harvesting (e.g., whole-tree harvesting versus sawlog-only harvesting) or based on expert opinion. However, very few studies have operationally evaluated the efficacy of biomass BHGs for retaining woody debris. In this study, we measured the quantity of woody debris and nutrients retained with and without the application of BHGs during biomass harvests. The BHGs examined used the metric of leaving one-third of small trees and one-third of the tops of large trees or all of the tops of large trees and no restrictions on removals of small trees. They were applied in oak-hickory stands in Missouri having low to moderate site quality. We found that the application of BHGs retained 1.7 times more woody debris on site following biomass harvesting with clearcutting compared to where no BHG was applied. Harvests conducted with BHGs also retained more woody debris than was left after roundwood harvests for products such as stave logs, sawlogs, tie logs, pulpwood, and small-diameter wood for pallets and blocking. However, there were no differences in retained woody debris in thinned units harvested for biomass regardless of BHG application. This suggests that as harvest intensity increases, the application of BHGs for retaining woody debris becomes more important. Nutrient retention trends followed those of biomass, and the quantity of nutrients retained in the woody debris generally exceeded nutrient removals in the harvested material. The only exception was for calcium, for which removals equaled retention where BHGs were applied and removals exceeded retention in the absence of BHGs. Overall, our findings suggest that BHGs based on retaining one-third of the small trees and one-third of the tops of large trees or all of the tops of large trees substantially increases the retention of woody debris and nutrients during harvests for bioenergy in oak-hickory stands of low to moderate site quality.

from 30 to 70 percent by volume, which reduces the available water capacity and nutrient supply in these soils (websoilsurvey.nrcs.usda.gov/app/, last accessed May 11, 2018). Clarksville soils occur extensively throughout the Ozark Highlands ecological section and were mapped on 2.7 million ac in Missouri, Arkansas, and Oklahoma (apps.cei.psu.edu/soiltool/, last accessed May 11, 2018).

When the study was initiated, the treatment units were typed as dry to dry-mesic hardwood forests. Oaks (*Quercus* L.) comprised 92% of the live basal area, of which the most abundant were white oak (*Q. alba* L.; 47%), black oak (*Q. velutina* Lam.; 36%), post oak (Q. stellata L.; 7%), and northern red oak (*Q. rubra* L.; 2%). Hickories (*Carya* Nutt.), including the species pignut hickory (*C. glabra* Mill.), mockernut hickory (*C. tomentosa Poir*. Nutt.), and black hickory (*C. texana* Buckl.), together comprised an additional 2% of the live basal area. Other species included shortleaf pine (*Pinus echninata* Mill.; 2%), black walnut (*Juglans nigra* L.; 1%), and blackgum (*Nyssa sylvatica* Marsh.; 1%). Site index (black oak basis, age 50 years) ranged from 55 to 60 ft (Sims 2013).

Study Design and Treatments

The study was a randomized complete block design with three blocks and eight treatments (Figure 1). Within a single forest compartment, blocks ranging from 33 to 39 ac were selected and subdivided into eight rectangular treatment units of 4 to 5 ac. The rectangular treatment units were oriented parallel to the slope so that harvested material could be removed with a rubber-tired skidder without crossing into an adjacent treatment unit. The eight treatments (Table 1) were designed to determine the quantity of woody debris that would be retained in clearcut and thinned stands by following two BHG alternatives compared to where

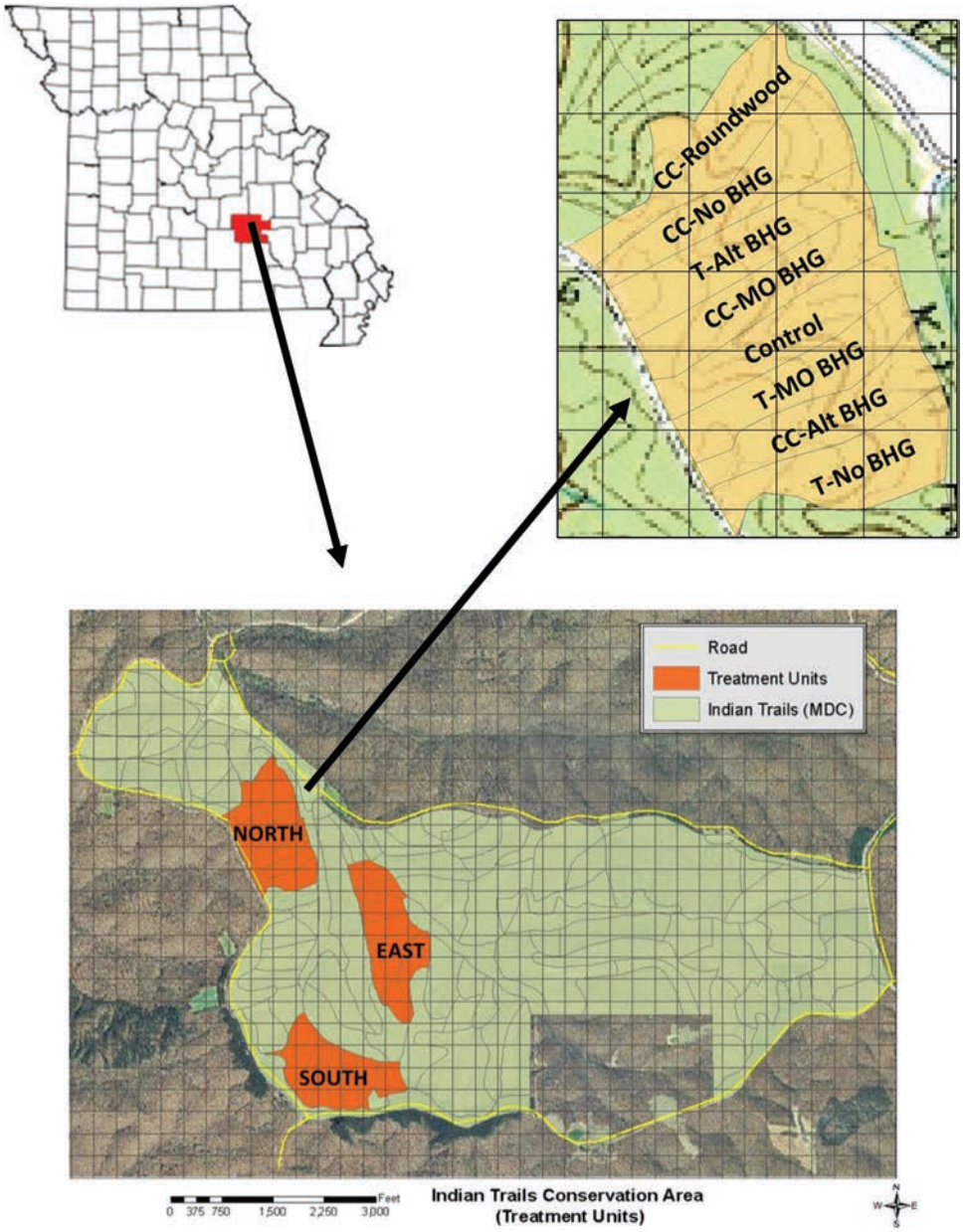

Figure 1. Location and example experimental unit layout for the study located at Indian Trail Conservation Area in Dent County, Missouri, USA. The study comprises three complete blocks; the random treatment allocation of the north block is illustrated in the figure. Harvest treatments are defined in Table 1.

Table 1. Harvesting methods, treatment designation, and residue retention guidelines.

Harvesting method	Designation	Guidelines for residue retention
Clearcutting (CC) including felling of all trees ≥3 in. dbh to facilitate the regeneration of the stand	CC-MO BHG	Roundwood and biofuel harvest following Missouri's (MO) biomass harvesting guidelines (BHG) for residue retention to retain 1/3 tops of trees ≥8 in. dbh and 1/3 of trees <8 in. dbh dispersed across the harvested area
	CC-Alt BHG	Roundwood and biofuel harvest following an alternative (Alt) biomass harvesting guideline for residue retention to retain tops of all trees ≥8 in. dbh dispersed across the harvested area with no restrictions on the removal of smaller trees
	CC-No BHG	Roundwood and biofuel harvest with no restrictions on residue removals
	CC-Roundwood	Roundwood harvest only; residues were retained from trees that could not be processed into logs at least 8 ft long having a small-end diameter ≥4 in.
Thinning (T) leaving a residual basal area of 60 ft^2 ac^{-1} to improve the quality, growth, and vigor of the residual stand	T-MO BHG	Roundwood and biofuel harvest following Missouri's biomass harvesting guidelines for residue retention to retain 1/3 tops of trees ≥8 in. dbh and 1/3 of trees <8 in. dbh dispersed across the harvested area
	T-Alt BHG	Roundwood and biofuel harvest following an alternative biomass harvesting guideline for residue retention to retain tops of all trees ≥8 in. dbh dispersed across the harvested area with no restrictions on the removal of smaller trees
	T-No BHG	Roundwood and biofuel harvest with no restrictions on residue removals
No cutting	Control	No removals

no BHGs were followed, to where only roundwood was removed (clearcuts only), and to where no harvesting was done (i.e., control treatment). Clearcutting included felling of all trees >3 in. diameter at breast height (dbh) and removing merchantable material. Thinning included felling trees marked for removal by a professional forester to a residual basal area of 60 ft^2 ac^{-1} to improve the quality, growth, and vigor of the residual stand. The BHG treatments included the current Missouri Biomass Harvesting Guideline (mdc.mo.gov/sites/default/files/downloads/woody_biomass_harvesting_bmp_book.pdf, last accessed May 11, 2018), which requires the retention of one-third of the tops of trees ≥8 in. dbh and one-third of trees <8 in. dbh to be retained (MO BHG). The second BHG included an alternative where all the tops of trees ≥8 in. dbh were to be retained, and no restriction was imposed on the removal of smaller trees (Alt BHG). This alternative was proposed because small trees can be removed more easily than large tops where skidding occurs through residual timber or adjacent but unharvested stands. The concern was that skidding large tops potentially would cause more damage to the residual stand than would skidding small-diameter trees. Personnel from the Missouri Forest Products Association were interested in knowing whether this alternative would leave similar quantities of woody debris as would occur from following the standard Missouri guidelines (i.e., the MO BHG treatment). However, there were no available data to indicate how much woody debris would be retained in the forest if this alternative BHG was followed. These two BHGs were compared to the application of no biomass BHGs. The eighth treatment was a clearcut conducted in the same manner as the other clearcuts (e.g., all trees >3 in. dbh were felled) but allowing for the removal of trees >8 in. dbh for stave logs, sawlogs, tie logs, blocking materials, and pallet wood and the removal of smaller diameter trees that could produce logs 8 ft long with a small-end diameter ≥4 in. as pulpwood but leaving all branches and tops and all cut nonmerchantable trees left on the site as logging slash. This treatment provided a means for comparing removals occurring with conventional harvesting to those occurring with biomass harvesting and served as a secondary control to which the BHG treatments were compared. For all harvest treatments, harvesting was conducted using a 169-h.p., rubber-tired feller-buncher with a rotary saw to cut and bundle trees that were skidded to landings with a 115-h.p., rubber-tired grapple skidder. Topping, limbing, and bucking operations were done within treatment units and, although not specified in the logging contract, logging debris was generally left evenly distributed within treatment units. An uncut control treatment was included to provide a reference condition for the amount of woody debris expected to occur in this forest type.

Sampling Methods

Each treatment unit was stratified into three equal areas, and within each a single, permanent, variable-radius plot center was randomly established (three per treatment unit) and its coordinates recorded. At each plot center, a 10 BAF prism was used to inventory trees ≥1.5 in. dbh. Information recorded included species, dbh, and status (live or dead). Prior to harvesting, the live standing basal area in treatment units ranged from 84 to 114 ft^2 ac^{-1} and the stocking (*sensu* Gingrich 1967) ranged from 73% to 102%.

Fine and coarse woody debris was inventoried by size class using a line-intercept method (Brown 1974). Two 41.3-ft transects per plot (six transects per treatment unit) were used during the woody debris inventory. Each transect originated at the plot center and was oriented at azimuths of 0° and 90°. The average slope of each transect was recorded. Fine woody debris <1-in. diameter was tallied along the first 4.3-ft transect segment and debris 1 to <3-in. diameter was tallied along the first 11.4-ft transect segment. Coarse woody debris ≥3 in diameter was inventoried along the entire length of each transect. Measurements included the diameter where each transect crossed the center of the coarse woody debris and the decay class based on a five-class system described by Spetich et al. (1999).

Biomass and Nutrient Concentration Calculations

Live and dead tree biomass was calculated using equations by Chojnacky et al. (2014) and the recommended parameters for each genus or family and by diameter class where relevant. For standing dead trees, we excluded the biomass of foliage using the component ratio equations for hardwoods and softwoods (Jenkins et al. 2003). Fine and coarse woody debris biomass was calculated by size class using the equations provided by Brown (1974). For fine woody debris calculation, we used estimated values for the average squared diameter (d^2) of the woody debris size classes (0.012 for the <0.25-in.-size class, 0.24 for the 0.25- to 1-in.-size class, and 2.5 for the 1- to 3-in.-size class). Specific gravity (s) estimates were 0.65, 0.58, 0.50 for the

<0.25-in., 0.25- to 1-in., and the 1- to 3-in.-size classes, respectively. For wood >3 in., we used 0.63 for sound wood (decay classes 1–3) and 0.30 for rotten wood (decay classes 4 and 5). Angle corrections (a) of 1.13 were applied to fine woody debris estimates, and a value of 1.40 was used for woody debris <0.25 in. for recent logging slash measured posttreatment. The slope correction procedure and other parameters were as reported in Brown (1974). Nutrient quantities in the harvested trees, the residual live and standing dead trees, and in the woody debris were estimated by multiplying their biomass by the reported nutrient concentrations in the harvested material from oak-hickory forests listed in Table 2. The biomass of harvested trees was reported in a separate time-and-motion study described by Sims (2013) and converted to dry weights by assuming 70% moisture (dry weight basis) and multiplying green weights by 0.59.

Statistical Analyses

The GLIMMIX procedure (SAS version 9.3, SAS Institute, Inc. Cary, NC) was used to examine treatment effects. Data were averaged by block and treatment prior to analyses, and visual inspections and normality tests of the posttreatment response variables suggested that the data were normally distributed (or best fit as a normal distribution for coarse woody debris). The effect in the model was treatment, and the treatment by block interaction was the error term. For significant effects, treatment least square means were compared using Fisher's least significant difference.

Results

Biomass and Nutrient Removals

Prior to harvesting, standing live tree biomass in treatment units ranged from 59 to 85 tons ac^{-1} dry weight (100–144 tons ac^{-1} green weight; Table 3). Standing dead trees provided an additional 2 to 6 tons ac^{-1} dry weight (3–10 tons ac^{-1} green weight). Total removals (roundwood plus biofuel) ranged from 31 to 40 tons ac^{-1} dry weight (53–68 tons ac^{-1} green weight) in clearcut units and from 11 to 16 tons ac^{-1} dry weight (19–27 tons ac^{-1} green weight) in thinned units (Table 4). There were significant treatment differences ($P < .03$) in removals, and the greatest amount of biomass was removed from the CC-MO BHG treatment and the least amount from the T-MO BHG treatment. On a dry weight basis, 85% of the biomass was removed as roundwood including stave logs, sawlogs, tie logs, pulpwood, and other low-grade trees used to produce blocking or pallet wood. Where harvesting for biofuel occurred, about 15% of the total biomass harvested was chipped and removed. There also were significant treatment differences ($P < .03$) in nutrient removals (Table 4). Calcium was removed in the greatest quantity, and relatively small quantities of Mg and P were removed in the harvested biomass. The general order of nutrient quantity removals by element was Ca > N > K > Mg > P, and nutrient removal amounts generally followed the harvest removal trends.

Woody Debris and Nutrient Retention

Regardless of treatment, the coarse fraction (≥3 in.) comprised about 50% to 71% of the total woody debris biomass, and the fine fraction (<0.25 in.) comprised only 1% to 3% of the biomass (dry weight) retained (Figure 2). Because this did not vary among treatments, we only presented the results of the statistical analysis of the total retained biomass. There were significant treatment differences ($P = .01$) in the total amount of woody debris retained. In clearcuts, greater quantities of woody debris were retained where biomass harvesting guidelines were applied compared to when no restrictions were placed on removals. In thinned units, there were no significant differences in the quantity of woody debris retained among units with and without BHGs and the retained woody

Table 2. Nutrient concentrations used for calculating nutrient capital in standing trees and woody debris.

Type	N	P	K	Ca	Mg	Source
	Percent					
Harvested wood						
Biofuel (chips)	0.284	0.014	0.171	0.904	0.049	Kabrick et al. (2013)
Roundwood	0.179	0.012	0.067	0.680	0.021	Johnson and Todd (1987)
Woody debris						
<3 in.	0.473	0.042	0.322	0.820	0.076	Kabrick et al. (2013)
≥3 in. (decay classes 1–3)	0.265	0.013	0.164	0.898	0.046	Kabrick et al. (2013)
≥3 in. (decay classes 4–5)	0.520	0.025	0.131	1.796	0.092	Kabrick et al. (2013)
Trees						
<8 in. dbh	0.265	0.013	0.164	0.898	0.046	Kabrick et al. (2013)
≥8 in. dbh	0.192	0.014	0.074	0.656	0.023	Johnson and Todd (1987)

Table 3. Pretreatment live and dead standing biomass and woody debris by treatment (tons ac^{-1} dry weight basis).

Treatment	Standing		Woody debris				
	Live	Dead	<0.25 in.	0.25–1 in.	1–3 in.	>3 in.	Total
CC-MO BHG	69 (10.7)	4.8 (4.8)	0.12 (0.01)	0.40 (0.23)	0.73 (0.14)	3.61 (1.81)	5.01 (9.23)
CC-Alt BHG	85 (9.5)	4.2 (1.2)	0.15 (0.07)	0.07 (0.04)	0.57 (0.16)	10.29 (9.11)	11.81 (9.23)
CC-No BHG	60 (6.8)	4.3 (1.1)	0.16 (0.01)	0.08 (0.05)	0.73 (0.28)	3.51 (2.13)	5.46 (2.25)
CC-Roundwood	69 (4.3)	4.9 (2.7)	0.13 (0.01)	0.30 (0.17)	1.62 (0.40)	1.62 (0.96)	4.08 (1.45)
T-MO BHG	65 (2.4)	6.0 (3.0)	0.18 (0.01)	0.79 (0.45)	1.22 (0.43)	7.39 (3.28)	10.26 (3.84)
T-Alt BHG	64 (10.2)	6.3 (1.5)	0.17 (0.03)	0.40 (0.23)	2.27 (0.78)	3.87 (2.21)	7.16 (2.90)
T-No BHG	59 (6.7)	2.2 (1.5)	0.15 (0.03)	0.34 (0.20)	0.97 (0.14)	6.86 (2.24)	8.54 (1.98)
Control	69 (4.3)	3.7 (0.6)	0.19 (0.05)	0.78 (0.45)	1.21 (0.61)	2.44 (0.89)	5.15 (1.59)

Means (standard error) for three treatment units. There were no significant pretreatment differences among designated treatments.
Treatments included clearcutting (CC) or thinning (T) with the Missouri biomass harvesting guidelines (MO BHG), alternative biomass harvesting guidelines (Alt BHG), no biomass harvesting guidelines (No BHG), compared to a roundwood harvest (Roundwood) and to Control. See Table 1 for more information about the treatments.

Table 4. Harvest removals (dry weight basis).

Treatment	Removals[1]						
	Roundwood[2]	Biofuel[3]	N	P	K	Ca	Mg
	tons ac^{-1}		lbs ac^{-1}				
CC-MO BHG	33 (1)A	7 (1)AB	161 (6)A	10 (1)A	70 (4)A	587 (20)A	21 (1)A
CC-Alt BHG	29 (2)AB	2 (1)CD	115 (1)AB	7 (1)AB	46 (2)AB	430 (7)AB	14 (1)AB
CC-No BHG	25 (2)B	9 (1)A	142 (16)A	9 (1)A	65 (8)A	505 (57)A	20 (3)A
CC-Roundwood	31 (1)AB	—	110 (1)AB	7 (1)AB	41 (1)AB	419 (2)AB	13 (1)AB
T-MO BHG	9 (4)C	2 (1)CD	40 (21)C	3 (1)C	17 (9)B	147 (74)C	5 (3)B
T-Alt BHG	15 (1)C	1 (1)D	59 (10)BC	4 (1)BC	23 (4)B	221 (34)BC	7 (1)B
T-No BHG	10 (1)C	4 (2)BC	60 (8)BC	4 (1)BC	28 (5)B	213 (25)BC	8 (2)B

[1]Mean (standard error); adapted from Sims 2013.
[2]Roundwood included product classes of stave logs, sawlogs, tie logs, blocking material, and pulpwood. Pulpwood included trees <8 in. dbh with logs 8 ft long having a small-end diameter ≥4 in.
[3]Biofuel included residues chipped and removed for bioenergy including tops, branches, leaves, twigs, and stems of trees that were not harvestable as roundwood.
Within columns, means followed by different letters indicate significant differences (α = 0.05) by Fisher's least significant difference.
Treatments included clearcutting (CC) or thinning (T) with the Missouri biomass harvesting guidelines (MO BHG), alternative biomass harvesting guidelines (Alt BHG), no biomass harvesting guidelines (No BHG), compared to a roundwood harvest (Roundwood) and to Control. See Table 1 for more information about the treatments.

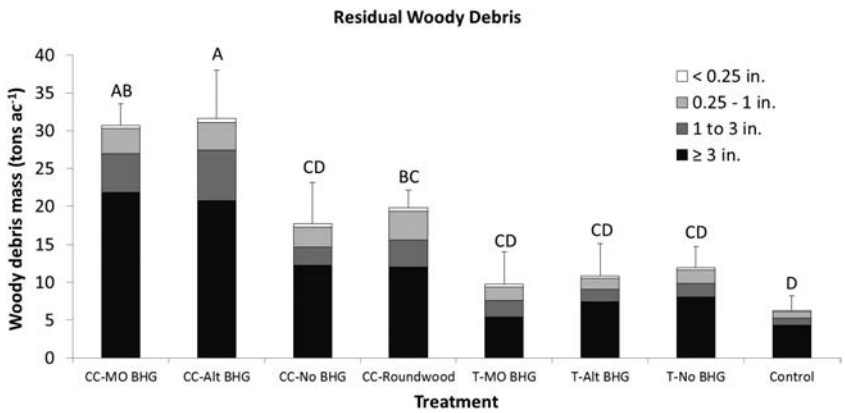

Figure 2. Residual woody debris in plots following clearcut (CC) and thinning (T) treatments where woody biomass harvest guidelines (BHGs) were or were not imposed: Alt BHG, alternative scenario where tops of tree tops are retained and no restriction on small tree removal; MO BHG, retain one-third of the tree tops and one-third of the small trees; No BHG, no restrictions on removals. Other treatments included clearcutting with roundwood removal only (CC-Roundwood) and no harvest control. See Table 1 for more information about the treatments. Bars headed by different letters indicate significant differences (α = 0.05) by Fisher's least significant difference.

debris biomass was nominally, but not significantly, greater than in the control. Nutrient retention trends were very similar to those of woody debris biomass retention, and significantly greater quantities of N, P, K, Ca, and Mg were retained in clearcuts where BHGs were followed (Figure 3). There were no significant differences in retained nutrients among the remaining treatments, and many of the other treatments were statistically the same as the control. Of the nutrients that we measured, calcium was retained in the greatest quantity and phosphorus was retained in the least.

Discussion

Woody Debris Removal and Retention

Study findings suggest that the application of BHGs for retaining woody debris during harvesting operations for roundwood and biofuel can significantly increase the total mass of woody debris retained in clearcuts. For roundwood and biofuel harvests, BHGs requiring the retention of one-third of the tops of large trees (≥8 in. dbh) and one-third of the small trees (<8 in. dbh) (i.e., CC-MO BHG) or the retention of all of the tops of large trees (≥8 in. dbh) (i.e., CC-Alt BHG) left about 1.7 times more woody debris (mass basis) on the ground than where removal restrictions were absent (Figure 2). In clearcuts, the BHG treatments increased the retention of woody debris compared to the CC-Roundwood treatment where only roundwood for stave logs, sawlogs, tie logs, blocking materials, pallet wood, and pulpwood were removed but where no other small-diameter trees were harvested.

In clearcuts, there was no significant difference in the mass of woody debris retained between the two BHG treatments. Within the dry to dry-mesic oak forest that we studied, cutting and leaving all of the tops of large trees (≥8 in. dbh) on the forest floor appears to retain the same mass of woody debris as the more complicated practice of leaving one-third of the tops of large trees (≥8 in. dbh) and one-third of the small trees (<8 in. dbh). This suggests that there is flexibility in implementing BHGs for biomass harvesting. Where the skidding of tops of large trees may damage standing timber, leaving large tops and not restricting small tree removals may be equally advantageous for retaining woody debris and more advantageous for maintaining timber quality. Data from this study also suggest that there are no substantial differences in the proportion of fine woody debris versus coarse woody debris with these two different BHGs.

One unexpected finding was the large quantity of woody debris (about 18 tons ac^{-1}) that was retained in clearcuts where there were

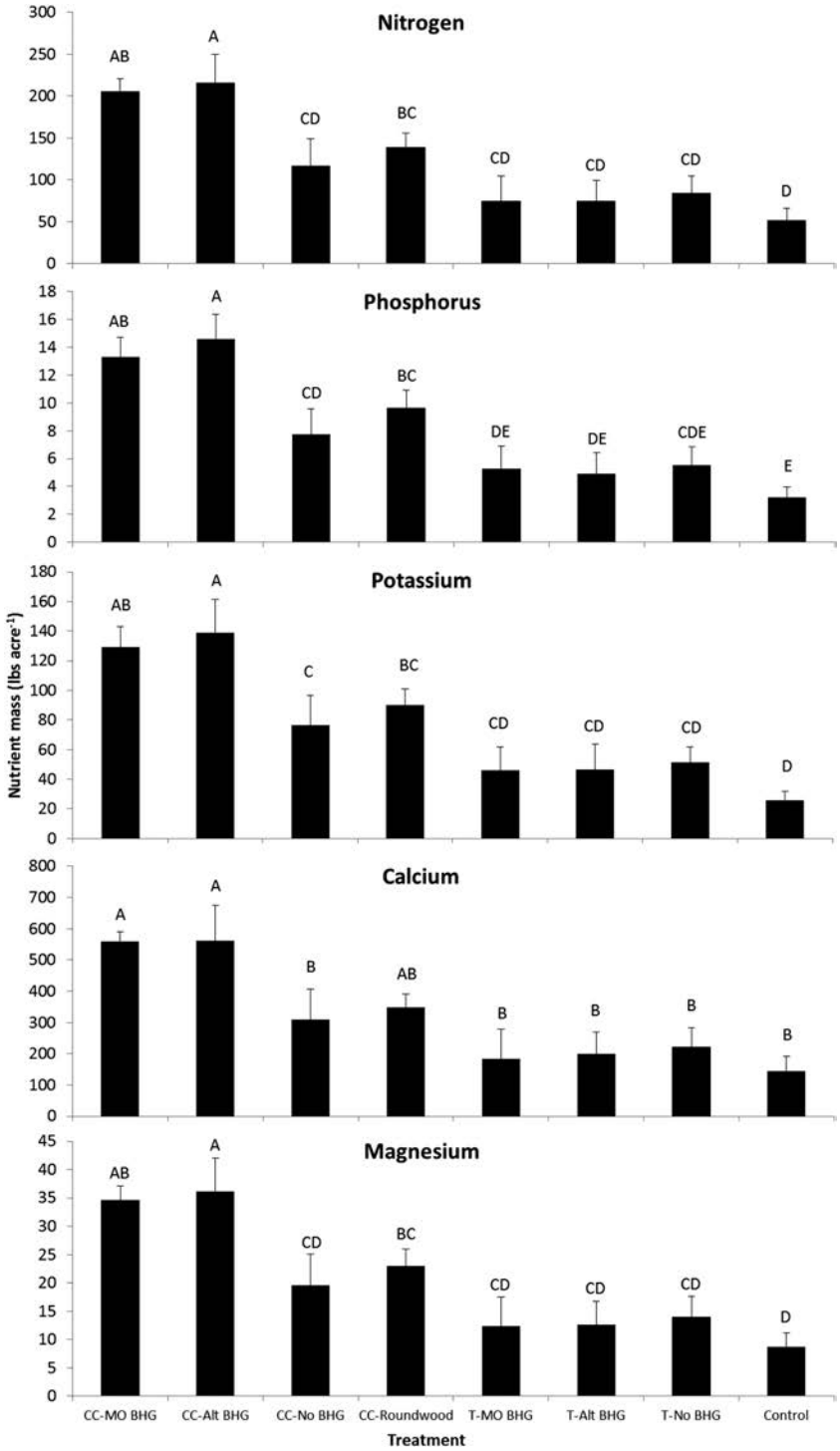

Figure 3. Nutrients retained in residual woody debris in plots following clearcut (CC) and thinning (T) treatments where woody biomass harvest guidelines (BHGs) were or were not imposed: Alt BHG, alternative scenario where tops of tree tops are retained and no restriction on small tree removal; MO BHG, retain one-third of the tree tops and one-third of the small trees; No BHG, no restrictions on removals. Other treatments included clearcutting with roundwood removal only (CC-Roundwood) and no harvest control. See Table 1 for more information about the treatments. For each nutrient, bars headed by different letters indicate significant differences (α = 0.05) by Fisher's least significant difference.

no restrictions on removals (CC-No BHG treatment). Because there were no restrictions on removals, we expected very little woody debris to remain following treatment. However, limbs and branches that were incidentally broken from tree crowns during felling and skidding operations remained dispersed across the treatment units (Figure 4). It was not economical to make additional passes to collect and remove these limbs and branches due to their low value for biofuel. We also observed that the boles of sawlog-size trees were left on site if they were hollow or had other obvious defect or were otherwise nonmerchantable and too large to be chipped and used as biofuel (Figure 4). This suggests that even in the absence of harvest restrictions, large quantities of woody debris

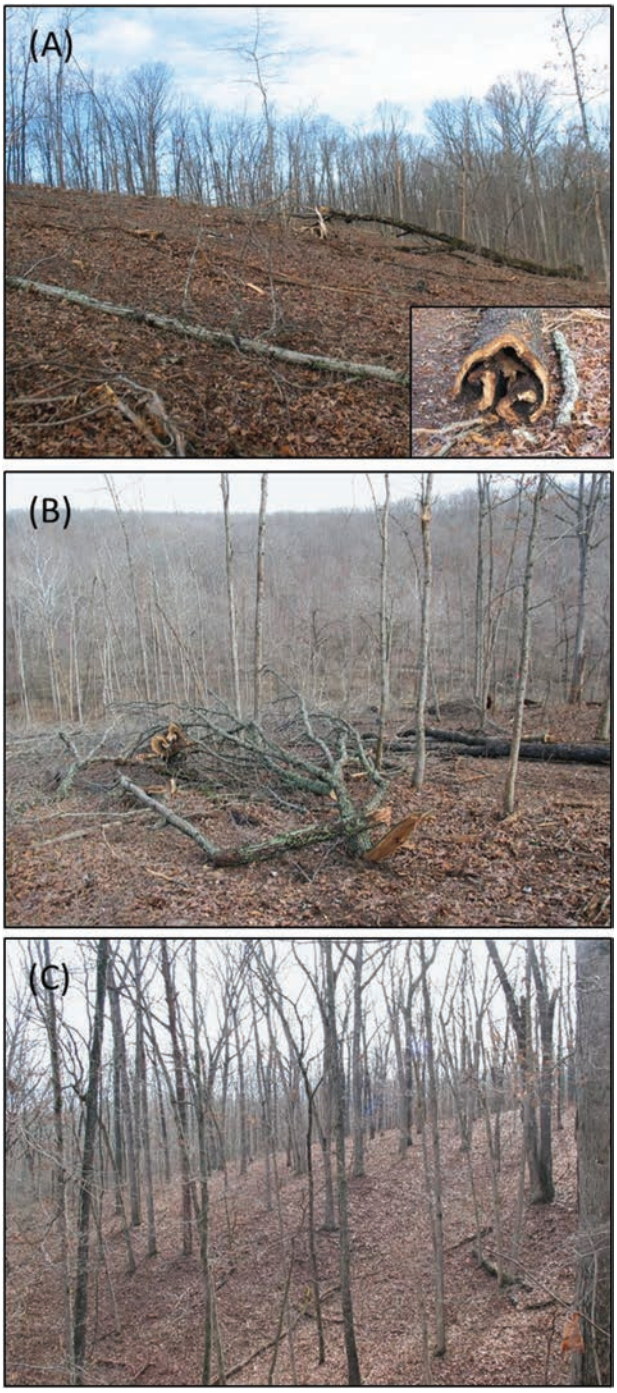

Figure 4. Image of the (A) CC-No BHG treatment where large quantities of woody debris are retained in harvested sites due to logistic and economic constraints associated with removing and processing woody debris. Panel (B) shows the CC-MO BMP treatment where one out of three small trees and tops of trees >8 in. dbh are retained, and panel (C) shows a nonharvested plot.

would likely remain on the site following biomass harvests due to the logistic and economic impracticalities associated with harvesting. Others have noted that large quantities of woody debris remain on site following harvesting, even where whole-tree harvesting has been practiced (Briedis et al. 2011, Klockow et al. 2013). We acknowledge that less woody debris would have been retained if there were fewer "cull" trees in the study. We postulate that larger quantities of woody debris are more likely to be retained in stands where the merchantable volume is lower, such as on low-quality sites and in stands that have a history of mismanagement, where defect is more prevalent. Similarly, if biofuels become more valuable, it may become economically feasible to utilize and remove more woody debris from the forest during a biomass harvest than under the current price structure.

The increases in retained woody debris during harvesting attributable to the BHGs occurred in the clearcuts. In stands that received an intermediate level of harvesting (i.e., a thinning), there were no differences in retained woody debris biomass among BHG treatments, and the amount of biomass retained was not significantly different from the woody debris biomass in the control treatment. This suggests that where harvest removals are minor, such as during thinning or other operations intended to improve rather than to regenerate the residual stand, applying BHGs will have little effect on the quantity of woody debris retained.

Several states in the in the eastern United States have developed BHGs (NEFA 2012) in response to concerns about harvesting for bioenergy (Evans et al. 2013), and many of the guidelines are very similar to those adopted in Missouri. For example, guidelines for biomass harvesting in Michigan, Minnesota, and Pennsylvania and by the Forest Guild for the northeastern United States recommend retaining as much as one-third of the tops, branches, and leaves or one-third of the woody residues (NEFA 2012). In Wisconsin, guidelines require retaining about one-tenth of the trees or 10% of the residues <4 in. in diameter from harvested trees, but only where nutrient depletion risk is considered minimal such as on the deeper (>20 inches to bedrock) mineral soils (Herrick et al. 2009). These guidelines were developed by managers, scientists, and policy makers using professional judgement rather than by extensive experimentation and verification (Herrick et al. 2009, Vance et al. 2014). Although research comparing the quantity of logging slash and other woody debris that remains after sawlog-only harvests and whole-tree harvests have been conducted extensively (Boyle et al. 1973, Freedman et al. 1981, Johnson and Todd 1998, Ponder et al. 2012), few have reported about the quantity of slash remaining in stands harvested for bioenergy where BHGs have been applied. One of the few studies that examined the efficacy of retention guidelines was described by Klockow et al. (2013) and was conducted in 55- to 68-year-old *Populus tremuloides* Michx. stands in Minnesota, USA, where retaining the tops and limbs of one out of five trees (20% retention) following a whole-tree harvest retained about 22 tons ac^{-1} of woody debris. This treatment retained nominally about 5 tons ac^{-1} (or about 25%) more woody debris than whole-tree harvests where all tops and limbs were removed except for incidental losses incurred during harvesting and skidding. In contrast, the retention level that we tested in our study (one out of three trees, or 33% retention) yielded disproportionately more woody debris (about 15 tons ac^{-1} or about 70% more) compared to where there was no restriction on removal. The differences between our finding and those of Klockow et al. (2013) are likely due to differences in species composition examined in these studies (e.g., broad-crowned oaks with high-density wood in our study compared to narrow-crowned *Populus tremuloides* with low-density wood in Klockow et al. 2013).

Nutrient Removal and Retention

There were no significant differences in the quantities of N, P, K, Ca, and Mg removed among the four clearcut treatments or among the three thinning treatments irrespective of BHG used (Table 4).

However, significantly greater quantities of nutrients were retained in clearcuts where BHGs were applied compared to clearcuts without BHGs or other restrictions (Figure 3). This suggests that where clearcuts are being conducted, BHGs can significantly increase the quantity of nutrients retained. Our results differ from those of Klockow et al. (2013) who found few significant differences in woody debris nutrient levels where guidelines recommended leaving tops and limbs of 20% of trees. However, the benefits of the BHGs in our study appear to be limited to where large quantities of wood are to be removed such as with even-aged regeneration harvests. Where intermediate harvests (thinnings) are being conducted, there were no significant differences in retained nutrient levels whether BHGs were applied, and nutrient levels retained were similar to those in the woody debris of the uncut control treatment.

Of the five nutrients examined in this study, Ca was removed in the greatest quantity in each treatment (Table 4). Except for Ca, nutrient removals in the harvested material were generally less than or equal to the quantity of nutrients retained in the woody debris (compare Table 4 and Figure 3). However, in the CC-No BHG treatment, about 1.6 times more Ca was removed in harvested material than was retained in the woody debris. This suggests that compared to the other macronutrients, there is a greater risk of Ca depletion where clearcutting for biofuel is practiced in the absence of guidelines requiring the retention of woody debris. While simple examination of nutrient removal and retention does not provide a complete biogeochemical understanding of nutrients at the study sites, previous research has raised concerns about forest harvesting and Ca depletion in soils with low concentrations of exchangeable Ca and few Ca-bearing minerals (Federer et al. 1989, Huntington et al. 2000, Kabrick et al. 2011). Release of Ca via mineral weathering in soils and atmospheric deposition would likely reduce the Ca deficit created by biomass harvesting (Kabrick et al. 2013). Retaining woody debris from species that have high Ca levels (e.g., oaks) will help reduce depletion. Additionally, the monitoring of exchangeable soil Ca concentrations in forests where biomass harvesting will occur will help ensure long-term forest sustainability.

Conclusions

The two BHGs that we examined each increased the biomass of retained woody debris by 1.7 times on this site following biomass harvesting with clearcutting compared to where no BHGs were applied. Harvests conducted with BHGs also retained more woody debris than was left after roundwood harvests that removed sawlogs, pulpwood, and small-diameter wood for pallets and blocking. However, there were no differences in retained woody debris in thinned units harvested for biomass regardless of BHG application. This suggests that as harvest intensity increases, the application of BHGs for retaining woody debris becomes more important. It is also important to recognize that in the absence of BHGs, large quantities of woody biomass remain on a site following biomass harvest because of logistic and economic constraints associated with skidding branches and limbs out of the forest and due to the presence of large but nonmerchantable trees that cannot be processed into biofuel. Nutrient retention trends followed those of biomass, and nutrients retained in woody debris generally exceeded nutrient removals in the harvested material. The only exception was for Ca, for which removal in clearcuts exceeded retention in the absence of BHGs. This suggests that monitoring of exchangeable soil Ca concentrations is needed in oak-hickory forests of low to moderate site quality harvested for bioenergy to ensure that Ca is not being depleted over time.

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