FIELD NOTE

Components and Nutrient Concentrations of Small-Diameter Woody Biomass for Energy

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ABSTRACT

The growing interest in using woody biomass for energy offers a potential opportunity to commercially remove cohorts of small-diameter trees (< 25 cm dbh) during thinning operations that otherwise have little or no economic value. However, there is little information about the quantity of biomass and the nutrients that would be removed during small-diameter harvests in oak stands of the Central Hardwood Region. The objectives of the study were to quantify biomass removals by component (foliage, twigs, bark, and stemwood) and the nutrient concentrations within components for estimating quantities of both wood and nutrients that would be removed under alternative harvest prescriptions. White oak was the most common species harvested; others included post oak, black oak, mockernut hickory, American elm, persimmon, white ash, and dogwood. Sampling indicated that heartwood and sapwood comprised most of the biomass (78–79%) followed by bark (15%), twigs (4–5%), and leaves (about 2%). Estimated nutrient removals during a small-diameter harvest in this region were 1.3–3 times greater than during conventional sawlog harvests. The relatively high nutrient removals that can occur for biomass harvesting compared to traditional sawlog harvests underscore an ongoing need to ensure that nutrient removals during biomass harvesting do not exceed inputs from soil mineral weathering and the atmosphere.

Keywords: biomass, small-diameter trees, harvesting, thinning, nutrients

The growing interest in using woody biomass for energy (Aguilar and Garrett 2009, Janowiak and Webster 2010) offers an opportunity to commercially harvest small-diameter trees that in the Midwest have little or no economic value. This is particularly true for oak forests of the western Central Hardwood Region where trees generally must be larger than 25 cm dbh to be merchantable. In oak stands, thinning small-diameter trees can be desirable for enhancing the quality, growth, and merchantability of the residual stand (Johnson et al. 2009). There also is increasing interest in restoring oak woodlands and savannas on hundreds of thousands of ha of closed-canopy and dense oak forest (Nelson 2005). This often requires thinning from below to open the midstory and understory to increase the light reaching the forest floor. Energy markets for biomass from small-diameter trees could reduce or eliminate the expense associated with removing small-diameter trees.

Along with this increased interest in woody biomass harvesting are concerns about nutrient depletion associated with increased harvest intensity (Page-Dumroese et al. 2010). Nutrient removals associated with harvesting are directly related to the quantity, size, species composition, and components of the trees removed from the site (Messina et al. 1986, Swank and Reynolds 1986, Johnson and Todd 1987, Page-Dumroese et al. 2010). Although stand inventory information can be used to estimate the total biomass of various size classes of trees in forests, the quantity of the biomass and nutrients that can actually be removed during small-diameter harvests remains unknown because of a number of logistical and economic constraints associated with its harvesting, skidding, and chipping.

We conducted a study in southeastern Missouri to estimate nutrient removals associated with biomass harvesting. We quantified the biomass removals for entire trees and by components (foliage, twigs, bark, and stemwood) and the nutrient concentrations within these. We used those results for comparing nutrient removals associated biomass harvests to those of sawlog harvests in the study region. Our findings provide a basis for estimating nutrient removals by tree size and component (stem, bark, twigs, foliage) for other actual or planned harvest of small diameter trees as well as for larger trees.

Methods

Study Area

The study was conducted within a 3.4-ha area of the Poplar Bluff Ranger District of the Mark Twain National Forest in Butler County in southeastern Missouri and within the Black River Ozark Border ecological subsection (Nigh and Schroeder 2002). The soils at the study site were mapped as Captina silt loam, 1–5% slopes. The Captina series is classified as fine-silty, siliceous, active, mesic Typic Fragiudults. Soils in the Captina series formed in loess over cherty pedisediments or cherty residuum from the underlying limestone, are moderately well drained, and contain a root-limiting

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; cubic meters (m^3): 1 m^3 = 35.3 ft^3; millimeters (mm): 1 mm = 0.039 in.; hectares (ha): 1 ha = 2.47 ac; kilograms (kg): 1 kg = 2.2 lb; megagrams (Mg): 1 Mg = 2,204.6 lb.

fragipan. When the study was initiated, the stand was at full stocking with 599 trees per ha. The dominant overstory species included white oak (*Quercus alba* L.), black oak (*Q. velutina* Lam.), post oak (*Q. stellata* Wangenh.), and mockernut hickory (*Carya tomentosa* (Poir.) Nutt.). Other species included white ash (*Fraxinus americana* L.), American elm (*Ulmus americana* L.), flowering dogwood (*Cornus florida* L.), and persimmon (*Diospyros virginiana* L.).

Treatments

The biomass harvesting treatment was a thinning from below to remove all trees < 25 cm dbh. This operation also would be similar to thinning from below to increase growth of the residual stand or to create a stand with open midstory and understory suitable for oak woodland restoration. Felling, skidding, and chipping of the harvested biomass material was done using small-scale equipment specifically designed for maneuvering around standing timber while removing small-diameter trees (Figure 1).

Measurements and Sampling

During the harvest, 10 bundles of trees skidded to the landing were selected for measurement and nutrient sampling. The bundles were evenly distributed throughout the harvest area and were selected in order of their generation by the harvester. Bundles comprised 5–10 trees that were stacked parallel to each other and oriented so that a grapple skidder could haul an entire bundle to the landing in a single trip. Prior to yarding, the species, total length, basal diameter, and approximate dbh of each tree in a bundle were recorded and used in equations by Jenkins et al. (2004) to estimate the biomass of each tree.

As each of the 10 bundles of trees was fed into the chipper, we used a large, fine-mesh net to collect from five to nine samples of the composite, chipped material as it exited the chipper. Whole trees were fed into the chipper two or three at a time. The collected chips were mixed and replicate 3.8-L samples were retained for further analyses. Each sample was sealed in a plastic bag to preserve the moisture content until it could be transported to the laboratory where it was stored at 6° C prior to processing.

Laboratory Procedures and Calculations

A 0.5-L subsample from each of the two replicate composite samples was removed and separated it into the components of foliage, twigs, bark, and stemwood. The components were weighed (green weight), dried for 48 hours at 60° C to a constant weight, and then reweighed to determine dry weight. The moisture content (dry weight basis) was calculated using the formula

$$moisture\ content = \frac{green\ weight}{dry\ weight} - 1 \qquad (1)$$

Separate estimates of the biomass components (foliage, twigs, bark, stemwood) and their nutrient concentrations for each tree bundle were averaged for the replicate chip samples taken from each bundle. We ground the component samples to pass through a 20-mesh (1-mm) screen using a Cyclone Lab Sample Mill plant grinder (UDY Corporation, Fort Collins, CO). Dried samples were sent to the University of Arkansas Agriculture Diagnostic Laboratory in Fayetteville, AR. Laboratory methods included N determined by combustion (FP-428 Nitrogen Analyzer, LECO Corporation, St. Joseph, MI). The nutrients P, K, Ca, and Mg were measured via inductively coupled plasma (SPECTRO Analytical Instruments, Inc., Mahwah, NJ) after plant material was dissolved using a HNO_3-H_2O_2 wet ashing digestion procedure (Plank 1992). Unless noted otherwise, sample means ± 1 standard error were calculated by averaging values observed for the 10 sampled tree

Figure 1. Felling was completed by a small excavator (John Deere 75C) with a Fecon shear head (A). Felled trees were placed in bundles that were transported to the landing using a 50 hp hydrostatic Turbo Forest skidder with a swing-arm grapple (B). Bundles taken to the landing were chipped using a 325 hp Morbark Typhoon chipper equipped with a small loader (C).

Table 1. Characteristics of harvested woody biomass by species[a].

Species	Diameter	Height	Biomass[b]	Total biomass
	cm	m	kg	%
American elm	8 (7–8)	7.6 (7.6–7.6)	16 (14–22)	<1
Flowering dogwood	6 (5–6)	5.3 (4.6–6.1)	8 (7–11)	<1
Persimmon	9 (NA)	9.1 (NA)	26 (NA)	<1
White ash	6 (5–8)	7.6 (6.1–9.1)	12 (5–22)	1
Mockernut hickory	10 (5–18)	8.8 (3.0–15.2)	38 (7–147)	25
Black oak	14 (12–16)	14.5 (13.7–15.2)	79 (59–114)	5
Post oak	16 (11–24)	13.0 (9.1–15.2)	121 (48–302)	17
White oak	10 (5–22)	9.3 (3.0–16.8)	41 (8–236)	50
All species	10 (5–24)	9.4 (3.0–16.8)	48 (5–302)	100

[a] Values are means and (range) determined by individual species regardless of the bundles from which they were identified.
[b] Estimated using equations of Jenkins et al. 2004.

Table 2. Average percent (± 1 standard error) of total green and dry biomass by foliage, twigs, bark, and stemwood[a].

	n	Green weight (%)	Dry weight (%)
Foliage	10	2.0 ± 0.5	1.7 ± 0.4
Twigs	10	4.5 ± 1.3	4.4 ± 1.2
Bark	10	15.3 ± 1.6	15.4 ± 1.5
Stemwood	10	78.1 ± 2.4	78.5 ± 2.3

[a] There were no significant differences between green and dry weights ($P > 0.64$) in the percent of biomass by component.

bundles. We compared differences in the proportion of biomass components before and after drying using analysis of variance (ANOVA; proc GLM, SAS Institute, Inc., Systems, Cary, NC).

Results

Composition and Characteristics of the Harvested Trees

Harvested trees ranged from 5 to 24 cm dbh, from 3 to 17 m tall, and from 5 to 302 kg in total biomass (Table 1). Species composition varied among bundles, but oaks were the dominant species making up > 72% of the harvested biomass with hickories (*Carya* spp.) making up an additional 25%. White oak was the most common oak species harvested (50% of the dry mass), but other oaks included post oak (17%) and black oak (5%). Mockernut hickory accounted for an additional 25% of the harvested biomass. Other species included American elm, persimmon, white ash, and dogwood with each contributing about 1% to the harvested biomass. No trees smaller than 5 cm dbh or 3 m tall were harvested.

Components and Nutrient Concentrations of Chipped Material

Stemwood (heartwood and sapwood combined) made up most of the biomass (78–79%) followed by bark (15%), twigs (4–5%), and leaves (about 2%) (Table 2). Oven drying reduced the mass of the leaves by 41% and the mass of twigs, bark, and stemwood by 30%. The moisture content expressed on a dry weight basis was about 69% for the leaves and about 43% for the twigs, bark, and heartwood. Drying did not significantly ($P > 0.64$) alter the relative proportions of each component by mass.

Foliage had the greatest nutrient concentrations, particularly for N, which was about 3 times greater than for twigs and bark and nearly 7 times greater than for the heartwood and sapwood (Table 3). For most other nutrients, the concentrations in the foliage were about 2–3 times greater than in the other components. The one exception was for Ca, which had concentrations 3–10 times greater in bark than in the other components. Because most of the biomass is derived from the stemwood (78%, dry basis), the composite nutrient concentrations most closely resemble those of the stemwood.

Discussion

Composition of Harvested Material

The species composition of the harvested biomass reflected the typical species composition of the < 25-cm-diameter trees in upland forests of the Ozark Highlands (Kabrick et al. 2004), particularly for forests growing on the Captina silt loam soil that has a low nutrient supply capacity (Soil Survey Staff 2013). This is an extensive soil in this region and was mapped on more than 42,000 ha (Center for Applied Research and Environmental Systems 2013). On these and on similar soils throughout the Ozark Highlands, oaks generally make up about 70% of the basal area (Kabrick et al. 2004). Hickories are abundant in the midstory on ridges and upper slopes throughout the Ozark Highlands (Kabrick et al. 2004). The other species listed in Table 1 commonly occur in Ozark forests but are seldom abundant.

Components of Chipped Material

On average, trees harvested in our study had a lower percentage of foliar biomass than trees in other regions. For example, Colannino (1976) reported that the proportion of biomass in leaves of white oaks in West Virginia ranged from 1.6 to 6.8% across a wide range in diameters. In the Georgia Piedmont, Monk et al. (1970) reported that foliage comprised about 2.7–7.2% (dry basis) for oaks and hickories. The relatively lower proportions of leaf biomass that we observed (1.7 ± 0.4%) may be due to the canopy position of the trees. Low light levels are common under the main canopy of fully stocked stands. Consequently, crowns were relatively small even for moderately shade-tolerant species such as white oaks and hickories. The proportion of biomass in bark we reported (15.4 ± 1.5%) was consistent with values reported for hickory elsewhere (17–23%; Wartluft 1977, Schnell 1978), but oaks in the mountains of North Carolina and in the Piedmont of Georgia and South Carolina (Phillips 1981) generally had about 24–28% of their aboveground biomass in bark.

Nutrient Content of Chipped Material

Nutrient concentrations among biomass components were similar to those reported elsewhere for similar species and size classes. As in this study, others have reported that Ca concentrations were greater in the bark and foliage than in the stemwood (Chase and Young 1978, Kennedy et al. 1986), particularly for oaks (Kennedy and Schlaegel 1985). Potassium, Mg, and P levels are typically greater in foliage than in stemwood, bark, or branches (Kennedy and Schlaegel 1985). Nitrogen concentrations were about 2–3 times greater in foliage than in branches, bark, or stemwood (Chase and Young 1978, Martin et al. 1998). Foliar N levels in our study were slightly lower than reported for oaks in other studies (Martin et al. 1998, Kabrick et al. 2005). However, foliar N is highly mobile and its concentrations have been shown to vary over the course of a growing season (Ponder et al. 1979, Scherzer et al. 2003). Our samples were taken in late summer (August) during a particularly dry period when foliage N levels would be expected to be lower than earlier in the growing season (Kennedy and Schlaegel 1985). The great variation reported in the literature suggests the importance of using species-, size-, and ecoregional-specific nutrient concentrations for estimating the quantities removed from stands by harvesting.

Table 3. Average (± 1 standard error) nutrient concentration (dry weight basis) by foliage, twigs, bark, and stemwood.

	n	N	P	K	Ca	Mg
				g kg^{-1}		
Foliage	10	14.34 ± 0.21	0.75 ± 0.02	6.24 ± 0.29	12.98 ± 0.36	2.04 ± 0.17
Twigs	10	4.71 ± 0.13	0.43 ± 0.03	3.21 ± 0.24	8.17 ± 0.36	0.76 ± 0.07
Bark	10	4.36 ± 0.12	0.19 ± 0.01	2.41 ± 0.11	36.66 ± 1.55	0.89 ± 0.09
Stemwood	10	2.19 ± 0.06	0.10 ± 0.01	1.40 ± 0.06	3.61 ± 0.21	0.36 ± 0.01
Composite	10	2.84 ± 0.05	0.14 ± 0.01	1.71 ± 0.06	9.04 ± 0.29	0.49 ± 0.06

Table 4. Estimated dry weight of biomass components and nutrients per metric ton of dry biomass for trees < 25 cm dbh calculated with and without foliage.

	Dry weight[1]	N	P	K	Ca	Mg
	kg			g		
With foliage						
Foliage	17	237	12	103	215	34
Twigs	44	209	19	142	363	34
Bark	154	670	30	370	5,631	136
Stemwood	785	1,721	75	1,097	2,834	283
Total	1,000	2,837	136	1,712	9,042	487
Without foliage[2]						
Twigs	45	213	19	145	369	34
Bark	157	681	30	376	5,728	139
Stemwood	798	1,751	77	1,116	2,883	288
Total	1,000	2,645	127	1,637	8,980	461

[1] Dry weight can be determined by dividing the green weight by (1 + moisture content), where the moisture content is expressed as a fraction of the dry weight.
[2] Values were calculated by dividing the dry weights and nutrient contents by 0.983, which is (1–0.017, where 0.017, or 1.7%, is the proportion of foliage in dry biomass shown in Table 2).

Application

The values reported here can be used for estimating biomass component and nutrient removals during a small-diameter harvest (trees between 5 and 25 cm dbh) in stands having low to moderate site quality and similar composition in the Central Hardwood Forest Region. Table 4 provides dry weights and nutrient content by biomass components per dry metric ton of biomass harvested. These values can be used for estimating nutrient removals that would occur during a small-diameter biomass harvest. For example, harvesting trees < 25 cm dbh would remove about 33–43 green metric tons ha^{-1} of woody biomass in mature upland oak stands in the Ozark Highlands (Missouri Forest Products Association 2011). Assuming a median value of 38 green metric tons ha^{-1} and a dry weight that is approximately 70% of the green weight (or 43% moisture content on a dry weight basis), this would yield approximately 27 metric tons per ha of dry biomass. The biomass and nutrient content values in Table 4 suggest that harvesting 27 metric tons of dry biomass per ha would remove about 77 kg of N, 4 kg P, 46 kg K, 240 kg Ca, and 13 kg of Mg per ha if harvested during the growing season when leaves were on the trees.

The nutrient yield data in Table 4 can be used to estimate nutrient removals per dry ton of biomass for foliage, twigs, bark, and stemwood, separately or in combination depending on the harvesting method. For example, nutrient removals occurring during a dormant-season harvest would exclude foliage and can be estimated (Table 4) by dividing the nutrient concentrations for the components other than foliage by 0.983, which is 1 minus the proportion of foliage in dry biomass (the value 0.017, or 1.7%, from Table 2).

Because of concerns about excessive nutrient removals associated with biomass harvesting (Page-Dumroese et al. 2010), we compared estimated nutrient removals associated with small-diameter harvesting to those that would occur during traditional sawlog-only harvests. With traditional sawlog-only harvests in this region, nonmerchantable trees remain standing or are felled and left in the woods. Likewise, tops and limbs of merchantable trees remain in the woods as logging slash. Data from the Missouri Ozark Forest Ecosystem Project (Shifley and Kabrick 2002) indicated that a single harvest entry using the combination of single-tree and group selection for uneven-aged management generally removes about 20 m^3 ha^{-1} (14 dry metric tons ha^{-1}) in merchantable sawlog stemwood and bark and an even-aged clearcut removes about 43 m^3 ha^{-1} (29 dry metric tons ha^{-1}) of merchantable sawlog stemwood and bark in mature stands that are at least 60 years old (Table 5). Using nutrient con-

Table 5. Comparison of estimated removals under different kinds of harvesting regimes applied in southeastern Missouri.

	Selection harvesting[b,c,d] (uneven-aged)	Clearcut harvesting[b,d] (even-aged)	Biomass harvesting[e] (stems < 25 cm dbh)	Biomass harvesting[f] (all stems > 3 cm dbh)	Atmospheric inputs[g] (average annual)
Volume harvested (m^3 ha^{-1})[a]	20	43	–	–	–
Dry biomass (tons ha^{-1})	14	29	27	101	–
			kg ha^{-1}		
N	27	58	77	222	5.0
P	1	3	4	16	Not reported
K	15	32	46	100	0.5
Ca	64	136	240	673	1.6
Mg	2	6	13	26	0.3

[a] Board foot per acre harvest data from Kabrick et al. (2002) converted to m^3 ha^{-1} assuming 5.5 board feet per cubic foot and a dry weight of 36 pounds per cubic foot plus an additional 16% added to account for bark weight on the sawlogs.
[b] Nutrient concentrations in sawlogs were estimated using merchantable stem section data from Swank and Reynolds (1986).
[c] Selection harvesting followed the Guidelines of Law and Lorimer (1986) and included single tree (using a guiding curve with a residual basal area equating to B-level stocking (Gingrich 1967), a maximum residual diameter = 45 cm dbh, and a q value of 1.5) and group selection (groups 1 to 2 tree heights in diameter and summing to 5% of harvested area). In the study region selection harvests are typically repeated on a 15- to 20-year interval.
[d] Removal of only sawlog boles with a minimum 27-cm dbh and a 22-cm top diameter.
[e] Estimates are from this study.
[f] Biomass estimated using Forest Inventory Analysis data for southeastern Missouri and nutrient concentrations from a biomass nutrient study in mixed oak stands in eastern Tennessee (Johnson and Todd 1987).
[g] Average annual atmospheric inputs estimated for years 1981–2008 with data from NTN MO-05 (University Forest, Butler County, Missouri) from the National Atmospheric Deposition Program (nadp.sws.uiuc.edu/; last accessed Jan. 7, 2013).

centrations for large trees of similar species composition (Swank and Reynolds 1986), we estimate that about 27 kg ha^{-1} of N and 64 kg ha^{-1} Ca would be removed with tree boles (including bark) harvested during a periodic uneven-aged sawlog harvest in a mature stand, and 58 kg ha^{-1} of N and 136 kg ha^{-1} Ca would be removed in sawlog boles and bark during a clearcut in a mature stand. By comparison, biomass harvesting, even when restricted to trees < 25 cm dbh, appears to remove greater total biomass (and cubic foot volume) and more nutrients than does traditional sawlog harvesting (boles and bark only) in this region. Compared to small-diameter trees removed with whole-tree harvesting for biomass, traditional sawlog harvests remove fewer nutrients per unit volume and less total biomass (or cubic volume). If trees ≥ 25 cm dbh at our study site were removed in addition to the biomass harvest of trees < 25 cm dbh, total nutrient removals would be about 5–10 times greater than for conventional sawlog harvests in this region (Table 5). In mixed oak stands elsewhere in the Central Hardwood Region where standing biomass can be much greater (e.g., on more productive sites), biomass and nutrient removals may be greater than we observed in Missouri. For example, if all trees were available for removal, Johnson and Todd (1987) estimate that 165 metric tons ha^{-1} of biomass, including 315 kg ha^{-1} N and 1000 kg ha^{-1} Ca, would be removed during a whole-tree harvest in mixed oak stands in Tennessee.

The relatively high nutrient removals that can occur for biomass harvesting compared to traditional sawlog harvests underscore a need for ensuring that nutrient removals do not exceed inputs from the weathering of soil minerals and from atmospheric deposition, particularly where soils have a limited capacity to supply base cations such as Ca and Mg (Kabrick et al. 2011). In this region, inputs from soil mineral weathering remain unknown but atmospheric inputs will exceed removals associated with small-diameter biomass harvesting in about 15 years for N, 45 years for Mg, 90 years for K, and 150 years for Ca (Table 5). Consequently, best management practices developed for biomass harvesting in Missouri (Missouri Department of Conservation 2011) require the retention of about a third of trees ≤ 25 cm dbh and the tops and limbs of trees > 25 cm dbh during a biomass harvest to reduce nutrient removals (Missouri Department of Conservation 2011).

With periodic sawlog harvests that remove only a small portion of the wood and bark from a site, there is little reason to be concerned about nutrient depletion because nutrient inputs exceed nutrient removals over the cutting cycle or rotation. But nutrient dynamics may need to be monitored during widespread intensive biomass harvests and other situations where a large proportion of wood, twigs, bark, and foliage are removed from the site. With the methods we describe here, it is possible to treat macronutrients as simply another dimension of forest growth and yield. Just as we monitor the accumulation and depletion of board feet, cubic feet, and biomass as forests grow and are harvested, we can (a) monitor the quantity of nutrients that are added to a site through atmospheric deposition or soil weathering, (b) estimate the accumulation of nutrients in boles, bark, twigs and foliage as trees grow, and (c) estimate the nutrients that will be removed through alternative harvest prescriptions. The capacity to do so will be enhanced by improved regional estimates of nutrient content in tree components.

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