CSIRO PUBLISHING

www.publish.csiro.au/journals/ijwf *International Journal of Wildland Fire* **2008**, *17*, 363–379

A comparison of five sampling techniques to estimate surface fuel loading in montane forests*

Pamela G. Sikkink[A,C] *and Robert E. Keane*[B]

[A]Systems for Environmental Management, PO Box 8868, Missoula, MT 59807, USA.
[B]USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, 5775 W US Highway 10, Missoula, MT 59808, USA.
[C]Corrresponding author. Email: pgsikkink@fs.fed.us

Abstract. Designing a fuel-sampling program that accurately and efficiently assesses fuel load at relevant spatial scales requires knowledge of each sample method's strengths and weaknesses. We obtained loading values for six fuel components using five fuel load sampling techniques at five locations in western Montana, USA. The techniques included fixed-area plots, planar intersect, photoloads, a photoload macroplot, and a photo series. For each of the six fuels, we compared (1) the relative differences in load values among techniques and (2) the differences in load between each method and a reference sample. Totals from each method were rated for how much they deviated from totals for the reference in each fuel category. The planar-intersect method, which used 2.50 km of transects, was rated best overall for assessing the six fuels. Bootstrapping showed that at least 1.50 km of transect were needed to obtain estimates that approximate the reference sample. A newly developed photoload method, which compared fuel conditions on the forest floor with sets of pictures calibrated for load by fuel type, compared well with the reference and planar intersect. The commonly used photo series consistently produced higher mean load estimates than any other method for total fine woody debris (0.05–0.20 $kg\,m^{-2}$) and logs (0.50–1.25 $kg\,m^{-2}$).

Additional keywords: fuel inventory, fuel sampling, line intersect, photoload, photo series.

Introduction

The design, implementation, and evaluation of successful fuel management activities ultimately depend on the accurate inventory and continual monitoring of the fuel loadings in forest and rangeland ecosystems (Laverty and Williams 2000). Picking the proper method to sample biomass of different types of fuels, however, requires extensive knowledge of the advantages and disadvantages of each sampling technique and expertise in how to properly modify each protocol to fit appropriate spatial scales or applications. Over the past 50 years, several distinct types of fuel sampling techniques have been developed to sample downed woody debris and to estimate fuel load. Determining how well each sampling technique assesses fuels under a variety of fuel conditions and spatial scales is critical to designing efficient sampling projects that assess the effects of fire exclusion, predict fire behaviour, evaluate wildlife habitat, and restore altered landscapes.

Historically, fuel load sampling procedures have ranged in scope from simple and rapid visual assessments to highly detailed measurements of complex fuelbeds along transects or in fixed areas that take considerable time and effort. The most common visual assessment technique is the photo series method that was initially developed by Maxwell and Ward (1976) and implemented by Fischer (1981*a*) and Ottmar *et al*. (2000). In the photo series method, fuel loads for disparate forests and rangelands are photographed using oblique photographs; then the forest and rangelands settings are sampled and quantified (e.g. Fischer 1981*b*; Sandberg *et al*. 2001). Theoretically, the load values can then be applied to sites that appear visually similar. Fuel loads in new study areas are estimated by visually matching observed fuelbed conditions with these photographs.

In contrast to the photo series, the transect, planar intersect, and fixed-area methods require significantly more time and effort to implement because downed woody debris is actually counted. The *line transect* method was originally introduced by Warren and Olsen (1964) and made applicable to measuring coarse woody debris by Van Wagner (1968). It is an adaptable technique that is rooted in probability-proportional-to-size concepts. Several variations on the original technique 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 *planar-intersect* method is a variation of the line-transect method that was developed specifically for sampling fine and coarse woody debris in forests (Brown 1971, 1974; Brown *et al*. 1982). It has the same theoretical basis as the line transect (Brown *et al*. 1982), but it uses sampling planes instead of lines. The planes are somewhat adjustable to plot scale

*The use of trade or firm names in the current paper is for reader information and does not imply endorsement by the US Department of Agriculture of any product or service. This paper was written and prepared by US Government employees on official time; therefore, it is in the public domain and not subject to copyright.

10.1071/WF07003 1049-8001/08/030363

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 planar- intersect method has been used extensively in many inventory and monitoring programs because it is relatively fast and simple to use (Busing *et al*. 1999; Waddell 2002; Lutes *et al*. 2006). It has also been applied in research because it is considered an accurate technique for measuring downed woody fuels (Kalabokidis and Omi 1998; Dibble and Rees 2005). In contrast to the probability-based methods, the *fixed-area* or *quadrat methods* are based on frequency concepts and have been adapted from vegetation studies to sample fuels (Mueller-Dombois and Ellenberg 1974). In fixed-area sampling, a round or rectangular plot is used to define a sampling area and all fuels within the plot boundary that meet a specified criteria are measured using methods that range from destructive collection to volumetric measurements (i.e. length, width, diameter). Because fixed-area plots require significant investments of time and money, they are more commonly used to answer specific fuel research questions rather than to monitor or inventory management areas.

In recent years, several new methods of assessing fuel loading have been developed to sample fuelbeds in innovative ways. The *photoload 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 2007*b*). The *stereoscopic vision technique* builds on the photo series by using computer-image recognition to identify large woody fuels from stereoscopic photos and compute loading volume (Arcos *et al*. 1998; Sandberg *et al*. 2001). *Transect relascope*, *point relascope*, and *prism sweep sampling* use angle gauge theory to expand on the line-transect method for sampling coarse woody debris (Stahl 1998; Bebber and Thomas 2003; Gove *et al*. 2005). *Perpendicular distance sampling* (Williams and Gove 2003) uses probability proportions to estimate log volumes without actually collecting detailed data on all log lengths and diameters. Several comparisons have been done between the traditional sampling techniques and these more contemporary methods to evaluate their performance, accuracy, and bias in measuring coarse woody debris (Delisle *et al*. 1988; Lutes 1999; Bate *et al*. 2004; Jordan *et al*. 2004; Woldendorp *et al*. 2004). However, no studies have yet examined the performance of various sampling techniques for measuring across multiple fuelbed components, such as combinations of fine and coarse woody debris, live and dead shrubs, and herbs on the forest floor – all of which are very important to flammability, inventory and monitoring of vegetation and fuels, and wildlife studies.

In the present paper, we explore how five diverse sampling techniques compare in their ability to assess shrub, herb, and downed woody debris loading. These techniques include: (1) the fixed-area strip plot; (2) the planar intersect; (3) photoloads; (4) a rapid-assessment version of photoloads that we call the photoload macroplot; and (5) photo series. We evaluated each technique based on: (1) how well its estimated load compared with a reference sample; (2) how much time was required to complete sampling; and (3) how much training was needed to implement the technique. Our goal is to provide a guide to the tradeoffs involved in using each of these fuel load sampling techniques and provide suggestions for matching the appropriate sampling method to resource- and fire-management applications.

Methods

For the present study, we limited our comparisons to downed dead woody surface debris, shrubs, and herbs because these elements are normally evaluated in most of the fuel sampling techniques and each is an important input to fire simulation models (Rothermel 1972; Albini 1976; Reinhardt *et al*. 1997). The downed woody debris was divided into four commonly accepted USA size classes (Fosberg 1970):

- Fine Woody Debris (FWD)
  - 1-h fuels – particles with diameters <0.64 cm (<0.25 inches) in diameter (1-h refers to the number of hours it takes debris of this size to dry enough to reach equilibrium moisture content)
  - 10-h fuels – particles between 0.64 and 2.54 cm (0.25–1.00 inches) in diameter
  - 100-h fuels – particles 2.54 to 7.62 cm (1–3 inches) in diameter
- Coarse Woody Debris (CWD)
  - 1000-h fuels consisted of fuel components >7.62 cm (>3 inches) in diameter. This class included all logs.

We also examined two other fuel components – shrub and herbaceous fuels – that included both live and dead plants. We did not evaluate the methods for estimating duff and litter loading because these components required additional time to sample properly and the methods normally used to sample them are quite different than those used in the present study.

We selected five sites on the Ninemile District of the Lolo National Forest in western Montana, USA (47°5′N, 114°12′W) to compare sampling methods for these six fuel components. The dominant overstorey at four of the sites was *Pinus ponderosa*. Tree cover ranged from 30 to 40%. Sites C1, S3, and K4 had 50–70% grass coverage in the understorey, which included mainly *Festuca scabrella* (C1) or *Calamagrostis rubescens* (S3, K4). Site C2 had <50% grass and herbaceous cover with the understorey dominated by *Balsamarhiza sagittata* and *F. scabrella.* Only site K4 had abundant shrubs (50% cover). Sites C1 and S3 had experienced some type of fuel reduction activity, but sites C2 and K4 represented natural fuel conditions. The fifth site, M5, was dominated by *Larix occidentalis*. Its understorey consisted mainly of *Berberis repens*. M5 was logged in 2004 and sampled for fuels in 2005 so slash was still abundant on the site. Together, these five sites adequately represented a range of fuel loads commonly found in montane forests of the northern Rocky Mountains (Fig. 1*a*, *b*).

At each site, we established a single 50 × 50-m permanently marked square plot in an area that was representative of typical forest conditions at the site. We refer to this large sampling area as ‘macroplot’ or ‘site’ throughout the present paper. Each macroplot was aligned with its outer edges oriented along the cardinal directions and then divided from north to south and east to west into twenty-five 10 × 10-m grid cells (hereafter referred to as subplots) (Fig. 2). Four different sampling areas were established within the plot’s grid. The size and arrangement of each sampling area were dictated by the requirements of the

Fig. 1. Range of fuel loads examined with five sampling techniques in the present study. (*a*) Site C1 with mostly fine fuels, herbs, and grass; and (*b*) site M5 with abundant logs.

five sampling techniques that were tested. Sampling occurred in the following order on each macroplot: (1) planar transects, (2) photoload microplots, (3) photoload macroplot, (4) photo series, (5) fixed-area plot, and (6) reference clipped sample. Although it is difficult to design a field-sampling plot structure that provides an objective and fair comparison of the sampling methods without any site or procedural bias, the protocols that follow were a compromise that accommodated all the types of

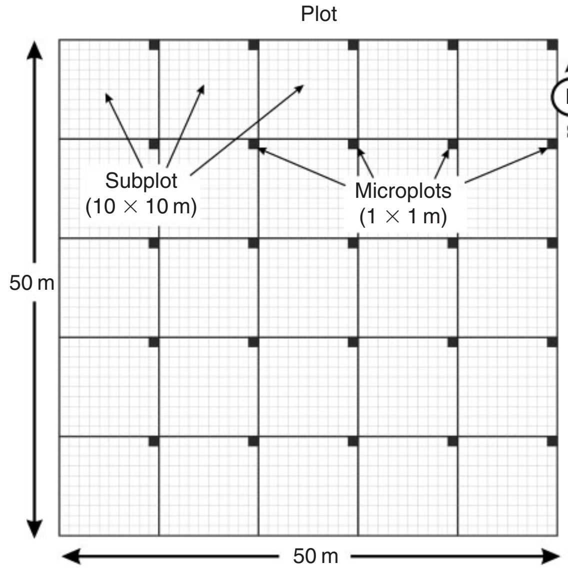

Fig. 2. Sample layout of the macroplot divided into subplots with microplots placed in the north-east corner of each subplot.

sampling for the downed woody debris and herbaceous material investigated in the current study.

Sampling techniques for the reference sample

Creating the perfect reference sample design that captured actual loadings by the six components for each sample site was logistically impractical because we did not have the resources to clip, collect, and weigh all the herb, shrub, and woody fuels within the 2500-m^2 plot and we could not handle the large volume of heavy and unwieldy log material in our laboratory. Therefore, we subsampled four woody size classes and ground cover components using nested microplots (Fig. 2). In the north-east corner of each subplot, we established a 1 × 1-m microplot using a plot frame made out of 1.9 cm of plastic PVC pipe (Fig. 2). Within the twenty-five 1 × 1-m microplots, we collected all of the FWD and clipped and collected all of the aboveground living and dead shrub and herbaceous material. Because this method of sampling was destructive, it was done only after data collection for all other sampling methods was completed. Only material that fell within microplot boundaries was collected. If it extended beyond the boundary, it was cut off and the in-plot portion collected. We sorted shrub, herb, and FWD by size class into labelled paper bags in the field, brought all samples back to the laboratory to be oven-dried for 3 days at 90°C, and finally weighed each to the nearest milligram. The average of the 25 microplot samples by size class constituted the loading estimates for FWD, shrub, and herbaceous material in each plot.

For the 1000-h fuels, or CWD, we measured the small-end diameter, large-end diameter, and length of each piece of debris greater than 7.62 cm that fell within each of the 25 subplots to get a 100% inventory of all logs on each site. If a log extended beyond a subplot boundary, the ends were measured at the boundary to calculate only the in-plot portion. We also assigned a decay class (i.e. classes 1 to 5) to each log using FIREMON guidelines (Lutes *et al*. 2006).

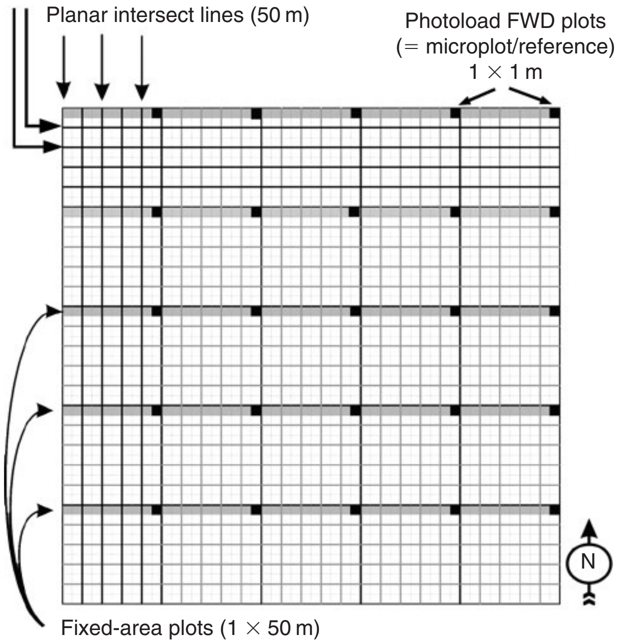

Fig. 3. Sample design for fixed area, planar-intersect, and photoload methods within each site. Fixed-area strip plots were established along the northern subplot edge using a width of 1 m. Planar intersect transects were 2 m apart in the north–south and east–west directions. Photoload fine woody debris (FWD) was assessed in the same microplots that were used to collect the reference fuel loads.

Sampling techniques for other tested methods

Five strip plots (1 × 50 m) were established at each site to assess the *fixed-area plot technique* (see Fig. 3 for placement). The FWD within each strip was sampled by measuring the length of each fuel particle (cm) by 1-h, 10-h, and 100-h diameter size classes within each subplot. The total lengths of debris for all subplots were then summed by size-class to get totals for the entire macroplot. The five strips effectively sampled 10% of the area at each site. Some portions of strip plots had such heavy fuel accumulations (i.e. the fine woody fuels were greater than 100 particles m^{-1}) that it was impractical to measure every fuel particle in each diameter size class; therefore, we counted all fuel particles and multiplied by an estimated average length for each particle in each subplot strip to get total length to use in the loading calculations. Lengths for the 100-h fuels and dimensions of all CWD (small- and large-end diameters and length) were always measured, never estimated, within the strip.

The sampling design for the *planar-intersect technique* used 52 line transects that were each 50 m long to estimate fuel loadings within the base plot. The beginnings and ends of each of these transects were located systematically at 2 m intervals along the outside edges of the plot (see Fig. 3). We tried to minimise bias from systematic sampling by taking the 1-h, 10-h, and 100-h samples in different 10-m sections along each of the 52 lines. The sampling plane was 2 m high with the bottom located at the base of the litter layer. For the 1-h and 10-h fuels, we assessed loading by counting the number of intersections crossing the sampling plane in 5-m sections along each of the 52 transects. For the 100-h fuels, we counted the number of intersections along 10 m of plane length and then summed all subplot values to get plot totals. For the 1000-h fuels, we recorded the diameter and rot class of each log at the point where it intercepted the sampling plane for the entire transect length (50 m). To keep sampling protocols consistent among sites, all planar-intersect sampling was guided by procedures detailed in FIREMON (Lutes *et al.* 2006). Shrub and herbaceous sampling were not applicable to planar-intersect techniques.

The development and evaluation of the *photoload sampling method* are discussed in detail in Keane and Dickinson (2007*a*). We invited 29 participants to visually estimate loadings of our six fuel classes using the photoload technique. Estimates were made within the same 1 × 1-m microplot that was used for the reference fuel sampling. Each participant was asked to match the fine-fuel, shrub and herb loading conditions that he or she observed within each of the 25 microplots to conditions portrayed in a set of downward-looking photographs of fuelbeds showing graduated picture sequences of increasing load (Fig. 4*a*). For the 1000-h fuels, each participant was asked to estimate load at the subplot ($10 \times 10\,\mathrm{m}^2$) scale, instead of the microplot, because the subplot best matched the scale of the photoload log pictures (Fig. 4*b*). We recorded the total time it took each participant to complete their photoload estimate of all six fuel components on all 25 microplots at each site. This time was used as a measure of efficiency for the technique. The participants varied in fuel sampling experience from those with little or no prior experience measuring fuel loads to those with extensive experience in all phases of fuel sampling. Each was given a 2-h training session in applying the photoload technique and in using the photoload pictures to estimate both fine and coarse fuels. There was not an established crew that worked all five sites together nor were the numbers of participants measuring loads constant from site to site.

In addition to applying the photoload technique on the microplots, as described above, the same participants were asked to estimate fuel loading within the entire macroplot (50 × 50 m) using two related visual-assessment methods. First, each participant used the photoload sequences to estimate one loading value for each woody size class using a general walk-through of the macroplot, which will be referred to in the current paper as photoload macroplot estimates. Next, they were asked to estimate loadings using the Fischer photo series (Fischer 1981*a*), which was specifically created for estimating downed woody debris in western Montana forests. Participants walked the entire macroplot and tried to determine which of the oblique photos most closely matched the observed downed woody debris conditions. Loadings were assigned to each fuel component using summaries presented by Fischer (1981*a*) for each selected photo. The photo series technique did not assess shrub and herb loadings.

Calculating loadings for comparative analysis

Reference plots

We standardised the reference loads for 1-h, 10-h, 100-h, live and dead herb, and live and dead shrub from each microplot to the base plot by summing the weights from the laboratory analysis of samples from each microplot by size class and dividing the total weights by total microplot area. For the 1000-h debris class, the weight of each log greater than 7.62 cm in diameter was computed from its volume and its density. Volumes were calculated as follows:

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

where a_s is the cross-sectional area (m^2) of the small end of the log, a_l is the cross-sectional area of the large end (m^2), and l is the length (m) (Keane and Dickinson 2007*a*). We used $400\,\mathrm{kg\,m^{-3}}$ for the density of sound logs in decay classes 1, 2, and 3, and $300\,\mathrm{kg\,m^{-3}}$ for the density of rotten logs in decay classes 4 and 5 because Brown (1974) suggested these densities for coniferous forests based on experimental work in wood specific gravity. The 1000-h loadings were also standardised to the base plot by summing the individual log weights and dividing the total weight by the total plot area ($2500\,\mathrm{m}^2$). These log loadings and the total loadings for fine woody debris, shrubs, and herbs from the laboratory analyses were combined to represent our 'actual' loadings for each site. The values became our reference dataset to evaluate the performance of all other tested methods on the plot.

Choosing an appropriate wood density value was an important decision for calculating the reference loading values and the load values for the other methods tested in the present study. Many of the traditional methods for measuring load assumed that the density of fuel ($\mathrm{kg\,m^{-3}}$) was constant across all size classes and species but different across various classes of decay (Brown 1974). However, research has shown that there are significant differences in fuel wood density between different species, rot classes, and size classes (van Wagtendonk *et al.* 1996). Even though we measured site-specific wood densities for each of our sites (Keane and Dickinson 2007*a*), we did not have the proper equipment (i.e. a Kraus Jolly specific gravity balance) to get reliable density estimates for the FWD components. Therefore, we decided to use Brown's (1974) density values in all load calculations, which allowed us to focus on results that were due to differences among methods, rather than due to differences in density values for each technique.

Other sampling methods

Weights of the 1-h, 10-h and 100-h woody fuel particles for each 50 × 1-m strip plot were calculated using the same volume–density procedure described above. The weights were summed across all twenty-five 10-m sections and then divided by total strip plot area (i.e. (50 × 1-m strip) × 5 strips = $250\,\mathrm{m}^2$) to get loading values ($\mathrm{kg\,m^{-2}}$) for the entire macroplot. The diameter of the fine woody fuel particles was the midpoint of each size class. The large- and small-end diameters were considered equal. The length was the total measured length of debris in each size class.

We followed the procedures detailed in Brown (1971, 1974) to calculate downed woody fuel loadings for the planar-intersect method. For most FWD calculations, we chose the average quadratic mean diameter (non-slash) values based on the dominant overstorey tree at the site (see table 2 of Brown 1974). For FWD on site K4, we used the composite value for mixed-species overstorey. We also used Brown's (1974) density values for each size class.

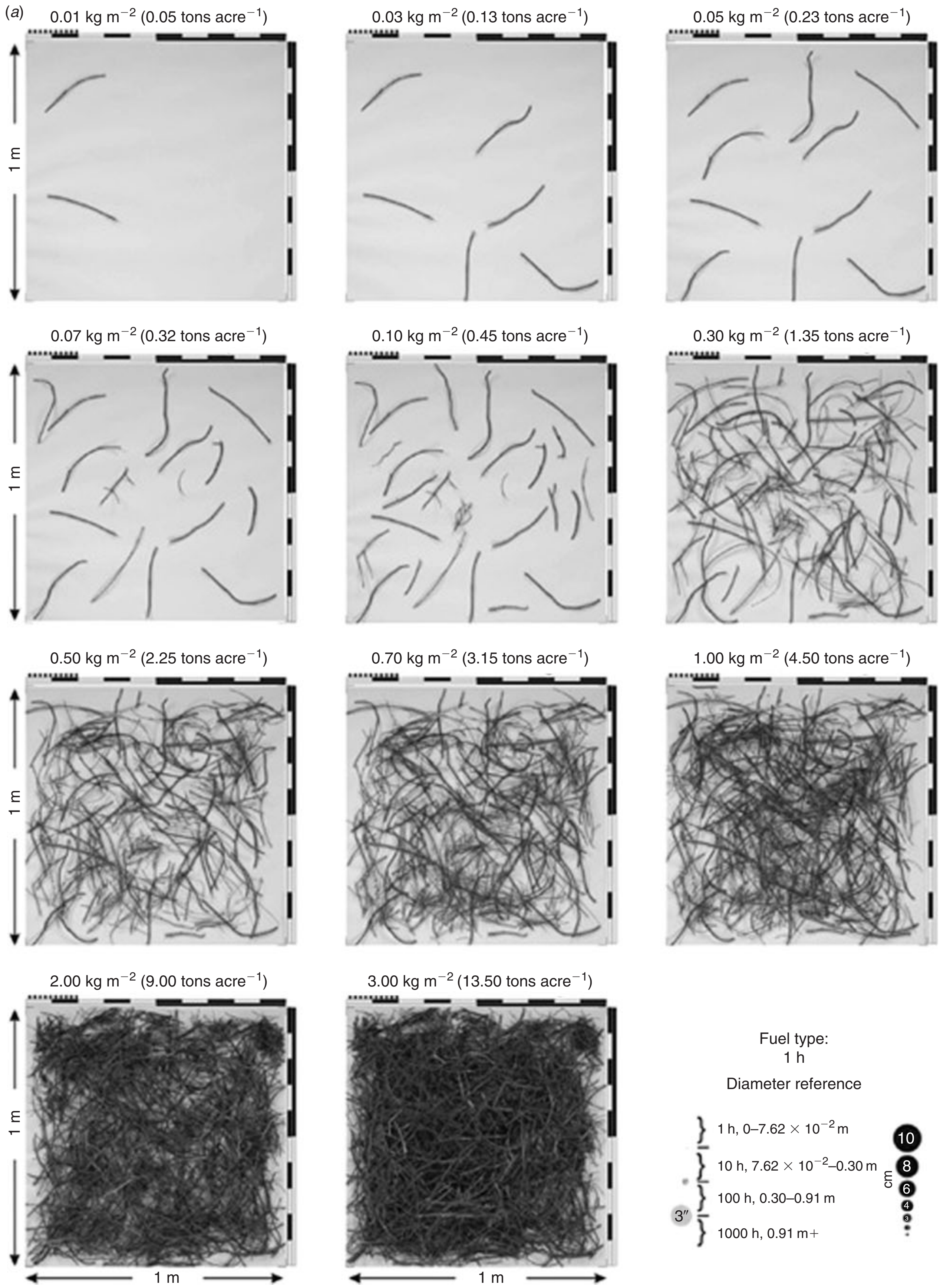

Fig. 4. Examples of photoload sequences for (*a*) microplot estimation of 1-h fuels and (*b*) subplot estimations of 1000-h fuels (reprinted from Keane and Dickinson 2007*b*).

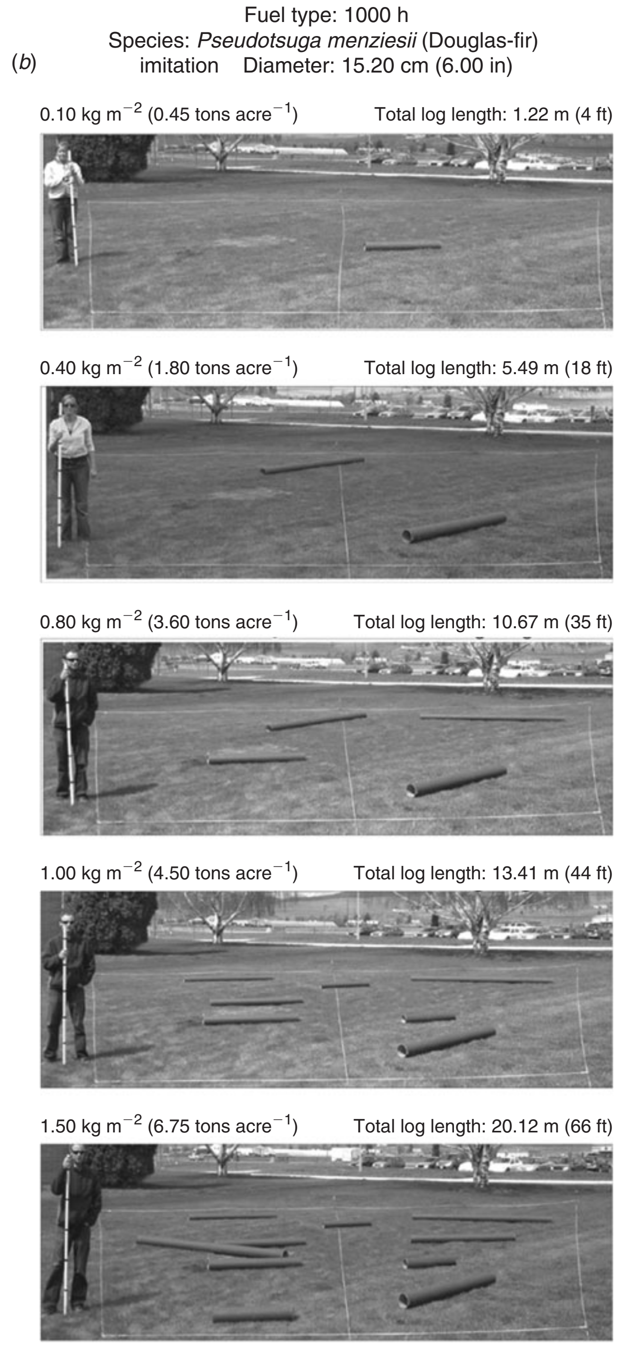

Fig. 4. (*Continued*)

Loading values for all of the photo-based techniques were calculated in similar ways. Load estimates made at each microplot were averaged for the photoload method using estimates made by all participants at each site. Site totals were obtained by summing the average values for each microplot by fuel class. Range was also computed to show the variation in loading estimates at each site. Estimates by all participants at each site were also averaged to obtain loading values for each photoload macroplot. For the photo series method, loadings were assigned to each component based on each participant's photo choice and then averaged by site.

Statistical comparisons

Statistical comparisons in the present study needed to account for two major issues: (1) the different sampling scales used for each method; and (2) the non-normal distribution of collected data for most fuel classes. To address the differences in sampling scales used for each method, the measured loadings from the reference sample and estimated loadings from the five sampling techniques were all standardised to the macroplot level by site as described in the previous section. To address the non-normal distribution of debris, we used two different procedures. The first procedure was used only to test (i) how expertise affected estimates in the photo-based methods and (ii) how a sample method affected estimates in individual fuel classes (e.g. 1-h fuels) without separating the fuels by site. We tested each fuel class for normal distribution and homogeneity of variance using Q-Q normal plots and Levene's tests (Levene 1960). Data were transformed to natural log values in all fuel classes except 10-h fuels to comply with parametric assumptions of the analysis of variance (ANOVA) and Tukey's B tests. Log-transformations of the 10-h fuel loadings only increased the lack of homogeneity, so we used the raw data for these comparisons. We used a second procedure for tests on how the quantity of fuel load at each site affected the estimates obtained using each sampling method. The difference between a site's reference sample and a method's estimate were computed from actual load data for each of the six fuel types and for total FWD and CWD. The 1-h, 10-h and 100-h fuels were grouped as FWD. The 1000-h fuels constituted the CWD. We calculated a mean error and standard deviation for the FWD, CWD, shrubs, and herbs from the difference values. We calculated between- and within-methods standard deviations for the overall project using a one-way analysis of variance (ANOVA) with site as the analysis factor. All statistical comparisons in the current study were considered significant if P was <0.05.

Determining which method might be appropriate for different sampling applications was most easily evaluated using a rating scale. Ratings were assigned to each method based on how closely its loading values matched the reference sample. Ratings ranging from 1 to 5 were given for total FWD, the 1000-h fuel class, and the total loading on site. Shrub and herb loadings were not included individually in the rankings because their loadings were sampled in only three of the five methods. Loadings that differed least from the reference sample were given a '1', sites that were second-best were given a '2', and sites that differed most were assigned '5'. To determine overall 'best' performance of the methods for each fuel class, a rank total was obtained by summing individual rankings over all sites. Low rank totals indicate that the method was consistently close to the results obtained for the reference sample for the respective fuel class.

The time needed to complete each technique was directly compared among methods. The two most time-consuming methods, namely the fixed-area and planar intersect, were also evaluated using bootstrapped samples to determine if putting in fewer lines might improve efficiency without sacrificing sampling error. Bootstrapping is a statistical way to increase sample size that randomly selects data values from the original dataset

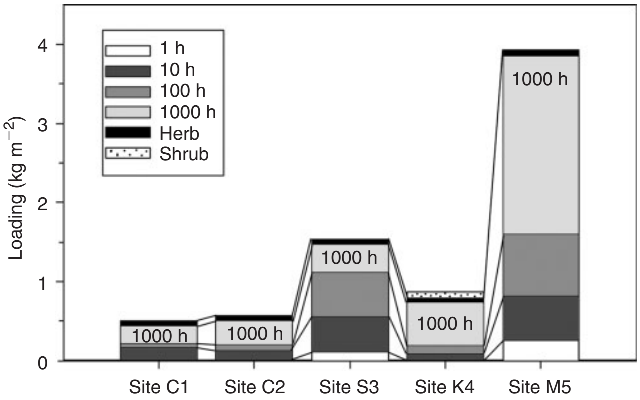

Fig. 5. Total fuel loading by site (reference samples only).

and creates a new set of observations of specified size. We used standard, with-replacement bootstrapping techniques in *S-Plus* (Insightful Corporation 2003) to create 2000 bootstrap observations for a range of sample sizes at each site. For the planar-intersect method, sample size ranged from 2 to 52 lines (i.e. distances of 20 to 2600 m using a horizontal plane). For the fixed-area plots, sample sizes ranged from 1 to 25, so sample areas increased in 10-m^2 increments from 10 to 250 m^2. For each fuel class, we calculated the mean loading for the 2000 bootstrap observations at each sample size, and tested how the variance of the means changed with increased sample size (see Jalonen *et al.* 1998 for details). We considered the recommended sample size for each 50 × 50-m macroplot to be the point where difference in variance was minimal compared with the effort needed to add additional samples (i.e. usually the inflection point found in the graphs). Although we did a bootstrap analysis for each fuel size class, only the results of the 1-h and 1000-h will be presented here.

Results

Reference samples

Load totals for the reference samples ranged from ~0.50 kg m^{-2} at sites C1 and C2 to 3.95 kg m^{-2} at site M5 (Fig. 5). Although all six fuel types were present at each site, the distribution of loading across components varied by several orders of magnitude among the sites. At sites C2, K4, and M5, 1000-h logs comprised over 50% of the total load, but site S3 had a majority of its load in FWD (>73%). Alternately, 1-h fuels, shrubs, and herbs comprised less than 1 to 7% of the total load at each site (Fig. 5).

Load comparisons

The difference between the estimated loadings of FWD and CWD for each method and each site's reference totals are shown in Figs 6 and 7. The load values and differences are also detailed by fuel type, method, and site in an Accessory publication to the present paper (Table A1). Overall, the mean errors obtained by using each sampling method ranged from −0.30 to 0.14 for FWD and from −1.76 to 2.02 for CWD. The between-site standard deviation of error ranged from 0.26 to 1.44 for the FWD, and from 0.35 to 2.79 for CWD. The within-site standard deviation was as great as or greater than the between-site deviation for both FWD and CWD in the photographic-based methods. The only case where the ANOVA F-value for the between *v.* within variation was not significant was in the photoload macroplot FWD. Shrub and herb differences for the photoload and photoload macrolot methods also varied as much between sites as they did within sites, but the absolute difference between most of these means was <0.05.

When the fuels types were examined for statistical differences among methods without separating the fuel data by site, the differences between the reference sample load and the method estimates were not statistically significant. However, there were significant differences within the 1-h to 1000-h fuels between the photo series and every other method. In each of the fuel classes, sampling with the photo series method, which was completed by the same people who did the photoload and macroplot methods, resulted in a higher mean value for load than any other estimating method did.

When the actual loadings of each method were ranked according to how they differed from the reference sample, each method had some fuel-size classes that were estimated better than others (Table 1). The fixed-area plot captured FWD most closely to the reference sample in four of the five sites. It, therefore, had the best overall ranking (i.e. lowest total) for the FWD fuels. The planar intersect and photoload captured FWD moderately well. The photoload macroplot (walk-through) and photo series methods were the least similar to the reference sample. In general, the photoload method usually underestimated FWD at a site whereas the photo series consistently overestimated all fuel classes (Table 1). The 1000-h fuels (logs) were best captured by the planar-intersect or photoload methods, except at site K4 where the photoload macroplot walk-through estimate of loading was closest to the reference load. Both the planar-intersect and photoload microplot method ranked well whether sites had high or low loads of CWD. Each site showed some degree of CWD clumping because, within the site, individual strip-plot lines differed in log load by up to 10-fold (e.g. sites C2 and M5). Overall, the planar intersect, with its 52 sample lines, best captured the different fuel classes and the spatial distribution of load on each of the five sites (Table 1).

The photographic-based methods, including the photoload, the photoload macroplot walk-through, and the photo series, were affected to varying degrees by a participant's prior experience in measuring fuels (i.e. whether they considered themselves an expert, intermediate, or novice) and by the amount of fuel loading on each site. In general, most participants tended to underestimate fuels at each site with photoload (see Accessory publication, Table A1). ANOVA showed that the photoload estimates differed significantly from the reference samples within the 10-h and 1000-h fuels even for the experts (Table 2). Differences among the expertise levels themselves were not significant at any site using this technique. For the photoload macroplot technique, statistically significant differences occurred mainly within the 1000-h fuels, but differences in estimating some of the finer fuels (1-h and 10-h) were also significant at some sites (Table 2). For the sites where Tukey's method could distinguish which group was different, all of the differences found using the photoload macroplot technique occurred between the reference

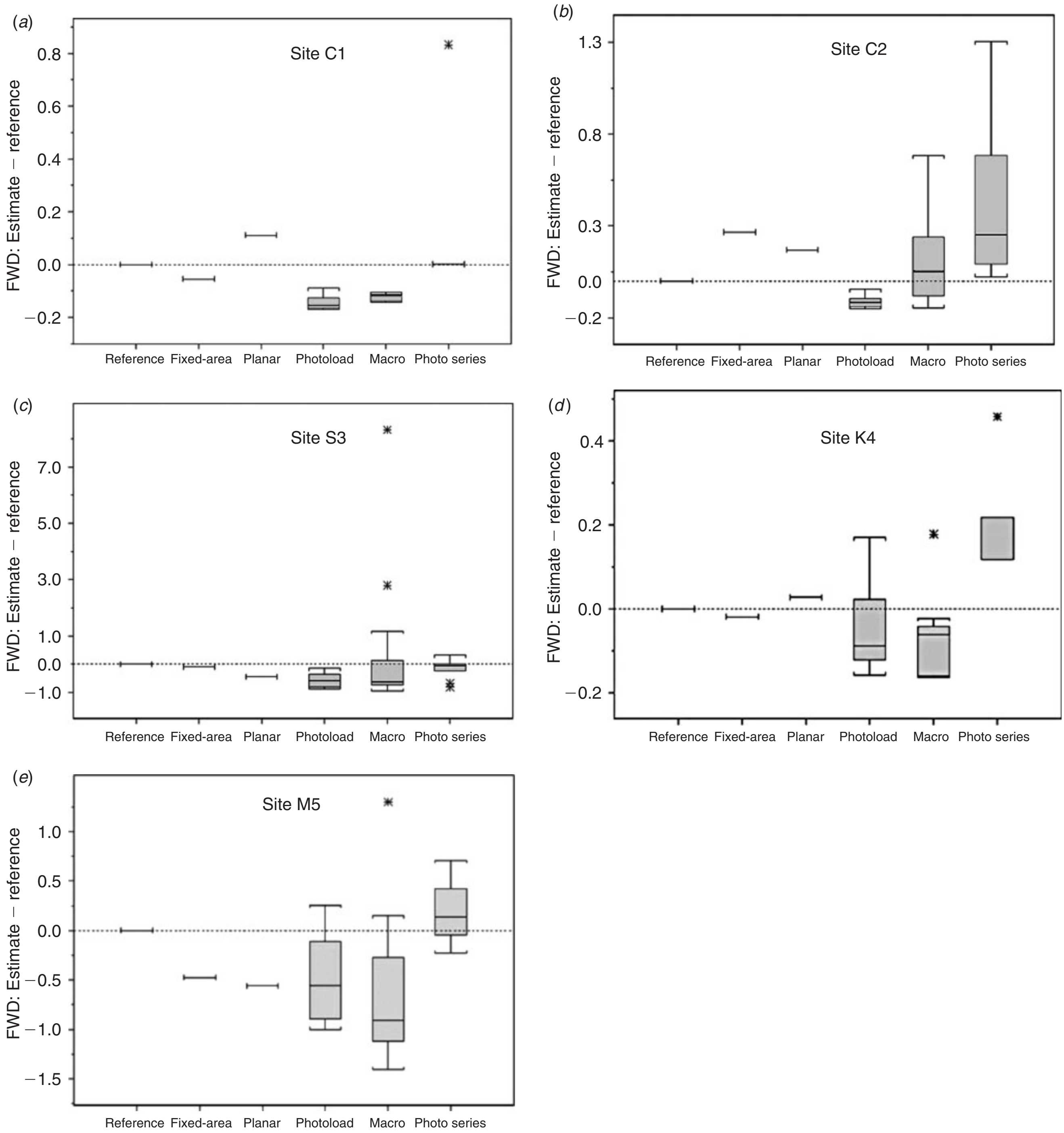

Fig. 6. Site differences between each method's load estimates for fine-woody debris (FWD) (1-h + 10-h + 100-h fuels) and the reference values for FWD. Planar, planar-intersect method; macro, photoload macroplot estimate method. Box limits are at the 25th and 75th percentiles. Whiskers are at 1.5 times the interquartile range. All values that fall outside of whiskers are outliers and designated as ✱. The dashed line is the zero difference line. Sites are listed as follows: (*a*) site C1; (*b*) site C2; (*c*) site C3; (*d*) site K4; (*e*) site M5.

and the expertise levels. Only site S3 had significant differences among expertise levels for the 1000-h fuels (Table 2). In contrast to the photoload or photoload macro methods, the photo series estimates had significant differences among expertise levels for the 1000-h fuels (Table 2). The groups that differed depended on site, but most of the differences were between (i) expert and intermediate and (ii) intermediate and novice (Table 2). Only M5 had significant differences between expert and novice. At two of the sites, differences were detected but there were not enough participants in one of the expertise groups to evaluate which

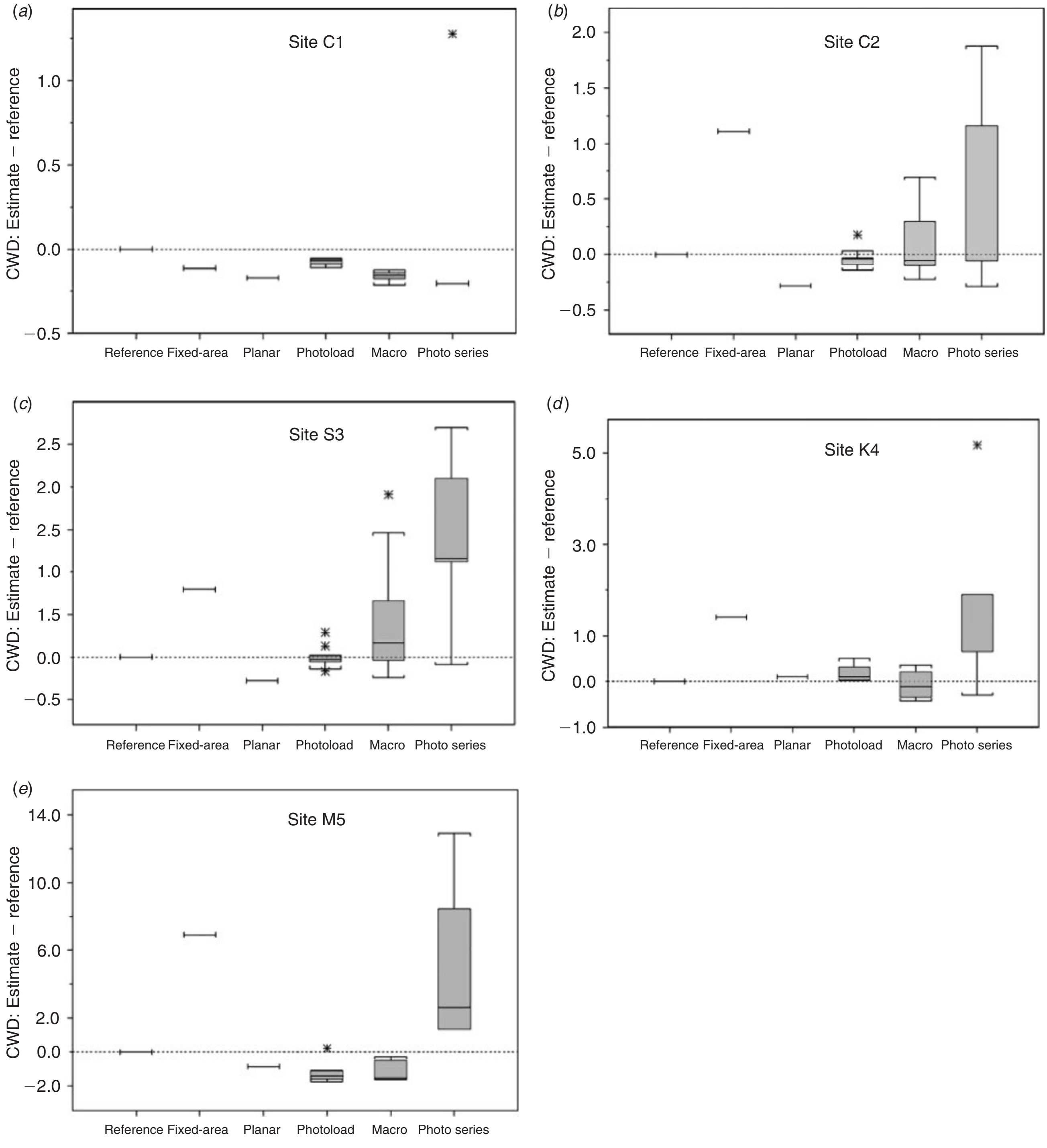

Fig. 7. Site differences between each method's load estimates for coarse-woody debris (CWD) (1000-h fuels) and the reference values for CWD. Planar, planar-intersect method; macro, photoload macroplot estimate method. Box limits are at the 25th and 75th percentiles. Whiskers are at 1.5 times the interquartile range. All values that fall outside of whiskers are outliers and designated as ✷. The dashed line is the zero difference line. Sites are listed as follows: (*a*) site C1; (*b*) site C2; (*c*) site C3; (*d*) site K4; (*e*) site M5.

group caused the differences. In general, on sites with low accumulations of downed woody debris, participants who considered themselves experts in measuring fuel loads picked photos within the photo series that more closely matched the reference sample values than novices did. At sites with high accumulations of debris (S3 and M5), however, experts did not estimate either FWD or CWD load significantly better with the photo series photographs than novices did (Table 2).

For planar-intersect and fixed-area methods, bootstrapping samples of incrementally increasing size showed that, in most

Table 1. Ratings of each method's ability to estimate load compared with the reference sample

A rating of 1 is assigned to the method that estimates load closest to the reference sample value; a rating of 5 is assigned to the method that estimates loads most differently from the reference sample. 'Overall scores' are sums of rankings for each respective fuel type. Dominant overstorey vegetation: Site C1, *Pinus ponderosa*; C2, *Pinus ponderosa*; S3, *Pinus ponderosa*; K4, *Pinus ponderosa/Pseudotsuga menziesii*; M5, *Larix occidentalis*. Fine woody debris (FWD) is sum of 1-h, 10-h, and 100-h fuel loads; Coarse woody debris (CWD) is 1000-h (or log) fuel loads. Total, ranking of the difference between the sum of the six load components estimated at each site and the sum of the six load components within the reference sample. Where herbs and shrubs could not be assessed for the total, their contribution to the sum was zero

	Site C1			Site C2			Site S3			Site K4			Site M5			Overall score	Overall score	Overall score
	FWD	CWD	Total	FWD	CWD	Total	FWD	CWD	Total	FWD	CWD	Total	FWD	CWD	Total	FWD	CWD	Total
Photo series	5	3	2	5	4	4	2	5	5	5	5	5	1	4	4	18	21	20
Fixed-area	1	4	3	4	5	5	1	4	3	1	4	4	2	5	5	9	22	20
Photoload	3	2	2	1	1	1	5	1	2	3	2	3	3	3	2	15	9	10
Planar intersect	2	1	1	3	2	2	4	2	1	2	3	2	4	1	1	15	9	7
Photoload macroplot	4	5	4	2	3	3	3	3	4	4	1	1	5	2	3	18	14	15

cases, sample intensity could be significantly decreased for all fuel classes (Fig. 8). For the planar-intersect method, which was sampled with 2500 m of line, most fuel classes would be adequately sampled using 750 to 1000 m of transects. Fine woody debris may require only 50 to 75 m and the very small 1-h fuels might be adequately sampled within a 50 × 50-m site using a 25-m sample line (Fig. 8). The sample size on the fixed-area plots (see Fig. 8, M5) might also depend on the total fuel load on the site. The 1-h fuels appeared to be adequately sampled using a 30 to 50 m^2 area (i.e. 2% of the total area) for most sites. At sites with very high fuel loads, samples may require 100 to 150 m^2, or 6% of the total area. These trends were similar in all of the FWD, shrub, and herb fuel classes that we tested with bootstrapping. For the 1000-h fuels, only 50 m^2 might be needed for sites with low fuel load whereas 100 to 150 m^2 might be needed for sites with high fuel loads (Fig. 8).

We tested for bias among the methods using the prediction error framework described by Freese (1960) and Reynolds (1984). Within this method, the difference between the reference and estimate (termed error) for each method is averaged. Bias is present if the mean error (i.e. average of the differences) falls outside of the range predicted by the 95% confidence interval for the samples. We found no bias in methods for either the FWD or CWD estimates even though some of the methods had relatively high standard deviations. The mean errors between methods for FWD ranged from −0.30 to 0.14 with standard deviations of 0.26 to 1.44. The mean errors for CWD ranged from −0.09 to 2.02 and standard deviations ranged from 0.35 to 2.79. The highest CWD standard deviations came from the fixed-area and photo series methods (2.79 and 2.66, respectively). The highest within and between standard deviations came from the photo series (5.10 and 2.66).

Discussion

Matching the appropriate fuel sampling technique to a specific management objective is probably one of the most complicated tasks in designing effective fuel sampling programs. Not only are there several sampling techniques to choose from, but fuels are highly variable across scales. Loadings from individual plots differ from stands where the plots were located, which will also differ from their respective landscapes. Developing sampling designs that accurately capture that variability is difficult (Van Wagner 1968; Pickford and Hazard 1978). Although each of the fuel sampling techniques discussed here provides some measure of loading by fuel component within an area, choosing one method for use in a sampling program while rejecting others inevitably involves important tradeoffs between accuracy, time, money, training, scale, and effectiveness. Before making such decisions, program managers must consider whether the sampling protocol will (1) meet specific program or study objectives; (2) be appropriate to measure the fuel component of interest; (3) scale to the appropriate spatial area; (4) work within the topographic and visual constraints of the study area; (5) be appropriate for the forest type and its disturbance history; (6) adequately capture the spatial distribution and amount of debris pieces on site; and (7) be implementable within resource limits available for the project. Choosing the most appropriate sampling method to meet these objectives is not straightforward.

Table 2. Comparison of reference means (kg m^{-2}) with means of estimates (kg m^{-2}) made using photoload, macroplot and photoseries at three expertise levels

Grey cells designate estimate means that differ significantly from the reference sample at $\alpha = 0.05$. Bold type and similar alphabetical superscripts indicate expertise levels that differ from each other at $\alpha = 0.05$

Site	Fuel component	Reference Mean loading		Photoload Mean loading estimate						Photoload macroplot Mean loading estimate						Photo series Mean loading estimate					
			n	Expert	n	Intermediate	n	Novice	n	Expert	n	Intermediate	n	Novice	n	Expert	n	Intermediate	n	Novice	n
C1	1 h	0.0019	25	0.0055	73	–	–	0.0013	15	0.0088	4	–	–	0.0150	1	0.0100	4	–	–	0.0000	1
	10 h	0.1649	25	0.0307	73	–	–	0.0300	15	0.0238	4	–	–	0.0450	1	0.1700	4	–	–	0.1300	1
	100 h	0.0513	25	0.0365	73	–	–	0.0620	15	0.0600	4	–	–	0.0450	1	0.2475	4	–	–	0.0900	1
	1000 h	0.0683	82	0.1450	70	–	–	–	–	0.0750	4	–	–	0.0100	1	0.3900	4	–	–	0.0200	1
	Shrub	0.0000	25	0.0001	73	–	–	0.0000	15	–	–	–	–	–	–	–	–	–	–	–	–
	Herb	0.0545	25	0.0641	73	–	–	0.0377	15	–	–	–	–	–	–	–	–	–	–	–	–
C2	1 h	0.0012	25	0.0069	124	0.0029	20	0.0066	70	0.0082	5	0.0050	1	0.0171	3	0.0320	5	0.0200	1	0.0267	3
	10 h	0.1297	25	0.0284	125	0.0369	20	0.0271	71	0.0826	5	0.0500	1	0.1100	3	0.1540	5	0.4900	1	0.1967	3
	100 h	0.0671	25	0.0538	125	0.1015	20	0.0399	71	0.1522	5	0.4000	1	0.2667	3	0.2580	5	0.9900	1	0.4600	3
	1000 h	0.0549	139	0.2869	125	0.1626	20	0.2794	71	0.4060	5	0.3000	1	0.4267	3	0.4000	5	2.1800	1	1.6733	3
	Shrub	0.0001	25	0.0016	125	0.0031	20	0.0286	71	–	–	–	–	–	–	–	–	–	–	–	–
	Herb	0.0659	25	0.0572	125	0.0216	20	0.0736	71	–	–	–	–	–	–	–	–	–	–	–	–
K4	1 h	0.0107	25	0.0133	98	0.0675	50	0.0169	119	0.0146	3	0.0200	2	0.0160	5	0.0550	4	0.0450	2	0.0440	5
	10 h	0.0709	25	**0.0221^{A}**	98	**0.0526^{A}**	50	0.0306	119	0.0173	3	0.0400	2	0.0340	5	0.2100	4	0.1350	2	0.1480	5
	100 h	0.1105	25	0.0973	98	0.1582	50	0.0724	119	0.0283	3	0.1600	2	0.0776	5	0.2150	4	0.1800	2	0.1220	5
	1000 h	0.0937	144	0.7781	98	0.5975	50	0.7400	120	0.5600	3	0.4300	2	0.4300	5	**1.815^{A}**	4	**4.08^{AB}**	2	**1.474^{B}**	5
	Shrub	0.0748	25	0.0697	88	0.0599	50	0.0227	94	–	–	–	–	–	–	–	–	–	–	–	–
	Herb	0.0581	25	0.0866	92	0.0870	50	0.1062	94	–	–	–	–	–	–	–	–	–	–	–	–
S3	1 h	0.1155	25	0.0555	175	0.0719	97	0.0647	69	0.0715	7	0.1975	4	0.1517	3	0.1200	7	0.0475	4	0.0733	3
	10 h	0.4390	25	0.1269	175	0.1319	97	0.1491	69	0.1107	7	0.5975	4	0.4467	3	0.3629	7	0.2750	4	0.2300	3
	100 h	0.5682	25	0.3850	175	0.3892	97	0.2317	69	0.5443	7	2.0650	4	0.9507	3	0.5614	7	0.7425	4	0.5300	3
	1000 h	0.0600	142	0.2782	175	0.3746	97	0.3761	69	**0.4193^{A}**	7	**1.2125^{A}**	4	**0.8833^{A}**	3	**1.924^{A}**	7	**1.345^{AB}**	4	**1.8733^{B}**	3
	Shrub	0.0123	25	0.0105	175	0.0342	97	0.0123	69	–	–	–	–	–	–	–	–	–	–	–	–
	Herb	0.0615	25	0.0572	175	0.0869	97	0.0644	69	–	–	–	–	–	–	–	–	–	–	–	–
M5	1 h	0.2586	25	0.2736	75	–	–	0.2693	119	0.1300	3	–	–	0.3420	5	0.1200	3	–	–	0.1240	5
	10 h	0.5567	25	0.3520	75	–	–	0.2971	119	0.1767	3	–	–	0.1970	5	0.7033	3	–	–	0.8700	5
	100 h	0.7849	25	0.4290	75	–	–	0.5440	116	0.2833	3	–	–	0.7250	5	0.9833	3	–	–	0.7860	5
	1000 h	0.0863	661	1.0670	75	–	–	1.0740	119	1.0693	3	–	–	1.1804	5	**8.3467^{A}**	3	–	–	**6.448^{A}**	5
	Shrub	0.0084	25	0.0065	75	–	–	0.0151	119	–	–	–	–	–	–	–	–	–	–	–	–
	Herb	0.0636	25	0.0369	75	–	–	0.0513	119	–	–	–	–	–	–	–	–	–	–	–	–

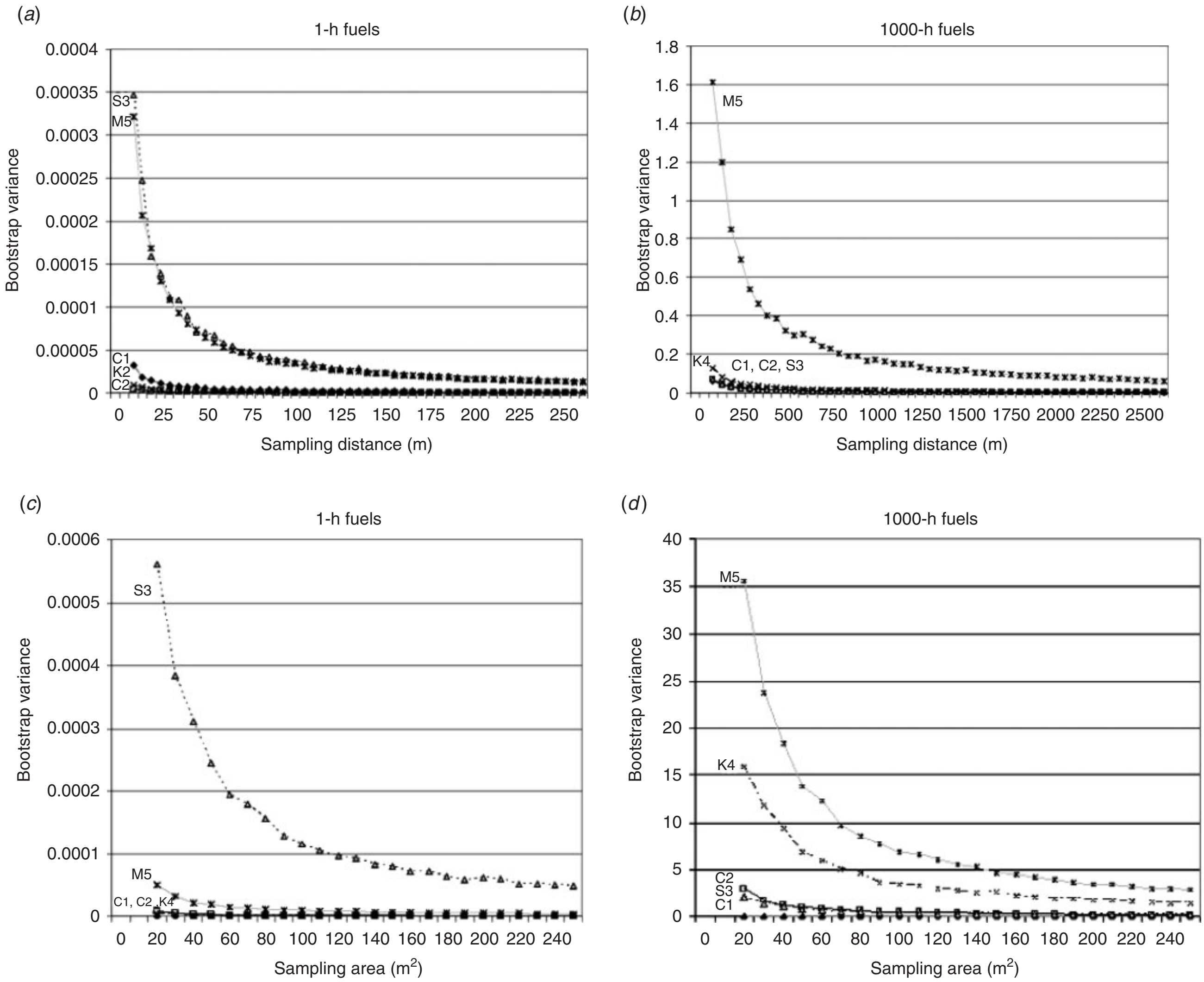

Fig. 8. Effect of sample size on the variance of each sample mean in planar-intersect and fixed-area sample methods for select fuels. (*a*) Planar intersect 1-h fuels; (*b*) planar intersect 1000-h fuels; (*c*) fixed-area 1-h fuels; and (*d*) fixed-area 1000-h fuels. Similar results were obtained for other fuel types.

Studies that compare fuel assessments on the same sites using a variety of methods are critical to guiding these decisions. The present study makes these comparisons for a greater variety of fuel types than has been done in the past.

Fire management agencies commonly use photo series for fuel assessment because the technique is easily taught, the photos are easily created, and it is easily implemented. It is also a rapid assessment technique. Generally, photo series estimates of fuel load take approximately 5 min to complete. However, Lutes (1999) found that these sampling times could more than double under certain fuel load conditions and that the loading estimates were not repeatable across sampling personnel and across sites. Lutes (1999) also found that the photo series did not quantify large downed woody debris well. In the present study, we found that loadings obtained using photo series were the least similar to the reference sample in all CWD and most FWD categories. For the forest types examined within this montane landscape, personnel consistently overestimated fuel loading in the 1-h to 1000-h fuel classes with the photo series, especially when a site had high fuel loads ($>2\,\mathrm{kg\,m^{-2}}$). Estimating fine fuel loadings is especially difficult using the oblique photographs because the pictures often inadequately portray conditions at the fine scale – fine fuel components are indiscernible or obscured by ground vegetation within the pictures. Some photos even portray vegetative cover that obscures the 1000-h logs. Even though shrubs and herbs may be abundant enough to hide the downed woody fuels in some photographs, they cannot be included in a site's fuel load calculations because fuel loadings for herbs and shrubs were not estimated or summarised for the Fischer photo series that was created for these western Montana forests. Therefore, these forest components, which may be very important to assessing fire hazard or wildlife habitat, cannot be realistically assessed using these photo guides.

The advantage of fixed plot sampling is that data or fuel components can be collected using a single-sized plot frame or nested plot frames of varying sizes. Nesting sampling frames enables the investigator to study loading at a scale that is appropriate to each study. The fixed-plot method has historically been considered the most accurate and unbiased method for sampling fuels (Harmon and Sexton 1996). Some studies have found no significant differences between results obtained with fixed-area plots and those obtained with a line transect for CWD (Lutes 1999; Herbeck 2000). However, Bate *et al*. (2004) found that fixed-area plots were 'more efficient and precise' than line transects for log variables that were important to wildlife use. Bate *et al*. (2004) and Lutes (1999) both found that fixed-area plots measured logs more efficiently than line transects. In the present study, we found that the five 1 × 50-m strips were not scaled appropriately to capture both fine fuels and clumped CWD equally well. The fixed-area plots captured FWD extremely well when compared with the reference (clipped) samples, but the 1000-h log load was overestimated at all sites (Fig. 7). The discrepancy in capture ability may indicate that two plot sizes may be necessary to sample the entire range of surface fuels well. CWD may need to be sampled with wider strips, such as the 2-m wide strips used by Bate *et al*. (2004), to adequately capture the larger fuel sizes or clumped fuel loads.

When we compared loadings from the fixed-area plots with the planar-intersect loadings, we found that fixed-area estimates were always lower than planar transect estimates for the 1-h and 10-h fuels and closer to the reference loading. For the 1000-h fuels, the fixed-area estimates were usually greater than the planar transect estimates. Unlike Woldendorp *et al*. (2004), who found that the fixed-area plot measured CWD better than line transects when loads were relatively low and their variability was high in Australian woodlands, we did not find that the variations in loading values using either of the techniques corresponded to the total amount of loading on a site for any of the size classes. The differences between the reference samples and the fixed-area samples, and the fixed-area and transect methods, were highly variable among size classes and among sites.

In terms of efficiency, we found that the five sites required a significant cost in effort and time to sample the five 1 × 50-m fixed-area strips well. Experts in fuel sampling took 60–120 min to sample each strip with sites having more load requiring the longer times. Bootstrap techniques showed that the sampling intensity could have been reduced approximately by half (i.e. 100–150 m^2) with little loss in the variance of the mean, but this might not be the case in other forest types. These sample times also did not include assessments of herbs, shrubs, duff or litter loading. If these elements are important as inputs to fire models or for evaluating objectives for a management area, then more time would be required to completely sample each site. The fixed-area method also requires a moderate amount of pre-sample training before it can be implemented correctly, although learning how to terminate debris counts at strip boundaries and tally and record lengths of every piece of debris in each size class takes less time than learning how to correctly set up and apply the planar-intersect method. Because they are so time-intensive and tedious, fixed-area plots are used most frequently in research – not in standard inventory or monitoring projects. Depending on the focus of the study and the spatial arrangement of different fuel types within a site, however, fixed-plot methods may be more appropriate to answer questions on fine fuels than any other method examined in the current study.

The planar-intersect method is perhaps the most commonly used sampling technique for estimating fuels for inventory applications. Implementing the procedure is easy. It requires nine simple steps and learning some tally rules (Brown 1974). Novice field technicians easily grasp the procedure with minimal training, and results are moderately repeatable (Hazard and Pickford 1978; Pickford and Hazard 1978). Like the fixed-plot technique, the planar-intersect method can be easily scaled to match the sampling unit and fuel conditions. Adjustments to the technique are also simple. They can usually be made by just altering the length of the sampling plane. Like photo series, the planar-intersect method only measures downed dead woody particles and other methods must be used to estimate loadings of shrubs, herbs, litter, or duff (Brown *et al*. 1982). The planar-intersect method captured loadings for the 1-h to 1000-h fuels on the five different sites better than any other method examined in the present study. Unlike the fixed-area method, which only described FWD loadings well, the planar method sufficiently captured loading for several fuel types (Table 1). The cost of this accuracy, however, was a significant input of time and effort. It took 100 to 180 min for expert samplers to complete the 52 transects used at each site (i.e. 2.0–3.5 min per transect). Bootstrapping indicated that, in these particular locations, each fuel class could have been adequately sampled with around fifteen to twenty 50-m transects (750–1000 m). However, our results also indicate that optimal transect lengths depended on (1) the fuel class of interest; and (2) the overall coverage of downed woody debris at the site (Fig. 8). For example, the 1-h fuels may have been adequately sampled with 10 to 75 m, but the 1000-h fuels could require up to 1000 m (Fig. 8*a*, *b*). Likewise, sites with higher overall fuel loads, such as S3 and K5, required more transects to reduce variance than sites with relatively low fuel loads (see Fig. 8*a*). Our findings disagree with Pickford and Hazard (1978), whose computer simulations of line-transect sampling that found 'sample size should decrease proportional to increases in density of pieces in the population' (p. 482). Whereas their results were based on oriented, randomly spaced debris pieces of uniform size and shape, our results are based on actual sampling of non-uniform debris whose spatial distributions are often clumped. Based on our results, we recommend using between 250 and 750 m of transect line for each 1 kg m^{-2} of load on a site when using the planar-intersect method and using the longer lengths with higher fuel loads (Fig. 8*a*, *b*). This sampling intensity means that sampling time would require up to 45 min per plot, which might be too long for many sampling efforts. In other landscapes with high piece density or highly variable fuel load, the length of these sampling transects may have to be increased even more to capture loading characteristics adequately. If so, time and effort would increase proportionally with each added sample transect.

The photoload technique (at the microplot and macroplot level) is a relatively new fuel assessment technique for estimating fuels quickly and accurately (Keane and Dickinson 2007*b*). We found that photoload consistently underestimated FWD and CWD at most sites (Figs 6 and 7) and underestimated total fuels by an average of 0.18 kg m^{-2} (Table A1). Keane and Dickinson (2007*a*) evaluated bias within the photoload method itself and found that absolute bias depended on which fuel components were examined. Specifically, they suggested that some bias may have been introduced by inadequate training for each participant – people needed better calibration for the visual comparisons. Using our error framework tests at the macroplot scale, the photoload methods were not biased compared with other sample methods. Compared with the reference samples, photoload estimated load much better than the photo series. As a detailed assessment, it estimated FWD and 1000-h fuel load almost as well as the 52 lines of the planar intersect in much less time. It did not describe total debris loading as well as the planar-intersect method, even though the intersect method lacks the estimates of shrubs and herbs included in the reference and photoload totals, but it could be used if time and resources for sampling are limited or if loadings for herbs and shrubs are important to management goals.

The photoload method is easily scalable to any plot size and sampling design by changing grid size within the sample area and visually comparing the fuel cover within each photograph with the cover observed in each new grid. Because the fuels are photographed by fuel component and each fuel component is portrayed across several loading levels, the photographs are much more appropriate for estimating site loads at various scales than estimating with a photo series where individual components like FWD are not directly visible. The technique required more training to implement than any of the other methods examined in the present study because it is so new (Keane and Dickinson 2007*b*) but the concepts underlying the method were not hard for novices to grasp and training the eye to discern small variations among pictures did not take longer than 1 h. For the current study, we averaged the estimates of participants of various skill levels to get loading results that we could compare with the other techniques. This, in effect, created an estimate that reduced the influence of extreme values from novices and experts alike, although, as Table 2 shows, expertise in fuel sampling was not highly significant for either photoload or the photoload macroplot at the site scale. The multiple-participant approach would probably not be an option for a single manager in standard inventory or monitoring studies, but it has been used in some vegetation studies (Thorne *et al*. 2002). Once personnel are trained using photoload, the advantages of this technique are that (1) each fuel component in the plot can be visually identified and individually assessed; (2) it is a relatively easy and quick method for collecting detailed fuel data in all six fuel categories; and (3) the estimates are somewhat repeatable (Keane and Dickinson 2007*a*). Depending on fuel sampling expertise, implementation on a 1 × 1-m plot took 5.0 to 7.5 min for all six components. Total time to complete the microplots for each site was 125 to 190 min. At this time, the main disadvantages of using photoload are (1) the loading representations for shrub and herbaceous species are extremely limited; and (2) new calibrated photographs must be created for each fuel type if it is used in forest types that are very different from those examined in the present study.

The photoload macroplot method (walk-through) has many of the same advantages and disadvantages as the photoload method but it is much faster to implement. It uses the same picture set as photoload, but visual estimates of fuel loading can be made for the entire site in only 6 to 7 min. Because the results were not statistically different than using photoload or any of the other tested fuel-assessment methods, it may be as viable an alternative to estimating load as any other if time and money are minimal. Participants using the technique neither consistently over- nor underestimated sites with low or high fuel loads. They estimated FWD as well as the photo series, and logs much better than with the photo series. They could also assess shrubs and herbs. As with the photo series, the tradeoff for rapid assessment using this technique was less accuracy in general, but, at some sites, participants were able to match references loadings fairly well (see Table 1, C2, K4). This technique will require considerably more study to determine if individuals consistently estimate as well with it as with photoload (Keane and Dickinson 2007*b*).

Although the error-prediction tests on the fuel-sampling methods did not show bias within any of the sampling methods, the results for the photo-based techniques may have been influenced by the order in which they were sampled. Using the more detailed photoload technique first could have resulted in preconceived notions for participants of what later photo estimates should be. Estimating each of the six fuel components in the microplots first may have also calibrated participants' eyes and enhanced their ability to estimate load in the later methods more accurately. The increased experience in comparing pictures with site conditions probably also affected the time participants took to make later photographic estimates that required similar visual comparisons. In any case, the sampling order used in the present study probably served to make the photo macroplot and photo series estimates more 'accurate' and efficient than they would have been if the sampling order had been completely random.

Obviously, the small number of plots (five) used in the current study limits statistical power and restricts how well the loading results may apply to other forested areas outside western Montana fuelbeds. The small size is indicative, however, of sizes that are used in real applications of these methods. Another limitation of the study is that the measured fuel loadings that were used as reference for comparing the methods may have influenced the comparison results. The only fuel component that was measured in its entirety within each macroplot was logs (1000-h downed woody debris). For all other fuel components, we used a subsample approach that, in effect, sampled only 1% of the total macroplot area. We used the subsample approach for the reference because it was costly and difficult to clip, collect, dry and weigh all fuels across the entire macroplot on all sites. As a result, the reference estimates of fine fuel components may not have adequately described plot-wide fuel loadings. In the present study, we assumed that the reference conditions were the 'actual' loadings, when, in fact, they were also a subsample of the macroplot. It is also obvious from the results of the current study that the high variability of fuels on the landscape (Fig. 5) is the most critical issue to address when designing sampling projects. Fine fuels may compose a relatively small proportion of the loading compared with 1000-h fuels, but they can vary so much across a macroplot that few techniques have superior ability to measure them precisely. At the landscape scale, the relative proportion of load in each individual fuel component, such as 1-h fuels, varies considerably and the total fuel load vary even more (see Fig. 5). The implication of this phenomenon is that it is difficult to craft a sample design that efficiently samples all fuel components at the same level of accuracy and precision. Future research in fuel sampling and classification should address the disparate variability across fuel components and scales in the sample design and account for it in the product.

Although results of the present study cannot and should not be applied to every forest type, they do provide an indication of the tradeoffs involved when using each of these sampling techniques in a sampling program. The tradeoffs in time, money, and effort associated with each sampling technique must always be balanced with project objectives and resources. Studies that compare a technique's accuracy and precision, and specifically address these resource tradeoffs, are very important to assessing how well newly developed methods like photoload will perform for research and management. More importantly, they are crucial to developing more targeted approaches to sampling fuels worldwide.

Management recommendations

Although the differences in fuel load found among the methods tested in the present study may not be large enough to affect computer simulations or systems modelling, they are significant in terms of sampling efficiency and rectifying the scale of sampling to the scale of fuels distribution. We recommend that managers determine an acceptable accuracy for their sampling programs and select a sampling method that is appropriate to their study objectives and to their precision limits. We also recommend that managers consider the distribution of their fuels in both the plot and the landscape to determine if more than one type of method might be appropriate for sampling them (i.e. sampling FWD with a strip plot and logs with photoload). We do not recommend changing methods or changing plot sizes just to save time or money in already established long-term monitoring programs.

We recommend that the planar-intersect technique continue to be used when measures of fuel loadings require high precision and accuracy, but we also recommend that the total length of transects increase to improve loading estimates from planar-intersect sampling. For example, FIREMON (Lutes *et al*. 2006) recommends three to seven 20-m transects for sampling logs on a macroplot (60 m total length). Our results show at least 180 m of planar intersect should be used to estimate the load of logs on 1/4 ha. The photoload technique may be a viable sampling alternative to planar intersect. It is faster, easier to use, and had approximately the same bias as the planar intersect in the current study. However, the photoload technique is new and warrants additional study before widespread implementation in other vegetation types. Photo series also have their place in fuel management, but the loadings estimated from the photos comprising the photo series in this area of the Rocky Mountains do not adequately represent the sample site, so it is difficult to recommend using them. Managers should consider more time-intensive sampling methods or independently evaluate how well the photo series for their area works for their objectives to ensure that the data they are getting for fuels is accurate enough for their needs.

Accessory publication

Table A1. Comparing fuel load totals at five montane-forest sites using five fuel-sampling techniques

This table is available from the *International Journal of Wildland Fire* website.

Acknowledgements

We thank Steve Slaughter and Laura Ward, Ninemile Ranger District, Lolo National Forest and Laurie Dickinson and Curtis Johnson from USDA Forest Service Rocky Mountain Research Station Missoula Fire Sciences Laboratory for sampling support. We also thank our coworkers from the USDA Forest Service Rocky Mountain Research Station and Systems for Environmental Management, who diligently sampled these sites as part of the field crews; Jim Kautz and Ian Grob from the Missoula Technology and Development Center, who granted use of the Center's photo laboratory and technical and creative assistance to create the photo sequences; Kathleen Gray, who provided statistical support; and Duncan Lutes, Helen Smith, Rudy King, and two anonymous reviewers, whose comments greatly improved the present manuscript.

References

Albini FA (1976) Estimating wildfire behavior and effects. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-30. (Ogden, UT)

Arcos A, Alvarado E, Sandberg DV (1998) Volume estimation of large woody debris with a stereoscopic vision technique. In 'Proceedings: 13th Conference on Fire and Forest Meteorology', 24 October–2 November 1996 Lorne, VIC, Australia. pp. 439–447. (International Association of Wildland Fire)

Bate LJ, Torgersen TR, Wisdom MJ, Garton EO (2004) Performance of sampling methods to estimate log characteristics for wildlife. *Forest Ecology and Management* **199**, 83–102.

Bebber DP, Thomas SC (2003) Prism sweeps for coarse woody debris. *Canadian Journal of Forest Research* **33**, 1737–1743. doi:10.1139/X03-097

Brown JK (1971) A planar intersect method for sampling fuel volume and surface area. *Forest Science* **17**, 96–102.

Brown JK (1974) Handbook for inventorying downed woody material. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report GTR-INT-16. (Ogden, UT)

Brown JK, Oberheu RD, Johnston CM (1982) Handbook for inventorying surface fuels and biomass in the Interior West. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-129. (Ogden, UT)

Busing R, Rimar K, Stolte KW, Stohlgren TJ (1999) Forest health monitoring vegetation pilot field methods guide: vegetation diversity and structure, down woody debris, fuel loading. USDA Forest Service, National Forest Health Monitoring Program. (Research Triangle Park, NC)

Delisle GP, Woodard PM, Titus SJ, Johnson AF (1988) Sample size and variability of fuel weight estimates in natural stands of lodgepole pine. *Canadian Journal of Forest Research* **18**, 649–652. doi:10.1139/X88-097

DeVries PG (1974) Multi-stage line intersect sampling. *Forest Science* **20**, 129–133.

Dibble AC, Rees CA (2005) Does the lack of reference ecosystems limit our science? A case study in non-native invasive plants as forest fuels. *Journal of Forestry* **103**(7), 329–338.

Fischer WC (1981*a*) Photo guide for appraising downed woody fuels in Montana forests: interior ponderosa pine, ponderosa pine–larch–Douglas-fir, larch–Douglas-fir, and interior Douglas-fir cover types. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-97. (Ogden, UT)

Fischer WC (1981*b*) Photo guides for appraising downed woody fuels in Montana forests: how they were made. USDA Forest Service, Intermountain Forest and Range Experiment Station, Research Note INT-288. (Ogden, UT)

Fosberg MA (1970) Drying rates of heartwood below fiber saturation. *Forest Science* **16**, 57–63.

Freese F (1960) Testing accuracy. *Forest Science* **6**, 139–145.

Gove JH, Williams MS, Stahl G, Ducey MJ (2005) Critical point relascope sampling for unbiased volume estimation of downed coarse woody debris. *Forestry* **78**, 417–431. doi:10.1093/FORESTRY/CPI040

Hansen MH (1985) Line intersect sampling of wooded strips. *Forest Science* **31**, 282–288.

Harmon ME, Sexton J (1996) Guidelines for measurement of woody debris in forest ecosystems. US Long Term Ecological Research Network, University of Washington, Publication No. 20. (Seattle, WA)

Hazard JW, Pickford SG (1978) Simulation studies on line intersect sampling of forest residue. *Forest Science* **24**, 469–483.

Herbeck LA (2000) Analysis of down wood volume and percent ground cover for the Missouri Ozark forest ecosystem project. In 'Missouri Ozark Forest Ecosystem Project: site history, soils, landforms, woody and herbaceous vegetation, down wood, and inventory methods for the landscape experiment'. (Eds SR Shifley, BL Brookshire) USDA Forest Service, North Central Research Station, General Technical Report NC-208. (St. Paul, MN)

Insightful Corporation (2003) '*S-Plus* 6.2 for Windows Professional Version.' (Insightful Corporation: Seattle, WA)

Jalonen J, Vanha-Majamaa I, Tonteri T (1998) Optimal sample and plot size for inventory of field and ground layer vegetation in a mature *Myrtillus*-type boreal spruce forest. *Annales Botanici Fennici* **35**, 191–196.

Jordan GJ, Ducey MJ, Gove JH (2004) Comparing line-intersect, fixed-area, and point relascope sampling for dead and downed coarse woody material in a managed northern hardwood forest. *Canadian Journal of Forest Research* **34**, 1766–1775. doi:10.1139/X04-051

Kalabokidis KD, Omi PN (1998) Reduction of fire hazard through thinning/residue disposal in the urban interface. *International Journal of Wildland Fire* **8**, 29–35. doi:10.1071/WF9980029

Keane RE, Dickinson LJ (2007*a*) Development and evaluation of the photoload sampling technique. USDA Forest Service, Rocky Mountain Research Station, Research paper RMRS-RP-61CD. (Fort Collins, CO)

Keane RE, Dickinson LJ (2007*b*) The photoload sampling technique: estimating surface fuel loadings from downward-looking photographs of synthetic fuelbeds. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-190. (Fort Collins, CO)

Laverty L, Williams J (2000) Protecting people and sustaining resources in fire-adapted ecosystems – a cohesive strategy. USDA Forest Service, Forest Service response to General Accounting Office Report GAO/RCED 99–65. (Washington, DC)

Levene H (1960) Robust tests for equality of variance. In 'Contributions to Probability and Statistics'. (Eds I Olkin, SG Ghurye, W Hoeffeling, WG Madow, HB Mann) pp. 278–292. (Stanford University Press: Stanford, CA)

Lutes DC (1999) A comparison of methods for the quantification of coarse woody debris and identification of its spatial scale: a study from the Tenderfoot Experimental Forest, Montana. MSc Thesis, the University of Montana.

Lutes DC, Keane RE, Caratti JF, Key CH, Benson NC, Sutherland S, Gangi LJ (2006) FIREMON: Fire effects monitoring and inventory system. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-164-CD. (Fort Collins, CO)

Maxwell WG, Ward FR (1976) Photo series for quantifying forest residues in the coastal Douglas-fir–hemlock type, coastal Douglas-fir–hardwood type. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, General Technical Report PNW-51. (Portland, OR)

Mueller-Dombois D, Ellenberg H (1974) 'Aims and Methods of Vegetation Ecology.' (Wiley: New York)

Nemec Linnell AF, Davis G (2002) Efficiency of six line intersect sampling designs for estimating volume and density of coarse woody debris. Vancouver Forest District, Research Section, Technical Report TR-021/2002. (Nanaimo, BC)

Ottmar RD, Vihnanek RE, Wright CS (2000) Stereo photoseries for quantifying natural fuels. Volume III: lodgepole pine, quaking aspen, and gambel oak types in the Rocky Mountains. National Wildfire Coordination Group, National Interagency Fire Center, PMS-832. (Boise, ID)

Pickford SG, Hazard JW (1978) Simulation studies in the line intersect sampling of forest residue. *Forest Science* **24**, 469–483.

Reinhardt E, Keane RE, Brown JK (1997) First Order Fire Effects Model: FOFEM 4.0 user's guide. USDA Forest Service, Intermountain Research Station, General Technical Report INT-GTR-344. (Ogden, UT)

Reynolds MR Jr (1984) Estimating the error in model predictions. *Forest Science* **30**, 454–469.

Rothermel RC (1972) A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service, Intermountain Forest and Range Experiment Station, Research Paper INT-115. (Ogden, UT)

Sandberg DV, Ottmar RD, Cushon GH (2001) Characterizing fuels in the 21st century. *International Journal of Wildland Fire* **10**, 381–387. doi:10.1071/WF01036

Stahl G (1998) Transect relascope sampling – a method for the quantification of coarse woody debris. *Forest Science* **44**, 58–63.

Thorne MS, Skinner QD, Smith MA, Rodgers JD, Laycock WA, Cerekci SA (2002) Evaluation of a technique for measuring canopy volume of shrubs. *Journal of Range Management* **55**, 235–241. doi:10.2307/4003129

van Wagtendonk JW, Benedict JM, Sydoriak WM (1996) Physical properties of woody fuel particles of Sierra Nevada conifers. *International Journal of Wildland Fire* **6**, 117–123. doi:10.1071/WF9960117

Van Wagner CE (1968) The line intersect method in forest fuel sampling. *Forest Science* **14**, 20–26.

Waddell KL (2002) Sampling coarse woody debris for multiple attributes in extensive resource inventories. *Ecological Indicators* **1**, 139–153. doi:10.1016/S1470-160X(01)00012-7

Warren WG, Olsen PF (1964) A line intersect technique for assessing logging waste. *Forest Science* **10**, 267–276.

Williams MS, Gove JH (2003) Perpendicular distance sampling: an alternative method for sampling downed coarse woody debris. *Canadian Journal of Forest Research* **33**, 1564–1579. doi:10.1139/X03-056

Woldendorp G, Keenan RJ, Barry S, Spencer DR (2004) Analysis of sampling methods for coarse woody debris. *Forest Ecology and Management* **198**, 133–148. doi:10.1016/J.FORECO.2004.03.042

Manuscript received 5 January 2007, accepted 11 August 2007