Forest Ecology and Management 260 (2010) 1088–1093

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Estimating the quadratic mean diameters of fine woody debris in forests of the United States

Christopher W. Woodall[a,*], Vicente J. Monleon[b]

[a] USDA Forest Service, Northern Research Station, Forest Investory and Analysis, 1992 Folwell Ave, St. Paul, MN 55108, USA
[b] USDA Forest Service, Pacific Northwest Research Station, Corvallis, OR, USA

ARTICLE INFO

Article history:
Received 5 May 2010
Received in revised form 20 June 2010
Accepted 22 June 2010

Keywords:
Fine woody debris
Quadratic mean diameter
Forest inventory
Carbon
Fuels

ABSTRACT

Most fine woody debris (FWD) line-intersect sampling protocols and associated estimators require an approximation of the quadratic mean diameter (QMD) of each individual FWD size class. There is a lack of empirically derived QMDs by FWD size class and species/forest type across the U.S. The objective of this study is to evaluate a technique known as the graphical estimation (GE) method for estimating FWD QMDs across forests of the U.S. Results indicate tremendous inter- and intra-specific variation in small FWD diameters. In addition, GE model fitting results demonstrated a lack of substantial difference in FWD QMDs between common forest types. It is postulated that the mixing, fracturing, and decay of both tree and shrub downed woody debris in diverse forest types across the U.S. can homogenate FWD QMDs at state/national levels. In the absence of site-specific empirical measurement of FWD QMDs, it is suggested that a general national set of FWD QMDs derived from the GE method be adopted for large-scale FWD monitoring efforts.

1. Introduction

Fine woody debris (FWD) is defined as dead and downed woody debris in forests that is less than a threshold diameter, typically between 5 cm and 10 cm. Estimates of FWD biomass are a component of large-scale fire/fuel and carbon monitoring efforts. Fine woody debris comprise a substantial portion of fuel loadings and determine to a large extent fire behavior (Albini, 1976; Burgan and Rothermel, 1984; Deeming et al., 1977). Recently, nationwide efforts have been initiated to both inventory and map FWD fuels across the U.S. (Woodall and Monleon, 2008; Rollins et al., 2004). FWD, as a component of the forest floor, is often reported as a forest carbon stock (IPCC/UNEP/OECD/IEA, 1997; Smith et al., 2006; Woodall et al., 2008) and may serve as an important indicator of climate change effects on dead wood carbon stocks (Woodall and Liknes, 2008).

Given the relative small size of FWD, inventory sample protocols typically tally individual FWD pieces according to broad size classes along a defined length of sampling transect. In contrast, the line-intersect sampling of large coarse woody debris (CWD) typically includes the actual measurement of its diameter at the point of intersection with a sampling transect (Van Wagner, 1968). The line-intersect method of inventory FWD has been employed for decades due its efficiency and ease of use (Brown and Roussopoulos, 1974). The FWD size classes most often used in line-intersect sampling correspond to three time-lag fuel classes (Deeming et al., 1977): small FWD, 1 h fuels, 0.00–0.62 cm; medium FWD, 10 h fuels, 0.63–2.54 cm; large FWD, 100 h fuels, 2.55–7.60 cm. Once a FWD transect is established in an area of interest, foresters typically tally the number of FWD pieces that intersect the sample transect, assigning counts to the three FWD size classes according to their diameter at the point of intersection with a sampling transect. Even the sample protocols for a national inventory of FWD do not require the measurement of the actual diameter of each FWD piece, only the number of pieces in each diameter class (Woodall and Monleon, 2008).

Most applications of FWD inventories require the estimation of FWD biomass per unit area. To estimate biomass, FWD volume must first be determined based on assigning a quadratic mean diameter (QMD) to each size class. QMD is defined as the square root of the average squared diameter. Since the FWD biomass estimator requires a QMD be squared, any substantial errors in QMD approximation can lead to larger errors in subsequent population estimates. The number of FWD pieces generally decreases as the FWD diameter increases, therefore using FWD size class midpoints in lieu of QMD has been viewed as a poor approximation (Fig. 1). Empirically derived FWD QMDs are typically species- and site-specific and are only available for a very limited number of species and sites across the U.S. (for examples see Van Wagtendonk et al., 1996; Roussopoulos and Johnson, 1973; Nalder

* Corresponding author. Tel.: +1 651 649 5141; fax: +1 651 649 5140.
E-mail address: cwoodall@fs.fed.us (C.W. Woodall).

0378-1127/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.foreco.2010.06.036

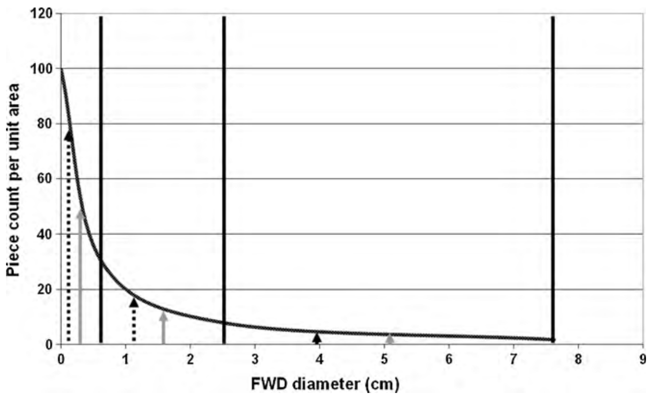

Fig. 1. Hypothetical distribution of FWD diameters: solid black vertical lines define FWD size classes, solid grey arrows denote FWD diameter class midpoints, and dotted black arrows denote midpoint of area under the FWD distribution curve (quadratic mean diameter approximation).

et al., 1997, 1999). Given the predominantly mixed species condition of forests across the nation, along with hundreds of tree and shrub species that also contribute to the FWD pool, empirically deriving FWD QMDs for all inventoried forests is unfeasible. Hence, research questions have arisen: how variable are FWD QMDs among the diverse tree species and forest types across the U.S.? How could FWD QMDs be estimated for such a diverse array of situations?

There are alternatives to empirical sampling FWD QMDs. Van Wagner (1982) was one of the first to identify the limitation of empirically derived FWD QMDs. As an alternative to conducting field work for every population of interest (unique forest types across the country), Van Wagner (1982) proposed the graphical estimation (GE) method for deriving QMDs involving no additional field work. Van Wagner (1982) assumed that the distribution of the number of FWD pieces as a function of diameter follows a power law such that the empirically derived FWD tally counts by FWD size class may be used to determine the slope of this function. With an estimate of the slope of the FWD size distribution, QMD may be estimated for each FWD size class. Woodall and Monleon (2009) explored using the GE method with a preliminary national FWD inventory, along with validation using empirical studies of FWD diameters. They found that the GE method may reasonably approximate FWD QMDs. However, the coefficient of variation between independent FWD QMD measurements for the same tree species exceeded 50% in all examined cases obscuring validation. A robust examination of the GE method using an expanded national inventory of FWD and refined model fitting techniques should increase both the understanding of FWD QMD variation across the diverse forest types of the U.S. and the precision of FWD population estimates.

The goal of this study was to use the GE method to estimate FWD QMDs across the U.S. by forest type groups using an approximation of small FWD diameters and a national inventory of downed dead wood diameter distributions with specific objectives including: (1) approximate small FWD diameters for most tree species in the U.S. using published botanical plates and assess intra- and interspecific variation among the measured diameters, (2) use a national inventory of FWD and CWD (along with the small FWD diameter estimates from objective one as an approximation of small FWD minimum diameter for initial model fitting) to determine the negative exponential slope and QMD of FWD size classes by forest type groups, and (3) evaluate the effect of variations in QMDs on subsequent FWD population estimates and suggest directions for large-scale FWD monitoring efforts.

2. Methods

2.1. Data

To approximate the variation in small FWD QMDs across the various tree species and resulting forest types across the U.S., the smallest twig diameter was measured using botanical plates across a range of dendrology publications. A selection of dendrology literature was identified that represented both a broad coverage of native U.S. tree species along with detailed botanical plates with scale information (e.g., actual size versus size reductions) (Table 1). For each botanical plate, the smallest diameter of each terminal bud twig was measured to the nearest 0.1 mm. In limited cases where needle clusters obscured measurement of the terminal twig (e.g., *Pinus* spp.), the nearest part of the twig before the needle bunches was measured. Although the definition of small FWD is a woody piece with a diameter <0.64 cm, the smallest twig diameter within a botanical plate was allowed to be in excess of 0.64 cm to capture the full range of small twig variability of any given species. It should be noted that there are issues of selection bias in studies using photographs or illustrations (Egan and Howell, 2001). These approximations of small FWD QMDs are merely used as initial model fitting values with the intraspecific coefficients of variation between independent botanical plates explicitly examined.

To fit the FWD size distribution curve and determine the negative exponential slope for each forest type group, actual field observations of both FWD and CWD were used. A total of 10,610 observations from single forest condition FIA sub-plots across the U.S. (sampled between 2002 and 2006) were included in this study with no observations in the states of CA, HI, LA, WA, WY, MS, NM, OK, OR, TX due to on-going implementation of a national annual inventory. Briefly, each FIA plot consists of four, 7.32 m fixed radius plots for sampling standing tree attributes. Within each subplot, a 7.32 m sample transect was established from plot center radiating outward at a 150° angle. Small and medium FWD were sampled on a 1.83 m slope distance portion of the established sampling transect (4.27–6.09 m on the 150° transect). Large FWD were sampled on a 3.05-m slope-distance portion (4.27–7.32 m from subplot center) of the 150° transect. Larger coarse woody debris (CWD) were sampled along the entire length of the 7.32 m transect. CWD pieces are defined as down woody debris in forested conditions with a diameter greater than 7.60 cm along a length of at least 0.91 m. Although CWD are sampled more extensively within FIA plots, only the CWD sample transect that coincided with the 1.83 m of the FWD sample transect was included in this study. Additionally, although each individual CWD piece diameter is recorded at the point of intersection with a sample transect, for the purposes of this study each CWD piece was assigned to one of two CWD size classes (7.63–32.99 cm and 33.00–68.58 cm) of increasing class width to maintain adequate piece counts. Each observation in this study consisted of FWD and CWD tally counts by size class along 1.83 m of the 150° transect (for further sample protocol information see U.S. Department of Agriculture et al., 2006; Woodall and Monleon, 2008). All FWD and CWD tally counts were standardized to a 3.05 m sample transect by size class.

2.2. Analysis

Using the botanical plate small FWD measurements, a range and mean small FWD diameter was determined by species. First, the scale factor and actual measurement of each botanical plate twig were multiplied to a standard 1× scale for all measurements. Secondly, using a weighting scheme based on the proportion of individual species occupying the average volume within forest type groups across the U.S. (Smith et al., 2006), a mean small FWD diameter was determined by forest type group. Coefficients of variation

Table 1
Botanical plate genus, number of constituent species, list of references (footnotes).

Genus	Number of species[a]	Number of measurements	References[b]
Abies	8	29	1–10
Chamaecyparis	3	9	2–6,9
Juniperus	3	15	1–10
Larix	3	13	1–10
Picea	8	34	1–10
Pinus	23	54	1–8
Pseudotsuga	1	5	1,3,4,7,8
Taxodium	1	5	3–5,8,9
Taxus	1	4	3,4,7,10
Thuja	2	12	1–10
Tsuga	3	12	1–4,6,7,9,10
Acer	11	56	1–10
Aesculus	1	8	1–9
Ailanthus	1	7	1–4,6,8,9
Alnus	1	10	1–10
Amelanchier	1	8	1–9
Asimina	1	5	1–3,5,6
Betula	6	33	1–10
Carpinus	1	6	1,2,5,6,8,9
Carya	8	39	1–6,8,9
Castanea	2	11	1–6,8,9
Catalpa	1	9	1,2,3,4,5–9
Celtis	3	11	1,2,4,5,6,7,8,10
Cercis	1	5	1,2,5,6,7
Cornus	2	8	1,2,4,5–9
Crataegus	1	9	1–9
Diospyros	1	6	2–6,9
Fagus	1	7	1–5,8,9
Fraxinus	6	33	1–6,8–10
Gleditsia	2	9	1,2,4,5,6–9
Gymnocladus	1	6	1,2,4,5,6,8
Ilex	1	5	2,5,6,8,9
Juglans	2	16	1–6,8,9
Liquidambar	1	8	1–6,8,9
Liriodendron	1	8	1–6,8,9
Maclura	1	7	1–3,6–9
Magnolia	1	7	2–6,8,9
Malus	1	6	1–3,7–9
Morus	2	15	1–9
Nyssa	2	9	1,2,4–6,9
Ostrya	1	7	1–3,5,6,8,9
Oxydendrum	1	3	5,6,9
Paulownia	1	3	2,5,9
Plantanus	1	8	1–6,8,9
Populus	8	48	1–10
Prosopis	1	2	8,9
Prunus	5	32	1–10
Quercus	36	144	1–6,8–10
Robinia	1	7	1,2,4–6,8,9
Salix	1	9	1,2,4–10
Sassafras	1	7	1–6,9
Sorbus	1	7	1–3,5,6,8,9
Tamarix	1	2	8,9
Tilia	2	11	1–7,9,10
Ulmus	7	26	1–9
Vaccinium	1	2	5,9

[a] Spp's included as individual species.
[b] 1, Barnes and Wagner (2004); 2, Brown (1938); 3, Fralish and Franklin (2002); 4, Hardin et al. (2001); 5, Hough (1936); 6, Illick (1928); 7, Johnson (1995); 8, Kuhns (1998); 9, Lance (2004); 10, Preston (1968).

(CV) were determined between the individual small FWD diameter measurements by species (intraspecific) and between species (interspecific). Finally, using the botanical plate measurements, the mean small FWD was determined for each forest type group for the purpose of estimating the FWD QMDs using the GE method.

Next, Van Wagner's (1982) GE method was used to estimate the QMD for FWD across the U.S. Van Wagner (1982) assumed that the distribution of FWD diameters follows a power law:

$$y = ax^b \tag{1}$$

where y is the number of FWD pieces, x the diameter (cm), and a and b are constants to be estimated. Following determination of b (Eq. (1)), the theoretical QMD for a FWD size class can be calculated analytically as (Eq. (5) of Van Wagner, 1982):

$$(\mathrm{QMD})^2 = \frac{\int_{x_1}^{x_2} ax^{b+2}dx}{\int_{x_1}^{x_2} ax^{b}dx} = \frac{(b+1)(x_2^{b+3} - x_1^{b+3})}{(b+3)(x_2^{b+1} - x_1^{b+1})} \tag{2}$$

where QMD is the quadratic mean diameter (cm), and x_1 and x_2 are the lower and upper diameter FWD class limits (cm), respectively. This equation is not defined when $x_1 = 0$, the theoretical lower limit of the small diameter size class. Van Wagner (1982) noted that the size of the smallest twig is peculiar to each species, but lacking better information, he suggested using an arbitrary lower limit. In this study, the small FWD diameters estimated from the botanical plates were used to provide an initial lower diameter limit for this class.

To estimate the QMD for each diameter class, the coefficient b is estimated from FWD and CWD sampling transect counts. For each forest type group, the number of intersections by size class was normalized to a unit width by dividing the frequency by the width of the diameter class. We fitted Eq. (1) using non-linear regression and linear regression after a log transformation. After examining the residuals, it was clear that the error structure was multiplicative and, therefore, the log-transformed approach was more appropriate. Separate estimates were computed for each forest type group. The slope of the regression model is used to determine the QMD, as the midpoint of the area under the estimated FWD diameter distribution (dotted arrows, Fig. 1). Since the QMD is a non-linear function of the estimated slope, the delta method was used to approximate its standard error (Casella and Berger, 1990, p. 328). A set of national FWD QMDs was determined by estimating a weighted mean FWD QMD based on the proportion of total land area for each forest type group by national total (Smith et al., 2004).

Plot-level FWD biomass estimates were based on estimators detailed in Woodall and Monleon (2008) (Eq. (3.1.2)). To compare differences in FWD estimates (Mg/ha) at the state and national level when different FWD QMD constants are used in population estimation procedures, two sets of FWD population estimates were compared: one based on a set of national conifer/hardwood QMDs and the other based on individual forest type group QMDs. These sets of QMDs were acquired during accomplishment of objective two of this study. The means and standard errors of these absolute and relative differences at the state and national level were computed assuming simple random sampling. It should be noted that the sample size was reduced in this particular analysis because individual FWD transects were combined into one plot-level estimate to reflect standard FWD analysis procedures.

3. Results

The range in individual measurements of minimum twig diameter (from the measurement of the smallest terminal bud twigs on botanical plates) ranged from a minimum of 0.02 to 2.10 cm (Table 2). The mean minimum twig diameter sizes ranged from 0.07 cm (*Chamaecyparis* and *Tsuga*) to 0.45 cm (*Quercus*) (Table 2). The majority of genera had mean small twig diameters between 0.10 cm and 0.40 cm. The associated standard errors of these means often overlapped for most genera, coupled with tremendous CVs. The CVs of 18 of the study's 22 genera exceeded 50% with 5 genera having CVs in excess of 100%. Within each genus, a mean of all intraspecific CVs was determined. The mean of intraspecific CVs was similar in scale to the inter-genera CVs with most CVs exceeding 50%.

The estimated slopes (b, Eq. (1)) of the FWD size distribution ranged from −1.96 (hemlock/sitka spruce) to −2.52 (western oak)

Table 2
Small FWD diameter range, mean, and CV within each genus, and mean CV within species of that genus based on botanical plate measurements.

Genus	SFWD range (cm)	Mean SFWD (cm)	*n*	S.E. (cm)	CV	Intraspecific	
						Mean CV	*n*
Abies	0.03–0.45	0.16	29	0.02	73	74	7
Chamaecyparis	0.03–0.11	0.07	9	0.01	37	37	2
Juniperus	0.05–0.20	0.09	15	0.01	51	49	3
Larix	0.05–0.60	0.20	13	0.04	79	57	3
Picea	0.05–0.80	0.15	34	0.03	97	64	7
Pinus	0.02–1.10	0.18	54	0.03	104	51	16
Thuja	0.05–0.60	0.16	12	0.04	93	77	2
Tsuga	0.03–0.10	0.07	12	0.01	37	25	3
Acer	0.02–1.75	0.33	55	0.05	112	113	9
Betula	0.02–1.00	0.19	33	0.05	142	116	6
Carya	0.03–2.10	0.40	39	0.06	98	81	8
Castanea	0.05–1.20	0.30	11	0.10	114	103	2
Celtis	0.03–0.15	0.08	16	0.01	42	38	4
Fraxinus	0.10–0.77	0.42	33	0.03	42	34	6
Juglans	0.10–1.00	0.45	16	0.08	71	73	2
Morus	0.05–0.50	0.20	15	0.03	66	63	2
Nyssa	0.05–1.05	0.44	9	0.11	75	66	2
Populus	0.05–1.00	0.31	43	0.04	78	69	7
Prunus	0.03–1.65	0.26	32	0.06	132	102	5
Quercus	0.02–2.10	0.49	142	0.03	84	77	25
Tilia	0.05–0.63	0.23	11	0.05	76	57	2
Ulmus	0.02–0.48	0.21	25	0.03	75	76	5

Note: Small FWD range allowed to exceed 0.64 cm to capture variability in smallest twig measurements.

for selected forest type groups across the U.S. (Table 3). All but one forest type group had an adjusted $r^2 \geq 0.93$ (Fig. 2). Despite divergences in the estimated slopes of the FWD size distributions, most of the estimated QMDs were nearly the same. The estimated FWD QMDs were between 0.18 cm and 0.30 cm, 1.17 cm and 1.27 cm, and 4.18 cm and 4.41 cm across all forest types for the small, medium, and large FWD classes, respectively. In contrast, the diameters at the mid-point were 0.30 cm, 1.57 cm and 5.07 cm, respectively. The differences between forest type groups were relatively small, especially when compared with the estimated standard errors. In fact, the estimate for the weighted national mean FWD QMDs were identical to many of those for individual forest type groups.

Comparisons between FWD biomass estimates (Mg/ha) using two different sets of QMDs (national weighted mean versus forest type group) indicated differences ranging from minimal to appreciable (−0.15 Mg/ha, −0.04 Mg/ha, and −0.01 Mg/ha for small, medium and large FWD, respectively) at the national scale (Table 4). Most of the negative differences in biomass estimates were found in eastern states dominated by hardwood forests, while conifer-dominated western forests tended to have positive differences. More meaningful comparisons of relative differences in FWD biomass estimates indicated a 7%, <1%, and <1% difference at the national scale for small, medium and large FWD, respectively (Table 4). Finally, FWD biomass estimates were compared using the national weighted mean QMDs and FWD class midpoints. The estimates based on midpoint diameters had a mean relative difference of 100%, 64%, and 38% greater than estimates based on QMDs for small, medium and large FWD, respectively.

4. Discussion

The botanical plate measurement results indicated tremendous intra- and inter-specific variation. Even in published empirical

Table 3
Estimated fine woody debris (FWD) quadratic mean diameters and associated standard errors (SE) along with the estimated beta parameter for the graphical estimation method by forest type group.

Forest type group	*n*	*b*	S.E.	Estimated FWD QMDs (cm)					
				Small	S.E.	Medium	S.E.	Large	S.E.
White/red/jack pine	51	−2.36	0.12	0.18	0.03	1.20	0.05	4.24	0.05
Spruce/fir	119	−2.28	0.18	0.19	0.05	1.21	0.08	4.27	0.08
Longleaf/slash pine	27	−2.21	0.34	0.26	0.08	1.22	0.15	4.30	0.15
Loblolly/shortleaf pine	178	−2.39	0.29	0.21	0.07	1.19	0.12	4.23	0.12
Pinyon/juniper	283	−2.37	0.17	0.21	0.04	1.19	0.07	4.24	0.07
Douglas-fir	102	−2.19	0.15	0.24	0.04	1.23	0.06	4.31	0.06
Ponderosa pine	83	−2.07	0.19	0.23	0.05	1.25	0.08	4.36	0.08
Fir/spruce/mtn hemlock	132	−1.99	0.06	0.22	0.02	1.27	0.03	4.40	0.03
Lodgepole pine	62	−2.11	0.10	0.23	0.03	1.24	0.04	4.35	0.04
Hemlock/Sitka spruce	35	−1.96	0.06	0.23	0.02	1.27	0.03	4.41	0.03
Other western softwoods	12	−2.09	0.17	0.20	0.05	1.25	0.07	4.35	0.07
Oak/pine	104	−2.23	0.21	0.22	0.05	1.22	0.09	4.30	0.09
Oak/hickory	673	−2.17	0.21	0.21	0.05	1.23	0.09	4.32	0.09
Oak/gum/cypress	46	−2.08	0.16	0.25	0.04	1.25	0.07	4.36	0.07
Elm/ash/cottonwood	81	−2.21	0.17	0.21	0.04	1.22	0.07	4.30	0.07
Maple/beech/birch	420	−2.13	0.18	0.20	0.05	1.24	0.08	4.33	0.08
Aspen/birch	159	−2.19	0.21	0.19	0.06	1.23	0.09	4.31	0.09
Western oak	46	−2.52	0.18	0.30	0.04	1.17	0.08	4.18	0.08
Other western hardwoods	20	−2.47	0.64	0.21	0.15	1.18	0.27	4.20	0.27
Weighted national mean	–	–	–	0.22	–	1.23	–	4.31	–

Table 4
Means of absolute (Abs.; Mg/ha) and relative differences (Rel. Diff.; Mg/ha) of small (SFWD), medium (MFWD), and large fine woody debris (LFWD) by state (for states with $n > 50$).

State	*n*	SFWD				MFWD				LFWD			
		Abs.[a]	S.E.	Rel. Diff.[b]	S.E.	Abs.	S.E.	Rel. Diff.	S.E.	Abs.	S.E.	Rel. Diff.	S.E.
Alabama	110	−0.01	0.03	−0.03	0.01	−0.18	0.06	−0.02	<0.01	−0.36	0.14	−0.01	<0.01
Alaska	71	0.04	0.13	−0.03	0.01	0.55	0.10	0.05	<0.01	1.16	0.24	0.03	<0.01
Arizona	146	0.09	0.04	0.08	0.02	−0.18	0.03	−0.03	<0.01	−0.34	0.08	−0.02	<0.01
Arkansas	95	−0.04	0.03	−0.03	0.01	−0.26	0.09	−0.01	<0.01	−0.44	0.20	−0.01	<0.01
Colorado	161	0.11	0.06	0.04	0.02	−0.02	0.06	−0.01	<0.01	0.05	0.11	<0.01	<0.01
Georgia	87	<0.01	0.03	0.03	0.02	−0.28	0.06	−0.02	<0.01	−0.52	0.13	−0.01	<0.01
Idaho	97	0.10	0.05	0.04	0.01	0.44	0.06	0.03	<0.01	1.26	0.21	0.02	<0.01
Maine	150	−0.76	0.10	−0.26	<0.01	−0.11	0.04	<0.01	<0.01	−0.16	0.08	<0.01	<0.01
Michigan	98	−0.33	0.05	−0.23	0.01	−0.02	0.03	<0.01	<0.01	0.05	0.07	<0.01	<0.01
Minnesota	114	−0.32	0.04	−0.23	0.01	−0.08	0.03	<0.01	<0.01	−0.18	0.07	<0.01	<0.01
Missouri	74	−0.08	0.01	−0.07	<0.01	0.04	0.02	<0.01	<0.01	0.12	0.04	<0.01	<0.01
Montana	160	0.14	0.02	0.07	0.01	0.22	0.04	0.02	<0.01	0.53	0.08	0.02	<0.01
New York	113	−0.58	0.10	−0.19	0.01	0.10	0.09	0.01	<0.01	0.21	0.10	<0.01	<0.01
North Carolina	82	0.01	0.06	−0.03	0.01	−0.33	0.17	−0.01	<0.01	−0.44	0.18	−0.01	<0.01
Pennsylvania	115	−0.31	0.05	−0.14	0.01	0.15	0.04	0.01	<0.01	0.16	0.24	0.01	<0.01
Tennessee	71	−0.12	0.01	−0.08	0.01	0.05	0.01	<0.01	<0.01	0.10	0.03	<0.01	<0.01
Utah	135	<0.01	0.06	−0.01	0.02	−0.48	0.10	−0.03	<0.01	−0.39	0.12	−0.02	<0.01
Virginia	72	−0.08	0.03	−0.06	0.01	−0.01	0.06	−0.01	<0.01	−0.07	0.11	<0.01	<0.01
West Virginia	51	−0.23	0.03	−0.13	0.01	0.13	0.03	0.01	<0.01	0.29	0.07	0.01	<0.01
Wisconsin	68	−0.28	0.04	−0.21	0.01	−0.01	0.04	<0.01	<0.01	0.06	0.09	<0.01	<0.01
National average[c]	2532	−0.15	0.01	−0.07	<0.01	−0.04	0.01	<0.01	<0.01	<0.01	0.03	<0.01	<0.01

[a] Absolute = estimates using FWD QMDs based on forest type groups – estimates using national FWD QMDs.
[b] Relative = (estimates using FWD QMDs based on forest type groups – estimates using national FWD QMDs)/estimates using national FWD QMDs.
[c] Includes all states regardless of number of observations.

studies in pure forest stands, the intra-specific CV was at the same magnitude as that seen in our study. In ponderosa pine forests, the CV among published small FWD QMDs (Brown and Roussopoulos, 1974; Ryan and Pickford, 1978; Sackett, 1980; Van Wagtendonk et al., 1996) exceeded 87% compared to the intraspecific mean CV of 51 for the *Pinus* genus in this study. It can be surmised that unanimity among empirical measurements of small FWD, even among pure species forests, may forever remain elusive. This finding is further exacerbated by the fact that the majority of forests across the U.S. are not single-species stands (Smith et al., 2004) and include shrubs and other sources of FWD. The mixing of inter- and intra-specific small FWD pieces across U.S. forests most likely homogenizes small FWD sizes at large spatial scales.

In theory, the GE method offers an attractive procedure for estimating FWD QMDs based on actual size-class field observations. This method combines the field efficiency of simple FWD size class tally counts (as opposed to measuring the diameter of every FWD piece) with a realistic theoretical size distribution of dead wood pieces that could be scaled according to a power function similar to living plant size/number distributions (see Enquist, 2002). Using a national inventory of FWD and CWD, the slopes (b coefficient in Eq. (1)) of FWD size distributions followed the theoretical model well, with variation among forest type groups. However, differences in the FWD size distributions did not substantially affect estimated QMDs. Even if two forest types with appreciable differences in their estimated slopes (white/red/jack pines, $b = -2.36$; hemlock/sitka spruce, $b = -1.96$) were compared, their slope difference did not translate into substantial differences in estimated QMDs (Fig. 3). Perhaps the large number of small FWD in forest ecosystems skews the FWD size distribution so far to the left that it takes considerable FWD diameter variation (e.g., right-skewed size distribution) to affect FWD size/density slopes. When viewing all estimated QMDs in terms of significant digits and model error, there is most likely no difference in estimated

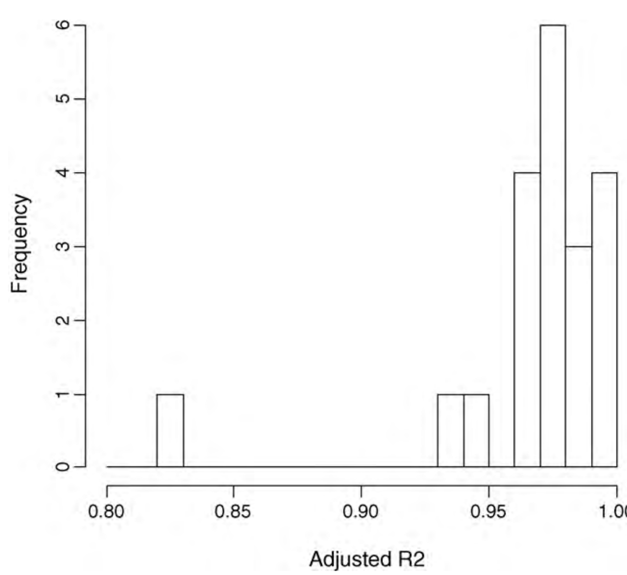

Fig. 2. Histogram of r^2s from fitting graphical estimation model to forest type groups across the U.S.

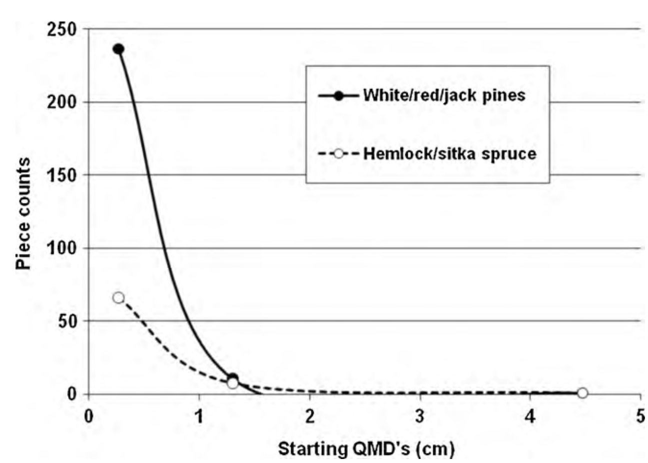

Fig. 3. Estimated FWD size distribution slopes fitted by the graphical estimation method for white/red/jack pine and oak/hickory forest type groups, U.S.

forest type group QMDs derived from the GE method across the U.S.

Based on the results of this study, it is postulated that the mixing of downed woody pieces in various states of structural integrity (e.g., decay and fracturing/splintering) from various sources (diverse tree/shrub species) causes a homogenization of FWD sizes at large scales. What impact does the selection of FWD QMD have on large scale FWD resource monitoring efforts (e.g., biomass assessments) and what QMD should be used in population estimation procedures? At the national level, there was only a slight effect of QMD selection on the resulting national FWD biomass means compared to using QMDs particular to specific forest type groups. An exception to this result is small FWD, which had appreciable differences in biomass estimates. At the state level, the majority of states demonstrated minimal effect of QMD selection on FWD population estimates. When examining states with greater than 50 observations, most relative differences in small, medium, and large FWD population estimates were below 10%, 2%, and 1%, respectively. The range in estimated large FWD QMDs across forest type group in this study was approximately 0.23 cm, or approximately 5% of the average large FWD QMD. Despite this slight variation, there is most likely far greater error in selection of the bulk density and decay reduction factor for FWD population estimation. Interspecific variation in bulk densities and decay factors for U.S. trees (Harmon et al., 2008) may vary to a greater extent than FWD QMD values. Furthermore, the use of national scale FWD QMD values based on fitting the GE method with national FWD and CWD size distributions may help partition FWD estimate variation to actual differences in forest types as opposed to being a spurious result of subjective estimates of FWD QMDs. Therefore, the weighted national mean QMDs of 0.22 cm, 1.23 cm, and 4.31 cm (small, medium, and large FWD, respectively) are suggested for large-scale FWD population estimation.

5. Conclusions

The lack of empirically derived FWD QMD values may not substantially affect efforts to monitor FWD resources across the U.S. As found in this and other studies, the intraspecific variation in FWD QMDs can often meet or exceed the interspecific variation. At small scales, empirically derived FWD QMDs may be optimal for FWD population estimation. Unfortunately, at large-scales the measurement of actual FWD diameters is cost-prohibitive while using forest type specific diameters may be unfounded given the mixing of FWD pieces in various states of decay/fracture from diverse sources (e.g., diverse tree/shrub species). As explored in this study, the GE method offers an objective method for broadly approximating regional/national FWD QMDs such that the adoption of national set of QMDs is suggested for the purpose of large-scale monitoring and may be preferable to using one empirically derived set of QMDs.

Acknowledgements

The authors would like to thank Dr. Mark Harmon for valuable suggestions regarding botanical plate measurements.

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