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Tracking downed dead wood in forests over time: Development of a piece matching algorithm for line intercept sampling

C.W. Woodall [a,*], B.F. Walters [a], J.A. Westfall [b]

[a] USDA Forest Service, Northern Research Station, Forest Inventory and Analysis Program, St. Paul, MN 55108, USA
[b] USDA Forest Service, Northern Research Station, Forest Inventory and Analysis Program, Newtown Square, PA 19073, USA

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ABSTRACT

Emerging questions from bioenergy policy debates have highlighted knowledge gaps regarding the carbon and biomass dynamics of individual pieces of coarse woody debris (CWD) across the diverse forest ecosystems of the US. Although there is a lack of long-term measurements of CWD across the diverse forest ecosystems of the US, there is an abundance of line intersect sampling (LIS) transects used for monitoring efforts such as fuel loadings. In order to provide an objective method for monitoring the carbon/biomass dynamics of individual CWD pieces for use with LIS, this study developed and tested a CWD piece matching algorithm for inventory plots where LIS was used to sample CWD at two points in time across the eastern US. Results indicated that a CWD piece matching algorithm may be constructed using three steps: (1) matching the location of each piece, (2) matching individual piece metrics (e.g., large-end diameter), and (3) scoring an index of many CWD attributes with adjustment by decay and measurement error (i.e., quality control tolerances). For most forest types in the US, this study's algorithm matched between 20% and 40% of CWD pieces over time (≈5 years). The algorithm performed poorly in forests potentially disturbed by floods and/or with relatively high mean annual temperatures and subsequent fast decay rates. Due to this influence of decay, the algorithm attained low match rates for highly decayed or small-sized CWD pieces. The algorithm should not be used to estimate changes in carbon/biomass within a stock change accounting framework. However, the algorithm may provide a method to aggregate a subset of paired LIS CWD observations over time to inform CWD dynamics research at large-scales.

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1. Introduction

Given the dynamic nature of forest ecosystems, they have emerged as one of the most important land uses when it comes to reducing greenhouse gas (GHG) emissions and possibly mitigating future climate change effects (Ryan et al., 2010; Malmsheimer et al., 2008; McKinley et al., 2011). Forests may reduce GHG emissions by sequestrating C through afforestation, wood substitution in building materials, and biomass substitution (Malmsheimer et al., 2008, 2011). In contrast, forests may contribute to GHG emissions through deforestation and/or management activities that inadvertently promote reduced C storage (Ryan et al., 2010). Given the complicated pathways of carbon (C) emissions/sequestration between the diverse components of forest ecosystems (e.g., pools such as live biomass and forest floor), there are substantial knowledge gaps regarding C implications of forest management activities (McKinley et al., 2011; Malmsheimer et al., 2011). In particular, fate of downed dead wood has emerged as a knowledge gap in bioenergy policy debates (MCCS, 2010; Lippke et al., 2011; Gunn et al., 2012). Coarse woody debris (CWD), one focus of bioenergy, can be defined as downed dead wood in forests that often exceeds a certain minimum size threshold (e.g., 10 cm diameter and 1 m length, Woodall et al., 2009). A freshly fallen piece of CWD that decays in 1 year (i.e., an almost immediate emission to the atmosphere) may have different C cycle implications versus a CWD piece that may take a century to fully decay. Rapid decay/emission could affect policies aimed at burning CWD for energy as both end points (i.e., combustion or decay) result in emissions over short time frames. The use of "life cycle" approaches has been suggested as an objective means to resolve such policy issues (Lippke et al., 2011). Within such an approach, C is tracked over time whether it is emitted through the "slow" decay of CWD pieces or "rapidly" through bioenergy production (Lippke et al., 2011). There is an important distinction between "stock change" and "life cycle" approaches to monitoring C in forest components. As CWD C stocks are a balance between accretion (e.g., tree mortality) and depletion (e.g., fire or decay) processes, the CWD C pool can be static over long time periods (e.g., slow decay with no disturbance) or experience dramatic changes over very short periods of time (e.g., combustion or harvest) (Woodall, 2010). It is the fate of individual pieces of CWD over time that has emerged as a substantial

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

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knowledge gap within dead wood ecology and broader bioenergy policy debates.

The sampling and monitoring of downed dead wood was originally borne out of a need to assess forest fuels (for examples see Van Wagner, 1968; Brown, 1974). These early efforts focused on relatively rapid fuel assessment sampling strategies, such as found with line intersect sampling (LIS) of logging residue (Hazard and Pickford, 1986), with little to no attention given to monitoring individual pieces of CWD over time. Line intersect sampling typically involves measuring a limited number of CWD piece attributes (e.g., species and transect diameter) at the point at which a CWD piece intersects a sampling transect (de Vries, 1986). A CWD piece inclusion probability is based on CWD piece length and transect length, which is turn are components of population attribute estimators (e.g., number of CWD pieces per unit area) (de Vries, 1986). As the critical role that CWD plays in forest ecosystems became more evident (e.g., nutrient cycling, facilitating regeneration, and carbon pool) (Harmon et al., 1986), sampling techniques were developed to monitor CWD resources over time (Harmon and Sexton, 1996). These "research oriented" techniques (as opposed to "resource inventory" techniques) often involve marking individual CWD pieces on permanent sample plots where individual pieces of CWD can be monitored over long time-steps (Harmon and Sexton, 1996). These long-term ecosystem research (LTER) strategies perhaps offer a method for tracking individual CWD pieces over time to inform CWD dynamics. Unfortunately, LTER study sites are only established in a limited number of forests and are often not subjected to the diversity of forest management activities that occur across the landscape. The nationwide monitoring of CWD in North American nations is predominantly done through LIS where individual pieces of CWD are not explicitly tracked (Woodall et al., 2009). Since 2000, the US has sampled CWD consistently across the Nation using LIS (Woodall and Monleon, 2008). Although LIS provides an adequate methodology for estimating C stock changes in CWD (e.g., time two minus time one stock estimates; Woodall et al., 2008; Woodall, 2010), it often does not provide for tracking individual CWD pieces over time. Although CWD pieces are located along sampling transects during LIS inventories, they are often not tagged for temporal tracking. In the US, the Nation's national inventory does not tag individual CWD pieces (Woodall and Monleon, 2008). However, in order to maintain statistical control of CWD inventories, the location of individual CWD pieces along sampling transects can sometimes be measured such as found in the US's CWD national inventory (Westfall and Woodall, 2007). Given the widespread use of LIS to monitor populations of CWD, development of methods for tracking individual CWD pieces complimentary to LIS might refine CWD dynamics research.

To date, no objective database techniques have been developed to match individual pieces of CWD sampled over time on the same LIS transects. Given the possibility that such techniques might inform CWD dynamics and related carbon/bioenergy policy, exploring such an exercise is highly warranted. The goal of this study is to develop and test the performance of a CWD piece matching algorithm compatible with LIS using the US's national inventory of CWD. Specific objectives were: (1) Develop CWD piece matching algorithm for use with LIS, (2) test the algorithm in terms of sensitivity to adjustment in parameter tolerances and attributes of matched and unmatched pieces for forests of the eastern US, (3) test performance of algorithm by site attributes (percent of matched pieces from time one in terms of max/min temperatures, precipitation, water code, and forest type) and using a blindly remeasured dataset (i.e., quality analysis and quality control data; QA/QC), and (4) examine changes in CWD piece attributes over time that were matched by the algorithm suggesting improvements/research needed for future application.

2. Methods

2.1. Data

The FIA program is responsible for inventorying the forests of the US, including both standing trees and dead wood on permanent sample plots established across the US using a three phase inventory (Bechtold and Patterson, 2005). During the inventory's first phase, sample plot locations are established at an intensity of approximately 1 plot per 2400 ha. If the plot lies partially or wholly within a forested area, field personnel will visit the site and establish a second phase inventory plot. FIA's second phase inventory plots consist of four 7.32-m fixed radius subplots for a total plot area of approximately 0.07 ha where standing tree and site attributes are measured (Fig. 1).

During FIA's third phase, one of every 16 phase two plots are sampled for down woody materials including CWD. Coarse woody pieces are defined by FIA as down woody debris in forested conditions with a diameter greater than 7.62 cm along a length of at least 0.91 m and a lean angle greater than 45° from vertical. Dead woody pieces with a lean angle less than 45° from vertical are considered standing dead trees (i.e., snags) and were not included in this study. Coarse woody debris are sampled on each of three 7.32-m horizontal distance transects radiating from each FIA subplot center at azimuths of 30°, 150°, and 270°, totaling 87.8 m for a fully forested inventory plot. Data collected for every CWD piece include location information (plot number, subplot number, transect identification, and horizontal distance along a sampling transect from subplot center to CWD location) and individual piece attributes (transect diameter, small-end diameter, large-end diameter, decay class (DC), length, and species). Transect diameter is the diameter of a CWD piece measured perpendicular to its center longitudinal axis at the point of intersection with a sampling transect using a diameter tape. Length is defined as the total length of the CWD piece between the small- and large-end diameter measurements. Decay class is a subjective determination of the amount of decay present in an individual CWD piece summarized across its entirety. A decay class of one is the least decayed (freshly fallen log), while a decay class of five is an extremely decayed log (cubicle rot pile) (Sollins, 1982; Harmon et al., 2008). The species of each fallen log is identified through determination of species-specific bark, branching, bud, and wood composition attributes

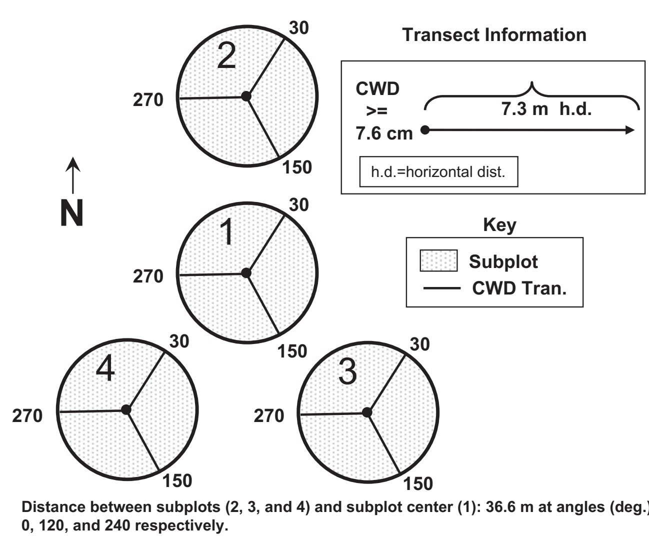

Fig. 1. Plot-level sample design for the USDA forest service's forest inventory and analysis program's inventory of coarse woody debris, 2002–2010.

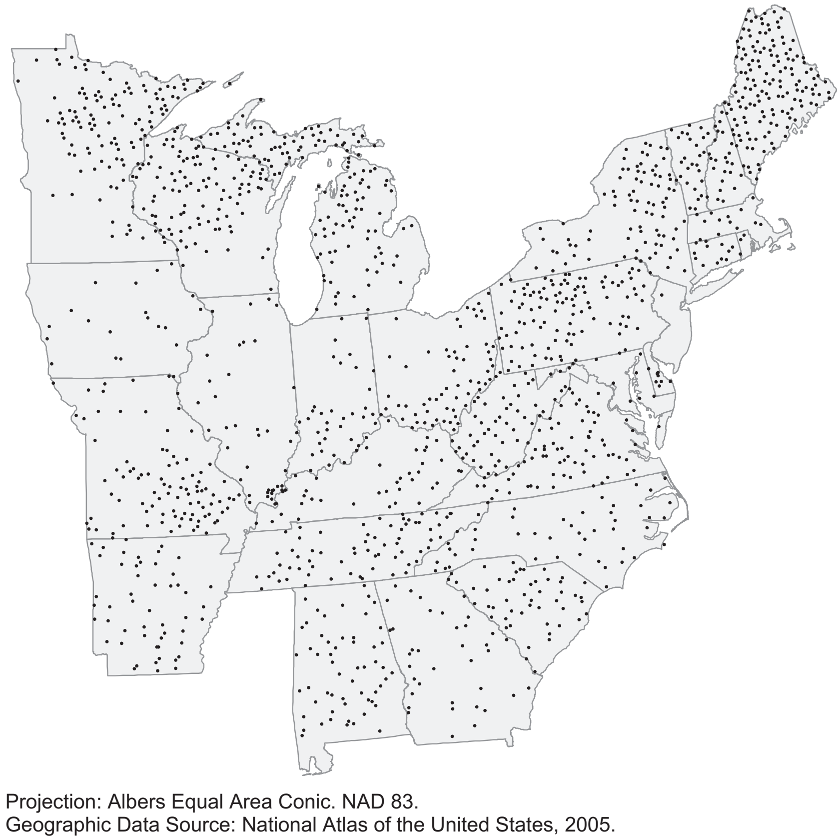

Fig. 2. Approximate locations of inventory plots used in this study, eastern US, 2002–2010.

Table 1
Counts of coarse woody pieces sampled in this study by individual attributes and by time one and time two, eastern United States, 2002–2010.

Attribute	Classes	Time 1	Time 2
Decay class	1	758	877
	2	2304	2552
	3	4301	5122
	4	2734	2270
	5	600	202
Transect diameter (cm)	7.62–17.62	7754	7944
	17.63–27.62	2225	2334
	27.63–37.62	541	570
	37.63–47.62	123	123
	47.63–57.62	30	34
	>57.63	24	18
Length (m)	0.91–3.91	4736	5008
	3.92–6.91	2872	2978
	6.92–9.91	1577	1556
	9.92–12.91	819	824
	12.92–15.91	362	366
	>15.91	331	291
Species group	Softwood	2775	3071
	Hardwood	6141	7688
	Unknown[a]	1181	62
	NA[b]	600	202

[a] Advanced field training on dead wood identification reduced "unknown" determinations in later field seasons.
[b] Species is not identified for decay class 5 pieces.

(excluding decay class 5 pieces) and grouped into four species groups for this analysis: hardwood, softwood, unknown and not applicable (i.e., decay class 5 pieces). Coarse woody pieces with a decay class of 5 are not measured for end point diameters in order to gain field efficiency. For further details regarding FIA's inventory, please refer to USDA (2007) and Woodall and Monleon (2008).

All remeasured annual FIA plots in eastern US where CWD was measured were included in this study (Fig. 2) (Table 1). Nearly 10,700 CWD pieces were measured at time one and over 11,000 CWD pieces measured at time two between the inventory years of 2002–2010 with an average remeasured interval of 5 years. The pieces were normally distributed about the decay class three (i.e., moderate decay). The pieces were overwhelmingly dominated by pieces less than 27.62 cm in transect diameter (over 90% of total pieces) and less than 6.91 m in length (over 70%). The majority of CWD pieces consisted of hardwood species.

A QA/QC dataset sampled during the 2009–2010 field seasons was used as a further evaluation of the matching algorithm's performance. A subset of 30 DWM plots across northern US states was randomly selected for immediate remeasurement of CWD following measurement by a FIA production field crew (for more QA/QC details please see Westfall and Woodall, 2007). Two hundred and 27 CWD pieces were remeasured during this QA/QC exercise. As these pieces were measured temporally as close as possible to the first measurement by expert field crews, one would expect minimal effects of decay and site disturbance on matching algorithm results.

2.2. Matching algorithm

Westfall and Woodall (2007) developed an initial matching algorithm that required subjective assessment by inventory analysts to resolve matching issues (e.g., one to many matches). Due to this experience and the need to explicitly examine a matching algorithm in detail, this study sought to create a new matching process independent of Westfall and Woodall's (2007) previous study. The matching algorithm in this study is intended as a basic, initial exploration based on fundamental CWD metrics (e.g., decay class and size) and FIA's sampling strategies (e.g., LIS). The intent is to match a CWD pieces sampled along a transect at time one (T_1) with potential CWD pieces sampled along the same transect in time two (T_2). The effects of decay and measurement error are incorporated into components of the algorithm. The first step in the algorithm (Fig. 3) is to align the plot, sub plot, and transect data at each time period such that the CWD records assessed in the matching algorithm were sampled on same transect but at two time periods. Along that transect, the algorithm identifies all T_2 pieces within 0.3 m of a T_1 piece location. The QA/QC standards for CWD piece measurement allow for a 0.3 m tolerance on CWD transect location repeatability (Westfall and Woodall, 2007). The second step in the algorithm is to use individual CWD piece metrics to rank matches from ideal to non-matched. Ideal matches are CWD pieces at T_2 that are not only in the same spatial location as T_1, but also ideally match the individual metrics of T_1 pieces. An ideal match will have a T_2 transect diameter ±34% of the T_1 transect diameter (the percentage of the measurement precision [2.54 cm] divided by the minimum CWD diameter [7.62 cm]), a T_2 large-end diameter $\leqslant$ of the T_1 large-end diameter, a T_2 decay class $\geqslant$ the T_1 decay class, and a T_2 length $\leqslant$ the T_1 length. The T_2 transect diameter is allowed to be larger than the T_1 diameter as this diameter is measured at the point of intersection with a sampling transect. If field crews are "off" by only a few degrees of a sampling transect's orientation then the transect diameter might be located at a different location along the CWD piece length (i.e., different transect diameter). In contrast, the large-end diameter attribute is not affected by errors in transect installation. After the matching algorithm determines "ideal" matches, a next step is necessary to identify many "potential" matches and develop an objective process for winnowing those matches. Given the many possible matches where inherent measurement error could result in the CWD piece metrics being only slightly outside ideal matching situations (e.g., T_2 length 0.5 m larger than T_1), a matching index is a final step in the matching algorithm to winnow the many possible matches. In addition, a matching index provides an objective

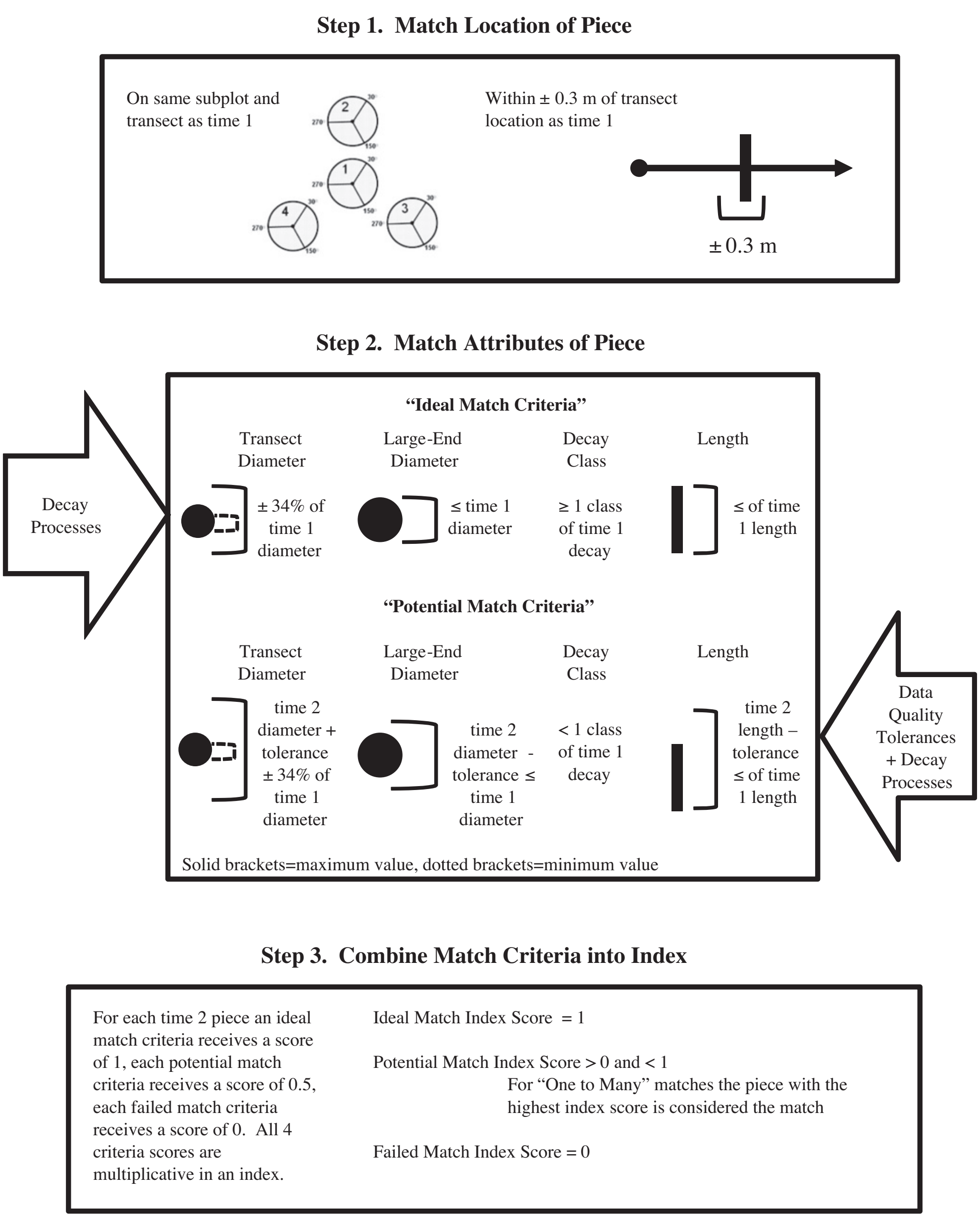

Fig. 3. Graphical illustration of the coarse woody debris matching algorithm for application with line intersect sampling.

Table 2
Counts, percent of total observations (including matched and unmatched), and lower/upper 95% confidence intervals (CI; lower, upper) of CWD pieces that were matched at T_1 and T_2 by classes by individual piece attributes at T_1 (decay class, transect diameter class, length class, and species group).

T_1 attribute	Classes	Match statistics		
		Count	Percent	CI
Decay class	1	317	41.8	38.3, 45.4
	2	891	38.7	36.7, 40.7
	3	1584	36.8	35.4, 38.3
	4	739	27.0	25.4, 28.7
	5	50	8.3	6.2, 10.8
Transect diameter (cm)	7.62–17.62	2284	29.5	28.4, 30.5
	17.63–27.62	996	44.8	42.7, 46.9
	27.63–37.62	227	42.0	37.8, 46.2
	37.63–47.62	52	42.3	33.4, 51.5
	47.63–57.62	15	50.0	31.3, 68.7
	>57.63	7	29.2	12.6, 51.1
Length (m)	0.91–3.91	973	20.5	19.4, 21.7
	3.92–6.91	1152	40.1	38.3, 41.9
	6.92–9.91	714	45.3	42.8, 47.8
	9.92–12.91	407	49.7	46.2, 53.2
	12.92–15.91	184	50.8	45.6, 56.1
	>15.91	151	45.6	40.2, 51.2
Species group	Softwood	1119	40.3	38.5, 42.2
	Hardwood	2074	33.8	32.6, 35.0
	Unknown	338	28.6	26.1, 31.3
	NA*	50	8.3	6.2, 10.8

* Species is not identified for decay class 5 pieces.

way to pick one match from a list of "one to many" CWD matches. In the matching index not only do all pieces need to be spatially aligned, but they also receive four scores for each of four matching metrics. Each piece receives a score of "1" when it falls within the earlier prescribed matching metrics (e.g., T_2 decay class $\geqslant$ the T_1 decay class). Each piece receives a score of "0.5" for each match where measurement error tolerance (Westfall and Woodall, 2007) needs to be incorporated to achieve a match. All scores of the four metrics are combined multiplicatively in an index such that failure in any one of the metrics will result in an index score of "0". If any CWD piece has an index score of "0" it is considered to have no match across the measurement interval. In contrast, CWD pieces that were considered matched across time have index scores greater than "0" ranging from 0.0625 to 1.0000. If a CWD piece has multiple matches, the match with the highest index score is selected. Thus, the algorithm is constructed such that spatial location and individual metrics as affected by measurement error and decay are incorporated into an index where most CWD matching situations can be objectively resolved.

2.3. Analysis

In order to test the CWD matching algorithm, the counts, percent of total observations and confidence interval of matches was determined by T_1 CWD piece attributes (decay class, transect diameters, length, and species group). To further test the influence of climate and disturbances on the algorithm, the counts, percent of

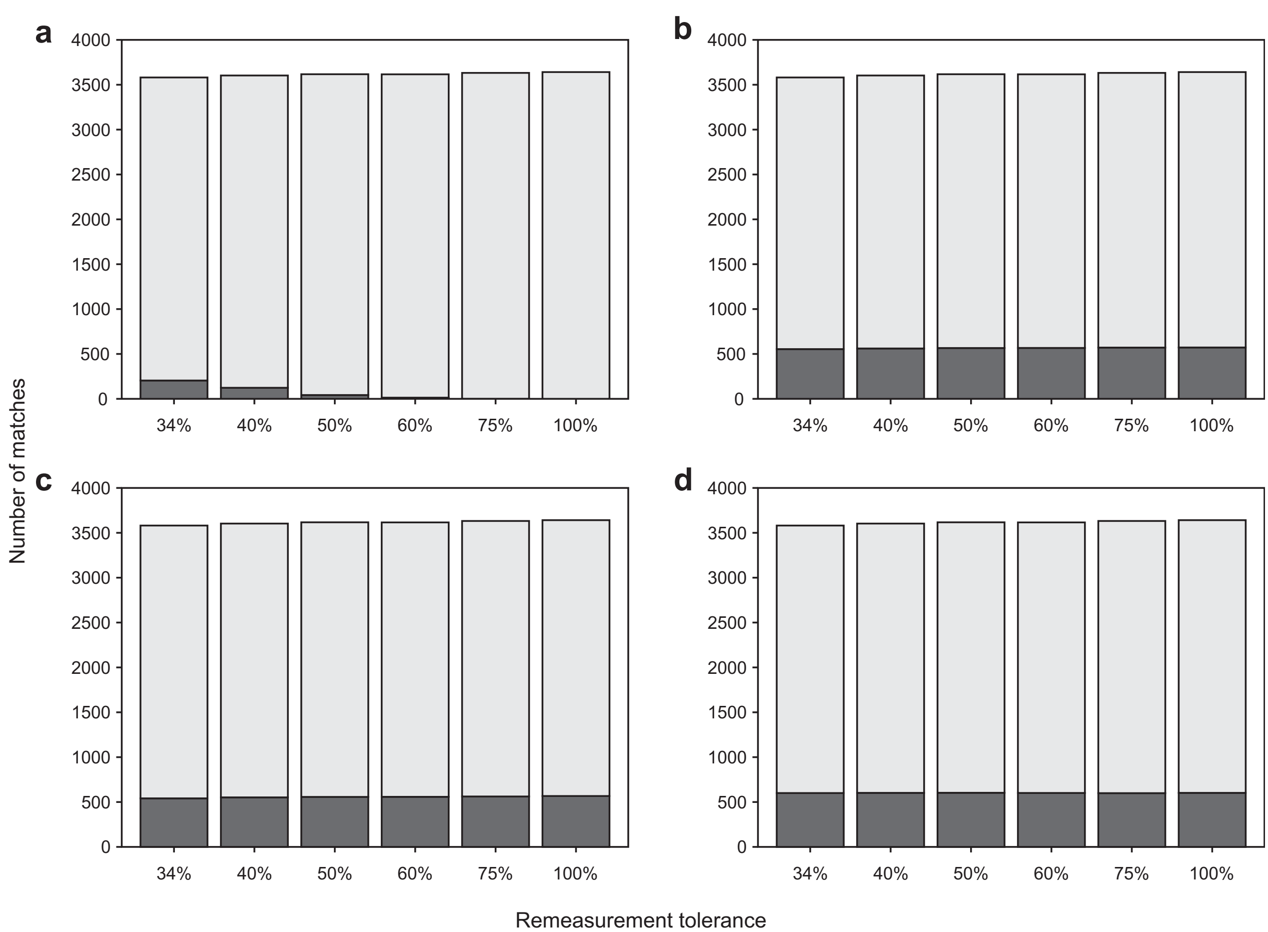

Fig. 4. Performance of the coarse woody debris matching algorithm as affected by adjustment in allowable measurement tolerances (i.e., allowable measurement error) by coarse woody debris metrics: (a) transect diameter, (b) decay class, (c) large-end diameter, and (d) length. Light grey bars are matching index scores of "1" while dark grey bars are matching index scores of "0.5".

total observations and confidence interval of CWD matches were examined by classes of average annual maximum/minimum temperature, average annual precipitation (PRISM, 2006), water disturbances on plot (water on plot codes; Woudenberg et al., 2010), and forest type groups at T_2. Finally, in an attempt to assess the potential influence of decay and site disturbance on the matching algorithm, the matching algorithm was used to match a QA/QC dataset of blindly remeasured DWM plots (i.e., expert field crew) to the production plot measurements. To assess the precision for match percentages within attribute classes, exact binomial 95% confidence intervals (Balakrishnan and Nevzorov, 2003) for the percentage of matched observations were computed for all match analyses in this study.

3. Results

The number, percent, and confidence interval of CWD pieces matched across time were examined by individual piece attributes at T_1 (Table 2). By decay class, the highest percentage of matched pieces was 41.8% for decay class one. The percentage decreased sequentially to decay class five where only 8.3% of pieces could be matched to T_2. Concomitant with the matching of highly decayed pieces at T_1, decay class one pieces at T_2 only had a match rate of 2.6%. By transect diameter, the match percentages were lowest for the smallest and largest T_1 size classes (29.5% and 29.2%, respectively). Intermediate transect classes (17.63–57.62 cm) had the highest matches rates between 40% and 50%. By length classes, the match percentages were lowest for the shortest CWD pieces (20.5%) at T_1 but increased sequentially up to a maximum 50.8% match rate for pieces with a length between 12.92 and 15.91 m. By species group at T_1, the highest match percentage was 40.3% for softwoods which decreased sequentially to hardwoods, unknown, and not measured (i.e., decay class five pieces) (33.8%, 28.6%, and 8.3%, respectively).

The matching algorithm was largely insensitive to adjustments in measurement tolerances. When the transect diameter tolerance was adjusted from 34% upward to 100% (i.e. T_2 transect diameter allowed to be double T_1), only a few dozen more matches were identified in addition to the nearly 3500 pieces already matched by the algorithm (Fig. 4a). Adjustments to measurement tolerances (i.e., QA/QC metrics) of other CWD individual piece attributes (e.g., length) used in the study had even less of an effect on match rates (Fig. 4b–d).

The CWD match statistics (e.g., counts) were examined by site attributes at T_1 (Table 3). Match percentages largely decreased with increasing maximum and minimum average annual temperatures. The highest match rates in the coldest climates (average minimum below −1 C and average maximum below 10.7 C) were approximately 36% compared to warmer climates at the other extreme (average minimum above 9.9 C and average maximum above 22.3 C) which had match rates of 20.7%. Match percentages demonstrated no clear trend across classes of annual precipitation ranging from 30.8% to 35.4%. Forest inventory field crews indicate the state of water (i.e., flood disturbances) on forest plots during plot measurement. Match percentages had no clear trend among water on plot codes, the strong exception being in flood zones where match rates only achieved 13.9%. Match percentages by

Table 3
Counts, percent of total observations (including matched and unmatched), and lower/upper 95% confidence intervals (CI; lower, upper) of all matched CWD pieces by classes of maximum/minimum average annual temperature (degrees Celsius), average annual precipitation (mm), water on sample plot codes, and forest type group at T_2.

Attribute	Classes	Counts	Percent	CI
Average annual minimum temperature (C°)	<−1.233	950	35.0	33.2, 36.8
	−1.233–2.486	1121	36.0	34.3, 37.7
	2.487–6.204	850	34.1	32.2, 36.0
	6.205–9.922	558	29.6	27.6, 31.7
	>9.922	102	20.7	17.2, 24.5
Average annual maximum temperature (C°)	<10.697	910	35.0	33.2, 36.9
	10.697–14.562	1299	35.7	34.1, 37.2
	14.563–18.428	627	34.2	32.0, 36.4
	18.429–22.294	612	31.0	28.9, 33.0
	>22.294	133	20.7	17.6, 24.0
Average annual precipitation (mm)	<828.5	672	34.3	32.2, 36.4
	828.5–1142.5	1621	35.4	34.0, 36.8
	1142.6–1456.5	1146	31.0	29.5, 32.5
	1456.6–1770.6	128	30.8	26.4, 35.5
	>1770.6	14	35.0	20.6, 51.7
Water on inventory plot codes	None	2773	33.5	32.5, 34.6
	Small permanent streams	195	35.1	31.2, 39.3
	Permanent bogs/swamps	217	38.1	34.1, 42.2
	Ditch/canal	13	46.4	27.5, 66.1
	Temporary stream	220	31.6	28.1, 35.2
	Flood zone	29	13.9	9.5, 19.4
	Other temporary water	134	36.2	31.3, 41.3
Forest type groups	White/red/jack pine	113	37.9	32.4, 43.7
	Spruce/fir	459	39.0	36.2, 41.9
	Longleaf/slash pine	4	19.0	5.4, 41.9
	Loblolly/shortleaf pine	67	23.4	18.6, 28.8
	Other eastern softwoods	2	14.3	1.8, 42.8
	Exotic softwoods	10	41.7	22.1, 63.4
	Oak/pine	172	34.9	30.7, 39.3
	Oak/hickory	1243	33.0	31.5, 34.5
	Oak/gum/cypress	34	15.9	11.3, 21.5
	Elm/ash/cottonwood	114	22.9	19.3, 26.9
	Maple/beech/birch	1049	38.9	37.1, 40.8
	Aspen/birch	335	32.5	29.7, 35.5
	Other hardwoods	40	36.0	27.1, 45.7
	Exotic hardwoods	3	37.5	8.5, 75.5
	Nonstocked	4	10.3	2.9, 24.2

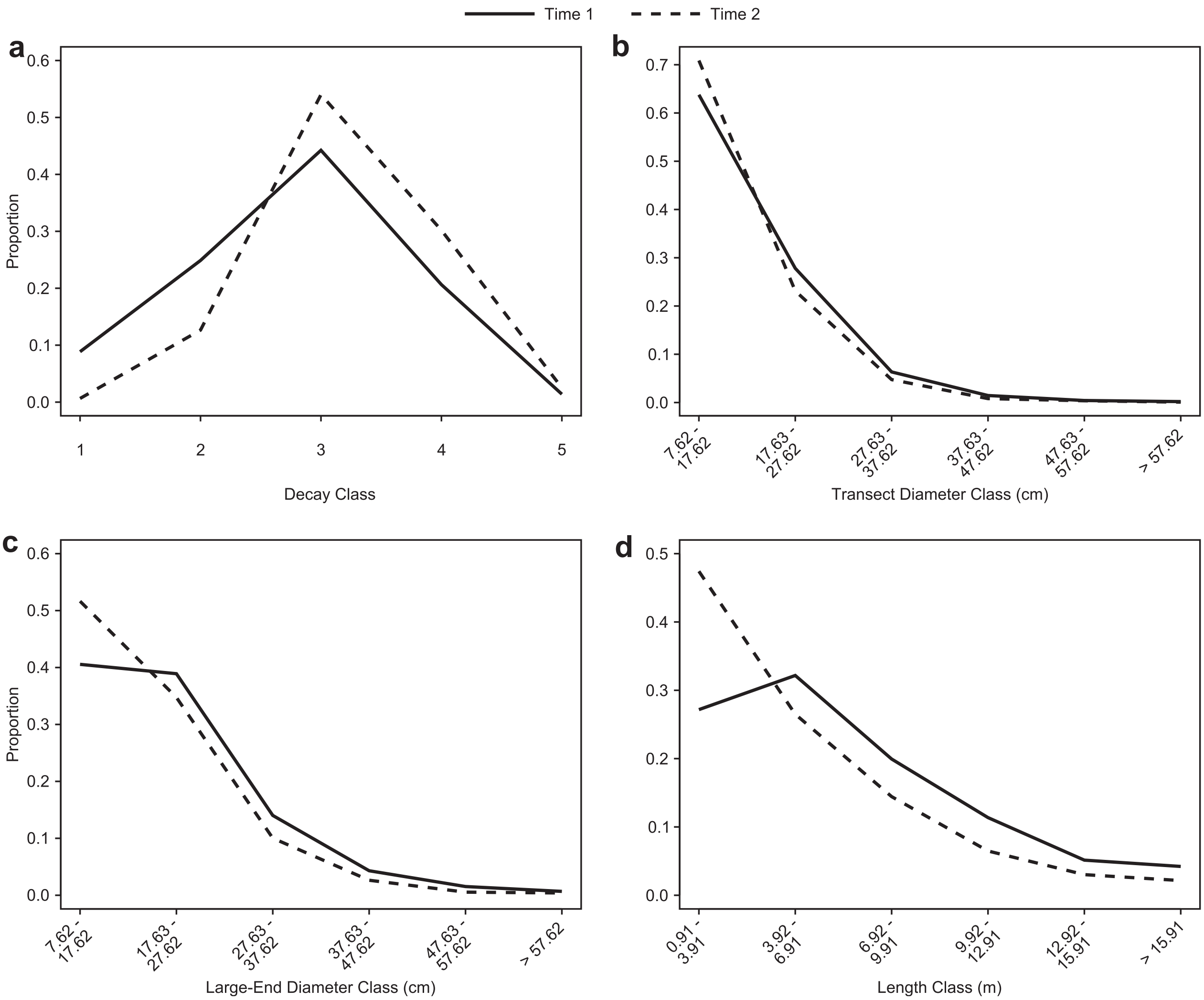

Fig. 5. Attributes of matched coarse woody debris pieces from time one (solid line) to time two (dotted line) by classes of: (a) decay, (b) transect diameter, (c) large-end diameter, and (d) length.

forest type groups had no clear trends. If forest types with small sample sizes are omitted (<100 matches), then the highest match rates are among forest types at the highest latitudes (39.0% and 38.9% for spruce/fir and maple/beech/birch, respectively) in contrast to forest types largely found at lower latitudes (22.9% for elm/ash/cottonwood).

The change in piece attributes for only matched pieces demonstrated trends one would expect given the decay of CWD pieces over time (Fig. 5a–d). The percent of pieces in decay class one dropped from approximately 10% at T_1 to nearly 0% at T_2. There was an even greater drop in decay class two pieces, from nearly 25% at T_1 to 11% at T_2. The trend reversed when advanced stages of decay were reached, with decay classes three, four, and five representing an increasing proportion of matched pieces at T_2 compared to T_1. There were no substantial shifts in transect diameter between T_1 and T_2 among matched CWD pieces. The proportion of T_2 pieces in smallest large-end diameter class (7.62–17.62 cm) increased approximately 10% from T_1 to T_2. The percentages in the larger large-end diameter classes were roughly similar across time for the matched pieces. A similar trend was found for percentages of matched pieces in length classes. The percentage of pieces in the smallest length class (0.91–3.91 m) increased from approximately 30–50%, while the percentages of T_2 pieces in longer length classes were all less than the pieces at T_1.

The matching algorithm attained higher match percentages when the QA/QC dataset was matched to field production measurements. As these two measurements occur temporally close together during the same field season, one would expect a diminished influence of decay with levels of non-matched pieces owed to measurement error. With the QA/QC expert field crew considered equivalent to T_1 measurement within the matching algorithm, a total match rate of approximately 74% was achieved (Table 4). The highest match rates (sometimes approaching 90%) were for CWD pieces that were moderately decayed and of moderate length. The lowest match rates were for highly decayed, small-sized CWD pieces. Examination of individual pieces in this particular exercise indicated that most of the unmatched pieces were due to discrepancies among "in" counts of CWD pieces. This was attributed to errors in transect installation and typos such as those documented in Westfall and Woodall (2007).

4. Discussion

Given the tremendous effort invested in sampling thousands of CWD transects across the US for the purpose of monitoring populations of CWD (Woodall and Monleon, 2008), an algorithm that enables tracking individual CWD pieces across time deserves investigation. Using an initial CWD piece matching algorithm

Table 4
The counts, percent of total observations (including matched and unmatched), and lower/upper 95% confidence intervals (CI; lower, upper) of matches by classes of individual piece attributes (decay class, transect diameter class, length class, and species group) at T_1 using a quality analysis/quality control blind remeasurement dataset where an "expert" field crew measurement (i.e., T_1) is matched with production field crew measurements (i.e., T_2) using this study's matching algorithm.

T_1 attribute	Classes	Match statistics		
		Count	Percent	CI
Decay class	1	12	70.6	44.0, 89.7
	2	54	76.1	64.5, 85.4
	3	91	77.1	68.5, 84.3
	4	10	55.6	30.8, 78.5
	5	2	50.0	6.8, 93.2
Transect diameter (cm)	7.62–17.62	129	72.9	65.7, 79.3
	17.63–27.62	29	78.4	61.8, 90.2
	27.63–37.62	8	72.7	39.0, 94.0
	37.63–47.62	3	100.0	29.2, 100.0
	47.63–57.62	–	–	–
	>57.63	–	–	–
Length (m)	0.91–3.91	61	62.2	51.9, 71.8
	3.92–6.91	49	80.3	68.2, 89.4
	6.92–9.91	30	83.3	67.2, 93.6
	9.92–12.91	17	89.5	66.9, 98.7
	12.92–15.91	4	66.7	22.3, 95.7
	>15.91	8	100.0	63.1,100.0
Species group	Softwood	37	75.5	61.1, 86.7
	Hardwood	129	74.1	67.0, 80.5
	Unknown	1	100.0	2.5, 100.0
	NA*	2	50.0	6.8, 93.2

* Species is not identified for decay class 5 pieces.

Table 5
Case study examples of individual pieces with T_1 and T_2 matches.

Match decision	Index score	Slope distance (m)		Transect diameter (cm)		Large-end diameter (cm)		Length (m)		Decay class	
		T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2
1	1	4.7	4.6	50.8	43.2	55.9	45.7	12.8	11.6	3	3
	1	6.4	6.4	20.3	17.8	25.4	20.3	6.7	2.1	3	4
2	1	4.7	0.3	50.8	20.3	50.8	22.9	4.7	14.0	3	3
	0.25	4.7	0.6	50.8	10.2	50.8	27.9	4.7	14.6	3	3
3	0.5	1.8	1.8	17.8	10.2	17.8	15.2	7.0	3.0	4	4
	0.5	5.3	5.4	22.9	17.8	22.9	17.8	7.6	7.3	3	2
	0.5	0.2	0.2	12.7	10.2	27.9	30.5	12.2	11.0	2	3
	0.5	4.9	4.9	12.7	10.2	15.2	15.2	4.3	5.5	3	4
	0.25	1.7	1.6	12.7	12.7	15.2	17.8	5.2	5.5	1	2
	0.125	5.7	5.8	40.6	25.4	40.6	27.9	14.3	14.9	4	3
4	0	4.9	5.2	10.2	25.4	10.2	27.9	3.7	9.1	4	4

Match decision key: (1) Matched: ideal match with all CWD metrics within defined ranges, (2) Matched: one to many match…piece pair with the highest index score selected as match, (3) Matched: incorporation of measurement error needed to meet match metrics, (4) Not matched: Length and diameter measurements far exceed match metrics.

compatible with LIS, thousands of potentially matched CWD pieces were identified across the eastern US. The application of this algorithm offers the potential to inform CWD dynamics if appropriately applied in situations where a subset of potential matches over time is needed to inform CWD dynamics research. It should be strongly noted that the algorithm should not be used within "stock change" C/biomass accounting approaches. The algorithm does not achieve match rates high enough to impart confidence for such an application. The algorithm itself is an initial foray into using LIS-derived CWD information beyond the intentions of the sample design. However, application/refinement of this study's algorithm in the context of assessing CWD dynamics (e.g., decomposition) is warranted.

If indeed sets of matched CWD pieces are used in studies of CWD dynamics can sources of potential bias be suggested? Measurement error certainly plays a role in the algorithm's performance. The matching of QA/QC data (remeasurement period of a few weeks) indicated that the algorithm could attain match percentages well above 70% with the remainder attributed largely to measurement error. With measurement error possibly removing a third of matched observations, the remainder of matches must inherently be reduced by decay/disturbance effects. The algorithm achieved match percentages roughly between 30% and 40% across a remeasurement interval of 5 years in forests of the eastern US. The matching algorithm had poor match rates (<30%) for pieces that were highly decayed, of a small size at T_1, and/or in a warm climate. Conversely, higher match rates (>40%) were achieved for pieces that were minimally decayed, large in size, and/or in cold climates. Whereas live trees will grow with concomitant in- and on-growth within fixed radius inventory plots, CWD will decay, combust, or be washed away such that a small and highly decayed CWD piece at T_1 will likely not be a member of the CWD population at T_2 nor sampled along a CWD transect. As evidence of the influence of disturbance, the matching algorithm had the poorest performance in flood prone sites. Given the demonstrated effect of decay and disturbance, the potential influence of these detrital ecosystem processes should be acknowledged when using this study's algorithm.

As there is no "truth" against which this algorithm can be objectively compared to, the evaluation of the algorithm's performance is unfortunately subjective. For some CWD pieces, positive matches at T_2 can be very obvious. Such matches may be large CWD pieces in the exact same location with nearly the same attributes (with decay adjustment) upon remeasurement (Table 5). Decay will slightly decrease the size metrics while slightly increasing the stage of decay. Other matches can be more problematic. There are cases of "one to many" matches where there will be more than one CWD piece at nearly same location as the T_1 or T_2 pieces (Table 5). An index aided with resolution of these situations in this study. The potential effect of measurement error was also highlighted in this study. A number of matches were pieces in the same location over time, but with slight increases in diameter or length. Incorporation of QA/QC measurement tolerances (Westfall and Woodall, 2007) was an important component of the matching algorithm. Although varying field personnel across a 5 year measurement interval certainly increases variance in sampling of CWD pieces, field crew biases were not evident in this study nor in another study by Ringvall and Ståhl (1999). The circumstance remains that if a CWD piece is found at almost the exact same location as T_1 with nearly the same attributes as T_1 minus decay effects and measurement errors, then it is probably the same piece. The insensitivity of the algorithm to adjustments to QA/QC tolerances is suggestive that there were not many alternative matches for T_1 pieces. An objective manner to determine confidence in matches is the greatest hurdle in application of such an algorithm. Even with a perfectly performing LIS matching algorithm the fact remains that CWD pieces will be removed (e.g., flood or harvest utilization) across time such that T_1 pieces cannot be matched to anything at T_2. Depending on unique stand/site attributes, sets of matched CWD pieces may be dominated with larger pieces in non-industrial forest land conditions (i.e., more likely to be matched and not salvaged/utilized), while it may be dominated with smaller/moderately decayed pieces in industrial timberland conditions (i.e., larger pieces salvaged/utilized). At large scales, such as those used in this study, the number of potential biases should be diminished leaving the lack of highly decayed and small sized CWD pieces as the obvious bias at large-scales.

Given the performance of this study's CWD matching algorithm for use with remeasured LIS transects, perhaps the optimal sampling strategy for monitoring individual CWD pieces over time is permanently marking pieces within fixed-radius plots such that the exact same CWD piece can be remeasured. Given the measurement errors associated with relocating CWD pieces along sample transects, the strength of LIS monitoring strategies lies in rapid CWD assessment, not in detailed tracking of CWD over time. Even alternative CWD sampling strategies such as line intersect distance sampling (Affleck, 2008), critical length sampling (Stahl et al., 2010), or perpendicular distance sampling (Williams and Gove, 2003) do not typically tag individual CWD pieces and maybe subject to the same matching algorithm issues as found with LIS. As this study's algorithm did not achieve a match rate over 50% for any eastern US forest type, it should not be used to track distinct CWD populations over time. The optimal application of LIS is within C stock change assessments where LIS may efficiently provide estimates of CWD C stocks at time one and two with differences as an estimate of sequestration/emission rates (Woodall, 2010). However, given the cost of establishing permanent CWD inventory plots across the US coupled with detailed CWD tagging (especially problematic with highly decayed pieces), the LIS matching algorithm may provide a reasonably objective and cost-effective method for identifying a set of remeasured CWD pieces for further evaluation of CWD dynamics. The matching algorithm in turn could be improved by perhaps incorporating the effect of CWD decay. As the influence of decay on CWD piece metrics was assumed to be linear (e.g., decay class three to decay class 4 over 5 years), incorporation of refined CWD decay models may impart a higher level of confidence to matches.

5. Conclusions

The optimal sampling strategy for tracking individual pieces of CWD over time, and thus informing CWD dynamics research, is the tagging of individual pieces with sampling strategies that reduce relocation errors (e.g., fixed area sampling). However, given the cost of maintaining such plots at the national-scale with adequate sample intensity to inform management decisions, the CWD matching algorithm developed in this study for use with LIS offers a plausible alternative. Although a LIS CWD matching algorithm may only be used to identify sets of matched pieces for subsequent CWD dynamics research, it allows use of widely sampled data to perhaps inform questions regarding the decay dynamics of CWD. The inherent bias of such an algorithm to match pieces that were not subjected to rapid decay nor disturbance (e.g., harvest or combustion) may be alleviated with future research into models of CWD decay and incorporation of individual site/stand attributes.

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