For. Sci. 63(4):413–419
https://doi.org/10.5849/FS.2016-065

biometrics

Estimating Aboveground Tree Biomass for Beetle-Killed Lodgepole Pine in the Rocky Mountains of Northern Colorado

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The recent mountain pine beetle (*Dendroctonus ponderosae* Hopkins) epidemic has affected millions of hectares of conifer forests in the Rocky Mountains. Land managers are interested in using biomass from beetle-killed trees for bioenergy and biobased products, but they lack adequate information to accurately estimate biomass in stands with heavy mortality. We destructively sampled live ($n = 7$) and mountain pine beetle-killed ($n = 7$) lodgepole pine (*Pinus contorta* Dougl. ex Loud.) trees in the northern Colorado Rocky Mountains to develop and compare diameter-based aboveground component biomass equations. We used the seemingly unrelated regression approach to simultaneously estimate the parameters in the system of allometric equations. The results show no significant difference in total aboveground biomass between live and dead trees. However, top, bark, and foliage components are significantly different between the two groups ($P < 0.05$). When logging residues (i.e., tree tops, branches, and foliage) are of interest as biomass feedstock, the allometric equations developed for beetle-killed trees could provide more accurate estimates of the resources available in beetle-killed stands than the existing live tree allometric equations.

Keywords: mountain pine beetle, bioenergy feedstock, allometry, seemingly unrelated regression, logging residue

Mountain pine beetle (*Dendroctonus ponderosae* Hopkins)-caused tree mortality is a significant forest management challenge in the interior western United States and Canada, affecting millions of hectares of forestland since 2000 (US Department of Agriculture Forest Service 2015). The biomass of beetle-killed trees in this region represents a vast bioenergy resource that requires no cultivation and may have a favorable carbon balance compared with that of fossil fuels. Removal and use of these trees are also tied to wildfire risk mitigation, especially when values at risk include homes and infrastructure. However, there remains considerable debate as to the quantity and condition of this resource, and more accurate estimation of recoverable beetle-killed biomass is needed to assess the feasibility, sustainability, and efficiency of using beetle-killed trees for biomass feedstock. Mortality affects the potential quality and quantity of recoverable biomass by altering the ratio of biomass components and the moisture content (Jenkins et al. 2008). Beetle-infested trees lose their foliage after dying and then drop fine branches and large portions of their crowns before falling to the ground. Depending on species and site conditions, the main stem may remain standing 4–10 years after the attack, but with low intact crown biomass (Schoennagel et al. 2012, Hoeger et al. 2014). The relationship between forest inventory measurements and the biomass of individual beetle-killed trees changes over time; however, no available biomass equations have considered those changes for beetle-killed trees. Such equations would be useful in evaluating a variety of stand characteristics, including the amount of biomass potentially recoverable from silvicultural treatments such as salvage harvesting and fuel reduction thinning.

In this study, we performed destructive sampling of live and mountain pine beetle-killed lodgepole pine (*Pinus contorta* Dougl. ex Loud.) trees in the northern Colorado Rocky Mountains to collect allometric data. The allometric equations of aboveground biomass and

Manuscript received August 22, 2016; accepted January 31, 2017; published online March 2, 2017.

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Acknowledgments: *This research was supported by Agriculture and Food Research Initiative Competitive Grant 2013-68005-21298 from the USDA National Institute of Food and Agriculture through the Bioenergy Alliance Network of the Rockies (BANR). Logistical support was provided by the Colorado State Forest State Park. We are grateful to Obie O'Brien, Brian Woodward, Elizabeth Reiling, and Ryan Anderson for data collection.*

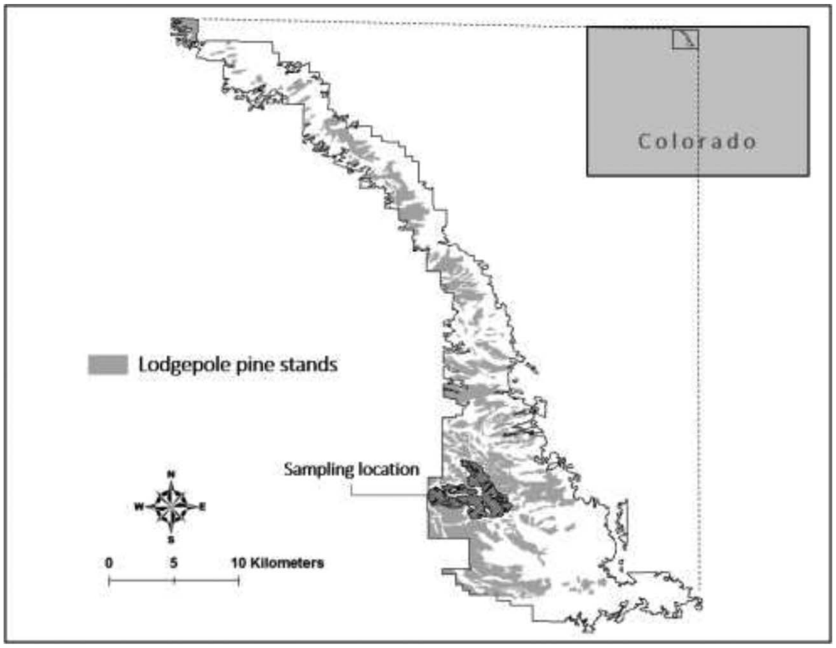

Figure 1. Map of the Colorado State Forest State Park showing the beetle-killed lodgepole pine stand selected for data collection.

its components were developed, and the allometric relationships were compared between live and dead tree groups.

Methods

Study Area

This study was conducted within the Colorado State Forest State Park, an approximately 29,000-ha property, located on the west side of the Medicine Bow Mountains in northern Colorado, USA (40°30′ N, 106°00′ W). Elevations in the forest range from 2,570 to 2,980 m above sea level, and mean annual temperature and precipitation are 1.5°C and 75 cm, respectively (PRISM Climate Group 2012). The forest is dominated by lodgepole pine and quaking aspen (*Populus tremuloides* Michx.) with Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) at higher elevations. The forest was burned in the early 20th century and extensively logged in the 1940s and 1950s. Since 2002, the forest and its surrounding areas have been heavily affected by mountain pine beetles, leaving 50% of lodgepole pine trees in the region dead (Schoennagel et al. 2012, Colorado State Forest Service 2015). The forest is currently managed for multiple use with timber production remaining a priority.

Seven live trees and seven dead trees were selected from an 813-ha beetle-killed lodgepole pine stand in the forest (Figure 1). Efforts were made to select a representative stand of the beetle-infested portion of the forest and to select trees that had no major forks or broken tops and a range of diameters reflecting the sizes of beetle-killed trees in the study area. The stand is located around 2,710 m above sea level on relatively flat terrain with an average ground slope of 14% and on north and northeastern aspects. Mountain pine beetles heavily affected the stand in 2007. The average dbh and height of trees in the stand were 23 cm and 17 m, respectively, and the average stand density was 764 trees/ha with 57% tree mortality.

Field Measurement and Data Collection

The 14 trees selected were destructively sampled in July 2014. All dead trees were in the gray stage and no longer had foliage. The sampled trees were cut and felled onto a large tarpaulin of 12 × 18 m spread on the ground to capture all crown components. We then measured dbh, total tree height, crown base height, and height to the top of the main stem where the bole's diameter reached 10 cm (4 in.).

The sampled trees were divided into five components for their measurements (Jenkins et al. 2003): bole, bark, top, branch, and foliage. The bole component is the main stem up to 10-cm top diameter, and the bark component is the bark on this bole. The top component is the rest of the tree stem including branches and foliage attached to the stem. The branch and foliage components consist of branches and foliage from the ground up to 10-cm top diameter, respectively, but not branches and foliage from the top component of the tree. Although collection of intact branch samples of live trees was fairly easy, it was difficult to collect those of dead trees in the field as most branches broke apart when the tree was felled and hit the ground. The following section describes in detail data collection methods applied to live and dead trees.

Live Trees

After the tree was felled, all crown branches that were directly attached to the main bole were measured for height to branch base and diameter at the base. We divided the crown distance into three equal strata and randomly selected two branches from each stratum for further measurements and oven drying (Poudel et al. 2015). For each subsampled branch, we measured its length and weight with foliage using a precision digital scale (OHAUS Valor 1000 model V11P6, maximum 6 kg, least count 0.001 kg). The woody material and needles from each subsampled branch were separated on a tarpaulin, weighed, and kept for oven drying. Cones were included with the woody material. All other crown branches were removed and weighed together in the field using a large digital scale (Tree LVS 700, maximum 320 kg, least count 0.1 kg). The top of the main stem has generally been disaggregated into other tree components in previous biomass studies (Wang 2006, Návar 2009) but was considered as a potential source of biomass feedstock for harvest

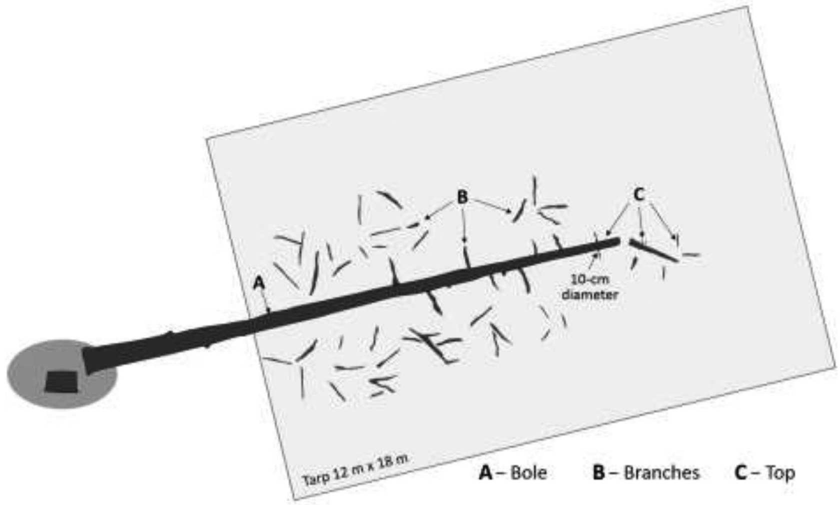

Figure 2. Collection of dead tree biomass components.

Table 1. Summary statistics of live and dead sample lodgepole pine (*Pinus contorta* Dougl.) trees used in this study.

Characteristic	Tree group	n	Mean	SE	Minimum	Maximum
dbh (cm)	Live	7	22.7	2.3	14.8	31.2
	Dead	7	24.5	2.2	16.5	33.6
Height (m)	Live	7	18.1	1.1	14.5	21.1
	Dead	7	19.4	1.2	14.3	22.4
Crown base height (m)	Live	7	8.1	1.1	3.8	10.8
	Dead	7	9.1	0.9	5.4	12.2
Dry weight biomass (kg)						
Total	Live	7	229.4	48.7	73.5	434.7
	Dead	7	242.3	52.1	69.3	470.1
Bole	Live	7	164.0	35.9	47.6	313.1
	Dead	7	198.5	42.4	54.6	384.3
Top	Live	7	29.2	3.9	17.6	45.7
	Dead	7	14.3	2.0	8.1	21.8
Bark	Live	7	10.7	2.2	3.1	19.2
	Dead	7	8.7	1.7	1.4	13.7
Branch	Live	7	16.2	4.8	0.8	37.2
	Dead	7	20.9	7.6	3.0	51.1
Foliage	Live	7	9.5	2.6	0.6	19.6
	Dead	7				

in this study. Therefore, each tree top was weighed in the field as a separate component with and without its branches and foliage. This approach was facilitated by the fact that lodgepole pine crowns in the study area tend to have a central stem from bole to tip and rarely have multiple forked tops. After all the branches and the top were removed, we cut the bole into 1.2-m (4-ft) segments starting from the base of the tree. After weighing, a wood disk was removed from the top of each segment as a subsample for the bole. Green mass of disks and four segments 90° apart along the disk edge were measured for thickness and diameter. The bark was then removed from the disk, and the same measurements were made without bark. A bark sample approximately 10 cm long was taken from each disk, and its width, length, and weight were recorded. The disk and bark sample were kept for oven drying.

Dead Trees

As it was impossible to collect intact branch samples for dead trees, all crown branches and branch pieces were separated from the top component on a tarpaulin after the tree was felled (Figure 2). Branches were then collected together and weighed in the field. No foliage remained attached to branches for dead trees. The top of the main stem and broken pieces from the top were collected and weighed in the field. A total of 10 branch subsamples were randomly selected from seven dead trees, weighed, and kept for oven drying for moisture content measurement. For the bole and bark components, the same sampling method as that for the live trees was used. However, there were several wood discs that did not have full bark coverage because of the bark slough off. For those discs for which the bark sample was not available to be taken, we collected all the bark from the entire disc, and the side area of the entire disc was used to estimate a dry weight to surface area ratio accordingly.

Table 2. Average moisture contents of biomass subsamples.

Biomass component	Tree group	n	Wet basis moisture content (%) Mean	SE	Minimum	Maximum
Disk	Live	82	51.5	7.2	27.9	64.6
	Dead	74	9.7	1.4	5.1	13.3
Bark	Live	82	56.4	6.5	28.5	66.6
	Dead	74	15.0	10.0	0.7	50.5
Branch	Live	42	42.0	6.1	13.7	50.3
	Dead	10	7.9	0.9	6.9	9.1
Foliage	Live	42	49.8	2.5	43.0	54.3
	Dead					

Table 3. Logarithmic regression equations for individual branch and foliage biomass of live lodgepole pine (*Pinus contorta* Dougl.) in the Rocky Mountains of northern Colorado (n = 42).

Biomass component	Statistical parameters a_b	b_b	Adjusted R^2
Branch	3.5368* (0.1981)	2.3816* (0.1390)	0.97
Foliage	3.4245* (0.2900)	1.9850* (0.2102)	0.94

Branch and foliage are in dry weight (g).
* Significant parameters in the estimated models ($P < 0.05$), and numbers in parentheses indicate SEs of estimated parameters.

Moisture Content and Dry Weight Biomass

Wood disks, bark samples, and branch wood from live and dead trees and foliage from live trees were dried in the laboratory at 105° C to determine moisture content (De-Miguel et al. 2014). During the drying process, weights were checked daily until sample

Table 4. Dummy variable regressions of total and component biomass for lodgepole pine (*Pinus contorta* Dougl.) in the Rocky Mountains of northern Colorado.

Aboveground component (y_i)	Statistical parameters			
	a	*b*	*c*	Adjusted R^2
Total biomass	−300.208* (34.713)	22.167* (1.353)	27.084 (14.978)	0.954
Bole	−222.694* (28.760)	17.210* (1.121)	−3.512 (12.409)	0.949
Top	−11.783 (6.859)	1.065* (0.267)	16.802* (2.960)	0.754
Bark	−9.615* (3.419)	0.747* (0.133)	3.342* (1.475)	0.706
Branch	−42.194* (9.184)	2.576* (0.358)	−0.042 (3.963)	0.798
Foliage	−13.923* (4.543)	0.569* (0.177)	10.494* (1.960)	0.713

All equations are in the form $ACB_i = a + b \cdot dbh + c \cdot SURV$, where ACB_i is the dry weight (kg) of aboveground components, *dbh* is the dbh (cm), and *SURV* is a dummy variable indicating the survival of individual trees with values 1 for live and 0 for dead.
* Significant parameters in the estimated models ($P < 0.05$). Numbers in parentheses indicate SEs of estimated parameters.

Table 5. Allometric equations for component biomass of live and dead lodgepole pine (*Pinus contorta* Dougl.) in the Rocky Mountains of northern Colorado.

Tree group	Aboveground component (y_i)	Statistical parameters		
		a	*b*	Adjusted R^2
Live	Bole	−2.358* (0.551)	2.361* (0.167)	0.976
	Top	−0.693 (0.537)	1.296* (0.169)	0.711
	Bark	−4.140* (1.016)	2.064* (0.310)	0.910
	Branch	−8.011* (1.566)	3.390* (0.469)	0.918
	Foliage	−6.984* (1.433)	2.912* (0.431)	0.908
	Total			0.911
Dead	Bole	−2.538* (0.727)	2.423* (0.216)	0.962
	Top	−1.021 (1.597)	1.151 (0.486)	0.542
	Bark	−3.249 (2.325)	1.678 (0.700)	0.505
	Branch	−8.135* (2.366)	3.450* (0.692)	0.878
	Foliage			
	Total			0.946

All equations are in the form $ACB_i = e^{(a+b\ln(dbh))}$, where ACB_i is the dry weight (kg) of the *i*th aboveground components, and *dbh* is the dbh (cm). Total aboveground biomass can be obtained using Total $AGB = \sum_i e^{(a_i + b_i \ln(dbh))}$, where a_i and b_i are the model parameters of the *i*th component equation.
* Significant parameters in the estimated models ($P < 0.05$). Numbers in parentheses indicate SEs of estimated parameters.

weights remained constant within 1 g for 3 consecutive days. Dry weight to wet weight ratios were calculated from oven-dried sample data and used to estimate the dry weight biomass of each tree component. The total bole biomass of a sampled tree was estimated as the sum of bole dry weights for all segments. For the bark component, dry weight was estimated for each bole segment by multiplying the surface area of the segment by the dry weight to surface area ratio obtained from the bark samples. Bark dry weight of each segment was then summed to estimate the total bark biomass.

Dry weight biomass estimation of branch, foliage, and top components was slightly different between live and dead trees as field data collection and sampling were different. For live trees, the relationships between branch diameter and woody material and foliage biomass were modeled and used to estimate dry weights of woody material and foliage for individual branches based on measured branch diameters (Equation 1). The top biomass of live trees was estimated as a sum of tree stem, branches, and foliage. The dry weight of tree stem was estimated using the field-measured green weight of the top component without branches and foliage and the moisture content of the wood disc collected adjacent to the tree top. For top branches and foliage, the weighted average moisture content was calculated using two average moisture contents (i.e., branch and foliage) and the average branch to foliage ratio obtained from the branch samples. This weighted average moisture content was then used to convert the combined green weight of top branches and foliage to dry weight biomass. For dead trees, the field-measured branch and top weights were converted to dry weights using the average dry to wet weight ratio obtained from the oven-dried subsamples.

Statistical Analysis

Woody material and foliage of individual branches in live trees were estimated by fitting the following logarithmic regression model (Poudel et al. 2015):

$$B_i \text{ or } F_i = e^{(a_b + b_b \cdot ln(diam_i))} \tag{1}$$

where B_i and F_i are oven-dried weight (g) of woody material and foliage, respectively, of branch *i* with the diameter of $diam_i$ (cm) at branch base, and a_b and b_b are model parameters. The total biomass of branch and foliage components in each sampled tree was estimated by summing these fitted values.

Before developing allometric equations for the beetle-killed lodgepole pine trees, we evaluated the need for presenting separate models for aboveground biomass components for the two tree groups (i.e., live and dead) using dummy variable regression analysis. We then used the seemingly unrelated regression (SUR) approach to simultaneously estimate the parameters in the system of allometric equations for component (Equation 2) and total aboveground biomass (Equation 3) (Parresol 2001, Poudel and Temesgen 2016). The error terms of component biomass equations within the system of equations are usually correlated because the component biomasses come from the same tree. By allowing the inclusion of dependencies among the error terms of the component biomass equations, the SUR method is known to provide more efficient parameter estimates than the traditional ordinary least-squares regression (Temesgen et al. 2015). The SUR system was constrained such that the predicted total biomass is same as the sum of the biomass predicted from component equations. The following logarithmic model form, common in biomass studies (Jenkins et al. 2003), was used for aboveground component biomass:

$$ACB_i = e^{(a + b \cdot ln(dbh))} \tag{2}$$

where ACB_i is aboveground component biomass (kg), *a* and *b* are model parameters, and *dbh* is the dbh (cm). Total aboveground biomass is obtained by summing the prediction of component equations as described below:

$$\text{Total } AGB = \sum_i e^{(a_i + b_i \cdot ln(dbh))} \tag{3}$$

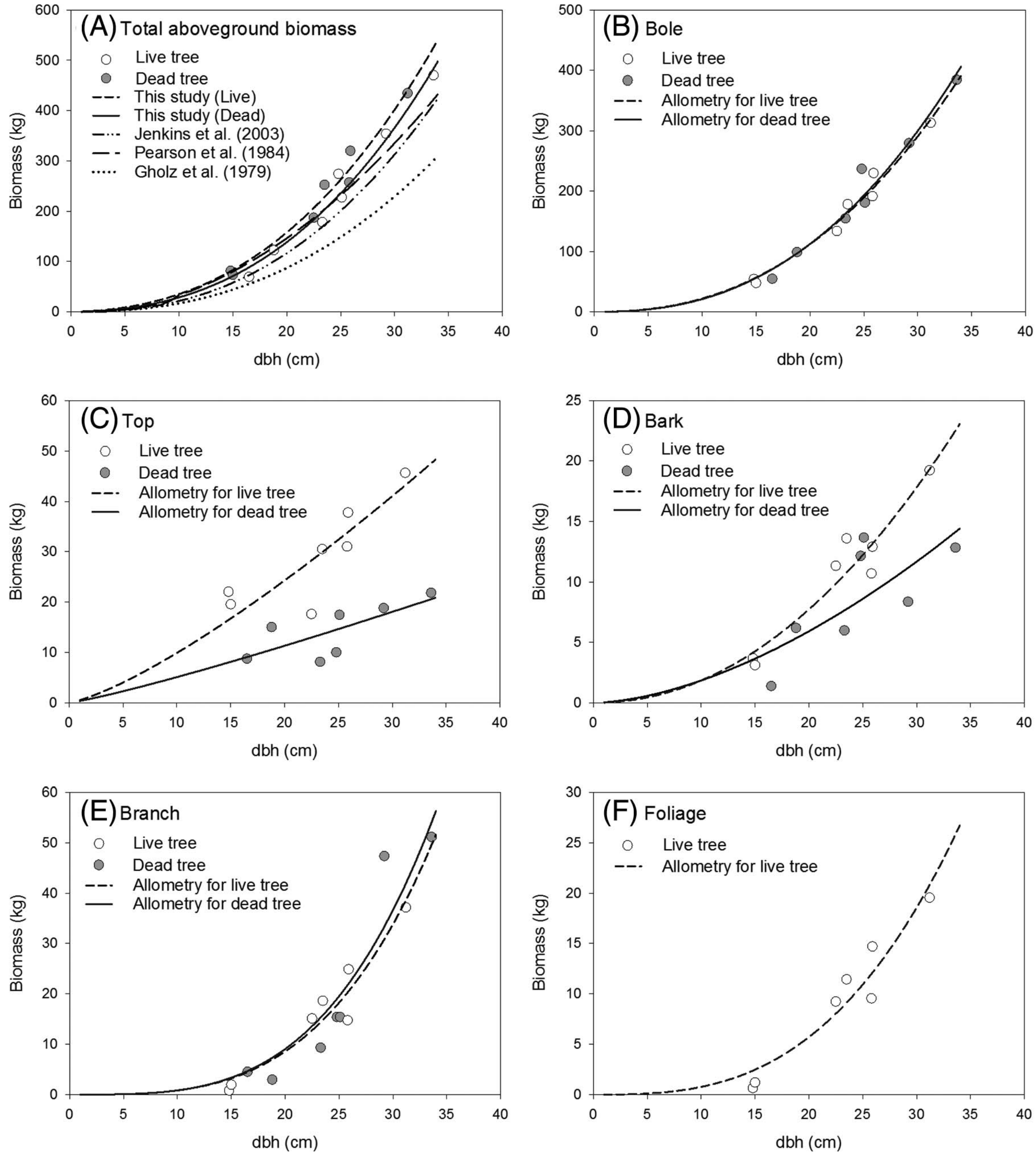

Figure 3. Allometry of total and component biomass for live and dead lodgepole pine (*Pinus contorta* Dougl.) in the Rocky Mountains of northern Colorado.

where Total *AGB* is total aboveground biomass (kg), a_i and b_i are the model parameters of the *i*th component equation, and *dbh* is the dbh (cm). All statistical procedures were performed using statistical software SAS 9.4 (SAS Institute, Inc. 2013).

Results and Discussion

Sample Trees

The dbh of sample trees ranged from 14.8 to 31.2 cm for live trees and from 16.5 to 33.6 cm for dead trees (Table 1). The mean height and crown base height were 18.1 m and 8.1 m, respectively for live trees and 19.4 m and 9.1 m for dead trees. The mean value of moisture contents of aboveground biomass components varied from 42.0 to 56.4% for live trees and from 7.9 to 15.0% for dead trees (Table 2). In both tree groups, branches had the lowest moisture content, whereas bark had the highest moisture content. The average estimated dry weights of each biomass component, as well as the total biomass from sampled trees are shown in Table 1. Branch and foliage dry weights of live trees were estimated using logarithmic regression models fitted to branch subsample data (Table 3). All parameters were significant in the models ($P < 0.05$), and the adjusted R^2 values were 0.97 and 0.94 for branch and foliage, respectively.

Live versus Dead Tree Biomass

The dummy variable regression results showed that there was no significant difference in the bole and branch biomass components between the live and dead tree groups, whereas top, bark, and foliage components were significantly different between the two groups

Table 6. A dummy variable regression of total logging residues for lodgepole pine (*Pinus contorta* Dougl.) in the Rocky Mountains of northern Colorado.

Aboveground component (y_i)	Statistical parameters (SE)			
	a	b	c	Adjusted R^2
Logging residues	−67.900* (12.833)	4.211* (0.500)	27.254* (5.537)	0.863

Equation is in the form $LRBi = a + b \cdot dbh + c \cdot SURV$, where LRB_i is the total dry weight (kg) of logging residues (top, branch, and foliage), *dbh* is the dbh (cm), and *SURV* is a dummy variable indicating the survival of individual trees with values 1 for live and 0 for dead.
* Significant parameters in the estimated models ($P < 0.05$). Numbers in parentheses indicate SEs of estimated parameters.

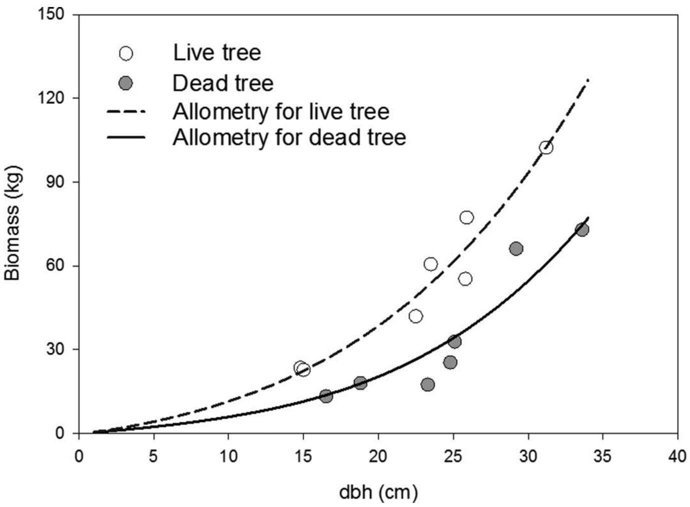

Figure 4. Allometry of logging residues for live and dead lodgepole pine (*Pinus contorta* Dougl.) in the Rocky Mountains of northern Colorado. Logging residues include top, branch, and foliage biomass components.

($P < 0.05$) (Table 4). Because the bole and branch biomass normally makes up a relatively high proportion of total tree biomass of lodgepole pine trees, the total aboveground biomass between the two tree groups was not statistically different.

The top component includes foliage in the top of the live tree, which most likely accounts for the difference between live and dead trees in the top component. The difference in the bark component between the two groups might be attributed to bark that sloughs off as dead trees dry and deteriorate. Lodgepole pine branches also deteriorate and drop after death, but in this case, 7 years since beetle infestation, branch biomass was not statistically different between the two groups.

Allometric Equations

The allometric equations generally fit the data well, and in most cases dbh explained more than 71% of the observed variation in component biomass, especially for the live trees (Table 5). However, allometric equations for the top and bark components of dead trees performed relatively poorly. All equations for live tree components except the top component, and bole and branch components of dead trees were significant ($P < 0.05$) for both model parameters.

Dead and live trees differ in allometric relationships, more so with top, bark, and foliage than with bole and branch components (Figure 3). It appears that as dbh increases the biomass difference in top and bark components between live and dead trees becomes larger. For the total aboveground biomass, a slight difference between live and dead trees was observed over the entire range of dbh (Figure 3A), although it is not significantly different ($P = 0.098$). The total aboveground biomass estimated for live trees in this study is larger than values reported for lodgepole pine forests of southeastern Wyoming (Pearson et al. 1984) and the Pacific Northwest United States (Gholz et al. 1979), and the estimates obtained from Jenkins et al. (2003) for pine species (Figure 3A).

These results have important implications for land managers who want to use beetle-killed trees for energy, wood, and fiber products. Previous studies documented that the beetle infestation can affect the commercial value of the tree after the beetle's attack (Feng and Knudson 2007, Dalpke et al. 2008), especially with regard to the negative effects of rot and fungal staining on sawlog quality. Obviously, this effect is intensified as dead trees age, subject to checking, cracking, rot, and other deterioration. However, even as the dead trees age, the trees could remain suitable for a variety of solid wood, fiber, and energy products with almost the same quantity of aboveground mass as a live tree, as long as the dead tree is harvested before degradation is severe enough to affect wood attribute and value (Woo et al. 2005).

Logging Residues

In many regions, tree tops and branches are traditionally considered noncommercial and are typically either burned for disposal or left on site. If these materials are considered as recoverable feedstock for bioenergy and biobased products, this study demonstrates that accurate estimates of these components for beetle-killed trees will be difficult to obtain if the existing allometric models derived from live trees are used. Our statistical analysis shows that logging residues consisting of top, branch, and foliage are significantly different between the live and dead tree groups (Table 6). Applying live tree allometric equations to dead trees would result in a significant overestimation of potential logging residues by a factor of 1.5–2 (Figure 4). When combined with yield and recovery information from harvesting operations, the allometric equations developed for beetle-killed trees in this study can be used to accurately estimate the amount of these resources available in beetle-killed stands.

Conclusion

Obtaining accurate and reliable estimates of biomass in beetle-infested forests is becoming more important as the production of feedstocks for bioenergy and biobased products becomes more commercially viable. Although our sample size was relatively small, our results demonstrate the influence of the mountain pine beetle infestation on tree biomass, which is the result of changes in the top, bark, and foliage component biomass after attack, death, and deterioration over time. We developed a set of allometric equations for estimating component biomass of beetle-killed trees in lodgepole pine forests of the northern Colorado Rocky Mountains that can be used for stand- and landscape-level applications. Depending on timber products to be produced, these differences affect estimates of biomass resources available from beetle-killed trees. When traditional logging residues (i.e., tree tops, branches, and foliage) are of interest as biomass feedstock, the allometric equations developed for beetle-killed trees could provide more accurate estimates of the resources available in beetle-killed stands than the existing live tree allometric equations. Allometric relationships for dead trees vary spatially and are affected by the level of tree deterioration and time passed since death, so the equations from this study may not apply in other regions or even in the same region if severe deterioration of standing trees has occurred.

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