A COMPARISON OF SAMPLING TECHNIQUES TO ESTIMATE WILDLAND SURFACE FUEL LOADING IN MONTANE FORESTS OF THE NORTHERN ROCKY MOUNTAINS

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Abstract. Designing fuel sampling methods that accurately and efficiently assesses fuel loads at relevant spatial scales requires knowledge of each sample method's strengths and tradeoffs. Few studies have evaluated sampling methods as to their effectiveness in estimating accurate fuel loadings across all surface fuel components. In this study, we will compare three sampling methods (planar intercept, microplot measurement, microplot photoload) for estimating eight surface fuel components (litter, duff, 1, 10, 100, 1000 hr, shrub, herb) using a duel approach where synthetic fuelbeds of known fuel loadings will be created for the fine woody fuels (1, 10, 100 hr) in the parking lot of the Missoula Fire Sciences Laboratory, and field sampling at various locations in western Montana, USA will be used to evaluate the all fuel components. For each of the eight fuels, we compare the relative differences in load values among techniques; and the differences in load between each method and a reference sample. We will also evaluate various sub-methods and sampling intensities within each of the three sampling methods. Totals from each method are rated for how much they deviate from totals for the reference in each fuel category. Results from this study will be used to guide fuel inventory and monitoring sampling designs to select the most appropriate techniques for each fuel component.

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

INTRODUCTION

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

It is difficult to compare surface fuel sampling techniques for many ecological, technological, and logistical reasons. Most comparison approaches compare the sampled fuelbed with actual known reference loadings. Quantifying the reference or actual fuel loadings is costly and sometimes impossible, because it is difficult to collect, sort, dry, and weigh all surface fuels within a common ecological sampling frame (250-500 m^2 plot) located in the natural environment because of the huge amount of biomass and the difficulty involved in determining the appropriate fuel component. Twigs, for example, are often embedded in the litter and duff so it is difficult to determine if the twig is a 1 hr fuel or part of the ground fuels, and the boundary between duff and mineral soil is often difficult to discern. As a result, most fuel sampling comparisons rely on subsampling using microplots or smaller sampling frames that are more suited for destructive sampling (Sikkink and Keane 2009). The problem there is that the standard error involved in subsample estimation can overwhelm the subtle differences between sampling methods. There are also major differences between sampling techniques that make comparisons difficult. The commonly used planar intercept sampling, for example, is difficult to validate because the two dimensional (length and height) sampling plane makes it difficult to relate to the reference sampling frame 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 photo series (Fischer 1981a) and photoloads (Keane and Dickenson 2006) have major sources of error due to differences between samplers. And, the major size, shape, and density differences between fuel components make comparisons difficult in that each component should be quantified at their inherent ecological scale. Keane et al. (2012[in prep]) found that 1 hr woody fuels varied across scales much smaller than 1000 hr fuels (2 m vs 60 m). Because of these reasons, and many others, there are few evaluations of the accuracy and efficiency across sampling methods.

This study takes a new approach in creating the reference fuelbed for comparing surface fuel sampling methods. Instead of destructively collecting and weighing the reference fuel loads for the fine woody fuel components in the field, we created synthetic fuelbeds using actual fuels collected in the field. We collected, sorted, dried, and weighed fine woody material from forests surrounding Missoula Montana to create a fuels library of 5 kg amounts of 1, 10, and 100 hr woody fuel. We then created synthetic fuelbeds in a 500 m^2 flat area (grass field) of known fuel loadings, and sampled the area using several fuel sampling methods. We added more fuel and re-sampled the area again with the various sampling methods. We also scattered the fuel in three patterns – uniform, clumpy, and jackpot. This was difficult to employ for logs, duff, and litter, so we used the standard approach of creating a reference plot in the field and subsampling these fuel components to obtain reference loadings. Results from this study will be useful in selecting the most appropriate sampling method for each fuel component, and designing sampling protocols for research and management fuels inventory and monitoring efforts.

Background

Historically, fuel load sampling procedures have ranged in scope from simple and rapid visual assessments to highly detailed measurements of complex fuelbeds along lines 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 (1976) and implemented by (Fischer 1981b). In the photo series method, fuel loads are estimated by visually matching observed fuelbed conditions with sets of oblique photographs that have been taken in disparate forests and rangelands settings. The fuel loads for each photographed forest and rangeland are sampled and quantified (e.g. Fischer(1981a) or Sandberg(2001)); and, theoretically, the load values can then be applied to sites that appear visually similar.

In contrast to the photo series, the transect, planar intercept, 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; and 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; Brown 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 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-transect method has been used extensively in many inventory and monitoring programs because it is relatively fast and simple to use (Busing *et al.* 2000; Waddell 2001; 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 defined 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 fuel beds 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 [in press]-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 probablility 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, monitoring, inventory, and wildlife studies.

In this study, we explore how five sampling methods compare in their ability to assess downed woody debris loading and also how a different set of three techniques compare when sampling shrub, herb, litter, and duff load. These down woody techniques include: 1) microplot measurement, 2) microplot photoload, 3) planar intercept, and 4) macroplot Photoload, and 5) macroplot photo series. The microplot methods will be used to assess shrub, herb, litter and duff. We will also evaluate various sampling intensities and sub-methods on their precision and accuracy. We evaluate each technique based on: (1) how its estimated loading compares to a reference sample; (2) how much time it requires to complete sampling; and (3) how much training is needed to implement it. 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 this study, we limited our comparisons across sampling techniques to only surface fuels because these elements are normally evaluated in several of the fuel sampling techniques and each is an important input to fire simulation models (Rothermel 1972; Albini 1976; Reinhardt *et al.* 1997). However, the woody fuels are sampled differently from the duff, litter, shrub, and herb so this study had to be divided into two phases:

(1) **Synthetic macroplot**. We will create 500 m^2 synthetic fuelbeds of the fine downed dead woody fuels (1, 10, and 100 hr) and employ sampling methods on these artificial fuelbeds; and
(2) **Field** reference fuelbed comparisons. We employed various fuel sampling techniques to estimate the loading of the shrub, herb, duff, litter and log (SHDLL) fuels.

Synthetic fuelbeds were used to minimize the error in estimating the reference fuel loading. Logs were not included in the synthetic fuelbed because they are too big to manipulate and carry on the plot and they can be easily and accurately measured in the field. Duff and litter were not included on the synthetic plot because of the tremendous volume of material that would have to be transported to the plot and it would have been difficult to create a realistic litter and duff layer after transport to the synthetic plot. Shrub and herbs were not represented in the synthetic plot because it would have been difficult to create realistic shrub and herb fuelbeds after cutting in the field and transport to the site. Moreover, we would have had to kill the plants.

In this study, we compared sampling techniques for the four downed woody debris accepted size classes (Fosberg 1970):

Fine Woody Debris (FWD) (Sample methods compared using the synthetic fuelbed)

- **1h fuels -** particles with diameters less than 0.64 cm (<0.25 in) in diameter
- **10h fuels -** particles between 0.64 and 2.54 cm (0.25-1.00 in) in diameter

- **100h fuels -** particles 2.54 to 7.62 cm (1-3 in) in diameter

Coarse Woody Debris (CWD) (Sample methods compared using field sampled macroplot fuelbed)

- **1000h fuels** consisted of fuel components greater than 7.62 cm (3+ inches) in diameter. This class included all logs.

Ground fuels (Sample methods compared using field sampled macroplot fuelbed)

- **Litter**. Freshly fallen non-woody fuels with discernable origins, such as needles, leaves, bud scales, pollen cones, and seeds.

- **Duff**. Decomposed organic material whose origins cannot be determined.

Live Fuels (Sample methods compared using field sampled macroplot fuelbed)

- **Shrubs**. Live and dead shrub material below 2 m tall.
- **Herbs**. Live and dead herbaceous material, such as grasses, sedges, and forbs, that is below 2 m tall
- **Tree**. Live and dead seedling and sapling tree material below 2 m tall

This study consists of various sampling designs, sampling intensities, and fuelbed constructions that form the experimental design of the evaluation and comparison study. The following is a detailed list of the various factors evaluated in this study (Table 1):

- **Fuel Loading**. We will have five different fuelbeds with different total loadings (0.01 kg m^{-2}, 0.05 kg m^{-2}, 0.10 kg m^{-2}, 0.15 kg m^{-2}., 0.20 kg m^{-2})

- **Fuel Distribution**. We will have three fuel distribution treatments.
  - Uniform. We will evenly distribute the fuels across the sampling macroplot.
  - Patchy. We will put 80 percent of the fuel on the north half of the macroplot and 20 percent on the south half.
  - Jackpot. We will put 50 percent of the fuel in the NW quadrant of the macroplot and the remaining 50 percent evenly distributed across the other quadrats (16 percent in each quadrat).

- **Sampling method**. We will evaluate five different sampling methods.
  - Planar intercept. Employ the Brown (1974) sampling technique.
  - Microplot measurement. Measure length and diameter of all fuel particles.
  - Microplot photoload. Visually estimate fuel loadings on microplot.

- **Sampling sub-methods**. We will evaluate variations of the major sampling methods. These will not be employed while sampling, but will be implemented during the analysis phase.
  - Count. Use the counts to estimate loading.
  - Diameter-Length. Use total lengths to estimate loading.
  - Diameters. Use traditional diameter classes, 1 cm, 2 cm, and actual diameters to estimate loadings.

- **Sampling Intensities**. Within each method/sub-method, we will explore the effect of sampling intensity on accuracy and variation. Here are examples of the investigation of sampling intensity:

- Microplot: Explore how many microplots are needed to adequately describe fuel loadings.
- Planar intercept: Explore how many meters of transect are needed to efficiently describe fuel loading.

Details of ***photoload sampling*** for this study are discussed in detail in Keane and Dickinson (2007). However, since this technique employs visual estimates for fuel loading, there will tend to be major differences between observers depending on observer skill, experience, and ability. To account for this source of variability, we will invite at least 10 participants to visually estimate fuel loadings of the three components. Estimates will be made within the same 1m by 1m microplot at the same time. Each participant will be asked to match the fuel loading conditions that he or she observed within each of the 20 microplots to conditions portrayed in a set of downward looking photographs of fuelbeds showing graduated picture sequences of increasing load. We will train each participant on photoload methods and use the Holley and Keane (2010) field guide to calibrate participant guess prior to sampling (Keane and Dickenson 2007).

The implementation of these various factors will be different between the synthetic fuelbed comparison experiment and the field fuelbed comparison experiment. A complete list of field equipment for establishing the synthetic plot or the field macroplots are provided in Appendix A. All plot sheets are contained in Appendix B.

Synthetic Fuelbed Comparisons

We collected over 100 kg of fine woody debris from forests surrounding Missoula Montana. We then sorted this fuel into the three size classes, dried the fuel at 80 deg C for three days, and weighed the fuel. We then divided the fuel into 5 kg lots and stored the lots in plastic crates in a dry place. We will then construct fuelbeds of known fuel weights in a rectangular area, and employ the various sampling techniques on the area. There will be two references areas: (1) a large synthetic macroplot within which we will sub-sample with systematically placed microplots, and (2) synthetic microplots where we will vary the loading by fuel component at a 1 square meter level.

Macroplot

We will establish a 25 m x 20 m (500 m^2) permanently-marked rectangular macroplot in an area devoid of vegetation and with a minimal amount of surface complexity (parking lot, mown lawn) to minimize confusion in visual estimates. The long sides (25 m) of this plot will oriented east and west sides, and the short side (20 m) will run north-south. Within this plot we will stretch cloth tapes at each 5 m marks (5, 10, 15, 20) and along the borders (Figure 1). We will establish a microplot in the NE corner of each 5x5 m subplot. Planar intercepts will be put at 1 m intervals along the 25 m sides (running north-south) and along the 20 m side (running east-west) totaling 24+19 or 43 transects (Figure 2).

We will then follow the following steps to create, measure, and evaluate sampling methods for fine woody fuels:

(1) **Choose a fuel distribution**. Select one of the three fuel distribution types described above. Start with the uniform fuel distribution.
(2) **Select a fuel loading**. Choose a target fuel loading starting with the lowest and increasing to the highest to continually add fuel to the plot.
(3) **Compute total fuel biomass**. Multiply target fuel loading by 500 m^2 to get kg of fuel to put on the plot. So, the first fuel loading of 0.01 kg m-2 is 5 kg of fuel.
(4) **Compute individual fine fuel component loadings**. Compute the loadings of the 1, 10, and 100 hr fuels to total the target fuel loading. Use the average proportions from the

FLM fuel classification (Lutes et al. 2009) or as collected in the field and represented in the fuel library. So if the 1, 10, and 100 hr loadings comprise 10, 40, and 50 percent of the fuelbed load, then for the first loading (0.01), the 1 hr biomass would be 0.5 kg, 10 hr is 2 kg, and 100 hr is 2.5 kg.

(5) **Spread fuel**. Manually spread the fuel across the plot using the selected fuel distribution method. If patchy or jackpot distribution is selected, the pre-weigh the fuel to achieve the correct distributions.

(6) **Take pictures**. Photograph the fuelbed from above and from the four sides. Use a scissor lift or ladder to get sufficient height to properly photographically describe the fuelbed.

(7) **Sample fuels using planar intercept**. Perform the following steps to conduct the planar intercept sampling. Be careful not to move or break the fuel particles Use the plot form in Appendix B. The transect code is the direction of origin combined with the distance on the tape so N22 signifies the transect is on the 25 m tape going north to south and it is stretched between the 22 m marks.

  a. **Stretch tape**. Start at the 1 m marks on the long 25 m tapes and stretch the cloth tape between these two marks with the zero end at the north.
  b. **Measure fuels**. Start at the north end and traverse down the stretched tape to the south end and at each woody fuel particle intercept, record the particle diameter and distance.
  c. **Move the tape**. Once finished with the measurements, move the tape down one meter and repeat steps a and b.

(8) **Sample fuels using microplot methods**. Stretch the seven cloth tapes between the 5 m marks on both transects (Figure 2).

  a. **Select a microplot**. Start in the NW corner of the NW 5x5m subplot. This would be microplot number 1 with number 2 being the NW corner of the next subplot directly to the east, and so on. Place the PVC microplot so it is in the NW corner of the subplot.
  b. **Take picture**. Stand on the south end of the microplot and take picture of microplot and compose the picture so the microplot boundary fills the photo.
  c. **Implement photoload methods.** Visually estimate the FWD loadings using the photoload procedures. Record loadings on plot sheet in Appendix B.
  d. **Measure woody fuel.** Measure the beginning, middle, and end diameter in mm of each woody fuel particle in the microplot. Measure the diameter where it intersects microplot boundaries as the beginning or end diameter. Then measure the length of each fuel particle in cm. For those particles that are forked or branched, measure each fork or branch as a separate particle. Use plot form in Appendix B.
  e. **Go to next microplot.** Pick up the PVC microplot frame and more it 5 m east to the next subplot and repeat steps a through d.

(9) **Repeat steps 1 though 8.** Implement another factor in this experiment by repeating steps 1-8 using new loads or new fuel distribution**.**

Microplot

When the entire experiment has been implemented and all fuel distributions and loadings have been sampled, we will perform another finer scale experiment by creating synthetic fuelbeds at the microplot scale. We will perform the exact same steps as above but there will be more fuel loadings and there will be only uniform fuel distributions. We will place eight 1 m planar intercepts transects at the 20 cm marks along the PVC microplot frame going north-south and east-west. The only difference is that we will pick up all the fuels, separate into the three size classes and weigh each fuel component to determine the difference between classes. Obviously, we will not employ macroplot methods in this sub-experiment.

Field Fuelbed Comparisons

We will take a different approach for the remaining surface fuel components (SHDLL). Instead of constructing pre-determined synthetic fuelbeds at the macro- and microplot scale, we will go into the field and attempt to sample a wide variety of fuelbeds that contain thin to thick duff+litter layers, small to large logs, and few to many shrubs and herb fuel layers.

We will perform these comparisons on at least five and hopefully ten study sites in western Montana. We will pick these sites so that they represent different SHDLL conditions. Sites must be flat, homogeneous, and representative of a major fuel type in western Montana. A 20 m by 25 m rectangular plot will be located in the most homogeneous portion of the sample site. Sides will be oriented in the cardinal directions. Each corner will be semi-permanently monumented using a wooden stake that is labeled as to site number and corner direction (NW, NE, SE, SW).

Creating the perfect reference sample design that captures actual loadings by the five SHDLL components for each of sample site is logistically impractical because we do not have the resources to clip, collect, and weigh all the herb, shrub, and woody fuels within the 500 m^2 plot and we could not handle the large volume of heavy and unwieldy log material in our laboratory. Therefore, we will subsample shrub, herb, and ground fuel components using nested microplots (Fig. 3). In the northeast corner of each macroplot, we will establish a 1 m x 1 m microplot using a plot frame made out of plastic PVC pipe (Fig. 2). Within the 25 microplots, we collected all of the fine woody debris (FWD) and clipped and collected all of the 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. We sorted shrub, herb, and FWD by size class into labeled paper bags in the field and brought them back to the lab to be dried for 3 days in a 90^{o}C oven and then weighed 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.

Reference sampling for logs is much easier. For the 1000h fuels, we will measure the small-end diameter, large-end diameter, and length of each piece of CWD greater than 7.62 cm to get a 100% inventory of all logs on the macroplot at each site. We will assign a decay class (i.e. classes 1 to 5) to each log using FIREMON guidelines (Lutes *et al.* 2006). The log volume is multiplied by a wood density to obtain a weight for each log in each subplot using equations presented in Keane and Dickinson (2007). The same wood density values will be used for all weight calculations; each was assigned based on decay class using the density values for debris from coniferous forests suggested by Brown (1974). The log weights will be summed and then divided by total plot area to calculate the reference estimate of log loading. Choosing an appropriate wood density value is an important decision for calculating reference loading values in this study. Many of the traditional methods for measuring load assume that the density of fuel (kg m^{-3}) is constant across all size classes and species but different across various classes of decay (Brown 1974). Recently, however, research has shown that there are significant differences in fuel wood density between different species, rot classes, and size classes (van Wagendonk *et al.* 1996). We will take a sample (cookie) of each log rot class represented at the site to compute our own density values. This involves cutting a “cookie” or cross section of about 2-4 cm from the log somewhere at least 0.5 m from the log’s end. The cookie weighed in the field and placed in a burlap bag for transport to the lab for drying and weighing to compute moisture content, dry weight, and volume.

We will use essentially the same procedure presented for the synthetic sampling when performing the field sampling with obvious exceptions. The following procedure will be employed at each sample site.

(1) **Set up macroplot**. We will establish a 25 m x 20 m (500 m^2) semi-permanently-marked rectangular plot in a homogeneous area of the sample site. The long sides (25 m) of this plot will be at the north and south sides of the plot and run east-west. Within this plot we will stretch cloth tapes at each 5 m marks (5, 10, 15, 20) and along the borders (Figure 1).

(2) **Take pictures**. Photograph the fuelbed from above and from the four sides. Use a ladder to get sufficient height to properly photographically describe the fuelbed.

(3) **Sample fuels using macroplot methods.** We will then visually estimate fuel loadings using the photo series and photoload techniques. All participants will NOT be informed as to the target fuel loading and they will be trained in the protocols to effectively and efficiently use these methods.

(4) **Sample fuels using planar intercept**. Perform the following steps to conduct the planar intercept sampling. Be careful not to move or break the fuel particles Use the plot form in Appendix B. The transect code is the direction of origin combined with the distance on the tape so N22 signifies the transect is on the 25 m tape going north to south and it is stretched between the 22 m marks.
   a. **Stretch tape**. Start at the 1 m marks on the long 25 m tapes and stretch the cloth tape between these two marks with the zero end at the north.
   b. **Measure fuels**. Start at the north end and traverse down the stretched tape to the south end and at each woody fuel particle intercept, record the particle diameter and distance. Do this for all woody fuels including logs.
   c. **Move the tape**. Once finished with the measurements, move the tape down one meter and repeat steps a and b.

(5) **Sample fuels using microplot methods**. Stretch the seven cloth tapes between the 5 m marks on both transects (Figure 2).
   a. **Select a microplot**. Start in the NW corner of the NW 5x5m subplot. This would be microplot number 1 with number 2 being the NW corner of the next subplot directly to the east, and so on. Place the PVC microplot so it is in the NW corner of the subplot.
   b. **Take picture**. Stand on the south end of the microplot and take picture of microplot and compose the picture so the microplot boundary fills the photo.
   c. **Implement photoload methods.** Visually estimate the shrub, herb, and FWD loadings using the photoload procedures. Record loadings on plot sheet in Appendix B.
   d. **Estimate cover and height of shrub and herb.** Visually estimate the cover and height for all shrubs and all herbs on the plot.
   e. **Clip shrub and herbs.** Cut all shrubs and herbs at the litter interface and place the shrub and herb material in separate paper bags for transport back to the lab. Label bags as to sample site, microplot number, date, and type (shrub, herb).
   f. **Measure woody fuel.** Measure the beginning, middle, and end diameter in mm of each woody fuel particle in the microplot except logs. Measure the diameter where it intersects microplot boundaries as the beginning or end diameter. Then measure the length of each fuel particle in cm. For those particles that are forked or branched, measure each fork or branch as a separate particle. Use plot form in Appendix B.
   g. **Collect woody fuel.** Pick up all woody fuel and place into paper bags according to 1, 10, and 100 hr size classes. Be sure to cut the sticks where they cross the

inside border of the PVC microplot frame. Label bags as to sample site, microplot number, date, and type (1, 10, 100 hr).

h. **Take litter and duff depths.** In the NW quarter of the microplot (50x50cm nanoplot) estimate the depth of litter plus duff using a plastic ruler and nail – insert the nail head down through the litter duff until the head encounters the mineral soil then mark the top of the litter on the nail and remove nail to measure depth. Do this for nine measurements – four in the corners, four at the side midpoints and in 10 cm, and one in the center. Attempt to estimate the percent of that depth that is litter.

i. **Collect the litter and duff.** Pick up the litter and duff layer inside the nanoplot using a shovel or trowel. Try to separate the litter and duff and store in separate paper bags or burlap sacks. Label bags as to sample site, microplot number, date, and type (litter, duff).

j. **Go to next microplot.** Pick up the PVC microplot frame and more it 5 m east to the next subplot and repeat steps a through d.

(6) **Measure logs.** The small and large end diameters and the log length will be estimated for each log in the macroplot. Log lengths are measured along the central axis of the log and the length terminates once it reaches the macroplot boundary, end of log, or the central axis of the log is under the litter. The rot class will be recorded for each log. Plot forms are in Appendix B**.**

(7) **Collect log cookies.** A 2-4 cm cross sectional area will be taken from a log in each rot class represented on the plot. We will select logs that represent the rot class. These cookies will be placed in paper bags or sacks that will be labeled as to sample site, and type (rot class).

Calculating loadings

Fine Woody Debris

Microplot Techniques -- For all woody fuel components, including FWD and CWD, the weight of each sampled piece of debris will be calculated using the volume and wood density method. Volumes are calculated as follows:

$$V = \frac{l}{3}\left[(a_s + a_l) + \sqrt{(a_s a_l}\right] \qquad \textbf{(1)}$$

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 [in press]-a). Particle weight (kg m-^{2}) will be calculated by multiplying the volume by wood density (kg m^{-3}). Wood density will be calculated by estimating the volume of the sampled cookie by immersing it in water and measuring the displacement and then multiplying it by dry mass estimated by putting the cookie into the oven at 80^{o}C for three days and weighing the cookie. This procedure will be used for all three reference plots: synthetic microplots, microplots within the synthetic macroplot, and microplots within field macroplots

We will investigate several levels of sampling intensities to calculate FWD loading from the microplot data. The following is a list of sub-methods used in this study followed by how the loadings will be calculated for each. This includes synthetic microplots, microplots within the synthetic macroplot, and microplots within field macroplots:

1. **Count method**. Calculate loading using a count. Obtain a count of all sampled woody fuel particles. Then multiply this count by an average woody fuel particle weight (diameter and

length to get volume then multiply by density). We will also experiment with using a loading by size class distribution to get loadings across all size classes.

2. **Diameter method**. Calculate loading by using the sampled middle diameter and an average particle length to get volume and multiply volume to get loading. Summarize this into the three FWD size classes.
3. **Diameter-Length method**. Calculate loading by computing volume of the two end-to-middle pieces of fuel particle and multiply by density and summarize into the three size classes.

Planar intercept -- We will follow the procedures detailed in Brown (1971; 1974) to calculate FWD downed woody fuel loadings for the planar intercept method but at two intensities. We will choose diameter values for the calculations based on the dominant overstory tree at the site (see Brown 1974, Table 2) except when the overstory is a mix of species (Table 1, S3 and K4). In mixed-species cases, we will use the composite value (Brown 1974). We will also use Brown's (1974) density values for each size class assuming non-slash fuels. Here are the two sub-methods that we will investigate for the planar intercept technique:

1. **Standard method**. Calculate loading using a count by size class and Brown's (1974) sampling parameters as discussed above.
2. **Diameter method**. Calculate loading by fuel particle by using the sampled diameter to calculate a loading using Brown's (1974) parameters and our pre-sampled wood densities. We will then summarize this into the three FWD size classes.

Photoload and Photo Series -- Loading values for both photo-based techniques will be done the same by averaging across all participants. Estimates by all participants at each site were also averaged to obtain loading values for each photoload macroplot. For the photo series method, loadings will be assigned to each component based on each participant's photo choice and then averaged by site.

Reference Measurements – The reference measurements for the FWD is taken from the following places depending on plot sampling frame:

- **Synthetic macroplot** – The fuel loadings by FWD fuel component are known because they were used as targets to create the synthetic fuel loads. However, the FWD actual loadings for each microplot is unknown so it will be approximated by the average across all microplots.
- **Synthetic microplot** – The fuel loadings by FWD fuel component are known because they were used as targets to create the synthetic fuel loads.
- **Field macroplot** – The FWD particles will be sorted, dried, and weighed by each microplot to determine actual loadings.

Duff and Litter

We will estimate the duff and litter loadings using the depth-bulk density method using different sampling intensities. We will calculate the loading of the duff and litter at each nanoplot using an average depth times the bulk density. The bulk density will come from two places: (1) from the destructively sampled duff and litter profile and (2) from the bulk densities in Brown (1983). The reference duff and litter loadings will be calculated directly from the removed profile by separating the duff and litter, drying the samples, and weighing the samples.

Coarse Woody Debris

Log loads will only be computed at the macroplot level and they will only use one sampling sub-method. Load reference loads will be computed by calculating log volume using equation (1), then multiplying this volume by the field sampled and lab-estimated densities by rot class. Planar intercept loadings will be calculated using Brown (1974) methods and the visual sampling techniques (photo series and Photoload) will be averaged across all observers.

Shrub and Herb

Shrub and herb loadings are only sampled using the Photoload technique at the microplot and macroplot levels. The reference loadings are estimated from the destructively removed shrub and herb samples that are dried and weighed to compute loadings.

Statistical comparisons

Statistical comparisons in this study must account for two major issues: 1) different sampling scales used for each method and 2) non-normal distribution of collected data for most fuel classes. To address the differences in sampling scales in methods' comparisons, the measured loadings from the reference sample and estimated loadings from the five sampling techniques will be standardized to macroplot -level for each site as described in the previous section and each fuel class will be compared separately. Loading values for each site will be tested for normal distribution and homogeneity of variance using Q-Q normal plots and Levene's tests (Levene 1960). Natural log transformations will be made on all fuel classes *except 10h fuels* to comply with parametric assumptions. Log transformations of the 10h fuel loadings may only increase the lack of homogeneity so we may use raw data to make these comparisons.

Statistical differences between the five sampling methods will be tested on the natural log of the loading; or, in the case of the 10h fuels, simply on the loading values. Differences will be tested using both one-way analysis of variance (ANOVA) and non-parametric Kruskal-Wallace rank sum tests. For analyses where both tests produced the same interpretative results, we only present the ANOVA results. Where interpretative results differed between the two analyses, we will present both parametric and non-parametric results. Determining which method(s) will be responsible for the significant differences will be accomplished using Tukey's HSD and Bonferroni comparisons within the ANOVA tests because they compared loading values for all methods simultaneously (i.e. not pair wise) in each analysis. To test whether fuel sampling experience made a significant difference to mean estimates in the photo-based methods, we ran separate one-way ANOVAs for each site using each site's reference values and the estimates of observers grouped by expertise levels.

Sampling intensities and sub-methods will be compared to the reference conditions and across all sampling methods. To simplify cross-methods comparisons, we will use some combination of the worse-to-best submethod and the minimum, optimum, and maximum sampling intensities. For microplots, we will use 5 and 20 for the minimum and maximum sampling intensities and compute the optimum from an analysis of the variance. We will use 10 and 955 m of transect for the minimum and maximum planar intercept with the optimum computed later. The following sub-methods and intensities:

- Least accurate sub-method with the minimum, optimum, and maximum sampling intensities.
- Most accurate sub-method with min, max, and optimum sampling intensity.

SAFETY

The field portion of this project may be somewhat dangerous for field crews. We plan to conduct daily safety sessions to remind crews of dangers in sampling surface fuels. The crews will be given extensive training and the state-of-the-art safety equipment to complete their tasks. Windy days when the crowns are swaying will also pose a risk to the crews, so sampling will also be curtailed during these days. This is especially true during thunderstorms when wind AND lightning are problems. Crews will be informed of the proper procedures to report accidents and we will train some crew members in first aid in case of an accident. This project will also require endless hours of driving to field sites so the proper precautions will be taken to ensure no automobile accidents including defensive driving. The major safety concerns in the synthetic fuel sampling phase is taking the pictures from a high vantage point, whether it be from a ladder or mechanical lift. This lift has a horn to alert pedestrians and other sampling crews. Walking across the cylindrical woody fuels also poses a safety hazard so proper care will be give to navigating and sampling among the woody sticks to prevent slipping.

PROJECT SCHEDULE

We would like to complete the Synthetic fuel sampling during the 2011 calendar year and the Field fuel sampling during the 2012 field season. We estimate it would take a crew of 4 approximately two pay periods or one month to perform the synthetic tasks and a crew of 4 approximately 3 pay periods to finish the field portion of this study. We will use the winter of 2011 and 2012 to analyze the data, revise methods, and select field sample sites. We will then use the winter of 2012 and 2013 to analyze the data and perform the lab portion of the field collected cookies and samples. The project will be written up during the summer of 2013 and delivered to a journal by October 1st, 2013.

PERSONNEL

Dr. Robert Keane has extensive experience in ecological modeling, wildland fuel science, and conducting large ecological field studies. Dr. Keane will support the project through his expertise in fuel sampling instrumentation and procedures, and through his experience in developing canopy fuel data for FARSITE. His is primarily responsible for the field sampling design. He will also write the various programs specified in this study plan.

BUDGET

This is an unfunded project to be supported by the FFS program of RMRS. It is estimated that this project will take approximately five pay periods for a crew of four GS-5 techs (5x4x$1300) and eight months of Keane's salary ($85K) totaling approximately $111,000.

DELIVERABLES

This project will result in several products that will be useful to managers in any agency with responsibility for fire management in conifer forests. Excepting the normal publication delays, all deliverables will be available at the conclusion of the study (Fall 2013).

The following are expected deliverables:

- A journal article comparing the loadings estimated from the sampling methods with the reference loadings.
- A USDA Forest Service GTR that describes the study and recommends a set of fuel sampling procedures.

TECHNOLOGY TRANSFER

Technology transfer will include:

- The teaching of study results in various fire management courses.
- Presentation of study results at conferences and workshops
- Publication of study results in popular literature

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Table 1: Sampling methods and designs evaluated in this study.

Sampling frame	**Sampling Technique**	**Design 1**	**Design 2**	**Design 3**	**Design 4**
Line intersect	Count	Traditional	2 cm size classes	1 cm size classes	
	Diameter				
Microplot	Count	Traditional size classes	2 cm size classes	1 cm size classes	Center diameter
	Diameter-Length	Traditional size classes	2 cm size classes	1 cm size classes	Center diameter
	Photoload	Traditional size classes			
Macroplot	Photoload	Traditional size classes			
	Photo series	Traditional size classes			

Figure Captions:

Fig. 1. Sample layout of the synthetic and field macroplot divided into subplots with microplots placed in the northwest corner of each subplot.

Fig. 2. Sample design for planar intersect. Planar intersect transects were 1 meters apart in the north-south and east-west directions.

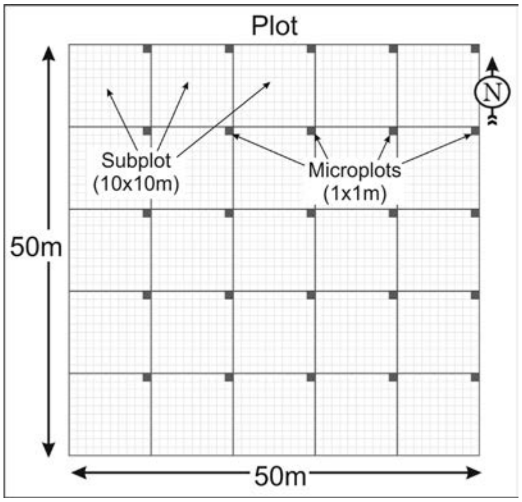

Fig. 2. Sample layout of the macroplot divided into subplots with microplots placed in the northeast corner of each subplot.

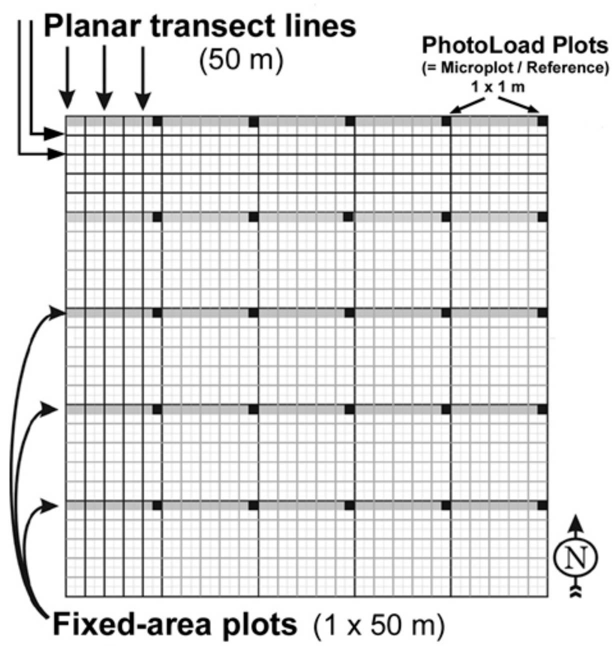

Fig. 3. Sample design for fixed area, planar intersect, and photoload methods within each site. Fixed area strip plots were established along the northern subplot edge using a width of 1 meter. Planar intersect transects were 2 meters apart in the north-south and east-west directions. Photoloads were assessed in the same microplots that were used to collect reference fuel loads. Offsets within each subplot for sampling FWD in planar-intercept method are not shown.

APPENDIX A

Equipment list

Plot setup

- Compass
- Cloth tape (11, 25 m tapes)
- Wooden Stake or rebar
- Logger's tape (DBH tape)
- GPS unit
- Flagging
- Mallet or large hammer
-

Sampling gear

- Pencils, field notebook
- Field sheets
- Calipers
- Clear plastic ruler at least 25 cm long
- 5, 100 meter cloth tapes

Microplot

- Microplot frame (1x1m) with graduated marks and string across quadrants
- Measuring probe
- Flagging
- Plot sheets
- Shovel (square nose and spade)
- Scoop, trowel,
- Burlap sacks, paper bags, large boxes
- Gloves
- Sharpie and labels
- Nails
- Clear plastic ruler
- Calipers

Photos

- Digital camera
- Ladder, lift
- Range pole

Field Sheets

- Tree data – FIREMON TD sheets
- Herbaceous canopy cover – FIREMON PD sheet adding a species listing option
- Fuel depths – total depth w/ estimates of litter, duff, masticated proportions
- Cover Microplot – FIREMON CM plot sheet
- Fuel Microplot –FM sheet (see this appendix)
    - Plot setup sheet to record tape bearings, witness trees, and photo numbers

APPENDIX B

Plot forms

See O:\RD\RMRS\Science\FFS\Projects\FuelDynamics\stix\docs\plot_sheets

For the most up-to-date plot sheets engineered for this study. The ones presented here are usually modified by the field crews for ease of use and to save paper.

Synthetic Plot Fuel Microplot Particle Form

Fuel Loading: Date: Person:

Fuel Distribution:

Microplot Number	**Diameters (mm)**			**Length (cm)**	**Rot**
	End	**Mid**	**End**		

Synthetic Plot Fuel Microplot Photoload Plot Form

Macroplot: Date: Crew: Page 1

Measurement	*Microplots*				
Microplot Number	**1**	**2**	**3**	**4**	**5**
1 hour					
10 hour					
100 hour					
Picture ID					
Microplot Number	**6**	**7**	**8**	**9**	**10**
1 hour					
10 hour					
100 hour					
Picture ID					
Microplot Number	**11**	**12**	**13**	**14**	**15**
1 hour					
10 hour					
100 hour					
Picture ID					
Microplot Number	**16**	**17**	**18**	**19**	**20**
1 hour					
10 hour					
100 hour					
Picture ID					

Synthetic Plot Planar Intercept Plot Form

Fuel Loading: Date: Person:

Fuel Distribution:

Transect (North)	**Diameter (mm)**	**Distance (cm)**		**Transect (East)**	**Diameter (mm)**	**Distance (cm)**

Field Plot Planar Intercept Plot Form

Macroplot: Date: Crew: Page 1

Transect (North)	Diameter (mm)	Distance (cm)		Transect (East)	Diameter (mm)	Distance (cm)

Field Plot Fuel Microplot Plot Form

Macroplot: Date: Crew: Page 1

Measurement	***Microplots***				
	Num:	**Num:**	**Num:**	**Num:**	**Num:**
Photoload Estimates (kg m^{-2})					
1 hour					
10 hour					
100 hour					
Shrub					
Herb					
Nanoplot duff-litter depths (cm) (duff+litter depth/%litter)					
1-NW corner					
2-NE corner					
3-SE corner					
4-SWcorner					
5-Grid 1					
6-Grid 2					
7-Grid 3					
8-Grid 4					
9-Center					
Shrub and Herb measurements (canopy cover % / height cm)					
Shrub					
Herb					
Collection Sample (y/n)					
Photo number					

Field Plot Log Form

Macroplot: Page 1

Log Number	***Log Characteristics***				
	Small Diameter (cm)	**Large Diameter (cm)**	**Length (m)**	**Decay Class**	**Notes**

Field Plot Fuel Microplot Particle Form

Fuel Loading: Date: Person:

Fuel Distribution:

Microplot Number	Diameters (mm)			Length (cm)	Rot
	End	Mid	End		