Comparison of Three Methods for Quantifying Coarse Surface Fuel Loading

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Abstract—We compared three commonly used sampling methods for estimating coarse woody surface fuel (>7.62 cm diameter) loading: fixed-area plot, planar intersect using one transect, and planar intersect using two transects. Sampling occurred in ponderosa pine/Douglas-fir (*Pinus ponderosa*/*Pseudotsuga menziesii*) dominated stands in the northern Rocky Mountains, USA. These methods commonly have tradeoffs in execution and accuracy that managers must consider. We found fixed-area plot sampling was more likely to capture log occurrence; planar intersect methods estimated zero loading on 23 to 47 percent of plots, but fixed-area sampling always captured some loading. Adding a second transect did not improve accuracy of sampling estimates at either high or low log loading when compared to fixed-area log loading. The three sampling techniques produced similar results at the unit level, but on an individual plot, the planar intersect method tends to overpredict log loading when actual loading is very low (<1.0 kg m^{-2}) and underpredict values as loadings increased beyond that level. These results suggest that planar intersect sampling can accurately be used to estimate log loading if numerous transects are installed. If sampling is constrained to one transect per stand, then fixed-area plot sampling is recommended.

Keywords: Brown's transects, fixed-area plot sampling, hazardous fuels, line intersect sampling, *Pinus ponderosa*, planar intercept, planar intersect sampling, monitoring, *Pseudotsuga menziesii*

INTRODUCTION

Evaluating the impacts and effectiveness of forest fuel reduction treatments commonly includes monitoring of surface woody debris loadings (Brown et al. 2003; Crotteau et al. 2016; Strom and Fulé 2007; Waddell 2002). Dead coarse woody surface fuels (i.e., logs >7.62 cm in diameter) influence intensities and residence times of fires and can have important ecological functions (Brown et al. 2003; Harmon et al. 1986; Schoennagel et al. 2012). Several fuel sampling methods exist to quantify coarse woody fuel loading, each with advantages and disadvantages, depending on fuel particle size (Keane and Gray 2013; Sikkink and Keane 2008). Two common methods for measuring dead downed surface fuels are planar intersect transects and fixed-area plot sampling (Keane 2015).

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Planar intersect sampling along linear transects was refined by Brown (1971, 1974) as a two-dimensional modification of Van Wagner's (1968) line intersect sampling for estimating dead and down woody surface fuels. In the planar intersect sampling method, woody debris pieces more than 7.6 cm in diameter that cross a vertical plane along a linear transect are tallied by diameter and decay class at the point of crossing (Brown 1974). From those intersect recordings, fuel loading is calculated on a mass per unit area basis. Planar intersect transects are adjustable to length and orientation and are generally quick to measure (Keane 2015). As such, they have become standard for many forest and fuel monitoring programs to measure both fine and coarse woody surface fuels (<7.62 cm and >7.62 cm diameter at point of intersect, respectively), as well as other live and dead fuels (e.g., Busing et al. 1999; Lutes et al. 2006; USDI National Park Service 2003).

While planar intersect transects are easily taught and learned, they have some major disadvantages. If transect direction is not adjusted throughout a stand, sampling may produce biased estimates of log loading if fuels are similarly oriented upslope or downslope (Brown 1971; Van Wagner 1968). Additionally, stands with highly variable downed woody fuel loading may require prohibitively large sample sizes or transect lengths for an accurate estimate of loading and its variability (Keane 2015; Lutes 1999; Woldendorp et al. 2004). On the other hand, the planar intersect transect sampling technique is adaptable to both management and research requirements and allows estimation of all woody fuel size classes.

Alternatively, fixed-area plot sampling is an equal probability sampling technique that uses a fixed sample area to estimate fuel loading. Fuels can be removed for weighing in the laboratory or fuel dimensions can be measured on-site (and loading later calculated from log volume and wood density). The fixed-area plot method may capture spatial variability more accurately than the planar transect method (Woldendorp et al. 2004), depending on plot size, size class of woody debris, and distribution of fuels (Keane 2015; Sikkink and Keane 2008), but fixed-area plots can be time-intensive to sample and are not always practical for resource-limited monitoring programs. For logs, fixed-area plot sampling may require plots as large as 0.04 ha to capture spatial variability (Keane 2015).

In this study, we compared planar intersect transect and fixed-area plot sampling methods for quantifying dead coarse woody surface fuel loading (kg m^{-2}). Fuels are intrinsically variable in distribution and abundance; either sampling method may produce significantly different results compared to the true mean. Greater sampling intensity, as a rule, should reduce error, but sampling costs are always a concern; balancing these two factors is key. This study had two objectives: 1) compare log loading by measurement method at a plot level, and 2) determine whether stand-level log loading estimates differed between fixed-area plot sampling and planar intersect transects. In this paper, we use the term "logs" to describe dead coarse woody surface fuels with a diameter over 7.62 cm at the point of intersect for planar intersect pieces or at the small end for pieces measured inside a fixed-area plot. The study's findings will help fire and fuels managers evaluate the tradeoffs associated with these sampling methods, and choose the method most informative for their project.

METHODS

Study Site

We sampled logs at the Lick Creek Demonstration Research Forest (Lick Creek) on the Bitterroot National Forest in southwestern Montana (46°5'N, 114°15'W). Lick Creek is predominantly on 10- to 30-percent south-facing slopes at an elevation of 1,300 to 1,500 meters AMSL (Gruell et al. 1982). This study is located in the Interior Ponderosa Pine forest cover type (Eyre 1980), consisting mainly of ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson var. *ponderosa* C. Lawson) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *glauca* (Beissn.)). On the upper slopes, the habitat types (h.t.s) (Pfister et al. 1977) are *Pseudotsuga menziesii/Calamagrostis rubescens* h.t., *Pinus ponderosa* (Douglas-fir/pinegrass h.t. ponderosa pine) phase, and *Pseudotsuga menziesii/ Symphoricarpos albos* h.t. *Calamagrostics rubescens* (Douglas-fir/snowberry h.t., pinegrass) phase (Gruell et al. 1982). On the lower slopes, the habitat types are *Pseudotsuga menziesii/Vaccinium caespitosum*

(Douglas-fir/dwarf huckleberry), and *Pseudotsuga menziesii/Vaccinium globulare* h.t. *Arctostaphylos uva-ursi* (Douglas-fir/blue huckleberry h.t., kinnikinnick) phase (Gruell et al. 1982).

There are 24 total units in this study containing 1- to 2-ha treated and control units that are part of a 1992 long-term experiment evaluating combinations of restoration-focused cutting and burning strategies (Smith and Arno 1999). Each of two sites contains a network of 0.04-ha fixed-area circular plots across 12 units, with 6 plots per unit, except for 1 unit with 4 plots (total = 142 plots). We used these treated and untreated units as representative of this common forest type and for the diverse range of fuel loads that they contain in one compact space. One site (72 plots total) had been treated with a thinning, followed by broadcast burn and no-burn treatments. The second site (70 plots total) had been treated with a retention shelterwood cutting, followed by broadcast burn and no-burn treatments. No management had been conducted at either site since 1994. We emphasize that the purpose of this study was simply to utilize this study area to compare sampling methods within these known contexts, and not compare sampling methods among specific treatments within this study or describe typical or desirable levels of coarse woody surface fuels.

Data Collection and Analysis

We remeasured the original (established 1993) planar intersect transects (Brown 1974) established within fixed-area plots in 2015 using the initial methods. Transects originated at plot center and extended 15.24 m, alternating either upslope or side-hill in orientation. To test whether doubling sampling intensity affected log loading estimate, we added a second 15.24 m planar intersect transect 90° clockwise from the original (producing two estimates of loading per plot: one estimate using only the first transect and a second estimate based on the average of both transects). Using the original 0.04-ha circular fixed-area plots from the study, we measured all logs over 7.62 cm in diameter within the plot area. We measured small-end diameter, large-end diameter, and log length and recorded whether the log was sound or rotten. Only the portion of the log occurring within the plot boundary was measured, and logs or log portions were sampled when the central axis was lying in or above the litter layer.

One- and two-transect log loading for each plot were estimated using the FEAT/Firemon Integrated (FFI) software program (Lutes et al. 2006), which uses Brown's (1974) formulas to calculate log loading. Wood density of sound material was 0.40 g cm^{-3} for sound logs and 0.30 g cm^{-3} for rotten logs. For fixed-area plot log loading, we calculated log volume (m^3) at the plot level using Smalian's formula (Avery and Burkhart 2002):

$$\text{Cubic volume: } \frac{(B+b)}{2} L$$

where B and b are the cross-sectional areas (m^2) of the log at the large and small ends, respectively, and L is the log length (m).

Volumes of logs on the plot were multiplied by wood density and then adjusted for plot area to estimate loading (kg m^{-2}). The wood density values for sound and rotten material were the same as used in FFI for calculating the load of logs sampled on transects. The sum of log load per plot was expressed on a per unit area basis.

To determine how measured loadings for fixed-area plots compared to transect estimates at the plot level, we used the loading from the planar intersect transect sampling method as the predictor variable and applied separate simple linear regression models to compare plot-level log loading from both one and two transects per plot. We compared these models against the measured log loading to determine how well planar intersect transect sampling compared to fixed-area plot sampling.

We calculated the average unit-level log loading using each method. We used analysis of variance (ANOVA) to test for differences in log loading estimates between the three sampling methods at the unit level ($\alpha = 0.05$). Because the unit-level estimates were right-skewed in all sampling methods, we log-transformed the data for the ANOVA test to satisfy normality.

Normality was tested using the Shapiro-Wilk normality test (Royston 1982) and assessed with quantile-quantile plots and histograms of the residuals. All tests were conducted using the R software program (R Core Team 2016).

RESULTS AND DISCUSSION

Plot-level fuel loadings sampled using the three methods ranged from 0.0 to 15.640 kg m^{-2}. Log loadings were similarly distributed among methods, though the planar intersect method failed to detect logs on many plots (fig. 1). Mean log loading ranged from 0.773 kg m^{-2} to 0.872 kg m^{-2} across sampling methods, but median log loading ranged from 0.232 kg m^{-2} to 0.430 kg m^{-2} (table 1). The lowest measured fixed-area plot log loading was 0.039 kg m^{-2}, whereas no logs were sampled on 61 plots (47 percent) using one transect and 33 plots (23 percent) using two transects.

At the unit level, there was no difference ($F_{2, 69}$ = 0.161; $p = 0.852$) in log loading estimates between the three methods. Measuring fuels using one planar intersect transect produced the lowest overall estimate; two planar intersect transects produced nearly equal means and standard errors as fixed-area plot (fig. 2). The overall estimate of log loading was 0.645 ± 0.104 kg m^{-2} for fixed-area sampling, 0.581 ± 0.093 kg m^{-2} using one planar intersect transect per plot, and 0.653 ± 0.105 kg m^{-2} using two planar intersect transects per plot. Comparisons of each method by unit demonstrated a lack of patterns or bias, but there were some cases where either one or two transects estimated much higher loading (fig. 3). Across all units, there was a great deal of overlap between each method's measured values, indicating that when six plots are used to calculate the average loading at the unit level, the three methods produced equivalent results.

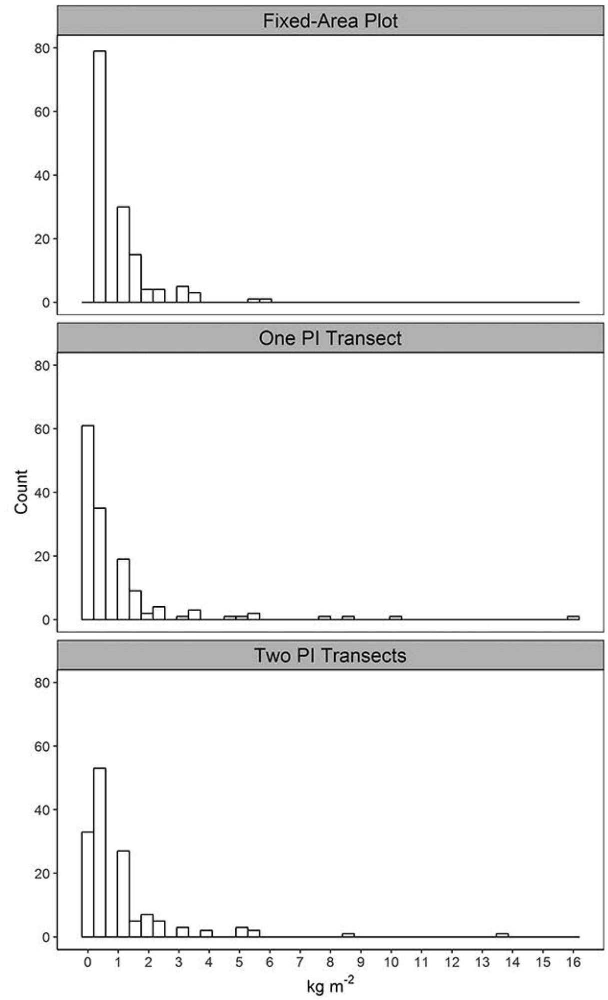

Figure 1—Distribution of plot-level (n = 142) log loading estimates by the three compared methods: fixed-area plot sampling, one planar intersect (PI) transect per plot, and two planar intersect transects per plot. Note: At the plot level, the lowest measured fixed-area plot loading was 0.039 kg m^{-2}, whereas 61 plots estimated zero loading using one PI transect, and 33 plots estimated zero loading using two PI transects.

Table 1—Log loading summaries (kg m^{-2}) at the plot level by sampling method: fixed-area plot, one planar intersect (PI) transect, and two PI transects per plot.

Sampling method	Mean	Standard error	Median	1st quartile	3rd quartile
Fixed-area plot	0.773	0.189	0.430	0.204	0.947
One PI transect	0.841	0.401	0.232	0.000	0.685
Two PI transects	0.872	0.336	0.336	0.091	0.803

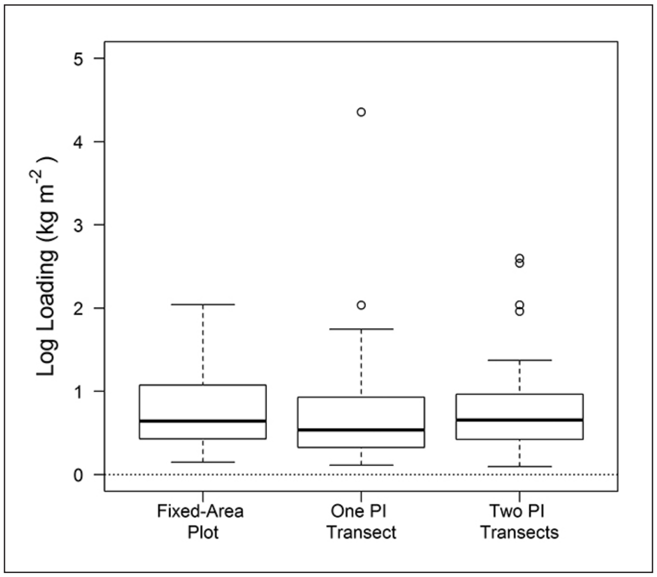

Figure 2—Unit-level (n = 24) log loading (kg m-2) estimates by method calculated from 6 plots per unit. Methods: fixed-area plot sampling, one planar intersect transect (PI) per plot, and two planar intersect transects per plot.

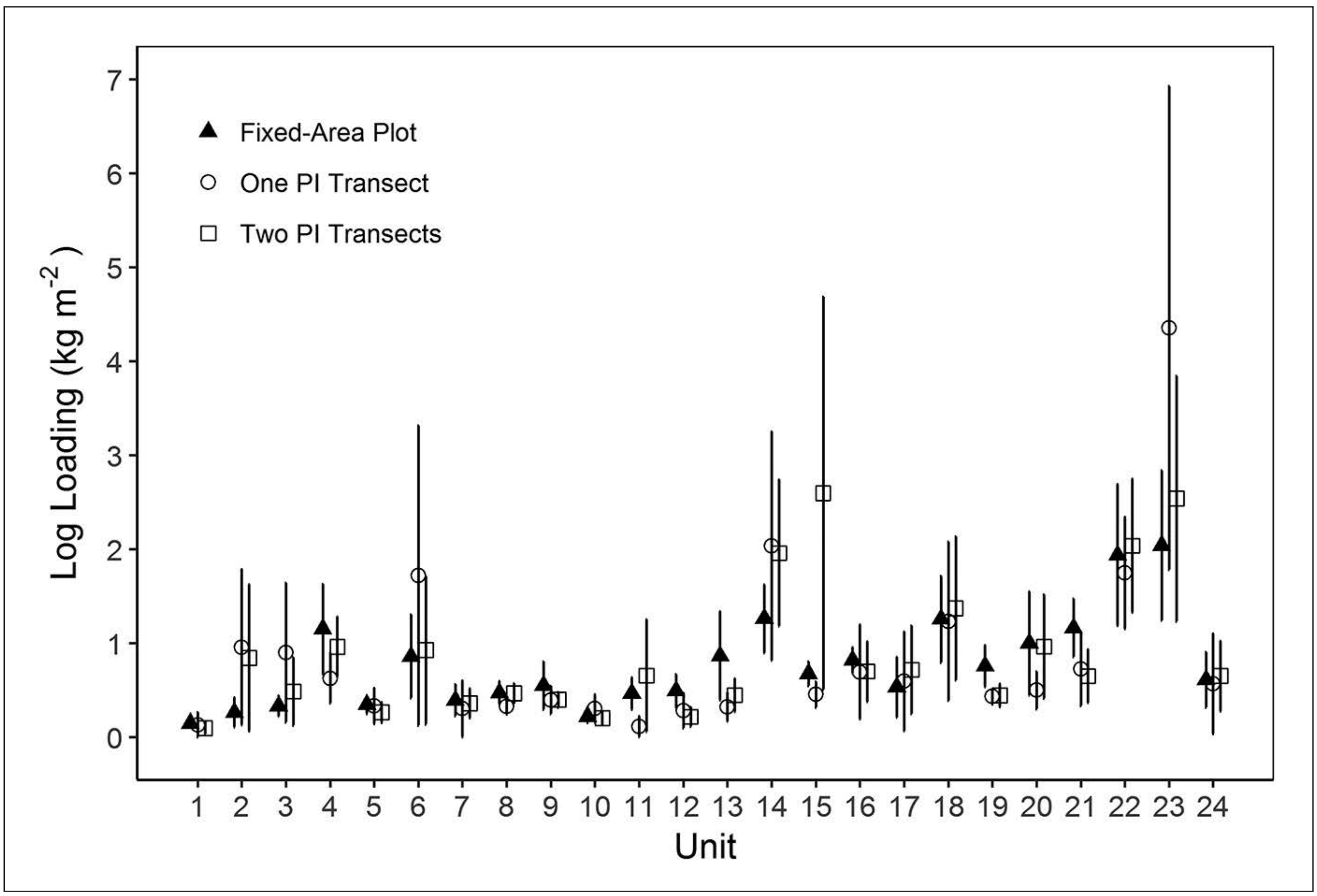

Figure 3—Comparison of mean log loading and one standard error at each unit by method. Methods included fixed-area plot sampling, one planar intersect (PI) transect per plot, and two planar intersect transects per plot.

At the plot level, model estimates of fixed-area log loading estimated from the measured loading using one planar intersect transect (equation 1) and two planar intersect transects (equation 2) are:

$$\textit{Log loading} = 0.541 + 0.275 \text{ x } \textit{Transect loading} \quad (1)$$

$$\textit{Log loading} = 0.485 + 0.329 \text{ x } \textit{Transect loading} \quad (2)$$

Compared to fixed-area plot sampling at the plot level, planar intersect transects captured only 33.8 percent (model 1) and 34.2 percent (model 2) of the variability in log loading. Transects underpredict at all fixed-area plot fuel loadings, except at the very lowest levels (<1.0 kg m^{-2}) (fig. 4).

We acknowledge that all three of our methods are estimations of fuel loadings as we did not weigh the samples. However, assuming the fixed-area plot sampling provides the most accurate estimate of log loading, planar intersect transects were a poor predictor of loading on a plot-by-plot basis. Every fixed-area plot captured at least some coarse woody surface fuels (range: 0.039–5.561 kg m^{-2}), but out of 142 plots, 47 percent of plots measured with one transect and 23 percent measured with two transects estimated zero loading (range: 0–15.640 kg m^{-2} using one transect and 0–13.049 kg m^{-2} using two transects). If only one plot is measured in a stand, our results indicate that there is a strong chance of not only incorrectly estimating log loading but estimating zero loading, when using the transect lengths used in this study.

In general, our mean log loadings were low for a northern Rocky Mountain ponderosa pine/Douglas-fir forest. Baker (2009) reported 10.44 ton ac^{-1} (2.34 kg m^{-2}) of coarse woody debris (of which 30 percent is rotten wood) in a typical Interior ponderosa pine/Douglas-fir forest, which is 368 to 403 percent greater than our observed estimates. That value was based on early Fuel Characteristics Classification System (FCCS) fuelbed loadings (Ottmar et al. 2007). The most recent FCCS estimates are 8.6 ton ac^{-1} (1.93 kg m^{-2}) of downed coarse woody fuels (also 30 percent rotten wood), which is 221 to 250 percent greater than our observed estimates (Ottmar et al. 2007). In recently treated northern Rocky Mountain ponderosa pine stands (i.e., <10 years), Keane et al. (2012) reported mean log loading ranging from 1.23 to

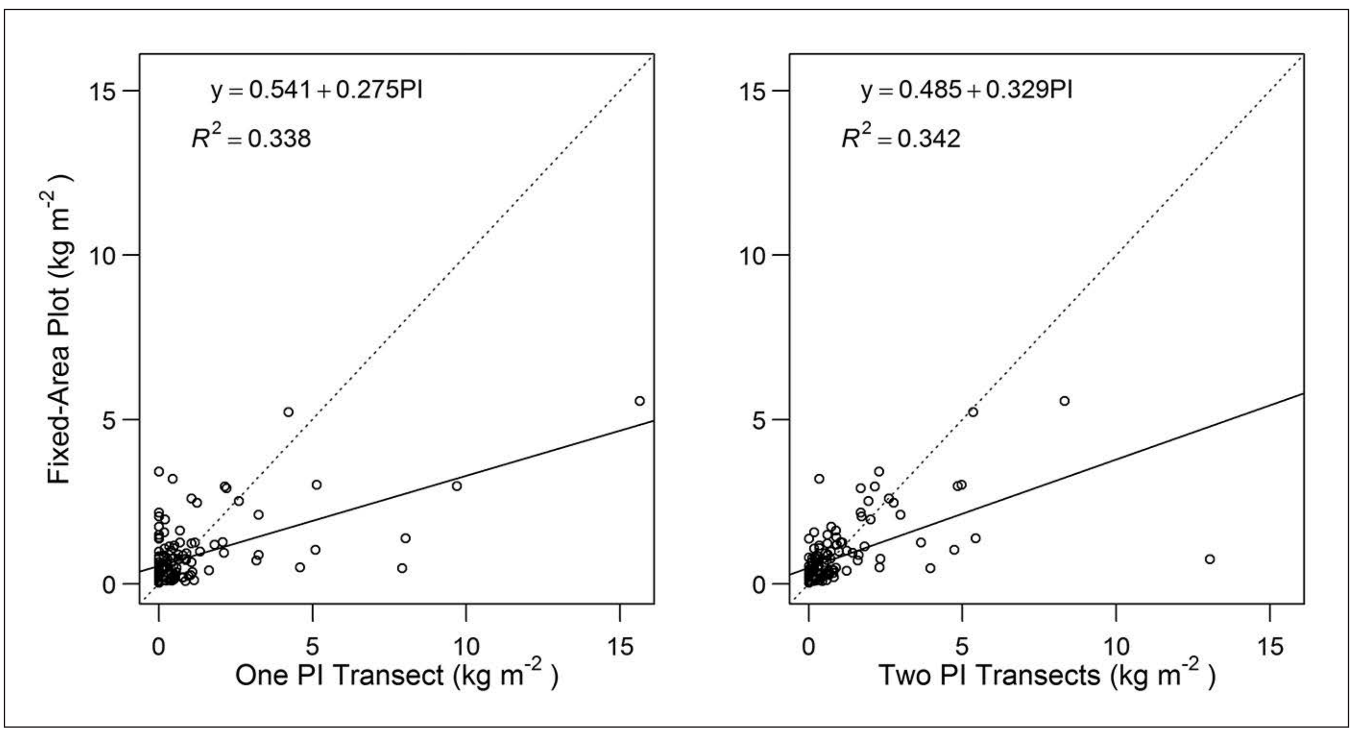

Figure 4—Observed plot-level fixed-area plot sampling estimates of log loading (kg m^{-2}) against planar intersect (PI) transects for one transect and two transects, with 1:1 line (dotted gray) and linear model line (black). Transects underpredict at all fixed-area plot fuel loadings, except at the very lowest levels (<1.0 kg m^{-2}).

2.92 ac-1 (0.276–0.657 kg m^{-2}), loadings similar or lower to our observations. Finally, Brown and See (1981) reported mean log loading of 5.3 tons ac^{-1} (1.18 kg m^{-2}) and standard deviation of 14.0 tons ac^{-1} (3.14 kg m^{-2}) in ponderosa pine cover types on the Bitterroot National Forest. These examples indicate the high variability of log loading in northern Rocky Mountain ponderosa pine forests. While mean log loading sampled in this study tended to be lower than other studies, it appears to fall with the typical range of the forest type. Our mean log loading likely better describes log loading in stands of this forest type that have been subjected to fuel reduction treatments within the last 25 years, but they may not represent other stands of the same forest type with different disturbance history.

Accurate coarse woody surface fuel inventorying is critical to monitor wildlife habitat, soil health, and fuel treatment effectiveness (Bull et al. 1997; Busing et al. 1999; Keane 2015; Waddell 2002). While not typically a driver of surface fire behavior modeling (Anderson 1969), coarse woody surface fuels are nevertheless an important component of fire severity: Larger logs smolder longer, leading to greater soil heating and higher severity (Albini and Reinhardt 1995).

Transect sampling is an efficient and appropriate method for measuring log volume and weight, especially with high log abundance, but transect length must be scaled accordingly (Bate et al. 2004; Lutes 1999; Sikkink and Keane 2008). Fixed-area plot sampling may be more time-consuming, but Bate et al. (2004) concluded that their measured log variables were more precise using fixed-area plot sampling. Therefore, having a good understanding of the advantages of measurement techniques is important for managers and researchers alike.

In summary, we conclude that the three sampling techniques produced similar results at the unit level, but that fixed-area plot sampling is more likely to capture the more rare occurrences of coarse woody fuels, and as such, provides a good estimate of the actual variance. On an individual plot, the planar intersect method tends to overpredict log loading at all levels except the very lowest. Additionally, doubling the number of transects per plot does not seem to avoid any sampling bias at either low or high log loading.

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