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Modeling below-ground biomass to improve sustainable management of *Actaea racemosa*, a globally important medicinal forest product

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A B S T R A C T

Non-timber forest products, particularly herbaceous understory plants, support a multi-billion dollar industry and are extracted from forests worldwide for their therapeutic value. Tens of thousands of kilograms of rhizomes and roots of *Actaea racemosa* L., a native Appalachian forest perennial, are harvested every year and used for the treatment of menopausal conditions. Sustainable management of this and other wild-harvested non-timber forest products requires the ability to effectively and reliably inventory marketable plant components. However, few methods exist to estimate below-ground biomass (rhizomes and roots) based on above-ground metrics. To estimate the relationship of above-ground vegetation components to below-ground biomass, data from a long-term sustainable harvest study of *A. racemosa* was used to develop a predictive model for rhizome mass. Over 1000 plants were extracted from two sites in the Central Appalachian Mountains of Virginia. Measurements of plant height and canopy dimensions were matched with corresponding green weights of rhizomes and roots. A multi-staged process was used to fit a mixed effects model. A random effects structure was selected using Akaike's Information Criterion, while the fixed effects structure was simplified through backward selection using likelihood ratio tests. Over 500 plants were harvested from three neighboring sites to evaluate the effectiveness of the model in predicting below-ground biomass based on above-ground metrics. The relationships between above and below-ground biomass of plants from the sustainability study sites and the validation study sites were similar, indicating effectiveness of the model. Predicted values for the validation data were, on average, slightly larger than the observed values, indicating a small bias. The 95% prediction intervals computed from the model, however, covered the true values more than 95% of the time. This study demonstrates that estimating marketable rhizome biomass of native medicinal plants is feasible at a stand level. The model will serve as a valuable tool for inventorying forest products, allowing estimation of below-ground biomass based on above-ground metrics. Use of this tool will aid in developing effective inventory and management strategies for wild-harvested medicinal plants. Adaptation of this model to other species will encourage efforts toward sustainable use of non-timber forest products worldwide.

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1. Introduction

Non-timber forest products, particularly from herbaceous understory plants, are being extracted at an astounding pace from forests worldwide to support culinary, floral, herbal medicine, and other 'non-traditional' forest product industries (Chamberlain et al., 1998, 2004; Peck et al., 2008). Muir et al. (2006) estimated the value of commercial moss harvest in the United States at about $11 million, annually. According to Schippmann et al. (2002) the 12 leading countries, exported more than 280,000 tons of medicinal and aromatic plants worth over $640 billion from 1991 through 1998. As these products, and other non-timber forest products, have been harvested for generations with little or no management, the potential for over-harvesting and endangerment of wild-harvested species is tremendous (Schippmann et al., 2002; Lawrence, 2003). Resulting population declines have been observed in *Panax quinquefolius* L. (American ginseng) (Nantel et al., 1996; McGraw, 2001), *Aquilaria malaccensis* Lam. (Agarwood) (Paoli et al., 2001), and *Hydrastis canadensis* L. (Goldenseal) (Sinclair et al., 2005), and many other native forest species (Chamberlain et al., 1998).

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Actaea racemosa L. (black cohosh) is one of many forest herbs native to the Appalachian Mountain region of eastern North America that is harvested for its commercial value (Foster, 1995; Predny et al., 2006; Small et al., 2011). Native Americans in deciduous forests of eastern North America harvested rhizomes to treat female conditions and a variety of other ailments (Predny et al., 2006). The use of black cohosh expanded when early European settlers adopted many of these treatments and started using the rhizomes to treat smallpox and cholera. Today, rhizomes of black cohosh are harvested primarily to support demand for herbal treatment of menopausal symptoms. Between 1997 and 2005, over 1 million kilograms of rhizomes were harvested from natural populations in eastern United States (Chamberlain et al., 2002; American Herbal Products Association, 2007) and, in the 1 year period ending June 1998, retail sales of black cohosh products increased more than 500% (Blumenthal, 1999). The American Herbal Products Association (2007) estimates that more black cohosh was harvested between 1997 and 2005 than any other medicinal plant tracked by the Association, with little effort to manage the plant as a natural resource (Chamberlain et al., 2002; Ticktin, 2004).

A fundamental element in the sustainable management of non-timber forest products is the ability to effectively and reliably inventory, *in situ*, the marketable stock of the harvested product. To date this is poorly understood. Few studies have focused on ways to inventory below-ground marketable biomass based on above-ground plant measures (Piper, 1989; Braly, 2007; Yonghua et al., 2008). Most black cohosh reproduction occurs vegetatively, through clonal expansion or bud growth of below-ground rhizomes. This below-ground biomass is the plant-part harvested for medicinal use and commercial sale. Rhizomes are harvested near the end of the growing season (August–October), as above-ground vegetation begins to senesce.

Increasing recognition that above and below ground plant components have tremendous influence on each other and that their interactions control ecosystem processes (Monk, 1966; Thornley, 1998; Wardle et al., 2004) has spurred a number of studies designed to predict root biomass based on shoot biomass, however most have focused predominantly at the population, forest, or regional level (Harris, 1992; Reynolds and Pacala, 1993; Yonghua et al., 2008). Obtaining accurate estimates of below-ground biomass is recognized as essential for determining its contribution to carbon storage. As such, most analyses have focused on correlations with factors associated with forest stand development: tree height, diameter, and tree density (Thornley, 1998; Vogt et al., 1998; Mokany et al., 2006). Niklas (2005) model assumes, in fact, that below ground biomass for non-woody and woody plants is only the result of root growth and does not recognize the contribution of rhizomes from clonal plants. This is an obvious deficiency for estimating yield of non-timber forest products such as black cohosh.

Foresters have a long-history of measuring timber and estimating species-specific growth and yields of forest stands, and accurate mensuration techniques and biometric estimators of timber products are well developed and accepted (Avery and Burkhart, 1983; Clutter et al., 1992). However, we lack this same knowledge for black cohosh and most other non-timber forest products. No methods exist to estimate below-ground growth and yield, or to inventory product volumes. As little is known about wild harvest impacts on black cohosh across its natural range, the potential for unsustainable use is considerable (Predny et al., 2006; Small et al., 2011). Adding to this challenge is the inability to determine how much rhizome biomass is available for harvest or how much rhizome biomass accrues or sloughs each year. Being able to estimate below-ground biomass based on above-ground metrics is essential in determining baseline inventory volumes for single patches and for determining whether harvest intensities are sustainable. The current study was conceived and designed to fill this gap in our knowledge. The purpose of this study was to develop and validate a model that would predict below-ground, harvestable biomass of black cohosh, based on above-ground measurable biomass. Our resulting model provides a practical, efficient, and simple approach to guide forest managers in the sustainable use of black cohosh, and should serve as a template in developing inventory and management plans for other non-timber forest products.

2. Methods

This study stemmed from previous work that examined the impact of wild-harvesting on the sustainability of black cohosh populations (Small et al., 2011). In 2005, long-term study sites were established to examine sustainable harvest in two Appalachian deciduous forest locations (Reddish Knob and Mt. Rogers) in Virginia, USA. Data were collected from these sites from 2005 through 2011. In 2011, the study was extended to three sites (Reddish Knob, Selu Conservancy, and Comers Rock) in Virginia, to provide data to evaluate the predictive ability of the model developed from the initial sustainability study.

2.1. Study sites and field methods

Two long-term study sites were established in healthy, robust natural populations of black cohosh, to examine the effects and sustainability of wild-harvesting practices on natural stands (Small et al., 2011). Sites were established in mixed oak stands in the George Washington–Jefferson National Forest, Virginia, USA (Fig. 1). The northern site (Reddish Knob (RKS)) was in Augusta County (38°26′33.52″N/79°15′51.80″W) at an elevation of ~1190 m, on a moderately steep southeast-facing slope. The southern site (Mt. Rogers (MR)) was in Wythe County, Virginia (36°45′36.56″N/81°12′57.66″W) at an elevation of ~1180 m, on a moderately steep north-facing slope. Populations were selected that were accessible to harvesters.

At each of the sustainability study sites (RKS and MR), initially one permanent 100 m transect was established along the upper contour of a population of black cohosh. Twelve shorter sub-transects, traversing the black cohosh stand, were established perpendicular to the main transect. Sub-transect lengths reflected the width of the populations being considered; for RKS sub-transects were 45 m and for MR they were 17 m. Three permanent 2 × 5 m sample plots were located along each sub-transect. Sample plots were assigned one of three harvest treatments (0%, 33% or 66%). In total, one-third of the 36 sample plots in each replicate were assigned to each harvest treatment. In each of the next 2 years, one additional replicate was set up at each site, proximal to the original replicate, resulting in three replicates at each site. Slightly different, but consistent, approaches were utilized at RKS and MR. At RKS all three plots along a sub-transect were randomly assigned to the same harvest treatment, while at MR each of the three plots along the sub-transect were individually, randomly assigned to a harvest treatment. Replicates established in subsequent years used the same protocols as the initial replicate at the same location. The same data collection procedures were followed at each site and replicate.

Within each sample plot, the location of every black cohosh stem (petiole) was mapped and the number of black cohosh stems emerging from the ground was counted. Plant height, from ground surface to the top of the main canopy of leaves, was recorded. Plant measurements were made with a meter stick accurate to a half centimeter or a meter tape accurate to half millimeter. Stems originating from discrete underground locations on rhizomes were treated as separate stems. Two orthogonal measurements of the

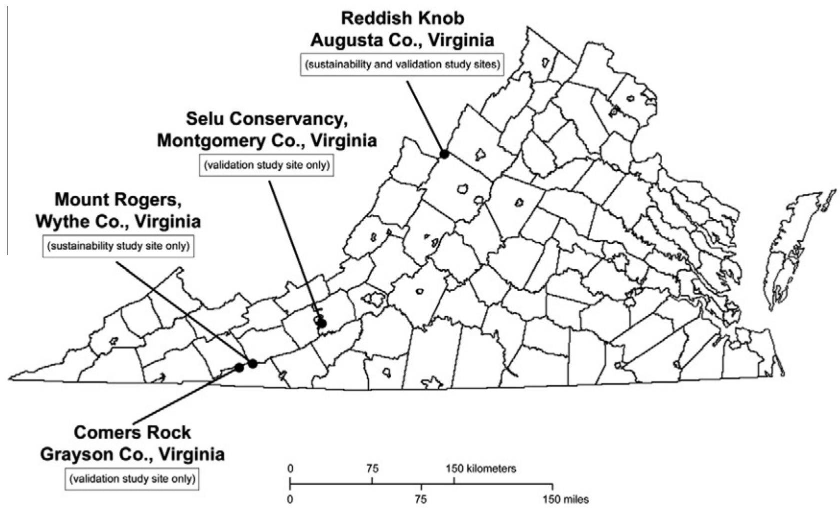

Fig. 1. Location of black cohosh populations used in the sustainability and validation studies.

main leaf canopy (crown) were taken at the widest points to calculate crown area (m^2). Based on observations that the canopy tends to be elliptical, we employed the equation: Area = $[\pi \times D_1 \times D_2]/40{,}000$, where D_1 and D_2 are orthogonal canopy diameter measurements (cm). In plots that were harvested, plants with the largest canopy were selected to mimic harvester practices. Above-ground vegetation (i.e., petiole, leaves, and flowering or fruiting racemes) was kept attached to the harvested below-ground biomass (i.e., rhizome and roots), yet weighed separately to analyze above- to below-ground relationships.

Comparisons, between sites, of the basic measurements of the plants harvested were performed by fitting three separate univariate random effects models with log root mass, log largest crown area, and log plant height as the response variables, site and month as fixed effects, and year, rep and plot as random effects. All measurements were log-transformed to improve normality of the residuals from the fitted models, and the random effects structure was needed to account for the complex nesting of data geographically and over time. Equality of the mean log root mass, largest crown area, and plant height across sites were then tested using likelihood ratio tests to compare models with and without site specific means.

2.2. Model development and fitting

Model fitting proceeded through the multi-stage process for fitting mixed effects models described by Zuur et al. (2009). As in Piper (1989) study of nine understory herbaceous species, we found that rhizome mass was linearly related to the above ground measurements on the log-scale, supporting our use of log-transformed measurements of root mass, crown area, and plant height, in all analyses. Computing was done with the statistical software R (R Development Core Team, 2011), using the package lme4 (Bates et al., 2011). A full model of fixed and random effects was, initially, fit to the data. The random effects structure was then simplified by removing terms judged not significant through comparisons of Akaike's Information Criterion (AIC). After fixing the random effects structure, the fixed effects structure was simplified through backward selection using likelihood ratio tests for model comparison. Conceptually, the full model was:

$$\begin{aligned}\text{Log (root mass)} = {} & \text{log (largest crown area)} + \text{log (plant height)} \\ & + \text{harvest month} + \text{year}_R + \text{replicate}_R \\ & + (\text{transect}|\text{replicate})_R \\ & + (\text{plot}|\text{transect}|\text{replicate})_R + \epsilon\end{aligned}$$

where:
Fixed effects

- log (largest crown area) = log transformed largest crown area of a plant;
- log (plant height) = log transformed height of a plant;
- harvest month = month in which harvest was done for a given site.

Random effects
- year_R = effect due to year of harvest;
- replicate_R = effect due to replicates;
- $(\text{transect}|\text{replicate})_R$ = effects due to transects nested in replicates;
- $(\text{plot}|\text{transect}|\text{replicate})_R$ + effects due to plots nested in transects nested in replicates;
- ϵ = error, assumed to be normally distributed with mean 0 and constant variance σ^2.

2.3. Forest-based validation

In 2011, the study was extended to evaluate the effectiveness of the model in predicting the relationship between above- and below-ground biomass of black cohosh at new locations. Three sites were selected based on their abundance of black cohosh and proximity to the original study sites. The first site (RKV) was near the original Reddish Knob sustainability site (RKS), in Augusta County, VA, at an elevation of approximately 1006 m with a southeast-facing slope. The second site (CR) was near the Mt. Rogers sustainability site (MR), but located in Grayson County, VA, proximal to Comers Rock, at an elevation of approximately 1178 m with a south-facing slope. The third site (SC) was located at Radford University's Selu Conservancy in Montgomery County, VA, at an elevation of approximately 640 m, with a nearly flat slope.

At each validation site (RKV, CR and SC), 36 1×1 m plots containing black cohosh plants were located randomly along transects. Transects at these sites were 84, 50, and 65 m long, respectively. Within each plot, every black cohosh above-ground stem was tagged and measured for plant height and crown canopy, following the procedures previously described. After all plants were measured, a 100% harvest was performed. Each rhizome was treated as an individual unit, and all above-ground vegetation was kept with the associated rhizome. Above-ground (stems, leaves, and flower or fruiting racemes) and below-ground (rhizomes and roots) biomass (green weight) were recorded for each rhizome.

The resulting above- and below-ground plant metrics were used to validate the original rhizome biomass predictive model.

We compared the distribution of residuals for the sustainability study data with the residuals for the validation study data to estimate the accuracy of the model. To demonstrate the effectiveness of using the mixed effects model, predicted values for the sustainability study sites were calculated in two ways: (1) using only the fixed effects, and (2) combining the fixed and random effects. The difference between the distributions of the residuals for these two cases indicates how much predictions can be improved with site specific information.

3. Results

3.1. Data summary and site comparisons

A total of 1164 [RKS, $n = 362$; MR, $n = 802$] rhizomes (including roots), and associated vegetation, were measured for the sustainability study that formed the basis for model development and fitting. To validate the model, 551 [CR, $n = 108$; RKV, $n = 357$; SC, $n = 86$] rhizomes and connected vegetation were measured (Table 1). A small number of observations did not have associated rhizome mass measurements and these were removed prior to computing summary statistics and modeling the relationship between above and below ground biomass.

We calculated statistics summarizing the distribution of the measurements of the plants harvested from each site over all years (Table 1). Rhizome mass ranged from a minimum of 0.2 g at CR to a maximum of 1612 g at RKS. Mean rhizome mass at each site ranged from a minimum of 21.6 g at SC to a maximum of 111.4 g at CR. Standard deviations also followed a similar pattern with a minimum of 25.01 g at SC to a maximum of 172.68 g at RKS.

Across all sites and years, crown area varied from 0.002 m^2 for RKV to 1.48 m^2 for MR (Table 1). The mean crown area of plants at CR was the largest ($\mu = 0.255$ m^2), while the mean crown area for plants harvested from SC were approximately 60% as large ($\mu = 0.151$ m^2). Standard deviations of the crown area followed a similar pattern, and were largest at CR ($\sigma = 0.229$ m^2) and smallest at SC ($\sigma = 0.109$ m^2).

Across all sites and years, plant height varied from 6 cm for a plant harvested from RKV to 110 cm for a plant harvested from MR (Table 1). Mean plant height over all years varied from 31.8 cm at SC to 47.9 cm at RKS. As with root mass and crown area, the standard deviation of plant height followed a similar pattern and was smallest at SC ($\sigma = 12.4$ cm) and largest at CR ($\sigma = 16.6$ cm).

Estimates of the year adjusted median root mass, crown area, and plant height along with standard errors and 95% confidence intervals obtained from the univariate random effects models are provided (Table 2). Testing for differences in largest crown area between sites/months of sampling produced a chi-square statistic of 0.00 with 5 degrees of freedom (DF) and resulted in a p-value of 1.00. The chi-square statistic for plant height was 10.16 (5 DF) with a p-value of 0.07. For root biomass we calculated a chi-squared statistic of 17.69 (5 DF) with a p-value of <0.01. We deduce from these that there is a statistically significant difference in median root biomass between sites/month of sampling, weak and inconclusive evidence of a difference in plant height, and no evidence of a difference in canopy area.

3.2. Model development

The final model from the sustainability data set included largest crown area (log transformed), plant height (log transformed), and month as fixed effects, and year, replication, transect, and plot as random effects. All location variables and year were retained as random effects in the final model, which is presented as:

$$\begin{aligned}\text{Log (root mass)} = {} & 3.33 - 0.02(\text{July harvest}) \\ & - 0.42(\text{August harvest}) + 0.76 \\ & \times \log(\text{largest crown area}) + 0.46 \\ & \times \log(\text{plant height}) + \text{year}_R + \text{replicate}_R \\ & + (\text{transect}|\text{replicate})_R \\ & + (\text{plot}|\text{transect}|\text{replicate})_R + \epsilon\end{aligned}$$

The variance for all random effects combined was much smaller than the residual variance (Table 3), indicating greater variation from plant-to-plant within a plot than across plots, transects, and replications. More than 82% of the variance is accounted for in plant-to-plant variation. The interaction term (largest crown area $\times$ height) and treatment effect over time were not significant and therefore were omitted from the final model ($P = 0.7673$, $P = 0.828$). Harvest month significantly affected root biomass ($P = 0.002$) and, therefore, was retained in the final predictive model. Exclusion of height and largest crown area showed both to be significant ($P < 0.0001$, $P < 0.0001$). Thus, these predictors remained in the model as explanatory variables.

3.3. Model validation

The relationships between above and below-ground biomass at the sustainability (original) study sites and the validation study sites were similar as evident by the considerable overlap in data points (Fig. 2). The black squares and triangular points illustrate the relationships found at MR and RKS between rhizome biomass

Table 1
Summary statistics black cohosh for root mass, largest crown area, and plant height for the sustainability and validation sites. SD = standard deviation.

	Sustainability study		Validation study		
	Mount Rogers (MR) ($n = 802$)	Reddish knob (RKS) ($n = 362$)	Comers rock (CR) ($n = 108$)	Reddish knob (RKV) ($n = 357$)	Selu (SC) ($n = 86$)
Root mass (g)					
Mean (SD)	48.0 (64.5)	104.5 (172.7)	111.4 (151.8)	29.5 (46.9)	21.6 (25.0)
Min	0.4	1.0	0.2	0.9	1.0
Max	753.0	1612.0	963.0	445.2	162.5
Largest crown area (m^2)					
Mean (SD)	0.22 (0.16)	0.25 (0.17)	0.26 (0.23)	0.16 (0.14)	0.15 (0.11)
Min	<0.01	0.01	0.01	<0.01	0.01
Max	1.48	0.87	1.20	0.69	0.53
Plant height (cm)					
Mean (SD)	40.2 (14.7)	47.9 (16.5)	41.2 (16.6)	35.5 (14.8)	31.8 (12.4)
Min	7.0	7.0	10.0	6.0	9.0
Max	110.0	88.0	86.0	75.0	90.0

Table 2
Estimated year adjusted median root mass, largest crown area and plant height, by site, with associated standard error and 95% confidence interval.

Plant Part and site	Median	Standard error	95% Confidence interval
Root mass (g)			
MR-August	18.03	8.73	(7.87–41.31)
MR-July	43.74	21.06	(19.16–99.87)
CR-July	111.58	74.39	(38.99–319.27)
RKS-June	38.46	15.73	(18.65–79.30)
RKV-June	34.85	17.26	(14.98–81.07)
SC-July	29.98	15.53	(12.51–71.84)
Largest crown area (m^2)			
MR-August	0.14	0.04	(0.08–0.24)
MR-July	0.17	0.05	(0.10–0.31)
CR-July	0.24	0.10	(0.11–0.50)
RKS-June	0.17	0.04	(0.10–0.27)
RKV-June	0.17	0.05	(0.10–0.30)
SC-July	0.17	0.06	(0.09–0.31)
Plant height (cm)			
MR-August	31.30	4.66	(23.49–41.71)
MR-July	39.51	5.85	(29.69–52.58)
CR-July	48.52	8.73	(34.38–68.48)
RKS-June	42.57	5.72	(32.83–55.21)
RKV-June	43.78	6.65	(32.67–58.66)
SC-July	38.66	6.08	(28.56–52.34)

Table 3
Estimates of the variance components for each random intercept as absolute values and as percentages of the total variability for years 2005–2011.

Nested variable	Variance	Percent
Plot:transect:rep	0.076	10.28
Transect:rep	0.008	1.08
Rep	0.009	1.22
Year	0.037	5.01
Error	0.609	82.41
Total	0.739	100.00

and largest crown area and plant height. The white circular, diamond and upside down triangular points illustrate the relationships of above and below-ground biomass variables at the three validation study sites (CR, RKV, and SC). The overlap of these points illustrates the similarities between study sites. Note that in the validation study, all plants were harvested and hence more small plants are evident. In the sustainability (original) study, large plants were selected to mimic harvesters' practices (Fig. 2). Largest crown area and plant height show clear positive linear trends, both increasing with increasing rhizome biomass.

The proficiency of the model in predicting below-ground biomass based on above-ground metrics is illustrated by comparing observed to predicted root mass (Fig. 3a). Ideally, all points on the scatter-graphs should fall on or close to the dashed line. The density plots of the residuals for the validation data and the sustainability (original) data, with and without the random effects, further illustrates the predictability of the validation study (Fig. 3b). The residuals for the data from the sustainability study used in model development are centered on zero, showing that the model provides unbiased prediction of the original data. The mean residual for the validation data was −0.18 units (on log-scale) compared with −0.01 and −0.02 for the residuals of the sustainability study data obtained from predicting log-root mass from models including the random effects or based on fixed effects alone (i.e., without random effects). The standard deviation of the residuals for the validation data was 0.86 compared with 0.78 and 0.82 for the residuals of the sustainability study data obtained from models with and without random effects. An *F*-test comparing the variances of the residuals from the validation data and from the model of the sustainability data without random effects showed that the standard deviation of the residuals from the validation data were significantly larger ($P = 0.04$) and a paired test also indicated a significant difference in the mean residuals ($P = 0.02$). These results indicate that the root mass for the plants harvested in the validation study sites were significantly smaller and slightly more variable than predicted by the model. On average, our model over-estimated the root mass of plants harvested from the validation sites by a value of 0.18 on the log-scale, which translates to an average over-estimation of approximately 20% on the natural scale.

Prediction intervals for data from the 2011 sustainability study covered the true log root biomass for 94.3% of the plants. This is very close to the nominal value of 95%. For the validation study, the prediction intervals covered the true log root biomass with an even higher rate of 96.8%. This result was not expected given that the model was developed from the sustainability study data

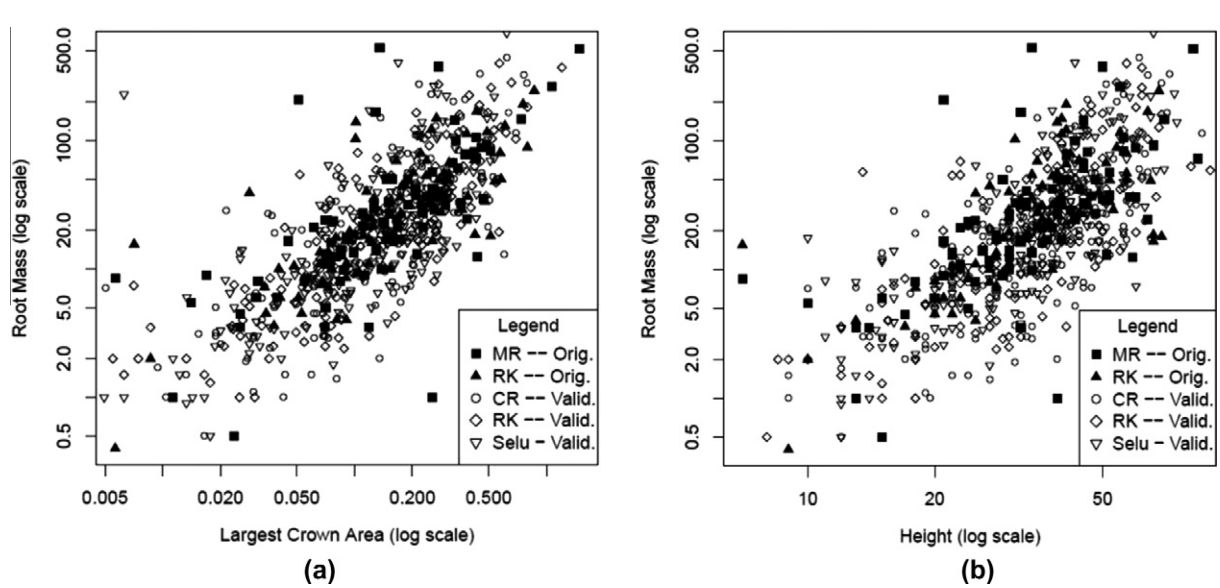

Fig. 2. The relationships between the above and below ground measurements for the sustainability study sites and the validation sites. The significant overlap of data points demonstrates the similarities between plants harvested from the two studies.

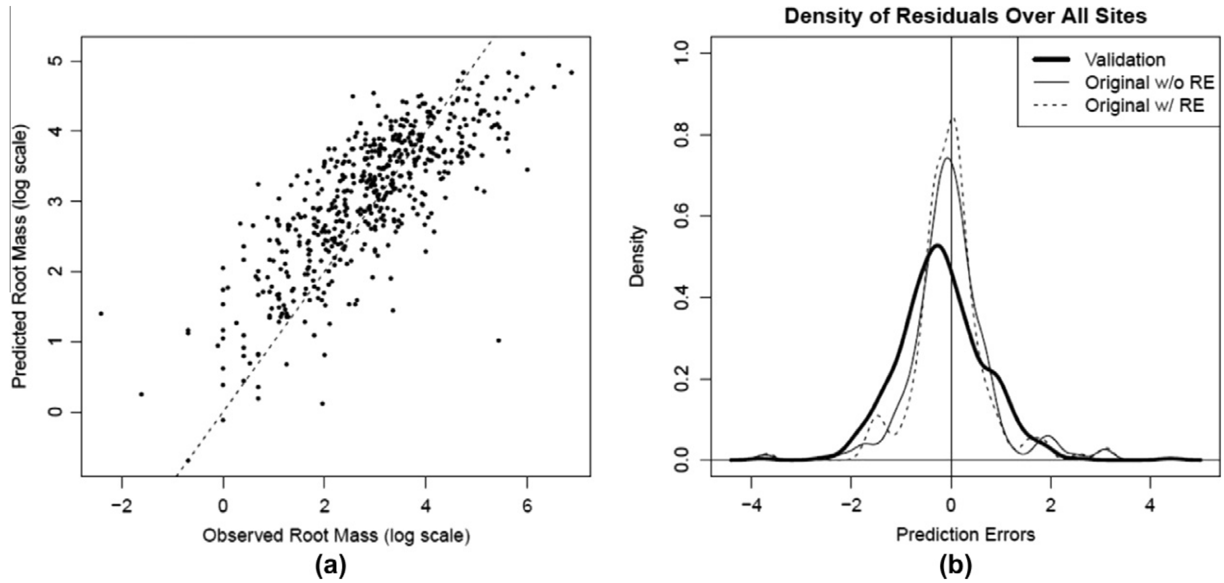

Fig. 3. Plots of predicted and residuals values illustrate the fit of the predictive model. The mean and standard deviation of the residuals for the validation data are −0.18 and 0.86 compared to −0.02 and 0.78 for the original data when using estimated random effects and −0.01 and 0.82 for the original data when using only the fixed effects (i.e., without random effects).

and that the residuals from the validation study sites showed a slight negative bias and slightly higher variance. The reason for this appears that the log root biomass values from the validation study are closer to normally distributed with less extreme values. The average width of the 95% prediction intervals was 3.77 indicating that the log root biomass for an individual plant can be predicted to with approximately ±1.89 units.

4. Discussion and conclusions

More than a hundred plant species from eastern forests of the US. have recognized medicinal properties, dozens of which are sold in international markets (Krochmal et al., 1969; Foster, 1995; Chamberlain et al., 2002). Over-harvesting has been suggested as a major cause of population decline in many of these species (Sinclair et al., 2005; Mulligan and Gorchov, 2003), including black cohosh (Small et al., 2011), and linked to broader ecological impacts such as increased plant susceptibility to herbivores, declines in avian diversity (with decreased fruit or seed availability), and ecosystem-level nutrient losses (Ticktin, 2004).

One kilogram of dried black cohosh roots contains an estimated 31 rhizomes (Predny et al., 2006). Based on previously mentioned export estimates, this suggests that more than 31 million rhizomes were exported from the U.S. from 1997 through 2005. To date, however, there is no effective way to predict the total abundance of below-ground plant material in natural populations without destructive harvesting. This basic information is essential to determine if harvesting practices are sustainable. Thus, developing a model to predict marketable below-ground biomass (rhizomes) based on above-ground (stems and vegetation) metrics is needed for the long term viability of this and other important non-timber forest products. While high variability between plants with the same above ground measurements makes it difficult to predict rhizome mass of a single individual, our model allows for adequate assessment of the volume of black cohosh rhizomes available for harvest at the stand level.

Few studies have attempted to model below-ground biomass based on above-ground metrics, although those that have provide a foundation for, and support the feasibility of developing predictive relationships between above- and below-ground parameters. Braly (2007) developed predictive models for root mass of *Sanguinaria canadensis* L. (bloodroot) based on various above-ground organs in western North Carolina. Using regression analysis, Braly (2007) found positive and significant relationships between rhizome weight and the number of leaf lobes ($R^2 = 0.54$, $P < 0.0001$), stem height ($R^2 = 0.65$, $P < 0.0001$) and stem diameter ($R^2 = 0.73$, $P < 0.0001$), respectively. In a greenhouse study of nine understory herbaceous species, including *Actaea rubra* (Ait.) Willd. (red baneberry), native to coniferous forests in the Pacific Northwest U.S., Piper (1989) found a significant linear relationship between natural log transformations of shoot and root dry biomass. Yonghua et al. (2008) used plant height as a simple predictor ($R^2 = 0.87$, $P < 0.001$) of root to shoot ratios in Alpine grasslands at a regional level in the Tibetan Plateau. Similarly, Anderson et al. (1993) found dry root biomass in American ginseng to be strongly correlated with factors such as shoot biomass ($r = 0.98$), stem height above ground ($r = 0.90$) and leaf area ($r = 0.88$).

In general, knowledge about the population biology of clonal, rhizomatous plants is lacking because of the difficulties of collecting data on below-ground organs (Wetzel and Howe, 1999). Assessing above-ground to below-ground biomass relationships in black cohosh, is challenging, as it is often difficult to identify individual genets. Excavating the plants reveals that multiple stems often are attached to a single rhizome. Under close scrutiny, we also found that multiple rhizomes often are closely tangled together. Van der Voort et al. (2003) report a similar rhizome arrangement in large populations of goldenseal, another eastern forest herb harvested for the medicinal properties of its rhizomes. They note that the 'tight interwoven clonal growth form makes it difficult to excavate individual plants with a high degree of care or precision." This phenomenon confounds efforts to predict below ground biomass at an individual plant level. For goldenseal and black cohosh, however, this growth form may result in broken, yet viable rhizomes and root fragments remaining in the soil after harvest and potentially contribute to vegetative recovery in these species (Van der Voort et al., 2003).

Our model developed from the sustainability study over-predicted rhizome mass from the validation study sites, despite the fact that data collected from the two studies were heuristically very similar. On average, the model over-estimated root mass by approximately 20% on natural measurement scales. This is contrary to models predicting root mass in trees (Robinson, 2004), that often under-estimate root biomass by as much as 40%. Niklas (2005) presented a model that assumes that below-ground biomass is the result of root growth alone, and yet claims that many species for which the model was developed also produce below-ground stem material (rhizomes). As a likely consequence, Niklas (2005) found that models of non-woody plants would either over or under-estimate biomass by as much as 46%.

In our validation study, root mass for plants with similar crown areas and heights tended to show greater variability than those from the sustainability study. The differences were more pronounced for plants harvested from the SC site. This may reflect adaptation to local edaphic conditions (Hammer et al., 1987; Marino et al., 1997; Sanders and McGraw, 2005). The SC site was considerably more xeric and much lower elevation that the other sites. We did not analyze the soils for this study, although our observations indicated that the soils at the SC site had less organic matter, were drier and more compacted than the other sites. The generally shorter plants and smaller rhizomes (Table 1) and considerably lower abundance (C. Small, unpublished data) also suggest that black cohosh populations are less vigorous at this site. Growth in clonal plants has been shown to vary significantly relative to light availability and soil fertility (Marino et al., 1997). Plants measured for the sustainability and validation studies were similar in height to black cohosh measured by Givnish (1982), who found competition for light a significant factor in determining plant height and crown area (Givnish, 1982). Soil chemical properties also have been demonstrated to be spatially variable (Hammer et al., 1987), which may further explain site variations.

Our scatter-plots (Fig. 2) relating above- and below-ground measurements show considerable overlap in data points between plants harvested from each of our study sites, despite the validation study having smaller plants. Two factors may explain these differences. First, the intensity of harvest differed between studies. All plants were harvested in the validation study and meticulous efforts were made to follow the rhizomes to their natural ending points. In the sustainability study, we attempted to mimic methods used by harvesters and selected clumps of stems and plants with larger crown areas. Also, not all plants were harvested for the sustainability study. We conducted harvests at moderate and intense levels, with some plots having 33% of the black cohosh removed, while others had 66% of the cover removed. Despite these differences, the allometric relationships we found between above and below ground biomass across our study sites hold true.

The high level of plant-to-plant variability makes prediction of root mass for an individual plant difficult. Mean root mass, however, for a stand can be modeled with considerable confidence using plant height and crown area, despite the fact that rhizome mass of plants with similar heights and crown area may vary considerably. Differences in below-ground biomass may reflect adaptation to local conditions, particularly soil moisture (Sanders and McGraw, 2005). A general assumption is that above and below ground biomass scale isometrically, but several studies have shown that root and shoot accumulation may not be isometric (McCarthy and Enquist, 2007). Relative growth rates of below ground biomass may be isometrically related to above-ground biomass in the early growth stages of rhizomatous plants, but plants may retain below-ground storage organs differently, depending on local conditions. Plants with similar height and crown canopy could, therefore, have significantly different root mass. Hence, our model is better used to predict root mass at a stand level. As stand-level considerations are more useful to managers who need to determine sustainable harvest levels, we do not see this as a major limitation to the usefulness of our model.

One intent of this project was to develop a practical tool for foresters to improve inventory and management of non-timber forest products. Based on results of this effort, the following model can be used to estimate the root biomass in stands of black cohosh, at a stand level. Predictions at new locations without previous information can be made based on the fixed effects alone. The model is set up to allow for predictions based on the month of harvest: a value of one is substituted into the equation for the month in which harvest occurs, otherwise the value is zero.

$$\begin{aligned}\text{Log (root mass)} = 3.33 &- 0.02(\text{July harvest}) \\ &- 0.42(\text{August harvest}) + 0.76 \\ &\times \log\ (\text{largest crown area}) + 0.46 \\ &\times \log\ (\text{plant height})\end{aligned}$$

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Sustainable management of wild-harvested medicinal plants, whether in the Appalachians forests of eastern North America or throughout the world, requires accurate estimation of marketable plant material. Long-term studies such as those reported, particularly those established in consultation with local harvesting practices, have been identified as particularly valuable research priorities for developing management plans to reduce harvest impacts (Ticktin, 2004). With plants that are harvested for below-ground storage organs, such as black cohosh, determining availability of below-ground biomass has been nearly impossible without excavation and destruction of the plants. Our predictive model allows for estimation of below-ground marketable rhizomes based on above-ground metrics, and provides a tool that can aid in the sustainable management of natural populations. Though focused on black cohosh, the protocols and model presented here likely are adaptable to other species harvested for below-ground storage structures. Thus, forest managers worldwide should benefit from the results of this study. Adapting the approach presented here to other non-timber forest products, particularly native medicinal plants, is an explicit objective of future research, and should help to improve management of economically important native species.

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