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Measurement repeatability of a large-scale inventory of forest fuels

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Abstract

An efficient and accurate inventory of forest fuels at large scales is critical for assessment of forest fire hazards across landscapes. The Forest Inventory and Analysis (FIA) program of the USDA Forest Service conducts a national inventory of fuels along with blind remeasurement of a portion of inventory plots to monitor and improve data quality. The goal of this study was to evaluate the measurement repeatability/biases of FIA's national inventory of fuels and suggest opportunities for improving data quality and application of sampling protocols. Results indicated that more than half of the attributes did not attain the desired levels of repeatability and about one-third exhibited a non-zero measurement bias. However, the bias generally had little affect on plot-level estimates. A number of factors that contributed to these results were examined and a holistic approach that considers all aspects of inventory was suggested to improve measurement repeatability.
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Keywords: Fuels inventory; Data quality; Measurement bias; Down woody material; Forest fire; Forest biomass

1. Introduction

Forest fuels may be described as combustible material in forest ecosystems typically comprised of both dead and living plant material (Burgan and Rothermel, 1984). Assessments of forest fuels are essential to many forest stand (e.g., slash treatments, see Hardy, 1996) and forest fire (e.g., wildfire containment) management activities (Rothermel, 1972). The forest fuels of dead and down woody materials, duff/litter, and shrub/herbs are important variables in many forest fire behavior models (for examples see Albini, 1976; Burgan and Rothermel, 1984; Finney, 1998; Reinhardt et al., 1997; Rothermel, 1972). As such, these variables are often assessed at various scales to aid with both forest and fire management activities. Less precise information may be acquired by rapid visual estimates using photo guides (Scott and Reinhardt, 2005), whereas more detailed data can be obtained through inventories using formal measurement protocols (Woodall, 2003; Woodall and Williams, 2005). Regardless of scale, high-quality measurement of forest fuel variables is critical for successful forest management activities.

Due to the intense fire seasons experienced in recent years, there is increasing interest in the inventorying of forest fuels at large scales in the United States (for example see Rollins et al., 2004). Even in other countries, the increasing data needs of international agreements such as the carbon reporting requirements of the International Panel on climate change have increased large-scale dead woody material inventory activity (for examples see Woldendorp et al., 2002; Kukuev et al., 1997; Fridman and Walheim, 2000). Unfortunately, there has been a lack of a concomitant increase in measurement repeatability assessment to maintain statistical control given the increased effort to inventory forest fuels. Measurements that are not consistently reproducible may introduce bias and additional error, which negatively affect the reliability of the estimates (Pollard et al., 2006).

The goal of this study is to assess repeatability of a national-scale inventory of forest fuels with specific objectives being:

(1) to determine the mean difference in paired fuel measurements based on blind remeasurement data,
(2) to determine adherence of blind remeasurement results to measurement quality objectives (MQO) established by the Forest Inventory and Analysis (FIA) program of the USDA Forest Service, and
(3) to suggest improvements for increased measurement repeatability of large-scale fuel inventories.

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2. Methods

2.1. Field data collection

The FIA program is responsible for inventorying the forests of the United States, including both standing trees and fuels on permanent sample plots established across the United States using a three phase inventory (Bechtold and Patterson, 2005). During the inventory's second 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 location and measure tree and site variables on plots that consist of four 7.32 m fixed radius subplots for a total plot area of approximately 0.07 ha (Fig. 1). All standing trees greater than 12.7 cm diameter at breast height (dbh) are inventoried on the plot, while trees less than 12.7 cm dbh are measured on a 2.07 m fixed radius microplot on each subplot. During FIA's third phase, 1 of every 16 phase 2 plots is sampled for fuel variables including coarse woody debris (CWD), fine woody debris (FWD), duff, litter, and the fuel ladders of shrubs/herbs. It should be noted that the measurement repeatability of variables measured during the second phase of the inventory, such as standing dead trees, were analyzed by Pollard et al. (2006).

Fuel sampling methods for FIA's third phase are detailed by Woodall and Williams (2005) and USDA (2005). 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 1.3 m. CWD, otherwise termed 1000+-h fuels, 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° (Fig. 1). Data collected for every CWD piece includes transect diameter, length, small-end diameter, large-end diameter, decay class, and species. FWD (1, 10, and 100 h fuels) are sampled on the 150° transect on each subplot. FWD with transect diameters less than 0.61 cm and 0.62–2.54 cm (1 and 10 h fuels, respectively) are tallied separately on a 1.83 m slope distance transect (4.27–6.09 m on the 150° transect). FWD with transect diameters of 2.55–7.59 cm (100 h fuels) are tallied on a 3.05 m slope-distance transect (4.27–7.32 m on the 150° transect). For more information on fuel class definitions, see Deeming et al. (1977).

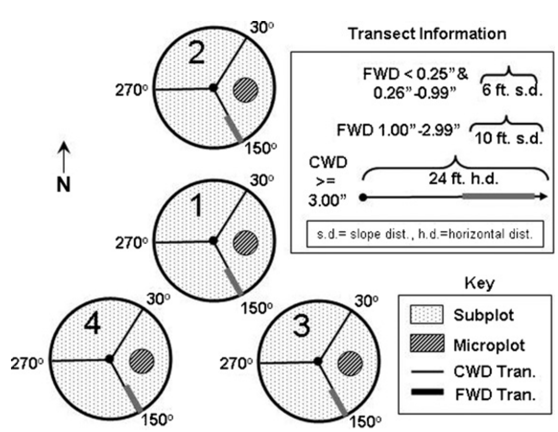

Fig. 1. Sampling design for the down woody materials indicator of the USDA Forest Service Forest Inventory and Analysis program. Distance between subplots (2–4) and subplot center (1): 36.6 m at angles (°) 0, 120, and 240 respectively. Distance between subplot center and microplot center: 3.66 m; shrubs/herbs sampled on microplot. Duff/litter sampled at 7.3 m slope distance on each CWD transect.

The FIA program defines duff as an organic forest floor layer consisting of decomposing leaves and other organic material. Individual plant parts should not be recognizable in the duff layer. Litter is defined as a forest floor layer of freshly fallen leaves, needles, twigs, cones, bark chunks, dead moss, dead lichens, dead herbaceous stems, and flower parts. The depth of duff and litter is measured at 12 locations (7.32 m slope-distance on each CWD transect) (Fig. 1). If a log or other large obstruction (e.g., boulder or slash pile) is present at the duff/litter sample location then no measurements are taken.

The FIA program samples five fuel ladder components: dead herbs, live herbs, dead shrubs, live shrubs, and litter coverage. Within each microplot, the cover and maximum height of each shrub/herb component is recorded. Shrubs are characterized as herbaceous plants with woody stems. Herbs are defined as nonwoody herbaceous plants, but also include ferns, moss, lichens, sedges, and grasses. The cover from 0 to 100% in 10% classes is ocularly estimated for each of the five fuel categories. The tallest height of all fuel categories (excluding litter) is estimated within the microplot.

Measurement repeatability is defined in terms of a tolerance and measurement quality objective (MQO). The tolerance defines the acceptable range of differences between independent measurements (e.g., ±7.62 cm for CWD diameter). The MQO is the acceptable proportion of differences that are within the tolerance (e.g., 90% of the time for CWD diameter). For the CWD diameter example, the data quality goal is achieved if 90% or more of the measurement differences are within ±7.62 cm. For more detail regarding the repeatability standards see the FIA field guide (USDA, 2005).

2.2. Data

The data used for these analyses are based on 139 FIA phase three inventory plots across the U.S. that were randomly chosen for QA inspection over the period 2002–2005. There are two sets of data from these 139 plots. The first set of observations was collected by the production crew during the regular inventory visits. The second set of data is from 'blind check' remeasurement of these plots by an independent field crew (QA crew) shortly after the production inventory measurement. The QA crew had no knowledge of the results of the original measurements—thus the term 'blind check'.

2.3. Analysis

Observations from the production crew and QA crew were matched in order to determine measurement repeatability and bias. All fuel variable measurements, except for CWD, could be matched based on the unique identifiers of microplot, transect, subplot, plot, and state; or some combination thereof. CWD measurements differ from all other fuel attributes in that individual pieces are identified and measured along each transect. Thus, the pieces measured by each crew need to be matched together in order to compute measurement differences. A matching algorithm was developed that used the location on the transect and size of each piece of CWD to determine appropriate pairings of data from the independent measurements. The process was designed to be conservative and only match pieces where the location and size attributes were in fairly close agreement. As such, there were a number of unmatched pieces remaining. These pieces were individually evaluated and either added to the matched data or set aside as extra pieces. The extra pieces were only used in comparisons of plot counts of CWD. This procedure was similar to that developed by Pollard et al. (2006) to match standing trees on FIA plots.

For MQO analyses of each DWM attribute, the distribution of the absolute differences was generated by pooling data from all QA plots nationwide. It is straightforward to determine the percentage of observations falling within the range of the tolerance level specified by the FIA program. Assuming that each absolute difference between crew measurements has equal probability of being within tolerance, exact binomial 95% confidence intervals are also provided (Balakrishnan and Nevzorov, 2003). To assess the adequacy of repeatability for each variable, these intervals are compared to the MQO. If the interval includes or is greater than the MQO, measurement repeatability is deemed acceptable. Measurement bias was assessed for each variable by computing the mean difference between crews. A statistically significant bias is indicated when the 95% confidence interval (assuming a *t*-distribution) does not include zero.

In order to evaluate the effects of measurement variability on overall plot-level estimate variability, the total plot level values for CWD, FWD, duff, and litter (tonnes/ha) were calculated for production and QA crews for each study plot (for estimation procedures see Woodall and Williams, 2005). The minimum, median, maximum, mean, standard deviation, and *p*-values (from *t*-distribution) were determined for the differences (QA plot estimate − production plot estimate) between plot-level estimates.

3. Results

3.1. Repeatability

Across the suite of measurement variables that comprise the fuels inventory of the FIA program, 15 of the 27 variables did not attain the desired repeatability levels. The upper point of the 95% confidence interval for these variables was less than specified MQO (Table 1). In the reporting of results, the percentages of observations within tolerance are followed with the upper value of the associated confidence interval (e.g., for 82.5% within tolerance and a 95% confidence interval of 70.1–94.9% the result would be 82.5%; *94.9%*).

For CWD measurements, slope distance, species, and total length did not meet the desired repeatability levels. The percent

Table 1
Repeatability statistics for down woody material variables based on 139 quality assessment plots across the United States

Variable	Tolerance	MQO (%)	% Within tolerance	95% CI	Mean difference	95% CI	Records
CWD slope distance	±0.3 m	90	**80.5**	**77.2**, **83.6**	0.01	−0.07, 0.09	622
CWD decay class	±1 class	90	93.4	91.2, 95.2	−0.02	−0.08, 0.03	622
CWD species	No tolerance	80	**66.2**	**62.2**, **70.0**			589
CWD intersection diameter < 50.8 cm	±7.6 cm	90	98.5	97.2, 99.3	**−0.46**	**−0.66**, **−0.28**	607
CWD intersection diameter > 50.8 cm	±20%	90	93.3	68.1, 99.8	−3.73	−9.60, 2.13	15
CWD small diameter < 50.8 cm	±5.1 cm	90	94.9	92.7, 96.5	**−0.38**	**−0.58**, **−0.20**	583
CWD small diameter > 50.8 cm	±10%	90	80.0	28.4, 99.5	−8.63	−27.05, 9.78	5
CWD large diameter < 50.8 cm	±5.1 cm	90	90.5	87.8, 92.7	**−0.74**	**−1.02**, **−0.46**	577
CWD large diameter > 50.8 cm	±15%	90	72.7	39.0, 94.0	−4.17	−12.78, 4.47	11
CWD total length	±20%	90	**72.2**	**68.5**, **75.7**	**−0.27**	**−0.53**, **−0.01**	622
CWD hollow	No tolerance	90	97.2	95.6, 98.4			579
CWD history	No tolerance	90	88.4	85.6, 90.9			588
CWD total plot count	±2 pcs/5%	N/A	90.4	83.0, 95.3	**−0.38**	**−0.70**, **−0.06**	104
FWD small count	±20%[a]	90	**25.7**	**21.8**, **29.8**	**1.16**	**0.42**, **1.90**	483
FWD medium count	±20%	90	**36.6**	**32.3**, **41.1**	0.05	−0.16, 0.25	483
FWD large count	±20%	90	**57.1**	**52.6**, **61.6**	−0.07	−0.22, 0.08	483
Duff depth	±1.3 cm	90	**75.0**	**72.7**, **77.2**	**−0.41**	**−0.61**, **−0.20**	1433
Litter depth	±1.3 cm	90	**69.8**	**67.3**, **72.2**	**−0.15**	**−0.25**, **−0.05**	1433
Live shrub cover	±1 class	85	**66.2**	**62.0**, **70.2**	−0.20	−1.44, 1.04	541
Live shrub height	±0.15 m	90	**54.7**	**50.4**, **59.0**	0.02	−0.07, 0.11	541
Dead shrub cover	±1 class	85	93.0	90.5, 95.0	0.28	−0.13, 0.69	541
Dead shrub height	±0.15 m	90	**62.8**	**58.6**, **66.9**	**0.08**	**0.01**, **0.14**	541
Live herb cover	±1 class	85	**66.9**	**62.8**, **70.9**	0.39	−1.13, 1.91	541
Live herb height	±0.06 m	90	**38.8**	**34.7**, **43.1**	0.02	−0.00, 0.05	541
Dead herb cover	±1 class	85	85.4	82.1, 88.3	0.90	−0.06, 1.86	541
Dead herb height	±0.06 m	90	**52.7**	**48.4**, **57.0**	0.02	−0.01, 0.04	541
Litter cover	±1 class	85	**60.3**	**56.0**, **64.4**	**−6.93**	**−9.47**, **−4.39**	541

Instances where the MQO was not attained or a statistically significant bias exists are in bold.
[a] Tolerance is: ±20% when transect count is 0–50; ±25% when transect count is 51–100; ±50% when transect count is 100+.

Table 2
Comparison of differences between plot-level estimates (metric tonnes/ha) for various DWM attributes

Variable	Minimum	Median	Maximum	Mean	S.D.	Prob < |t|
Small FWD	−1.28	0.02	1.35	0.04	0.42	0.40
Medium FWD	−10.22	0.00	5.42	−0.09	1.88	0.62
Large FWD	−22.78	0.00	35.37	−0.59	5.54	0.29
CWD	−252.15	−0.20	87.22	−3.39	28.39	0.23
Duff	−677.35	−0.34	145.19	−12.40	76.25	0.11
Litter	−41.20	1.32	49.29	3.23	11.07	0.00
Total	−681.81	−0.36	148.49	−13.21	82.84	0.11

of observations within tolerance for slope distance (80.5%; *83.6%*) and total length (72.2%; *75.7%*) were lower than expected given the nature of these variables (i.e., distance measures). Although the percent agreement (66.2%; *70.0%*) on species identification is below the MQO (80%), the results are not particularly noteworthy given the various stages of decay that are encountered for CWD. The remaining CWD variables met the MQO, although the diameter measurements for pieces larger than 50.8 cm have relatively few observations. Counts for FWD were all below the specified MQO (90%), with repeatability levels being correlated with the size of the pieces in each category. Small, medium, and large size FWD attained repeatability statistics of (25.7%; *29.8%*), (36.6%; *41.1%*), and (57.1%; *61.6%*), respectively. Depth measurements for duff and litter also did not attain the desired MQO of 90%. The percent of measurements within the1.3 cm tolerance for duff (75.0%; *77.2%*) and litter (69.8%; *72.2%*) depth were of similar magnitude.

Live herb cover and live shrub cover had similar repeatability statistics (∼66%; *∼71%*), but the desired MQO of 85% was not realized. Dead herb cover and dead shrub cover both attained the 85% repeatability level. The differences between repeatability of cover estimates may depend on whether the vegetation was live or dead. The percentages of observations where both crews observed no dead cover were 45.1 and 33.5% for shrubs and herbs, respectively. Whereas the percent of records where both crews observed no live cover for shrubs and herbs was only 15.9 and 7.8%, respectively. Height measurement repeatability was somewhat better for dead vegetation when compared to live vegetation. However, none of the height variables achieved the specified MQO standard of 90% within tolerance. Live herb height showed the least consistency in measurement (38.8%; *43.1%*), while dead herb heights were more repeatable (52.7%; *57.0%*). Shrub heights showed better consistency than herb heights, with repeatability statistics of (54.7%; *59.0%*) and (62.8%; *66.9%*) for live shrubs and dead shrubs, respectively. Measurements of litter cover were (60.3%; *64.4%*) repeatable at the tolerance level of ± class, which did not attain the 85% MQO specification.

3.2. Bias

Measurement bias was evaluated by computing the mean difference and 95% confidence interval for all attributes except nominal categorical variables (Table 1). As an indicator that bias may exist is when the 95% confidence interval about the mean difference does not include zero. Although the magnitude of the mean difference was relatively small, a statistically significant bias was found for small (−0.38 cm), intersection (−0.46 cm), and large (−0.74 cm) CWD diameters less than 50.8 cm, CWD total length (−0.27 m), and CWD plot count (−0.38 pcs). The mean difference for each of these variables was negative, indicating the production crew tended to sample more pieces and record larger diameters and lengths than the QA crew.

Negative mean differences that were significantly different from zero were also noted for duff (−0.41 cm) and litter (−0.15 cm) depth measurements, as well as litter cover (−6.93%). Although the magnitude of the mean difference for litter cover seems large, this attribute is generally observed in 10% classes, so the mean difference is less than one measurement class. Variables where the QA crew tended to observe larger values than the production crew included counts of small FWD (1.16 pcs) and dead shrub heights (0.08 m).

The plot-level estimates of fuels between the production and QA crews were also assessed (Table 2). For the FWD variables, the distribution of differences was fairly well-balanced with magnitudes of minimum and maximum values being similar. More importantly, the mean differences were not significantly different from zero with *p*-values of 0.40 (small FWD), 0.62 (medium FWD), and 0.29 (large FWD). The distribution of differences for CWD and duff were skewed with more extreme negative values than positive values, resulting in considerable deviation between the median and the mean. Nonetheless, the mean differences were not significantly different from zero with *p*-values of 0.23 and 0.11 for CWD and duff, respectively. Differences between crews for plot-level summaries of litter tended to have more observations where the QA crew recorded more litter than the production crew. This resulted in a mean difference of 3.23 metric tonnes/ha, which was significantly different from zero (*p*-value = 0.004). The sum of total plot level CWD, FWD, duff, and litter provided an estimate of total down woody fuels for each plot. The mean difference (−13.21 metric tonnes/ha) for these totals was not significantly different between the production and QA crews (*p*-value = 0.11).

4. Discussion

The national-scale inventory of forest fuels demonstrated poor repeatability with instances of possible bias. Despite these findings, differences in measurements between production and

QA field crews did not translate into significant differences in plot-level estimates of forest fuels. Nonetheless, an examination of the potential causes of poor repeatability, impacts of bias, and corrective actions should be undertaken.

A host of factors may contribute to poor measurement repeatability. First, variables not attaining the MQO may be affected by the time lapse between production and QA field crew visits (e.g., small FWD, litter, and litter cover). Even though the QA crew remeasures the plot typically within 2 weeks of the production crew, weather events (e.g., thunderstorms) can have significant effect on fuels. This phenomenon may be reduced by scheduling the two independent plot measurements as closely as possible in time. Second, disturbance of the plot by the production crew is a major concern. An indicator that conditions along transects are being disturbed are the results for CWD slope distance since CWD pieces are readily identified along a transect. Our analysis shows that these distance measures were within ±0.3 m only about 80% of the time. Pollard et al. (2006) reported that repeatability of distances measures from plot center to tree locations for FIA's standing tree inventory to be roughly 95% repeatable at ±0.3 m or less. This suggests that significant disturbance along the transect may be occurring during the initial plot measurement. Third, a factor that is often overlooked when trying to maximize data quality is recording errors (recording the wrong numeral or misplacing a decimal point). Mistakes of this nature have the potential to bias population estimates. We found that plot-level estimates of CWD could be 50 times higher when recording errors were not corrected. Finally, difficulty in obtaining accurate measurements under field conditions is the most likely source of measurement variability. These difficulties are often variable-specific and are not easily overcome. For instance, accurate determination of species for a heavily decayed piece of CWD may be nearly impossible through visual inspection alone. Similarly, duff and litter depth measurements require determination of a point where these attributes begin and end. In many cases, there is a transition zone between mineral soil, duff, and litter. This subjective element adds uncertainty to the measurements.

Variables whose confidence intervals for the mean difference were not inclusive of zero were identified as potentially having measurement bias. Do these potential biases have a practical impact? The biases for the diameter of small CWD pieces (less than 50.8 cm) ranged from −0.38 to −0.74 cm. These diameters are measured to the nearest 2.5 cm, making the bias far less than the measurement precision. Other variables having measurement precision that exceeds the estimated bias include CWD total length, CWD plot count, litter depth, and litter cover. The bias for CWD total length is −0.27 m, which may be of concern. If each piece of CWD is, on average, nearly 0.3 m too long, the total amount of CWD could be overestimated. In contrast, there were variables where the bias exceeded the measurement precision. The most egregious bias was associated with duff depth, where the mean difference between crews was −0.41 cm and the measurement precision is 0.25 cm. However, there were situations where bias exceeding measurement precision had no practical impact. The bias for FWD small count was approximately one piece, which contributes little to the plot total. A similar argument may be made for the 0.08 m difference in dead shrub heights. Differences in plot-level estimates for various DWM attributes were not biased, with the exception of litter. This result is somewhat alarming, as litter generally comprises 10–15% of the plot total. This outcome indicates that a within-plot bias for litter depth is occurring, despite the relatively small overall bias found when analyzing individual measurements over all plots.

The poor repeatability and potential biases for some components of FIA's large-scale fuels inventory, despite having a limited effect on overall plot-level estimates, is unacceptable and can be ameliorated. First, the MQOs may need to be adjusted. For most attributes, the MQO was a 'best guess' of what experienced field crews should be able to achieve. Since initial establishment, these standards have not been re-assessed for conformance with FIA program needs and actual measurement variability among field crews. Second, the entire QA process may need to be evaluated to account for circumstances such as FWD changing between field visits and disturbance of duff/litter. Third, the scope of real-time assessments of crew measurement accuracy needs to be expanded. Currently, checks conducted simultaneously with field crew measurements are sporadic and primarily focus on new, inexperienced crews. Performing these types of checks more frequently and including all field crews should improve measurement consistency. Fourth, efforts to improve data quality should initially focus on variables that have substantial impacts on overall plot-level estimates of fuels such as litter and duff depths. Increased emphasis on these variables during crew training should result in better repeatability of field measurements and reduce differences between plot-level estimates. Fifth, feedback mechanisms should be established where crews may rapidly respond to QA results. Currently, there is little protocol for how blind remeasurement information is provided to field crew supervisors for training field crews and improving data quality. These exercises in statistical control need to be linked back to actual field crew measurements in an effective and timely manner. Sixth, some measurement protocols should be altered or some variables removed due to excessive subjectivity (e.g., shrubs/herbs, cover/height). Finally, data recording errors should be reduced, particularly for duff depths and CWD diameters. Given that most data is now collected with electronic recorders or converted to electronic form at some point after collection, these types of errors can be greatly reduced via application of programs that check for illogical and/or extreme values. These checks are particularly useful if employed on data recorders, where errors can be fixed while the crews are still in the field.

5. Conclusions

Despite efforts to create a national-scale inventory of forest fuels with repeatable inventory methods, QA analysis results indicated only poor to moderate repeatability and some potential biases. Although these results may not translate into substantial impacts on overall plot-level estimates of forest fuels, they reflect the reality of attempting to quantify the dead and decaying components of forest ecosystems. There are many challenges to overcome in order for the measurement repeatability of dead wood resources to match those of traditional forest inventory variables (e.g., standing tree diameter). Increasing measurement repeatability and reducing biases in large-scale fuels inventory may require a holistic approach where all inventory aspects from measurement protocols to data management programs to QA techniques are considered.

Analysts should be aware of the levels of variability and potential bias found in this study. The two primary uses of the data are for computing estimates of population parameters and as inputs into forest fire models. Although it was shown that plot-level estimates remained largely unaffected, the additional uncertainty due to measurement variability should be taken into account. Further research includes evaluation of geographic differences in measurement variability and quantification of how this additional error source impacts analyses of forest fuel estimates and fire model outputs.

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