

Comparing three sampling techniques for estimating fine woody down dead biomass

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Abstract. Designing woody fuel sampling methods that quickly, accurately and efficiently assess biomass at relevant spatial scales requires extensive knowledge of each sampling method's strengths, weaknesses and tradeoffs. In this study, we compared various modifications of three common sampling methods (planar intercept, fixed-area microplot and photoload) for estimating fine woody surface fuel components (1-, 10-, 100-h fuels) using artificial fuelbeds of known fuel loadings as reference. Two modifications of the sampling methods were used: (1) measuring diameters only and both diameters and lengths and (2) measuring diameters to (a) the nearest 1.0 mm, (b) traditional size classes (1 h = 0–6 mm, 10 h = 6–25 mm, 100 h = 25–76 mm), (c) 1-cm diameter classes and (d) 2-cm classes. We statistically compared differences in sampled biomass values to the reference loading and found that (1) fixed-area microplot techniques were slightly more accurate than the others, (2) the most accurate loading estimates were when fuel particle diameters were measured and not estimated to a diameter class, (3) measuring particle lengths did not improve estimation accuracy, (4) photoload methods performed poorly under high fuel loads and (5) accurate estimate of fuel biomass requires intensive sampling for both planar intercept and fixed-area microplot methods.

Additional keywords: fixed-area plot, fuel inventory, fuel loading, line intersect, monitoring, photoload, planar intercept.

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Introduction

Successful wildland fuel management activities will ultimately depend on the accurate inventory and monitoring of the biomass of forest and rangeland fuels (Conard *et al.* 2001; Reinhardt *et al.* 2008). Wildland fuel loadings are important direct inputs to fire effects models and are used to create fuel classifications that are inputs to predicting fire behaviour from common fire management software such as BEHAVE, FARSITE and FLAMMAP (Finney 2004, 2006; Andrews 2008). More recently, fuel loadings have become critical inputs for estimating fuel consumption (Reinhardt and Holsinger 2010), smoke emissions (Hardy *et al.* 2000), soil heating (Campbell *et al.* 1995), carbon stocks (Reinhardt and Holsinger 2010), wildlife habitat (Bate *et al.* 2004) and site productivity (Hagan and Grove 1999; Brais *et al.* 2005). Wildland fuel biomass is the one factor that can be directly manipulated to achieve management goals, such as restoring ecosystems, lowering fire intensity, minimising plant mortality and reducing erosion (Graham *et al.* 2004; Ingalsbee 2005; Reinhardt *et al.* 2008). As a result, comprehensive and accurate estimates of fuel loadings are needed in nearly every phase of fire management including fighting wildfires (Chen *et al.* 2006; Ohlson *et al.* 2006), implementing prescribed burns (Agee and Skinner 2005), describing fire danger

(Deeming *et al.* 1977; Hessburg *et al.* 2007) and predicting fire effects (Ottmar *et al.* 1993; Reinhardt and Keane 1998).

It is often difficult to estimate surface fuel biomass for many ecological, technological and logistical reasons (Keane *et al.* 2012). A fuelbed consists of many fuel components, such as litter, duff, twigs, logs and cones, and the properties of each component that influence biomass measurements, such as shape, size, particle density and orientation are highly variable even within a single fuel particle. Fuel component properties vary at different spatial scales (Kalabokidis and Omi 1992; Habeeb *et al.* 2005; Keane *et al.* 2012) and fuel loadings are so highly variable that they are often unrelated to vegetation characteristics, topographic variables or climate parameters (Brown and See 1981; Rollins *et al.* 2004; Cary *et al.* 2006). However, it is the uneven distributions of fuel across spatial scales that confound many fuel sampling and mapping activities. Therefore, picking the proper method for sampling fuel biomass is important, especially when there are disparate sampling techniques for the different surface fuel components (Lutes *et al.* 2006, 2009).

Several sampling techniques have been developed to sample downed woody fuel biomass for fire management. The most commonly used woody surface fuel sampling method is the

planar intercept (PI) (often called line intercept) where diameters of fuel particles that intercept a vertical sampling plane are measured and converted to biomass loading (Van Wagner 1968; Brown 1971, 1974). Fixed-area microplots (FMs) are often used to estimate biomass for research applications where diameters and lengths of woody fuel particles are measured within microplots to compute fuel volume that is then converted to loading using the wood particle density and microplot area (Sikkink and Keane 2008). A new technique, called photoloads (PHs), provides a set of photographs of increasing fuel loadings for the user to select a photo that best matches the observed fuelbed to estimate loading (Keane and Dickinson 2007a, 2007b). Each of these techniques has strengths and weakness when applied to fuel inventory and monitoring, so determining how well each sampling technique performs under a variety of fuel loadings is critical to designing efficient sampling projects.

In this study, we explored how the three surface fuel sampling methods (PI, FM and PH) compared in their ability to assess downed dead fine woody debris biomass (FWD; woody particles less than 8 cm in diameter). We also modified two of these techniques (PI and FM) to improve accuracy and compared results from the modifications across and between techniques. This study is somewhat unique in that we conducted fuel sampling on a 500-m² square plot established in a parking lot within which we placed FWD in known fuel loadings in various spatial distributions. Loadings from each technique were compared with the known reference loading to determine accuracy and precision. Hazard and Pickford (1986) performed a similar experiment, but they used simulation modelling instead of real fuels. Our goal was to determine the tradeoffs involved in using each of these sampling techniques to inform the design of sampling projects for research, resource and fire management applications.

Background

The line transect method was originally introduced by Warren and Olsen (1964) and made applicable to measuring coarse woody debris by Van Wagner (1968). Its development is rooted in probability-proportional-to-size concepts and several variations have been developed since 1968, including those that vary the line arrangements and those that apply the technique using different technologies (DeVries 1974; Hansen 1985; Nemec-Linnell and Davis 2002). The PI method is a variation of the line-transect method that was developed specifically for sampling FWD and coarse woody debris (CWD) in forests (Brown 1971, 1974; Brown *et al.* 1982). It has the same theoretical basis as the line transect, but it uses sampling planes instead of lines. The planes are somewhat adjustable because they can be any size, shape or orientation in space and samples can be taken anywhere within the limits set for the plane (Brown 1971). The PI method has been used extensively in many fuel inventory and monitoring programs because it is fairly fast and simple to use (Busing *et al.* 2000; Waddell 2002; Lutes *et al.* 2006). It has also been used in many research efforts because it is often considered an accurate technique for measuring downed woody fuels (Kalabokidis and Omi 1998; Dibble and Rees 2005). The problem is that it is difficult to integrate PI sampling

designs with other fixed-area plot designs such as those used for estimating canopy fuels because the method was designed to sample entire stands, not fixed-area plots.

In contrast to probability-based methods, FMs are based on frequency concepts and have been adapted from vegetation composition and structure studies to sample fuels (Mueller-Dombois and Ellenberg 1974). In fixed-area sampling, a round or rectangular plot is used to define a sampling frame and all fuels within the plot boundary are measured using diverse methods that range from destructive collection to volumetric measurements (i.e. length, width, diameter) to particle counts by size class (Keane *et al.* 2012). Because fixed-area plots require significant investments of time and money, they are more commonly used to answer specific research questions rather than to monitor or inventory fuels for management action.

In recent years, a new method of assessing fuel loading has been developed to sample fuel beds using visual techniques. The PH method uses calibrated, downward-looking photographs of known fuel loads to compare with conditions on the forest floor and estimate fuel loadings for individual fuel categories (Keane and Dickinson 2007a, 2007b). These ocular estimates can then be adjusted for diameter, rot and fuel height. There are different PH methods for logs, fine woody debris, shrubs and herbaceous material, but there are no methods for measuring duff and litter fuels. Photoload methods are much faster and easier than fixed-area and planar intercept techniques with comparable accuracies (Sikkink and Keane 2008). The PH technique differs from the commonly used photo-series technique (Fischer 1981) in that assessments are made at smaller scales using downward pointing photographs of graduated fuel loadings.

It is somewhat problematic to compare surface fuel sampling techniques because of the difficulty in estimating the actual fuel biomass for reference (Sikkink and Keane 2008). Successful comparison studies contrast sampled fuelbeds with the actual known biomass, but quantifying these reference or actual fuel loadings is costly, and often impossible, because it is difficult to collect, sort, dry and weigh the heavy amount of fuel biomass within a commonly used ecological sampling frame (250–1000-m² plot) located in a natural setting. As a result, most fuel sampling comparisons relied on subsampling using FMs and destructive sampling (Sikkink and Keane 2008), but the standard errors involved in subsample estimation may overwhelm the subtle differences between sampling methods. There are also major differences between sampling techniques that make statistical comparisons difficult. The commonly used PI sampling, for example, is difficult to compare with other methods because the two dimensional (length and height) sampling plane makes it difficult to relate to area-based reference sampling frames because fuel loads must be destructively sampled in three dimensions (microplot; length, width and height). Loading estimates from visually based fuel sampling methods, such as PHs (Keane and Dickinson 2007a), have major sources of error because of differences between samplers and their ability to accurately estimate fuel loadings using visual cues; and size, shape and density differences between fuel components make comparisons difficult in that each component has its own inherent ecological scale (Keane *et al.* 2012).



Fig. 1. Layout of fine woody debris (FWD) surface fuelbeds in the parking lot of the Missoula Fire Sciences Laboratory for the three fuel distributions: (a) uniform – even distribution of FWD across the 500-m² plot, (b) patchy – 80% of FWD is evenly distributed in half the plot and (c) jackpot – 50% of fuel is evenly distributed in a quarter of the plot and the remaining 50% is evenly distributed across the other 75% of the plot.

Methods

Synthetic fuelbeds

We collected fine woody fuel from Douglas-fir (*Pseudotsuga menziesii*), ponderosa pine (*Pinus ponderosa*) and lodgepole pine (*Pinus contorta*) forests in western Montana USA, then sorted, oven-dried (3 days at 80°C) and weighed the fuel in the laboratory to create a reference fuel consisting of ~10% of load comprised of particles with diameters of 0–6 mm (1 h), 45% of loading of 6–25-mm diameter particles (10 h) and 45% of loading of 25–80-mm diameter particles (100 h), similar to FWD fuelbeds we found in the field (Fischer 1981; Sikkink and Keane 2008).

We established a 25 × 20-m (500-m²) semi-permanently marked rectangular plot in the parking lot of the Missoula Fire Sciences Laboratory to serve as the spatial reference for sampling method and techniques comparison (Fig. 1). The long sides (25 m) were oriented east and west, and the short side (20 m) ran north–south. We then created twelve synthetic fuelbeds in the parking lot plot for four known fuel loadings scattered in three patterns – uniform, patchy and jackpot (Fig. 1). We then sampled the area using the three methods with multiple technique modifications. We sampled only FWD for logistical reasons; small dead and down woody

surface fuel particles were (1) easiest to create synthetic fuelbeds, (2) most common elements across fuel sampling techniques and (3) important inputs to fire simulation models (Rothermel 1972; Albini 1976; Reinhardt *et al.* 1997). Logs were not included because they were too big to manipulate on the plot, and duff and litter were not included because of the tremendous volume of material that would have to be transported to the plot and the difficulty of creating realistic litter and duff layers after transport. Shrub and herbs were not included because it would have been difficult to create realistic shrub and herb fuelbeds after cutting in the field and transport to the site.

Study design

This study explored the influence of fuel loading and distribution on sampling methods and techniques using a set of factors (see Table 1). The first two factors described the synthetic fuelbed with the first factor called Loading and it had four treatments that consisted of four different levels of fuel loadings (0.05, 0.10, 0.15 and 0.20 kg m⁻²) with the proportion of 1-, 10- and 100-h fuel held constant at 10, 45 and 45%. The next factor was Spatial Distribution that described how fuel particles were distributed within the rectangular plot. There were three fuel

Table 1. Experimental design of this fine woody fuel sampling study that assessed the accuracy of three sampling methods using known fuel loadings as reference

Factor	Treatments				Description
	1	2	3	4	
Loading (kg m ⁻²)	0.05	0.10	0.15	0.20	Reference synthetic fuelbeds were created using field collected fine woody fuel at four loadings. Loadings were distributed across the 1-, 10- and 100-h fuels at 10, 45 and 45%.
Spatial distribution	Uniform	Patchy	Jackpot		Woody fuels are evenly distributed across the sampling plot (uniform); 80% of the fuel on the north half of the plot (patchy); 50% of the fuel in the NW quadrant of the plot (jackpot) (Fig. 1).
Sampling method	Planar intersect (PI)	Fixed-area Microplot (FM)	Photoload (PH)		Three sampling methods: Brown (1974) PI as implemented in Lutes <i>et al.</i> (2006), FM as implemented in Keane <i>et al.</i> (2012) and Keane and Dickinson (2007a), PH as implemented in Sikkink and Keane (2008).
Sampling technique	Diameter (D)	Diameter-length (DL)			Only particle diameter and an average measured length for a 25% subsample was used to compute volume (Diameter); two end diameters and particle length were used to compute volume (Diameter-length). Loading was computed by multiplying volume by particle density as measured from a 25% subsample of particles.
Diameter size class	Measured (M)	Traditional (T)	1-cm (1 cm)	2-cm (2 cm)	Fuel particle diameters are classed in the traditional classes (0–0.625, 0.625–2.5, 2.5–8 cm), 1-cm classes and 2-cm classes. Midpoints were used to compute volume. The measured treatment uses the direct measurement of diameter to 0.1-cm accuracy.

distribution treatments used to mimic conditions in the field (Fig. 1):

- Uniform. We evenly distributed fuels across the sampling plot (Fig. 1a).
- Patchy. We put 80% of the fuel on the north half of the plot and 20% on the south half (Fig. 1b).
- Jackpot. We put 50% of fuel in the NE quadrant of the plot and the remaining 50% evenly distributed across the three other quadrats (Fig. 1c).

The third factor was the Sampling Method that we used to estimate fine woody loadings and these three methods are detailed in the next section:

- Planar intercept (PI). We employed the Brown (1974) sampling technique where fuel particles that intersect a sampling plane were measured.
- Fixed-area microplot (FM). Within microplot boundaries, we measured the two end diameters, the centre diameter and the length of each fuel particle to the nearest 0.1 cm as documented in Sikkink and Keane (2008).
- Photoload (PH). We visually estimated fuel loadings within a 1 m² microplot using techniques documented in Keane and Dickinson (2007b).

Related to the sampling methods were the sampling procedures used to implement these methods in the field. The Sampling Technique factor used several variations of some sampling methods to evaluate method performance. These techniques were not employed while actual sampling, but rather were implemented during the analysis phase:

- Diameter. We used particle diameter and an average particle length (Table 2) to compute volume that was then used to estimate loading.
- Diameter-length. We used the two end diameters and particle length to compute volume then loading.

The last factor was Diameter Size Class and it consisted of four treatments that grouped particles into four different diameter size classes to compute loadings – measured, traditional, 1- and 2-cm classes. Measured diameter classes are where particles were measured to 0.1-cm resolution. The traditional size classes are the unequally distributed diameter ranges (0–0.6, 0.6–2.5 and 2.5–8.0 cm), and the other two size classes (1, 2 cm) represent evenly distributed diameter ranges. We used the average midpoints of these classes to compute loadings (mean diameters in Table 2).

We could not implement all sampling technique and diameter class size treatments for all sampling methods because of methodological issues. The PH, for example, could only be used for the traditional diameter classes (Table 1) because the graduated photos were only taken for the traditional size classes. The PI method could not employ the Diameter-length technique because particle length is not a variable when computing loading using standard PI algorithms (Brown 1974).

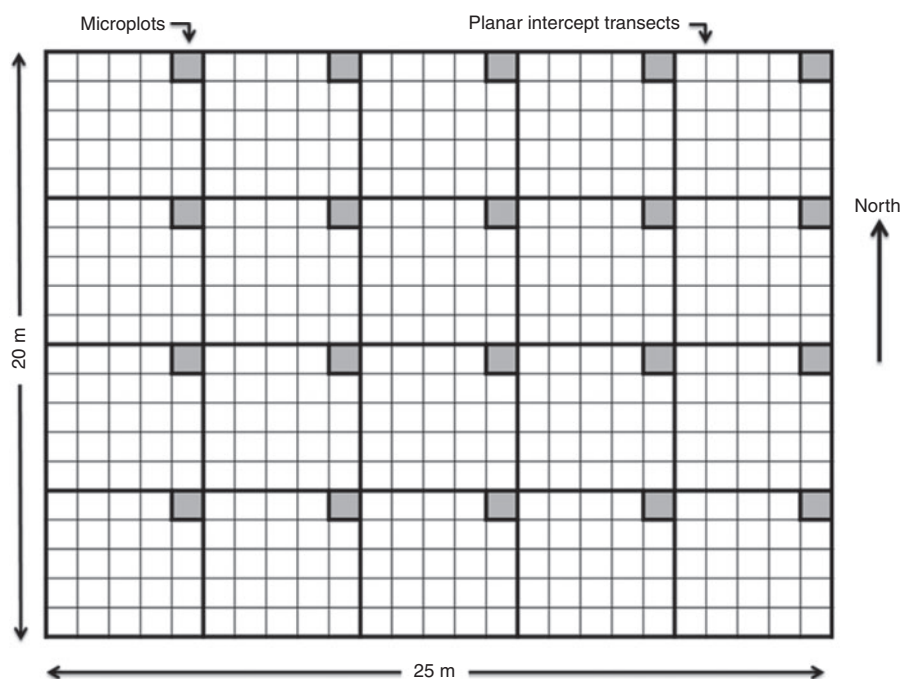
Sampling methods

PI transects were established at 1-m intervals along the 25-m sides (running north–south) and along the 20-m side (running east–west) totalling 24 + 19 or 43 transects that were a total of 955 m in length (Fig. 2). We measured a particle's diameter perpendicular to the central axis of the particle where it crossed the right side of the cloth tape (Brown 1974) to the nearest 0.1 cm. We measured particle diameters along the entire length of each transect for all particles. The orientation bias was set at 1.0 because all fuel particles were set flat on the pavement.

The FM method involved measuring the two end and centre diameters, and length of all fuel particles that were contained within 20 × 1-m² square microplots nested within the 500-m² plot (Fig. 2). We stretched cloth tapes at each 5-m mark (5, 10, 15 and 20) and along the borders (dark lines in Fig. 2) and established microplots in the NE corner of each 5 × 5-m

Table 2. Ancillary measurements done to support the calculation of fuel loading for the three sampling methodsStandard errors are presented in parentheses. These agree with values in Keane *et al.* (2012)

Fuel attribute	1-h woody (0.0–0.625-cm diameter)	10-h fuel (0.625–2.5-cm diameter)	100-h fuel (2.5–8.0-cm diameter)
Particle density (kg m^{-3})	601.10 (8.18)	566.38 (5.82)	521.51 (5.81)
Mean particle length (cm)	10.735 (0.252)	10.572 (0.344)	24.121 (2.988)
Mean diameter (cm)	0.351 (0.0042)	1.323 (0.0255)	4.266 (0.288)

**Fig. 2.** Sample layout of the parking lot plot divided into 5×5 -m subplots (thick lines) with 1×1 -m microplots (shaded) placed in the north-east corner of each subplot and the planar intercept transects (thinnest lines) at 1-m intervals going east–west and north–south.

subplot. Within microplot boundaries, we measured the diameters and length of each particle, and when fuel particles extended outside the microplot, we measured the diameter perpendicular to the central axis of the particle where it crossed the microplot frame.

The PH sampling method was employed using protocols specified by Keane and Dickinson (2007b) where loadings are visually estimated by matching photographs showing graduated loadings for a fuel size class to the actual conditions within each microplot. We used a variety of people to visually estimate loading and most were novice users of the photoload technique. Loadings could only be estimated for the traditional fuel size classes because those were the only photos available.

Ancillary measurements

Several additional parameters were needed to compute sampled biomass of fine woody fuels. First, fuel volumes from FM techniques were converted to loading by multiplying volume by particle wood density (S , kg m^{-3}) (Keane *et al.* 2012). We

estimated wood densities for particles in the traditional fuel sizes by measuring dry weight and volume of a 25% random sample of fuel particles (~ 200 sticks per traditional size class, Table 2). Particles were weighed to the nearest 0.01 g after drying in an oven at 80°C for 3 days, whereas volumes were estimated by immersing each particle in water and recording its displacement and gain in weight. We used the average particle density for each of the three sizes in all our calculations. Results of all ancillary measurements are shown in Table 2 to provide critical information needed to understand the analysis methods.

Because of subtle differences in species branch morphology, an average particle diameter and length within each traditional diameter size class was needed to minimise bias when computing biomass for the PI method (Brown 1971). We calculated the midpoint particle diameter in each of the three traditional size classes by measuring the two end and centre diameters of each randomly selected particle used in the calculation of particle density and taking the average of all diameters that fell in the 0.0–0.1, 0.1–2.5 and 2.5–8.0-cm ranges (Table 2).

Loading calculation

Planar intercept

We followed the procedures detailed in Brown (1971, 1974) to calculate downed woody fuel loadings using the following formula from Van Wagner (1968) and Brown (1974) for the PI method:

$$W = \frac{S a c \pi^2 \sum d^2}{8l} \quad (1)$$

where W is the loading (kg m^{-2}), S is the specific gravity (kg m^{-3}) measured for that particle diameter class (Table 2), d is particle diameter (m), a is a correction factor for orientation bias (assumed to be 1.0 in this study), l is the length (m) of the planar transect (20 or 25 m in this study) and c is a slope correction factor (assumed to be 1.0 for the parking lot). The particle diameter is assigned the midpoint of the diameter class or the average particle diameter for the traditional size classes. As mentioned, PI was only used with the diameter Sampling Technique. Actual measured diameters (d) were used to compute W in Eqn 1 for the measured diameter class treatment, then measured particle diameters were grouped in diameter classes using the traditional (Table 1), 1- and 2-cm size classes (e.g. 1-cm class ranged from 0 to 1 cm; 2-cm class, 1–2 cm, etc.). We used midpoints for diameters in the traditional, 1- and 2-cm classes loading calculations.

Fixed-area microplot

For all fine woody fuel components measured within the 1-m² microplot, the weight of each sampled particle was calculated using the volume (V , m³) and wood density method:

$$V = \frac{L}{3} [(a_s + a_l) + \sqrt{a_s a_l}] \quad (2)$$

where a_s is the cross-sectional area (m²) of the small end of the particle, a_l is the cross-sectional area of the large end (m²) and L is the length (m) (Keane and Dickinson 2007a). Particle weight (kg m^{-2}) was then calculated by multiplying the computed volume (V) by wood particle density (S , kg m^{-3}) (Table 2) taken as the average across the three traditional size classes. We used the centre diameter as both of the end diameters and the average particle length for each of the traditional size classes under the diameter treatment for the sampling technique factor (Table 2). Again, we used midpoints for diameters in the traditional, 1- and 2-cm classes loading calculations. To calculate FWD loading, particle weights were calculated and summed for all twigs.

Statistical comparisons

For the PI method, loadings were calculated at the transect level. The standard error for the PI method was calculated as a pooled standard error of the individual transects. Because the transect lengths were slightly different (20 v. 25 m), longer transect lengths were given a slightly higher weight in the standard error calculation to accommodate the increase in information we obtained from these larger transects. The estimated loadings were compared with reference loadings by calculating the bias for each factor (reference loading–estimated loading).

To incorporate both biasness and variance of each fuel load, 95% confidence intervals were calculated using t -procedures and each microplot or transect was assumed to be independent. Because there were at least 20 microplots or transects for each method, normality was not checked because of the robustness of the t -procedures for this analysis. Confidence intervals that included the relative reference load value were considered not statistically different from the actual loading ($P > 0.05$).

To examine the effect of sample size on the precision of each estimator, random samples were taken of incrementing sample sizes. To estimate the variance at a particular sample size, 1000 bootstrap samples were obtained and graphs of the bootstrap standard deviation by sample size was used to estimate standard error at a particular sample size. These graphs were created to examine whether fewer microplots or transects would be adequate to predict loadings. All statistical analysis was performed using R (R Development Core Team 2007).

Results

In general, the variability of FWD biomass estimates increased as (1) fuel loading became higher (0.2 kg m^{-2} had the highest variability), (2) fuel spatial distribution became more patchy (highest variability in jackpot distributions) and (3) particle diameters were more coarsely measured (measuring diameters are more accurate than classifying into a diameter class) for all methods (Figs 3–5; note y -axis scale different for each loading to accommodate all values). As a result, the most accurate estimates of fuel loadings occurred at the lowest, uniformly distributed loading using the finest diameter measurement. Although variability was greatest when fuels were more patchy (i.e. jackpot), it appears that all methods performed approximately the same across all fuel distributions when assessing the mean, especially for the FM method (Fig. 6). The 2-cm diameter class had by far the worst resolution for estimating FWD biomass across all methods, and the traditional and 1-cm diameter class had comparable accuracies for most methods. These are general observations across all three methods and the two techniques; evaluations by method are next.

Planar intercept (PI) method

Considering the long length of all transects (955 m), the PI method did not perform as well as expected with sampled loadings statistically similar to reference loadings for only the measured and 1-cm diameter classes (Tables 3–5; Figs 3–5). A major finding is that it is much better to measure fuel particle intersect diameters at the highest resolution; diameter classes had the least accuracy (Table 3; Fig. 3). None of the measured loadings using the traditional or 2-cm diameter classes were statistically the same as the reference loadings across the twelve combinations of the four reference fuel loads (0.05, 0.1, 0.15 and 0.2 kg m^{-2}) and three fuel distributions (uniform, Table 3; patchy, Table 4; jackpot, Table 5). But when each particle diameter was measured to 0.1 cm, 12 of 12 combinations were statistically the same as the reference fuel loads ($P > 0.05$). And 5 of 12 matched the reference fuel loadings for the 1-cm diameter measurement resolution (Table 6).

PI estimates consistently had low standard errors (s.e. < 0.038) for all techniques and fuel distributions. The highest standard errors were for the highest reference fuel

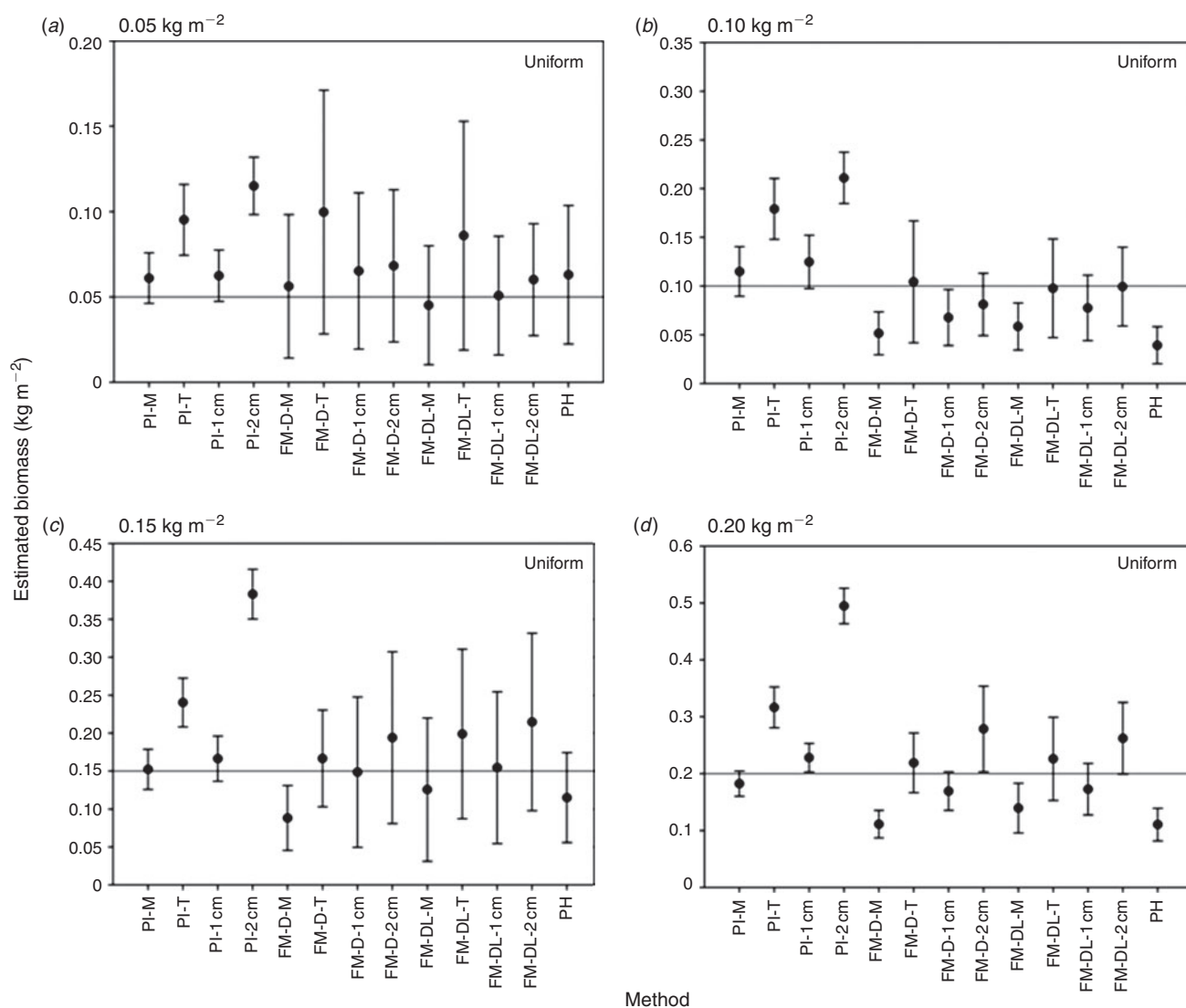


Fig. 3. Performance of all FWD sampling methods and techniques under uniform fuel distributions for the four reference fuel loadings (a) 0.05, (b) 0.10, (c) 0.15 and (d) 0.20 kg m⁻². Sampling methods: PI, planar intercept; FM, fixed-area microplot; PH, photoload. Sampling techniques: D, diameter only; DL, diameter and length; and the diameter size classes: M, measured; T, traditional; 1 cm; 2 cm (Table 1). The whiskers indicate approximately a 95% confidence interval ($P > 0.05$).

loadings with the range for 0.05 kg m⁻² reference load at 7.5×10^{-3} – 12.8×10^{-3} (15–26% of mean) and 2.4×10^{-3} – 38.0×10^{-3} (12–19% of mean) for the 0.2 kg m⁻² reference load. The PI method consistently overestimated loadings, especially as reference fuel loads increased and as the resolution of diameter measurement decreased, regardless of fuel distribution. The PI had lower standard errors than the FM method, and comparable standard errors with the PH method, but the highest disagreements with reference conditions were found with 2-cm diameter class PI method.

Fixed-area microplot (FM) method

The FM method appeared to perform better than PI and PH across most techniques and diameter classes (Tables 3–5; Figs 3–5) even though standard errors were greater. Standard errors were generally higher with heavier fuel loads and coarse

diameter measurement techniques. The FM method produced the most comparable estimates to the 48 reference loading-distribution combinations with 37 agreements for the FM diameter technique and 40 agreements with the FM diameter-length technique compared with only 21 agreements for the PI method (Table 6) (agreements are when measured loads are not statistically different than reference loads across the three fuel distributions). In general, the FM method worked well across all reference fuel loadings, except when particle diameters were actually measured (no agreements for the 0.20 kg m⁻² across the three fuel distributions) (Table 6). The diameter-length technique was somewhat better than the diameter only technique (40 v. 37 agreements) with lower biases and standard errors (Tables 3–5).

Interestingly, coarser diameter class resolutions (2 cm and traditional) performed marginally better than finer diameter classes for both the diameter and diameter-length techniques

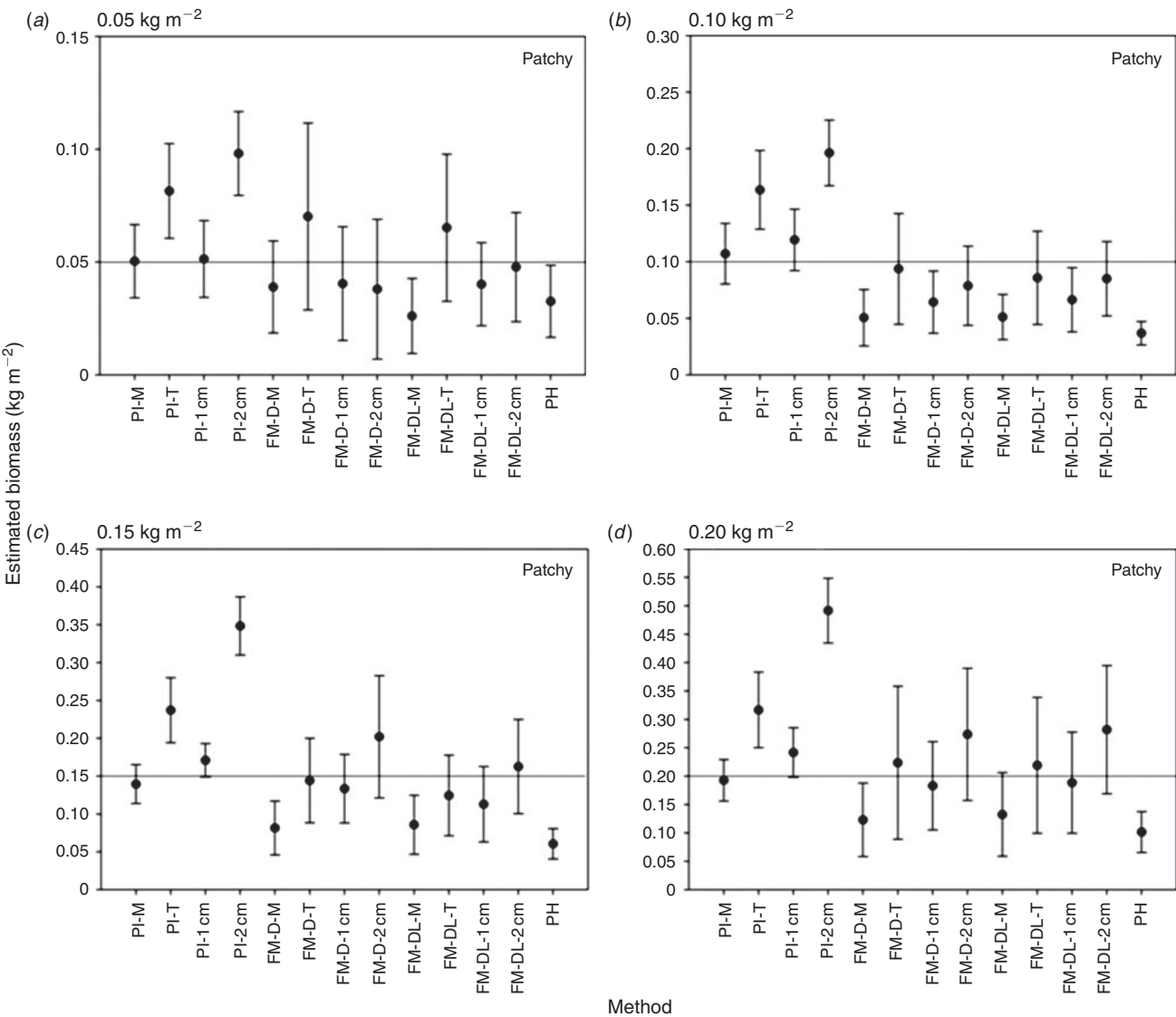


Fig. 4. Performance of all FWD sampling methods and techniques under patchy fuel distributions for the four reference fuel loadings (a) 0.05, (b) 0.10, (c) 0.15 and (d) 0.20 kg m⁻². Sampling methods: PI, planar intercept; FM, fixed-area microplot; PH, photoload. Sampling techniques: D, diameter only; DL, diameter and length; and the diameter size classes: M, measured; T, traditional; 1 cm; 2 cm (Table 1). The whiskers indicate an approximate 95% confidence interval ($P > 0.05$).

(Table 6). There were more than twice as many agreements for the traditional diameter classes (11 and 12) as compared with when diameters were actually measured to the 0.1 cm (4 and 6) for both techniques. However, the coarser diameter classes had the highest standard errors, often double those for the measured diameters (Tables 3–5). Both techniques and the coarsest diameter classes performed well across the entire range of fuel loading, but there was statistically significant underestimation for the higher reference fuel loads when the diameters were measured to 0.1 cm.

Photoload (PH) method

The PH method performed the worst of the three methods with only 3 out of 12 reference fuel loadings for the load-fuel distribution combinations statistically comparable to the visually

estimated fuel loading, both for the lowest fuel reference loading (0.05 kg m⁻²). PH estimates were consistently underestimated as the reference loadings increased with PH estimates only half (0.10–0.12 kg m⁻²) of the highest 0.20-kg m⁻² reference loading. The PH method performed equally poorly across the three fuel distributions in that the estimates are approximately the same regardless of fuel distribution. Even though PH estimates were wrong, they had the least amount of variation (low standard errors), indicating the inability of PH evaluators to properly estimate high fuel loadings using the method.

Discussion

Our results show how difficult it is to measure FWD loadings accurately. We found it takes over 400 m of PI transects and 14 FMs to get biomass estimates that are within 20% of the

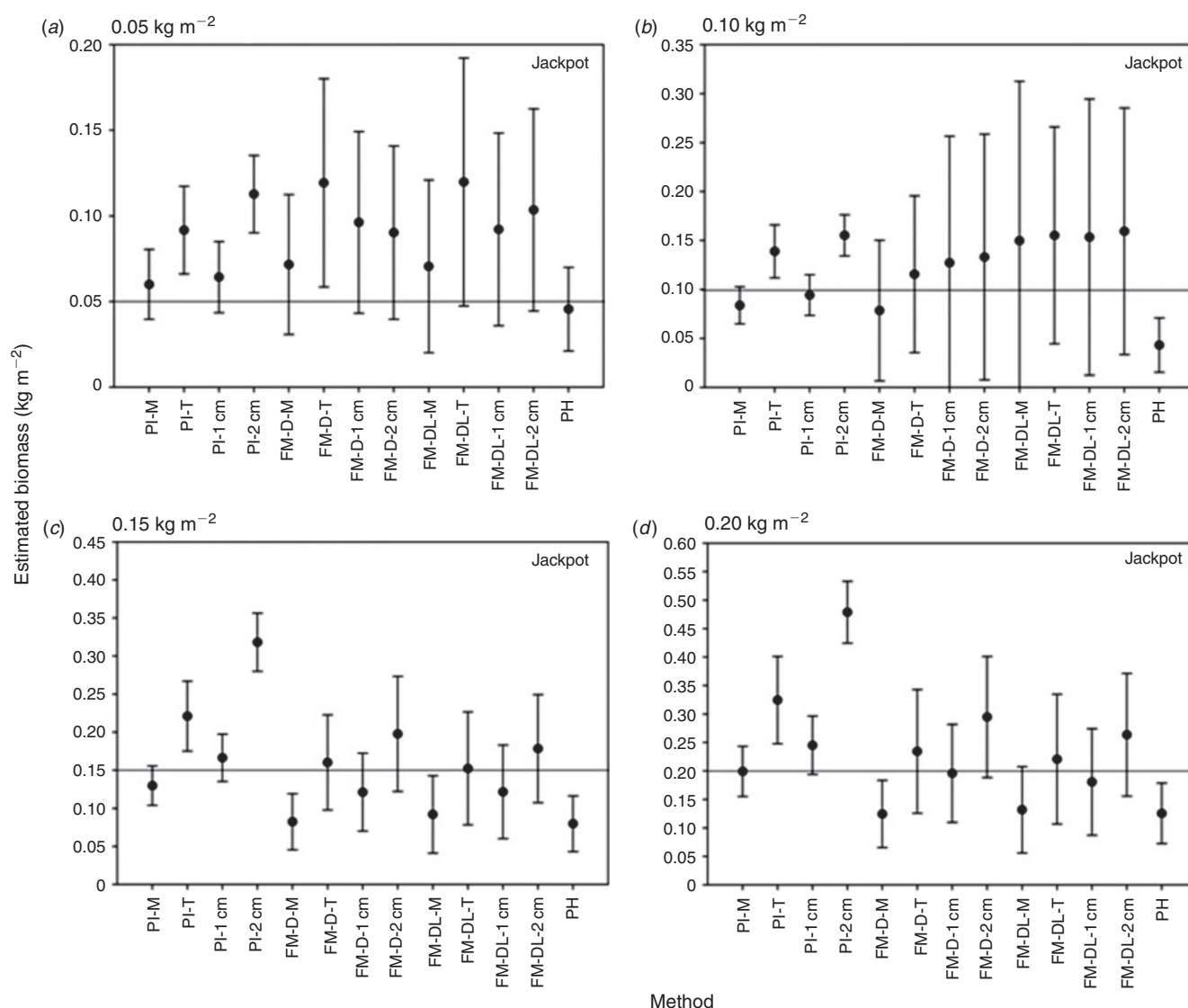


Fig. 5. Performance of all FWD sampling methods and techniques under jackpot fuel distributions for the four reference fuel loadings (a) 0.05, (b) 0.10, (c) 0.15 and (d) 0.20 kg m⁻². Sampling methods: PI, planar intercept; FM, fixed-area microplot; PH, photoload. Sampling techniques: D, diameter only; DL, diameter and length; and the diameter size classes: M, measured; T, traditional; 1 cm; 2 cm (Table 1). The whiskers indicate an approximate 95% confidence interval ($P > 0.05$).

mean (Fig. 7). We also found that PI measurements are less accurate but more precise than FM estimations (Figs 3–5). And, the PH method performed well for low fuel loadings but extensive training is needed to obtain accurate measurement for higher fuel loads. For the PI and FM method, it appears that it is better to measure each fuel particle to the finest resolution (0.1 cm) but 1.0-cm size classes are also acceptable. Paradoxically, this high resolution of measurement does not always guarantee accurate estimations of loading for the FM method. In fact, it appears that using diameter classes for particles in microplots results in small decreases in accuracy. Even the time-consuming measurement of diameters and length of each fuel particle to the nearest 0.1 cm (FM diameter-length technique) (Tables 3–5) did not perform any better than some of the other FM techniques (Fig. 6).

Three major biological factors are responsible for this high level of uncertainty in sampling methods. First, wood density is highly variable both within and across the fuel particles used in this study (Table 2), so the assumption that a mean density adequately represents all particles may be somewhat flawed (Keane *et al.* 2012). We suspect better estimates could have been made if we estimated a density or rot class for each sampled particle. This will also be true for operational sampling designs. Second, woody fuel particles are not cylinders, but rather complicated volumes of highly variable cross-sections and contorted lengths. Therefore, the assumption that a woody fuel particle can be approximated by a frustum using diameters and lengths (Eqn 2) may be oversimplified and our techniques of measuring fuel diameters using rulers and gauges may be too coarse. And last, FWD diameters are not static and often

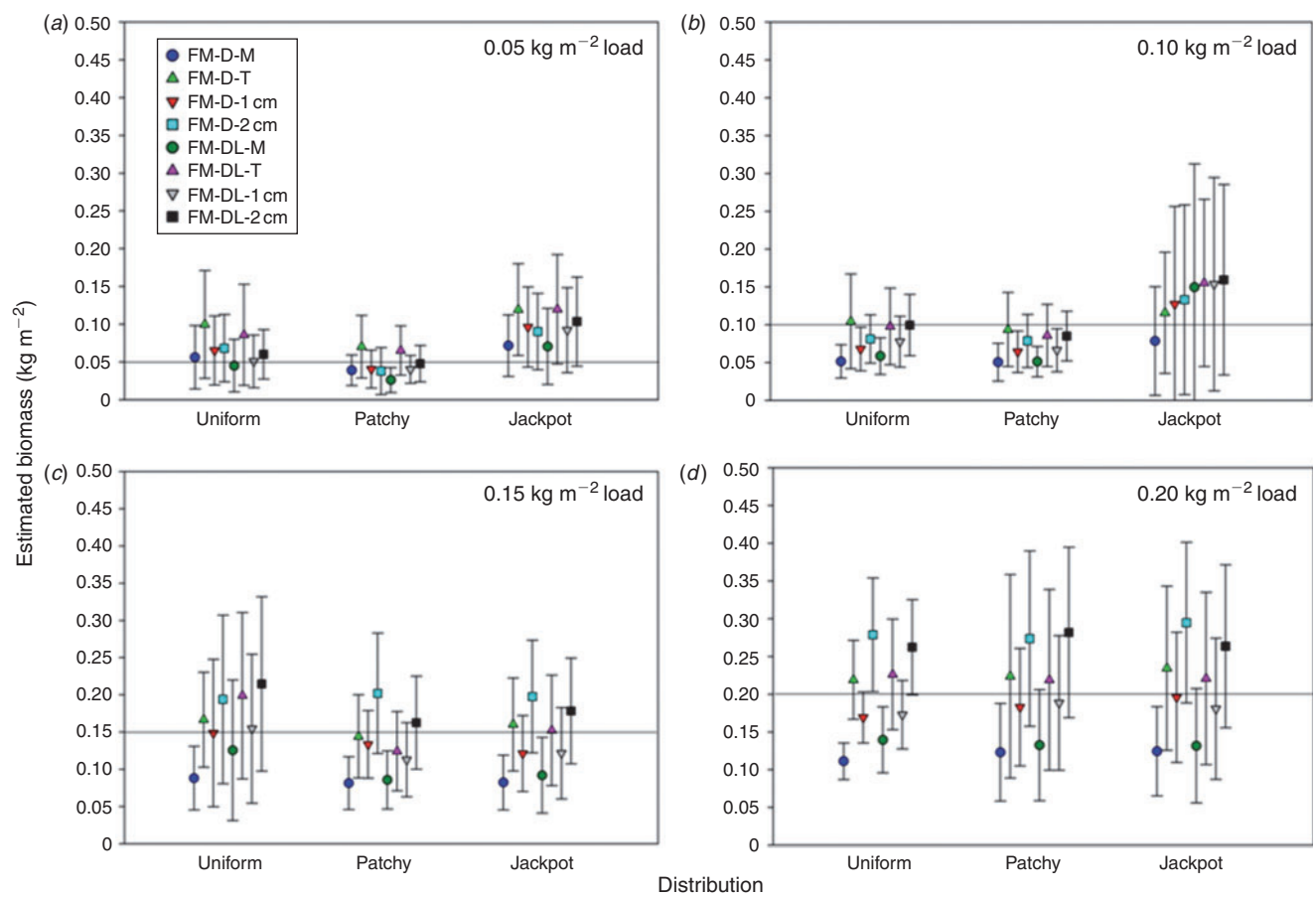


Fig. 6. Performance of the FM (fixed-area microplot) FWD sampling method techniques and diameter classes across the three spatial fuel distributions (uniform, patchy and jackpot) for the four reference fuel loadings (a) 0.05, (b) 0.10, (c) 0.15 and (d) 0.20 kg m⁻². Sampling techniques: D, diameter only; DL, diameter and length; and the diameter size classes: M, measured; T, traditional; 1 cm; 2 cm (Table 1). The whiskers indicate an approximate 95% confidence interval ($P > 0.05$).

Table 3. Estimated loadings for each sampling method, technique and diameter class for each of the reference fuel loadings for the uniform fuel distributions

Numbers in parentheses are standard errors (s.e.) and data in bold are loadings not significantly different from the reference loading ($P > 0.05$). NA, not applicable

Sampling method	Sampling technique	Diameter class	Reference fuel loadings for uniform distribution (kg m ⁻²)			
			0.05	0.10	0.15	0.20
Planar intercept	Diameter	Measured	0.0610 (0.0074)	0.1150 (0.0127)	0.1522 (0.0132)	0.1824 (0.0111)
		Traditional	0.0952 (0.0104)	0.1792 (0.0156)	0.2403 (0.0161)	0.3166 (0.0179)
		1 cm	0.0624 (0.0075)	0.1248 (0.0137)	0.1663 (0.0149)	0.2281 (0.0126)
		2 cm	0.1150 (0.0084)	0.2110 (0.0132)	0.3831 (0.0164)	0.4947 (0.0156)
Fixed-area microplots	Diameter	Measured	0.0562 (0.0210)	0.0515 (0.0110)	0.0881 (0.0214)	0.1112 (0.0121)
		Traditional	0.0997 (0.0357)	0.1044 (0.0313)	0.1666 (0.0319)	0.2190 (0.0262)
		1 cm	0.0652 (0.0229)	0.0678 (0.0144)	0.1486 (0.0495)	0.1692 (0.0169)
		2 cm	0.0682 (0.0223)	0.0812 (0.0160)	0.1939 (0.0566)	0.2786 (0.0377)
	Diameter-length	Measured	0.0451 (0.0174)	0.0585 (0.0121)	0.1255 (0.0472)	0.1394 (0.0219)
		Traditional	0.0859 (0.0335)	0.0978 (0.0253)	0.1989 (0.0559)	0.2261 (0.0366)
		1 cm	0.0508 (0.0174)	0.0776 (0.0168)	0.1545 (0.0500)	0.1728 (0.0227)
		2 cm	0.0601 (0.0164)	0.0995 (0.0202)	0.2147 (0.0585)	0.2622 (0.0315)
Photoloads	NA	NA	0.0630 (0.0203)	0.0393 (0.0095)	0.1150 (0.0296)	0.1105 (0.0144)

Table 4. Estimated loadings for each sampling method, technique and diameter class for each of the reference fuel loadings for the patchy fuel distributions

Numbers in parentheses are standard errors (s.e.) and data in bold are loadings not significantly different from the reference loading ($P < 0.05$). NA, not applicable

Sampling method	Sampling technique	Diameter class	Reference fuel loadings for patchy distribution (kg m^{-2})			
			0.05	0.10	0.15	0.20
Planar intercept	Diameter	Measured	0.0504 (0.0081)	0.1071 (0.0134)	0.1395 (0.0128)	0.1927 (0.0183)
		Traditional	0.0815 (0.0105)	0.1635 (0.0174)	0.2370 (0.0214)	0.3166 (0.0333)
		1 cm	0.0514 (0.0085)	0.1193 (0.0136)	0.1709 (0.0140)	0.2416 (0.0218)
Fixed-area microplots	Diameter	2 cm	0.0981 (0.0093)	0.1962 (0.0045)	0.3484 (0.0192)	0.4915 (0.0285)
		Measured	0.0390 (0.0102)	0.0505 (0.0125)	0.0814 (0.0178)	0.1230 (0.0323)
		Traditional	0.0702 (0.0207)	0.0937 (0.0245)	0.1441 (0.0279)	0.2236 (0.0674)
	Diameter-length	1 cm	0.0405 (0.0126)	0.0643 (0.0137)	0.1334 (0.0227)	0.1828 (0.0389)
		2 cm	0.0380 (0.0155)	0.0787 (0.0175)	0.2020 (0.0404)	0.2735 (0.0581)
		Measured	0.0261 (0.0083)	0.0512 (0.0100)	0.0857 (0.0195)	0.1325 (0.0368)
		Traditional	0.0652 (0.0163)	0.0858 (0.0206)	0.1244 (0.0266)	0.2190 (0.0598)
		1 cm	0.0402 (0.0092)	0.0664 (0.0142)	0.1128 (0.0249)	0.1884 (0.0445)
		2 cm	0.0478 (0.0121)	0.0850 (0.0164)	0.1626 (0.0312)	0.2818 (0.0564)
		Photoloads	0.0326 (0.008)	0.0368 (0.0052)	0.0605 (0.0100)	0.1014 (0.0180)

Table 5. Estimated loadings for each sampling method, technique and diameter class for each of the reference fuel loadings for the jackpot fuel distributions

Numbers in parentheses are standard errors (s.e.) and data in bold are loadings not significantly different from the reference loading ($P < 0.05$). NA, not applicable

Sampling method	Sampling technique	Diameter class	Reference fuel loadings for jackpot distribution (kg m^{-2})			
			0.05	0.10	0.15	0.20
Planar intercept	Diameter	Measured	0.0600 (0.0102)	0.0838 (0.0095)	0.1298 (0.0129)	0.1991 (0.0024)
		Traditional	0.0917 (0.0128)	0.1389 (0.0135)	0.2210 (0.0230)	0.3244 (0.0383)
		1 cm	0.0642 (0.0104)	0.0943 (0.0104)	0.1663 (0.0155)	0.2451 (0.0256)
Fixed-area microplots	Diameter	2 cm	0.1127 (0.0113)	0.1553 (0.0105)	0.3182 (0.0191)	0.4787 (0.0272)
		Measured	0.0716 (0.0204)	0.0785 (0.0359)	0.0823 (0.0184)	0.1244 (0.0295)
		Traditional	0.1193 (0.0304)	0.1156 (0.0400)	0.1602 (0.0312)	0.2344 (0.0543)
	Diameter-length	1 cm	0.0962 (0.0265)	0.1272 (0.0646)	0.1212 (0.0255)	0.1958 (0.0431)
		2 cm	0.0902 (0.0253)	0.1331 (0.0627)	0.1977 (0.0378)	0.2947 (0.0562)
		Measured	0.0705 (0.0252)	0.1497 (0.0813)	0.0920 (0.0254)	0.1317 (0.0379)
		Traditional	0.1198 (0.0362)	0.1552 (0.0553)	0.1523 (0.0371)	0.2208 (0.0570)
		1 cm	0.0921 (0.0281)	0.1535 (0.0705)	0.1216 (0.0307)	0.1806 (0.0467)
		2 cm	0.1035 (0.0295)	0.1594 (0.0629)	0.1783 (0.0355)	0.2635 (0.0539)
		Photoloads	0.0455 (0.0122)	0.0432 (0.0138)	0.0796 (0.0183)	0.1256 (0.0265)

changed with weather conditions, often becoming thicker when wet and cracked when dry, making diameter measurements difficult and further complicating the frustum assumption. Distributions of diameters and lengths are also highly variable across woody particles (see Table 2), but oddly, we found that using the mean diameter and length did not influence FWD sampling accuracies.

The PI method performed adequately in this study but only because we estimated loading from 955 m of transects. The uncertainty of PI estimates certainly increased as the length of measurement went down (Fig. 7) and, as expected, accuracies of PI estimates increased with increased resolution of woody particle diameter measurement (e.g. measured v. traditional). One limitation of this study is that we quantified the variability of PI-derived biomass by averaging across transects, whereas most management applications simply sum all intercepts across

the entire length of sampling transects. The calculated PI variability is highly dependent on the transect length (20 and 25 m in this study) (Brown 1974), so if we had different plot dimensions (Fig. 2) we would have different transect lengths; therefore, different variability estimates. So, the standard errors in Tables 3–5 and Figs 3–5 reflect the specific transect lengths we picked for this study and might have been different if another study design was used.

The FM method, unlike the PI method, had the same or better accuracies when coarser diameter classes were used. This might be explained by the large standard errors involved in each of the loading estimates (Figs 3–5). We originally thought that this was because there weren't enough microplots to fully evaluate the performance of the FM method, but results of the bootstrap variance analysis show that 20 microplots were sufficient (Fig. 7d). Findings of previous studies (Sikkink and Keane 2008;

Table 6. Summary of performance of methods, techniques and diameter classifications across the four reference fuel loadings

Shown are how many of the measured loadings statistically agreed with the reference loading ($P > 0.05$) across the three fuel distributions (uniform, patchy and jackpot). Numbers in parentheses are the average bias (reference loading minus estimated loading) across the three distributions

Sampling method	Sampling technique	Diameter class	Number of agreements to reference loads (bias, kg m ⁻²)				Total agree
			0.05	0.10	0.15	0.20	
Planar intercept	Diameter	Measured	3 (0.007)	3 (0.002)	3 (−0.009)	3 (−0.009)	12 of 12
		Traditional	0 (0.039)	0 (0.061)	0 (0.083)	0 (0.119)	0 of 12
		1 cm	2 (0.009)	3 (0.013)	3 (0.018)	1 (0.038)	9 of 12
		2 cm	0 (0.059)	0 (0.088)	0 (0.200)	0 (0.288)	0 of 12
	Totals		5	6	6	4	21 of 48
Fixed-area microplots	Diameter	Measured	3 (0.006)	1 (−0.040)	0 (−0.066)	0 (−0.080)	4 of 12
		Traditional	2 (0.046)	3 (0.005)	3 (0.007)	3 (0.026)	11 of 12
		1 cm	3 (0.017)	1 (−0.014)	3 (−0.016)	3 (−0.017)	10 of 12
		2 cm	3 (0.015)	3 (−0.002)	3 (0.048)	3 (0.082)	12 of 12
	Totals		11	8	9	9	37 of 48
	Diameter-length	Measured	2 (−0.003)	1 (−0.014)	1 (−0.049)	2 (−0.065)	6 of 12
		Traditional	3 (0.040)	3 (0.013)	3 (0.009)	3 (0.022)	12 of 12
		1 cm	3 (0.011)	2 (−0.001)	3 (−0.020)	3 (−0.019)	11 of 12
		2 cm	3 (0.020)	3 (0.015)	3 (0.035)	2 (0.069)	11 of 12
	Totals		11	9	10	10	40 of 48
	Photoloads		2 (−0.003)	0 (−0.060)	1 (−0.065)	0 (−0.088)	3 of 12

Keane *et al.* 2012) also indicated that 20 microplots would be enough to quantify the variation. Similar to the PI method, the variability of FM estimates would have been different if different sized microplots were used; standard errors would probably have been lower if the microplot area was 4 m² rather than the more commonly used 1 m², which was used in this study because more FWD particles would have been measured (Sikkink and Keane 2008; Keane *et al.* 2012). FM methods are accurate but not precise (highly variable) because of the heterogeneous spatial distribution of FWD (Fig. 6), especially at high loadings.

The PH method did not perform as well as expected in this study. It performed well under low fuel loading conditions and under uniform fuel conditions, but its accuracy declined as loadings increased above 0.1 kg m⁻². This finding is quite different from that found by Sikkink and Keane (2008) where PH estimates were as good if not better than PI methods. This is probably due to the inability of technicians to properly assess high fuel loading conditions and a mismatch of wood densities in the photographed particles and the particles used in this study. We used many technicians to evaluate fuel loadings but most had received minimal training viewing mostly low fuel loading conditions in the field. Additional training and more visual calibration, especially for high fuel loads, would surely have increased PH accuracy (Keane and Dickinson 2007a). This is the major limitation of the PH method (Sikkink and Keane 2008); however, there are other limitations as well, including the inability of the method to (1) increase resolution in diameter classes without creating a new set of pictures, (2) adjust for changes in particle wood density and (3) account for differing accuracies across users. In contrast, PH estimates could be completed in a fraction of the time it took for all the other techniques (informal estimates range from 5–25 times faster). Perhaps it could be integrated with PI and FM methods to fit research and management objectives provided extensive training is available.

Summary and management implications

Results from this study indicate that the way to increase the accuracy of PI, FM and PH FWD biomass measurements is to increase sampling intensity by increasing the lengths of transects or number of microplots, and also by finely measuring particle diameters. The best way to obtain accurate PH FWD load estimates is to extensively train field crews (Holley and Keane 2010). Results from the often used PI method indicate that transect sampling lengths should be increased to over 400 m within a stand or plot to get the variability of the estimate below 20% of the mean. Current guidelines specify only 50–150 m of transect length for CWD and ~10–20 m for FWD, and although this low sampling intensity might provide the resolution needed for most management decisions and the fire models, more intensive sampling might be needed to more accurately estimate loadings for research and some important fire management concerns such as smoke, fuel consumption and carbon inventories. Our results also indicate that fewer transects are needed when sampling higher fuel loads to get within 20% of the mean, but there is also a greater variability, and it is probably best to have the same sampling lengths be used for all fuel loading conditions. We also suggest that FWD particle diameters be individually measured to the nearest millimetre if possible but no coarser than 1.0 cm to ensure accurate FWD biomass estimates. Traditional diameter classes always resulted in erroneous biomass estimates.

The FM method appears to be a desirable method for obtaining accurate FWD biomass estimates, even though it has higher variabilities around the mean (less precise). It is recommended because it can easily be adjusted to reduce sampling times without compromising accuracy; it appears that estimating diameters to diameter classes has the same or better accuracies than actually measuring the diameters (Figs 3–5), which is a different result from PI. Second, FM methods and

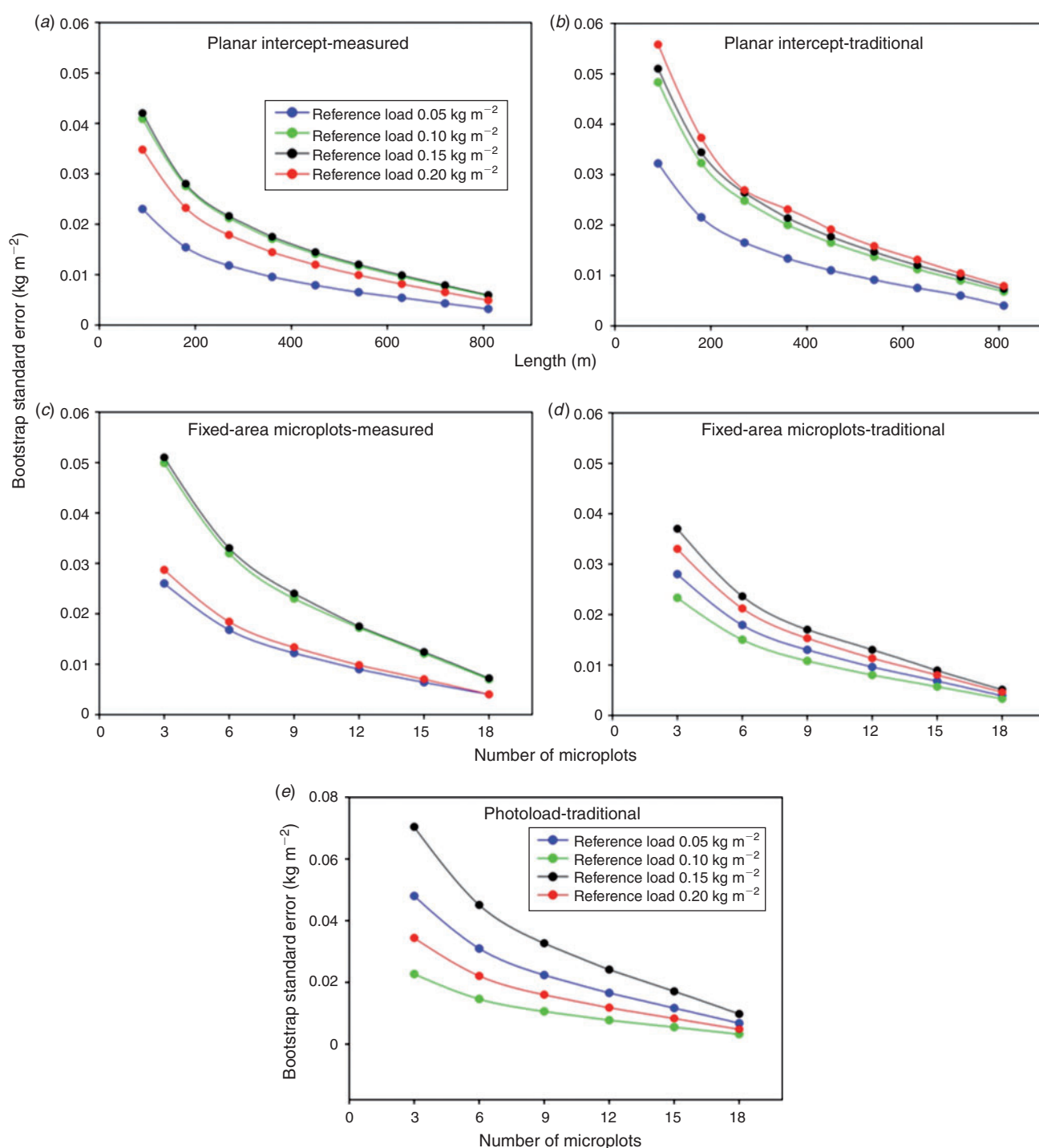


Fig. 7. Relationship of bootstrap standard error to distance (m) for four reference fuel loadings (0.05, 0.10, 0.15 and 0.20 kg m⁻²) for only the uniform fuel spatial distribution to sampling intensity for the (a) planar intercept (PI) with diameters measured technique, (b) PI using traditional size classes, (c) fixed-area microplots (FM) with diameters measured technique, (d) FM using traditional size classes and (e) photoload (PH) microplots for traditional size classes.

techniques had mean estimates that were closer to the reference loading than any other method (Table 6). In addition, the fixed-area design of FM makes it much easier to design sampling protocols that are (1) easily integrated with other fixed-area sampling designs (e.g. collect fuels data on large circular plots

used to collect tree data for canopy fuels), (2) appropriately scaled to the spatial distribution of fuels (FWD are distributed at smaller scales than CWD; Keane *et al.* 2012), (3) flexible enough to sample other fuels characteristics, such as shrub, herb and litter loadings (Keane *et al.* 2012), (4) expandable to

incorporate other fuel sampling methods such as PHs and (5) quicker and easier than PI (see Discussion).

We did not formally keep track of the time it took to perform the measurements for each method in this study because it greatly changed with sampling technique, diameter class employed, field technician, weather conditions and fuel loading. However, after all measurements were concluded, we informally estimated that it took ~11 min per PI transect and 12 min per FM to measure individual diameters of particles and 1 min per PH microplot, resulting in 220 min for optimal PI sampling (400 m; Fig. 7), 168 min for optimal FM sampling (14 microplots) and ~14 min for optimal PH sampling (14 microplots). Operational sampling will be anywhere from 10–50% of these estimates depending on sampling objective. Therefore, from these coarse time estimates and other study results, fuel specialists should be able to design FWD sampling strategies that balance accuracy with available resources, sampling experience, fuel loading conditions and management objectives.

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