An integrated study investigating masticated fuels: developing sampling methods, describing fire behavior, and evaluating fire effects

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ABSTRACT

Many fire management agencies are exploring a wide variety of fuel treatments to lower fire intensities and severities and restore ecosystems to historical conditions and one fuel treatment that is currently gaining favor with many fire managers is fuel mastication. Masticating fuels is a mechanical treatment that breaks, shreds, or grinds canopy (seedlings, saplings and pole trees) and surface fuels (fine and coarse woody debris) into smaller sizes and depositing the treated fuels on the ground to a compact layer with a high bulk density. The mastication is accomplished using a variety of specially designed equipment that shred, flail, and crush fuels to create fuelbeds that, when burned, support slowly spreading fires that are somewhat easy to control. This project will consist of four fully integrated phases to successfully accomplish study objective. In one phase of this study, we will describe masticated fuel characteristics by measuring fuelbed properties that are important to the prediction of fire behavior and effects. Another phase involves developing a fuel sampling protocol that can easily quantify fuel loadings for a variety of management purposes. Still another phase will describe the behavior of fire burning in a masticated fuelbed and this information will be used to develop a set of fuel models to use to predict fire behavior in other masticated fuelbeds. And the last phase is to study the ecological effects of creating a masticated fuelbed. These effects are evaluated for burned and unburned masticated fuels and they include major ecosystem elements of vegetation response, fuel consumption, soil heating, and nutrient cycling.

INTRODUCTION

Uncontrolled wildland fires are a major concern among many forest managers in the western US and Canada because they have increased in frequency, intensity and size from historical averages in many areas (Mutch et al. 1993, Arno and Brown 1988). Abnormally severe fires have now become common in many forests, especially those low elevation coniferous forests that frequently experienced fires prior to European settlement, because of over seven decades of successful fire exclusion (Keane et al. 2002). Historically, fires in many forests were non-lethal surface fires or mixed severity crown fires that caused relatively little damage and were easy to control. However, the successful US fire suppression program has kept fire out of many fire-prone forests, and this has resulted in excessive buildups of fuel, specifically surface and crown fuels, which has, in turn, increased the chances and intensities of severe fires. Many fire management agencies are exploring a wide variety of fuel treatments to lower fire intensities and severities and restore ecosystems to historical conditions. Reducing fuel hazard can be done with many methods, including prescribed fire, silvicultural cuttings, and timber harvest, but one fuel treatment that is currently gaining favor with many fire managers is fuel mastication.

Masticating fuels is a mechanical treatment that breaks, shreds, or grinds canopy (seedlings, saplings and pole trees) and surface fuels (fine and coarse woody debris) into smaller sizes and depositing the treated fuels on the ground to a compact layer with a high bulk density (Figure 1). The mastication is accomplished using a variety of specially designed equipment that shred, flail, and crush fuels to create fuelbeds that, when burned, support slowly spreading fires that are somewhat easy to control. Masticated fuel treatments are now in wide use across the western United States to meet hazardous fuel treatment acre targets and its continued use is likely. It is a somewhat expensive treatment but poses little risk to the fire manager when compared with prescribed burning.

Figure 1--Masticated fuelbed

While the mastication treatment reduces fuel depth, it can also result in a more continuous and compact horizontal surface fuel layer and cause mixing of the woody material into the duff and litter layers. This type of fuelbed is quite new to wildland fire science and, because mastication is a relatively new fuels treatment, it is unclear how these treatments will affect surface fire behavior or the resulting fire effects. Mastication may give immediate results in mitigating potential high intensity fire behavior and restoring historical stand structures, but there are also many unknowns about this treatment. First, very little is known of the characteristics and properties of masticated fuel beds such as bulk density, particle size class distribution, and mineral content. Second, there are no standardized methods to estimate fuel loading of the masticated fuelbeds and assessing changes in fuel loading is the first step towards quantifying fire behavior and effects. Commonly used fuel sampling methods, such as planar intercept (Lutes et al. 2006[in press]), are probably not appropriate for assessing loadings of fuels that have been masticated because the assumptions used by these methods are not applicable for these types of fuels (Hood and Wu). Next, very little is known about how these fuels burn under various moisture scenarios and weather conditions. This, in turn, has contributed to the lack of development of fire behavior fuel models that are appropriate for masticated fuelbeds. Last, the effects of the masticated fuelbed on ecosystem processes, such as nitrogen cycling, soil water availability, and tree regeneration, are relatively unknown, and, more importantly, the effects of fire in masticated stands that are burned are even a greater unknown and concern. Managers need to be aware of the beneficial and adverse effects of mastication to more effectively manage ecosystems, especially those in the Wildland Urban Interface (WUI).

This study will investigate the effects of masticated fuels on ecosystems using an integrated approach involving multiple disciplines and scientists designed to be repeated across many ecosystems and treatment conditions. One phase of this study will involve describing masticated fuel characteristics by measuring fuelbed properties that are important to the prediction of fire behavior and effects: 1) loading, 2) bulk density, 3) particle size distribution, and 4) mineral content. Another phase is to develop a fuel sampling protocol that can accurately, consistently, and comprehensively quantify masticated fuel loadings for a variety of management purposes including smoke emission prediction, fire behavior calculation, and soil heating description. Still another phase will describe the behavior of fire burning in a masticated fuelbed and this information will be used to develop a set of fuel models to use to predict fire behavior in other masticated fuelbeds. And the last phase is to study the ecological effects of creating a masticated fuelbed. These effects are evaluated for burned and unburned masticated fuels and they include major ecosystem elements of vegetation response, fuel consumption, soil heating, and nutrient cycling. This study is designed so that more phases can be integrated as more scientists become interested and more types of masticated fuelbeds can be included as they are created by fire management.

BACKGROUND

Mastication

Masticating fuels is a mechanical treatment that breaks, shreds, or grinds canopy (seedlings, saplings and pole trees) and surface fuels (fine and coarse woody debris) into smaller sizes and depositing the treated fuels on the ground to a compact layer with a high bulk density (Figure 2). The mastication is accomplished using a variety of specially designed equipment that shred, flail, chip, and crush fuels to create fuelbeds that support slowly spreading fires that are somewhat easy to control. The cost of mastication is influenced by many factors, such as the type of masticator used, the distance it must be hauled to the site, the live and dead fuel conditions on the treatment area, but it ranges somewhere between $300-$800 per acre.

Figure 2--Mastication with a tree shredder

The masticated fuelbed is extraordinary in its composition, structure, and physical properties. It is not similar to any other fuelbed that has been studied for prescribed burning and wildfire effects. Activity fuelbeds created by conventional harvesting, thinning, and felling, do not resemble masticated fuelbeds because of the mechanical treatment used to masticate live and dead material. The mechanical treatment tends to separate tree bark from stems and the bark often becomes incorporated into the ground layer to create an odd fuelbed composition. Broken slivers of woody fuel, mixed with small severed pieces of fine fuels (twigs and branches), tree bark, green foliage, and broken rotten wood, creates a compact fuelbed with high bulk density and low surface area to volume ratio. The mastication treatment also drives fuel into the ground or mixes the fuel with the duff, litter, and mineral soil, and this causes the fuelbed to have a high mineral content that may dampen fire behavior and mitigate severe fire effects.

Currently, it looks as though there are four general mastication methods:

- **Shredding**: Machines are used to shred aboveground vegetation using a rotating drum.
- **Flailing**: Machines contain rotating chains or cables that are spun at high speeds to break up fuels
- **Crushing.** Heavy machines are driven across the ground, sometimes with a roller, to crush fuel under the tremendous weight and break up particles and drive into the ground.
- **Chipping.** Machines with chippers (rotating drums with blades) are used to cut the fuels and deposit them on the ground.

Masticated fuelbeds are difficult to sample because their characteristics are not well suited for the standardized sampling methods for estimating fuel loadings. Since woody fuel particles have been broken and cut, their size and distribution does not match the assumption used in the planar intercept method (Brown 1974). Moreover, the mechanical treatment tends to mix broken slivers of woody fuel, pieces of fine fuels (twigs and branches), bark, foliage, and rotten wood to create a compact fuelbed with high bulk density and low surface area to volume ratio. To make matters worse, the high mineral content of masticated fuels because the fuel is pushed into the ground to mix with the duff, litter, and mineral soil. As a result, the loading of this strange fuelbed is not easily measured by conventional methods because of its odd properties. To accurately sample masticated fuelbed loadings, we first must describe the fundamental properties of the fuelbed that pertain to fire dynamics, and then develop a sampling method that addresses and accounts for these peculiar fuelbed properties in the sample design.

Figure 3--A burning masticated fuelbed

This uniqueness of the masticated fuelbeds is also the reason why there is relatively little data and observations on fire behavior and effects of this mechanical treatment. Fire behavior information is especially scarce because these treatments often remain unburned because the mechanical treatment alone may accomplish fuel hazard reduction objectives. However, it is important to know how a fire behaves in these treated stands, especially those fires started by arson or lightning, to better protect property and life in the WUI. Fire behavior characteristics that are important to describe include rate of spread, post-frontal combustion intensity, flame lengths, fireline intensity, and soil heat pulse. Many believe that the most important fire behavior to quantify is the heating of the soil layer by smoldering combustion in the thick and dense fuel layer with a high mineral content. It could be that the masticated fuelbed might pulse so much heat to the lower soils layers that it could kill many roots and soil organisms, and alter nutrient dynamics, and destroy anthropological artifacts.

There are many aspects about this treatment that concerns fire managers and researchers. First, what are the effects of the treatment on the above-ground and below-ground biota? Many worry that the placement of such a large amount of organic material with low nitrogen concentrations will act as a nitrogen sink and thereby limit the amount of nitrogen available for plant growth. Moreover, the relatively large amount of organic material may absorb rainfall, especially during the critical growing season, and thereby cause higher water stress in the remaining plants. On the other hand, the high amount of organic material may also

Figure 4--High crown scorch resulting from intense heat generated by burning of a masticated fuelbed

act as a layer to limit the amount of soil evaporation.

Even less is known on the long and short term effects of burning a masticated fuelbed. Recent studies have shown that deep soil heating can result from the long smoldering times in a masticated fuelbed (Figure 3). Longer fire retention times can also happen in fuelbeds consisting of deep organic material and this can cause greater tree mortality (Figure 4).

Sampling Fuels

There are five general methods for sampling fuels. ***Fixed plot methods*** are those that use a plot frame of a fixed area to delineate a sampling area and all fuels within that area are collected, dried, and weighed to determine loadings (mass per unit area). The advantage of this method is that all fuel components (woody, litter, duff, and so on) can be collected using the same plot frame or nested plot frames of varying sizes and this is easily the most accurate method of sampling fuels. The disadvantage is that the fixed plot method is extremely time and cost intensive and therefore rarely ever used in standardized inventories and mostly used for research efforts. It is also difficult to determine the number of fixed plots to accurately capture the variability within the sample unit (stand, polygon, landscape) because fuels are highly variable in space and time and are often clumped in jackpots.

Planar intercept methods are often the common sampling techniques for sampling fuels for inventory applications. This involves counting or measuring fuel particles as they intercept a vertical sampling plane that is of a fixed length and height (Brown 1970, Brown 1974). These intercepts can then be converted to loadings using standard formulae. The advantage of this method is that is easy to use and can be easily scaled to match the sampling unit and fuel conditions by altering the dimensions of the sampling plane. The method can be taught to novice field technicians and results are highly repeatable. However, this method only pertains to downed dead woody particles and may require a large number of sampling transects (bottom of sampling plane) under heavy and highly variable fuel loads.

Recent research has found that ***angle gauge methods*** are effective at measuring loadings of coarse woody debris. Here, an angle gauge is used in a point sampling strategy to identify all logs that should be sampled. The angle of the gauge is used to sight which logs are “in” or “out” based on the log’s diameter. This method is very quick and effective but only is used for coarse woody debris (large logs) and has limited use for fire behavior fuel inventories that require loadings of fine fuels.

An often-used, fast, and easy fuel sampling technique is the ***photo series method.*** In this method, the field person walks into the sampling unit (stand, landscape) and visually matches the observed conditions with a photograph from a set of oblique photos characterizing common vegetation types and site conditions (Fischer 1981, Sandberg et al. 2001). This quick and dirty method is used by number of fire management agencies to get an estimate of fuel loads. It is easily taught and the photos are easily created. However, this technique is highly inaccurate and is not repeatable (Lutes 1999). Loadings of all fuel components must be estimated from only one photo and this is nearly impossible because fuels vary by component across small spatial scales. Often, the fine fuel components (1, 10, 100 hour downed woody) are not visible within these photos so this technique is often useless for fire behavior fuels inventories.

The next fuel sampling strategy, called the ***fuel model method,*** is perhaps the easiest and quickest but it is also the least accurate and repeatable. A fuel model is a set of loadings for a discrete set of fuel components (Sandberg et al. 2001). Fuel models are then linked to specific vegetation, site, and stand history characteristics. A sampler would key the fuel model from the conditions observed within the sampling unit. This technique is quite useful in fuel mapping efforts because it provides a means for extrapolating sampled fuels across the landscape based on the keyed characteristics. However, this method is rarely accurate for fine scale fuel inventories because, like the photo series method, the fuel models are oversimplifications of actual fuel conditions and fuel components are independent and highly clustered. The number of fuel models is usually increased to increase the accuracy of fuel loadings but this usually results in an overly complex fuel model classification that is very difficult to use in the field.

One last fuel sampling technique is relatively new and not fully tested is the ***photoload method*** that uses a graduated series of downward looking photos as reference and the user simply matches the loading conditions observed in the field with one of the photos (Keane and Dickinson 2007[in press]). Each photo portrays a specific loading and there are photos for six fuel components. This method is relatively quick and easy to learn. It appears that the photoload method is more accurate than the photo series and fuel model method, and roughly equivalent to the planar intercept method.

Another fuel sampling technique, the ***cover-depth method***, is a newly proposed sampling method for masticated areas. This method requires estimating cover of masticated material and recording depth in $1m^2$ frames. Fuel loadings are then estimated from pre-determined bulk densities (Hood and Wu 2006 [in press]). Although this method has not been thoroughly tested, if accurate would be a quick and repeatable method for estimating masticated fuel loadings. It could also be used in conjunction with the ***photoload method*** to estimate dead and down, unmasticated material, such as activity fuels and blowdown areas. We will further test this method in the current study.

PROJECT OBJECTIVES AND SUMMARY

The project has one primary objective and a number of specific objectives. The primary objective is to:

- *Investigate the effects of masticated fuels on various ecosystem processes and characteristics*

More specifically, this study uses a set of integrated secondary objectives to accomplish the primary objective. These secondary objectives are:

- *Describe the characteristics and properties of masticated fuelbeds*
- *Develop a sampling protocol to estimate the loading of masticated fuelbed*
- *Describe fire behavior in burning masticated fuelbeds*
- *Evaluate the effects of masticated fuelbed on the ecosystem*

These secondary objectives can include other objectives at a later date if other scientists are interesting in this integrated project. Currently, this study consists of only the four objectives and they are treated separately in this document.

Results from this study should be of great interest to many fire managers and scientists, especially those involved with planning fuel treatments for the WUI and sensitive areas.

MATERIALS AND METHODS

As mentioned, this project will consist of four fully integrated phases to successfully accomplish the objectives. In one phase of this study, we will describe masticated fuel characteristics by measuring fuelbed properties that are important to the prediction of fire behavior and effects. Another phase involves developing a fuel sampling protocol that can easily quantify fuel loadings for a variety of management purposes. Still another phase will describe the behavior of fire burning in a masticated fuelbed and this information will be used to develop a set of fuel models to use to predict fire behavior in other masticated fuelbeds. And the last phase is to study the ecological effects of creating a masticated fuelbed. These effects are evaluated for burned and unburned masticated fuels and they include major ecosystem elements of vegetation response, fuel consumption, soil heating, and nutrient cycling.

This is an integrated study because, to successfully accomplish the four phases, the study must be designed so that measurements appropriate to each phase are taken prior to the mastication treatment, directly after the mastication treatment, and after burning the masticated fuelbed. This involves the complex coordination of many scientists measuring various fuelbed and ecosystem properties in an integrated sampling protocol that minimizes redundancy and allows the measurements to be available to all scientists in all phases. Hopefully, the design is able to accommodate additional phases as more scientists become interested.

This study will be implemented in two stages. The first stage, called the prototype stage, involves the application of the methods detailed in this report on a study site to prototype the study's design and refine the sampling and measurement methods to more consistently implement the second stage of the project which is to implement the refined methods on a variety of masticated fuel treatments and study sites across the western United States. The two stages are necessary because masticated fuelbeds are relatively new to most scientists and it will take time to familiarize the people involved in this study with the odd characteristics of this mechanical treatment.

Study Sites

Study sites will be selected by two criteria: ecosystem type and mastication method. These criteria will be used to fill in an ever-increasing two-dimensional matrix. Study sites will be selected based on an opportunistic protocol where we will find sites that will be treated in the near future by fire management agencies and determine if they fulfill an unsampled combination of ecosystem type and masticated method. Ecosystem types will most likely be describe by existing major cover type or land type classifications such as (Kuchler 1975) or (Eyre 1980, Shiflet 1994) and a structural stage classification. For example, the ecosystem type for one study site might be Ponderosa Pine/Douglas-fir cover type with multistrata pole canopy.

We will use the following grouping of mastication methods to guide our site selection:

- **Shredding**: Machines are used to shred aboveground vegetation using a rotating drum.

- **Flailing**: Machines contain rotating chains or cables that are spun at high speeds to break up fuels
- **Crushing.** Heavy machines are driven across the ground, sometimes with a roller, to crush fuel under the tremendous weight and break up particles and drive into the ground.
- **Chipping.** Machines with chippers (rotating drums with blades) are used to cut the fuels and deposit them on the ground.

Here is a possible matrix for targeting site selection for this study:

Cover Type	**Shredding**	**Flailing**	**Crushing**	**Chipping**
Ponderosa Pine				
PP/Douglas-fir				
Douglas-fir				
Pinyon Juniper				
Mixed conifer				

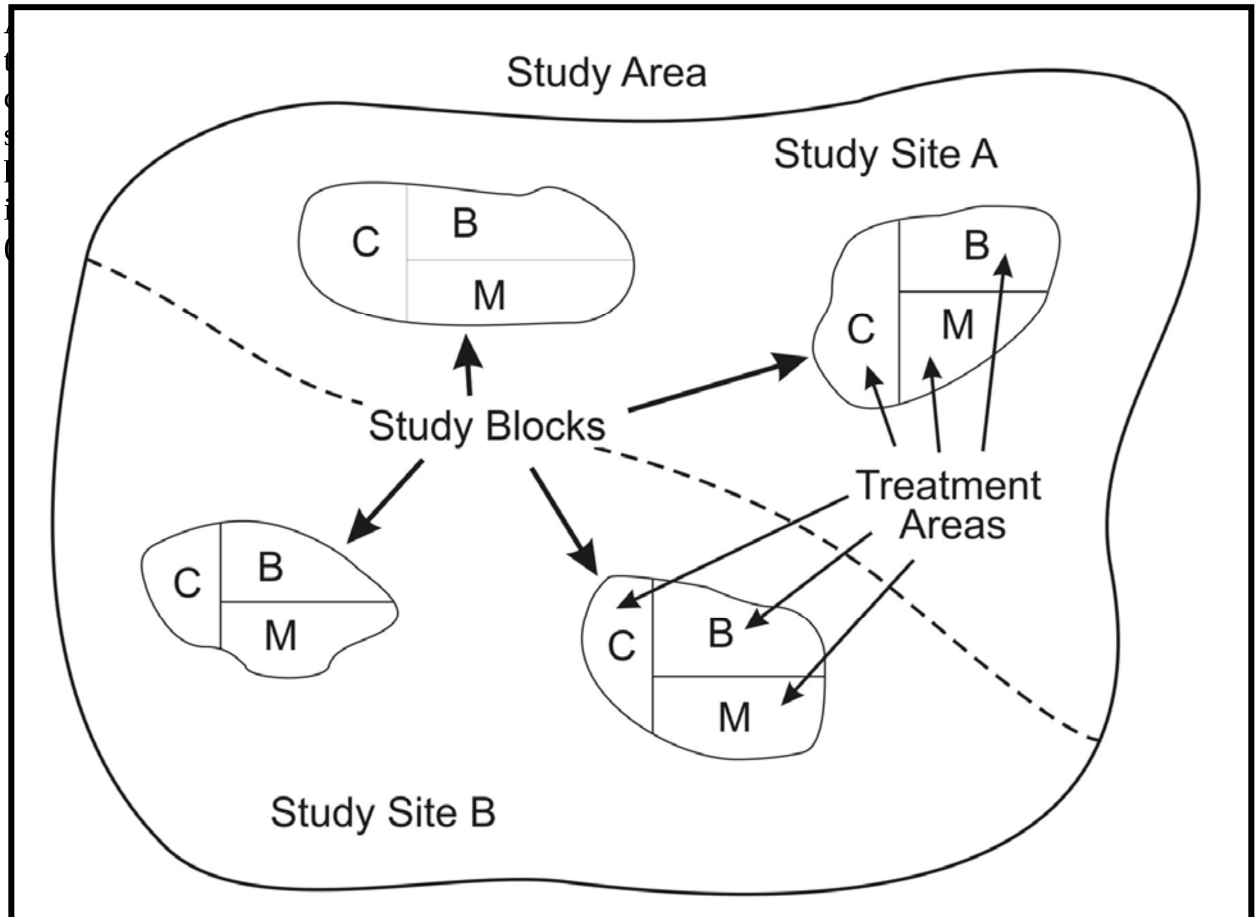

Figure 5-Study design showing a study area composed of two study sites with two blocks per site and each block containing the three treatments: C-control, M-masticated, B-burn

Each study site can consist of multiple blocks, which are the replication within the study design (Figure 5). Each block will consist of exactly three treatment areas. The first treatment area is the **control (C)**, and it is an area where there is NO mastication and burning treatment (Figure 1). The second area has the **masticated treatment** ONLY **(M),** while the third area is the **mastication and burn** treatment **(B)**. If possible, we will have a fourth **burn** treatment (**P)** which is just burning without any masitication. However, this treatment will be optional. We might also have a **slash treatment** (**S**) where the material is slashed to the ground and NO masitication is done.

Study areas are named for geographical location, study sites are named for the ecosystem-mastication combination, study blocks are consecutively numbered, and study treatment areas are labeled by the above letters. Obviously, the installation of a study area will take extensive coordination by land management personnel and the study scientists.

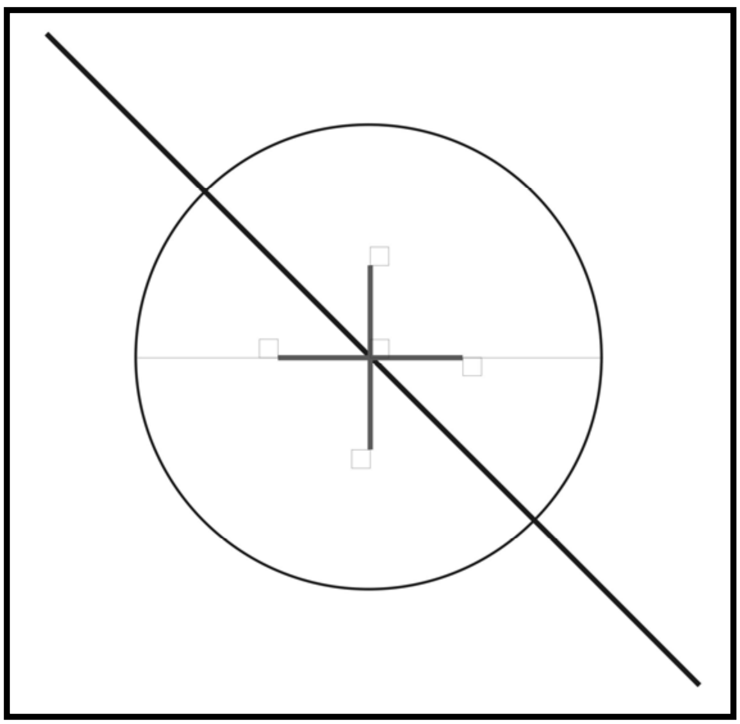

Figure 7--Sampling design at the plot level showing the two large fuel transects, circular plot boundary, and set up of the five microplots

Plot Installation -- We will install five plots in each of the treatment areas (Figure 6). Each plot will be circular and 500 m^2 in area (radius of 12.61 meters or 41.3 feet) (Figure 7). The plots will be systematically located in the treatment area in a grid that is designed to fit in the area and allow easy relocation of the plots. The only specification is that the plots are at least 50 meters from each other's plot center. Each plot will be permanently installed using a 2 foot iron rebar stake that is ½ inch in diameter and driven into the ground so that 6 inches are visible. The visible rebar is then painted orange and marked with orange flagging, and we will wire a steel tag to the rebar that identifies the block-treatment-plot number. We will also place two 8 inch spikes exactly 6 inches north and south of the rebar in case it is pulled out of the ground. The UTM coordinates of the rebar will be taken with a GPS unit and recorded on the FIREMON PD form in the appropriate field.

There will be a set of five square microplots that are 1 m^2 in area permanently installed within each plot. These microplots are installed 5 meters from plot center in each of the four cardinal directions and at plot center (Figure 2). The microplots are installed so that the frame is pointed in the clockwise direction (Figure 2). Two corners of the microplot that are in line with plot center are permanently marked using 10 inch spikes driven into the ground and marked with orange flagging. We will fill out two forms at each microplot. First, we will complete a cover frequency form (FIREMON CF method) and then we will fill out the fuel microplot form (see appendix). The fuel microplot form contains fields for 13 duff/litter/fuel depth measurements, woody cover quadrat estimates, photoload fuel loading estimates, LAI-2000 LAI estimates, hemispherical digital photograph numbers, and digital photograph information.

Figure 8--The Kootenai NF prototype study area

All plots will be measured at four or more times during this study. They will be measured:

1) prior to mastication treatment,
2) after mastication treatment,
3) after fire treatment, and
4) five years after the mastication treatment.

The post-fire treatment may be limited to only the burn (B) treatment area if only one year has passed since mastication.

The prototype study site -- In the prototype stage of this study, we have a study site on the Kootenai NF (Figure 7). It is a 15 acre ponderosa pine stand with a dense understory of Douglas-fir (Figure 7 and Figure 8). It is on a flat, droughty, riverine terrace near the Libby Airport and surrounded by human development (Figure 8). The Kootenai fire managers have been through the NEPA process and this stand is ready to treat.

Figure 9-Aerial photo of the prototype study site

The primary purpose of the prototype stage is to make sure our methods will work and the burning requirement may not be possible in one year. We will probably only install ONE block in the prototype stage but this block will include all treatments: control (C), masticated (M), and masticated and burn (B) treatments.

Each phase of the study is discussed

next. The phases are identified by specific tasks and there are names assigned to each task (in capital letters with the parenthesis).

Describing each biophysical characteristics of the plot

Plot Level Information -- We will sample four general characteristics of the plot as a whole using the FIREMON sampling protocols (Lutes et al. 2006[in press]) at each of the sample times. First, we will fill out the FIREMON Plot Description form that describes general plot site conditions. This may only need to be done once at the beginning of the study for each plot. The plot will be georeferenced using a GPS unit and UTM coordinate system. All fields will be completed for this Plot Description protocol. We will also take a digital photo from 5 meters west of plot center facing east and 5 meters south of plot center facing north being sure to have the plot rebar clearly visible in the bottom of the photo.

Next, we will record tree population data using the FIREMON Tree Data method. This will need to be done at each sampling time. We will tag all trees above 10 cm DBH and measure the DBH, tree height, canopy fuel base height, crown class, crown position, and live crown ratio. We will install the tags at groundline, facing plot center using aluminum tags for all but the burn (B) treatment area where we will use steel casket tags. We will also take the age of the two oldest trees on the plot determined from size and growth characteristics. This will be done with an increment borer inserted at groundline. We will also record any growth defects, insect, and disease infections for each tree. We will tally all trees less than 10 cm DBH but greater than 1.37 meters in height (saplings) on Table 2 of the FIREMON TD plot form. The saplings will be individually recorded by species and 2 cm (1 inch) DBH size classes, canopy base height, and height as specified in FIREMON for the entire 500 m2 plot. Seedlings (trees < 1.37 meters in height) will be counted by species and height classes on the TD Table 3 within the five microplots as discussed later.

We will also sample fuels characteristics using the FIREMON Fuel Loading method. Here, we will establish two, 25 meter transects radiating out from plot center (Figure 2) in the following directions (Plot 1: 0, 180 degrees, Plot 2: 60, 240 degrees, Plot 3: 120, 300 degrees, Plot 4: 0, 180 degrees, and Plot 5: 60, 240 degrees). We will measure fine fuels (1 and 10 hour timelag) along three meters of the two transects starting at the five meter mark. The 100 hour fuels will be measured along five meters, also starting at the five meter mark. The logs (>7 cm diameter logs) will be measured along 20 meters starting at the 5 meter mark. A 10 inch spike driven 9 inches into the ground and marked with wire flagging will be placed at the 25 meter mark and the 12.61 meter mark to show the boundary of the plot. We will also measure duff plus litter depth at the 12.61 and 20 meter marks along each transect using the FIREMON methods. We will also estimate the fuel loading of the 1, 10, and 100 hr fuels inside the microplots (Figure 8) using the photoload sampling technique (Keane and Dickinson 2007[in press]) as discussed later.

Microplot Level Information -- We will determine the cover and height of all plants inside the microplots (Figure 8) using the FIREMON Cover Frequency (CF) methods. We will collect voucher specimens for all vascular plant species that cannot be positively identified. We will use the 6-letter acronyms as specified in FIREMON. We will not estimate nested rooted frequency; we will only estimate canopy cover (FIREMON cover class) and height (cm).

We will also estimate the fuel loading of live and dead shrub and herbaceous fuels using the photoload sampling technique (Keane and Dickinson 2007[in press]). We will also estimate photoloads for all downed dead woody fuels, shrubs (live and dead), and herbaceous material (live and dead). We will use the Fuel Microplot plot form (see appendix) to record these data.

Next we will estimate the cover of woody fuel by quandrant within the microplot. We will use the FIREMON cover classes and record for NW, NE, SE, and SW quandrants in that order. Woody fuel cover is estimated four times in the microplot for each of the four quadrants by dividing the microplot into four 0.25 m^2 areas (50 x 50 cm). Cover is ocularly estimated by the same person for each quadrant, microplot, and plot. We will also take a photograph of the microplot by standing above the microplot on the side of the microplot towards the rebar and taking the photo at approximately eye level pointing downward.

Then, we will take the fuel depth measurements. Fuel depths are measured nine times in the microplot frame using a 3x3 grid marked with lines going across the microplot face at 25 cm intervals along the frame sides. We will also take depth measurements in the four corners of the microplot and along the intersections of the grid lines with the plot frame to obtain 13 more depth measurements. Fuelbed depth is measured from the mineral soil to the topmost particle keeping the probe perfectly vertical. At times, we may have to pull away material to determine the mineral soil interface. Fuel depth will contain duff, litter, and incorporated masticated material.

We will also take a hemispherical photograph using the NiKon Coolpix 4500 digital camera mounted level on a tripod approximately 4.5 feet above plot center (rebar). The number for this digital photo is recorded on the Fuel Microplot plot form (see appendix). We will also take LAI using the LAI 2000 at each plot. We will program the LAI-2000 to take one calibration reading outside the stand in the open, then take nine readings within the plot, and a last calibration reading outside the stand in the open. The nine plot readings are done at all the plot nails facing north, and plot center. The LAI-2000 readings will only be taken in heavy overcast days or near dawn or dusk. Measurements are written of the fuel microplot plot form (see appendix) in the column for the plot center microplot.

There may be additional measurements that need to be recorded by other scientists for their specific experiments using the block design.

Describing Fuelbed Characteristics

We will describe five characteristics of the masticated fuelbed. These characteristics were selected because they have been proven to be important to predicting fire behavior and effects, and they are major inputs to fire models. These characteristics are also important in developing the masticated fuels sampling protocol. The characteristics are:

- *Loading or biomass* – The mass per unit area of the masticated layer (kg m^{-2}).
- *Particle Density* – The mass per unit volume of the fuelbed particles (kg m^{-3})

- *Particle size class distribution* – The distribution of diameter by loading for a fuelbed.
- *Bulk Density* – The mass per unit volume (kg m^{-3}) of the entire masticated fuel layer. If possible, we will attempt to measure the duff and litter layer separately, but this may be impossible for many masticated methods.
- *Mineral content* – The proportion of biomass that is mineral (proportion or percent).

The measurements of these five characteristics are completely integrated in our proposed sample design and they will be discussed individually next.

Loading – We will measure masticated fuel loading using two methods. We will first estimate loadings using a prototype of the cover-depth sampling protocol (discussed in next section) where fuel depths and masticated coverage are estimated on the microplots. Fuel depths are measured nine times in the microplot frame using a 3x3 grid marked with lines going across the microplot face at 25 cm intervals along the frame sides and in the microplot corners (see above). Woody fuel cover is estimated four times in the microplot for each of the four quadrants by dividing the microplot into four 0.25 m^2 areas (50 x 50 cm). We will also take digital photos, looking directly vertical, of all microplots after each treatment. We will also take a photograph of the microplot by standing above the microplot on the side of the microplot towards the rebar and taking the photo at approximately eye level.

After mastication, we will also collect all fuels from the northern microplot within one quadrant (50x50cm) of the microplot (northwest) and bring these fuels to the lab to oven-dry and weigh. Fuel particles will be cut at the quadrant boundaries if they extend outside the quadrant. Prior to the actual collection, we will first take two digital photos of the fuelbed looking directly down – one from the southern side and one from the eastern side of the microplot -- and then we will measure fuelbed depth within the collection quadrant nine more times using the same 3x3 grid as in the sampling protocol only adjusted for the quadrant. Collected material will be placed into paper bags, boxes, ziplock bags, or burlap sacks depending on the amount of fuels. The dried and weighed collected material will be placed aside for additional analysis to describe fuel characteristics. We will then take some material representative of the masticated fuelbed from outside the macroplot boundaries to achieve a predetermined loading (wet weight). We will adjust this wet weight to dry weight once we measure it from the collected material. The predetermined loading will be determined through a process that involves creating fuelbeds that ramp up in loading from no fuels to the heaviest loadings observed within the sampling unit.

The digital pictures will be used to create photoload sequences for masticated fuels (Keane and others 2007[in press]). We may be able to use these sequences to estimate loadings in a third method later in the study once several study sites have been installed. The material that is brought back to the lab will be used to create simulated masticated fuelbeds of graduated loadings in the lab for photoload sequences.

We will also create 10 synthetic fuelbeds outside macroplot boundaries and independent of the sampling effort to ensure all possible fuelbed types and loadings are represented. These synthetic fuelbeds will be created using wet weight loadings of masticated material found outside of any plot boundaries. We will place the material in a bag and ensure the collections and the fuelbeds have consistent properties to the masticated fuelbeds found on the ground in the treatment area (size class distribution, duff/litter composition). These fuelbeds will be identified by four nails driven in at the corners of each of the 10 microplots. We will take pictures of these fuelbeds before and after the burn treatment. We will also collect all the material within the fuelbed right after the burn treatment to determine consumption.

We will also create a synthetic fuelbed of uniform loading in each of the masticated only treatments outside of any plot boundaries. We will collect a sample of this fuelbed as described above immediately, 1, and 5 years after mastication in order to determine changes in fuelbed bulk density over time.

All collected fuels will be dried and weighed at the lab. However, it may be that there is so much material that it all can't fit into the oven. In this case, we will have to take the wet weight of the fuel and then take a subsample to determine moisture content. This will be done by throwing all collected fuel into one sample, taking a small part of that sample, determine the sample's wet weight, dry for three days, and weigh again to determine dry weight. Use the dry and wet weights to determine moisture content (dry/wet) and then adjust all measurements based on that proportion.

Particle Density – The particle density of various pieces of material in the fuelbed will be measured using standard techniques. This will be done by weighing oven-dried pieces collected from the microplots and then calculating a volume by immersing the particle in liquid and recording the displacement. We may have to coat the smaller particles with wax or paraffin to reduce water absorption into the wood. We will select particles based on size and type. Size classes of woody fuels, including bark and stems, are in 2 mm diameter classes. We will measure at least 10 particles per collected fuelbed.

Particle Size Class Distribution – We will sort the collected material for the quadrant fuelbed into 1 cm size classes and record the dry weight per size class to determine the size class distribution for the masticated fuelbed. The size class distribution is important to the modeling of fire behavior and effects because it can distribute sampled loadings across various diameters of woody fuels so that they can be input into the fire models. We will do this by laying a woody fuel particle on a surface with a ruler. Then, the diameter of the particle will be taken at one end of the particle. The lab tech would then use calipers to determine when the diameter change of the particle is greater than 2 mm. The length and the new diameter is then recorded and this process is repeated until the end of the particle is the last diameter measured. We will measure at least 10 particles per collected fuelbed.

Fuelbed Bulk Density – Measurement of the fuelbed bulk density is perhaps the most important fuelbed characteristic because it will probably be used in the developed sampling protocol to determine loading. We will estimate fuelbed bulk density by dividing the over-dried weight of the quadrant fuelbed (loading) by the volume of the fuelbed calculated by multiplying the average of the nine depth measurements to the square of the quadrant side length (50 cm).

Mineral Content – An assessment of mineral content of the masticated fuelbed is important because mineral soil is often incorporated into the fuelbed due to the mechanical crushing and twisting, and this added mineral content will affect fire behavior and the subsequent effects. We will measure mineral content by grinding a portion of the collected quadrant fuelbed and burning the portion in a muffle furnace and then weighing the ash.

Developing Sampling Methods

We will develop standardized methods for estimating masticated fuelbed loadings that can be easily taught to managers and can be easily and quickly implemented by field crews to obtain the values that are input to fire models. We will first present a proposed cover-depth method and then test this proposed method using the measured fuels collected from the quadrant mentioned above. The proposed method is as follows:

- Create a plot frame that is 1 meter square and contains the 3x3 grid as detailed in the previous section
- Lay the frame on the ground on a systematic grid that covers the stand in question. This grid does NOT have to mimic that used in this study, but it should contain enough microplots to adequately describe fuelbed loadings for the stand and yet still be possible with the resources and expertise available.
- Measure fuelbed depth at nine places in the grid using a graduated probe
- Average the nine depth measurements and convert the average depth to meters
- Multiply the depth by fuelbed bulk density to obtain loading. The bulk density will be obtained by matching ecosystem type and mastication method with the site conditions.

Loadings estimated using the developed sampling protocol will be compared to actual loadings collected from the quadrants using the extensive set of statistics presented in Keane and Dickinson (2007) where the bias, variability, and precision accuracies are calculated by plot, treatment area, and block.

We will also estimate fuel loadings using the photoload sequences once they are developed using the methods described in Keane and others (2007). Loading estimates obtained using the two protocols will be compared to the loading destructively measured from the quadrant to determine if the protocols are valid and repeatable. If photos taken in the field do not seem adequate for determining loading, we will create masticated fuelbeds using the collected material in the lab and take pictures of these simulated fuelbeds using methods presented in Keane and Dickinson (2007[in press]).

The sampling protocol will be refined and improved based on the results of the comparison with actual loadings. We will then write a sampling protocol with sufficient detail to formally include in the FIREMON system. This protocol will contain sufficient figures, illustrations, step-by-step instructions, and recommendations so that anyone can learn the method and training will be easily accomplished.

Describing Fire Behavior in Masticated Fuelbeds

We will measure several fire behavior characteristics as the Burn (B) treatment areas are burned using prescribed fire. The primary characteristics are:

- Spread rate – measured using
- Fire intensity –
- Flame length

Soil heating will be described in this study by installing a set of thermocouples into the soil profile using equipment developed at the Missoula Fire Sciences lab. We will install three thermocouple sets per burned masticated fuel treatment area within the boundaries of three randomly selected plots. Hopefully, we will be able to install these under one of the microplots so that we know the fuel loading.

We will then use the observed and measured fire behavior estimates to create a customized set of fire behavior fuel models to augment the ones developed by (Anderson 1982, Scott and Burgan 2005). We will use the methods described by (Burgan and Rothermal 1984) to develop the fuel models so they can be used as input in fire behavior modeling systems such as BEHAVE (Andrews and Bevins 1999) and FARSITE (Finney 1998).

Assessing Effects of Mastication

Another important facet of masticated fuels treatment is the effect of the treatment on various ecosystem elements, whether the fuels are burned or left unburned. This effect might be immediate, such as the death of plants from burning or covering with masticated material, or long term, such as changes to the nutrient cycle, invasion of weeds, and prevention of tree regeneration. These effects can either be exacerbated or mitigated by burning the masticated fuels layer. To evaluate these effects, we will perform the following measurements within the plot design and repeat these measurements at each of the sampling periods.

Undergrowth Vegetation Response -- We will measure the cover, height, and nested rooted frequency of vascular and non-vascular plants within the five, one m^2 subplots in each plot following the FIREMON protocols for the Cover Frequency method.

We will also implement methods for monitoring weed invasion and rare species.

Tree Mortality -- We will monitor the health of each tagged tree in the plot to determine its fate as a consequence of the mastication treatment and the burn treatment. We will record any wounding that the tagged trees receive during the mastication process, and we will estimate char height, scorch height, and percent crown volume scorched for tagged trees in the burned unit using the FIREMON TD method. The seedling and sapling mortality will be evaluated from the four re-measurements of the microplot and circular plot.

Nutrient Cycling – It is our hope to involve a below-ground scientist to quantify the effects of mastication on nutrient dynamics, specifically nitrogen.

Water Dynamics – We will monitor the soil water balance using the latest technology. We will also measure pre-dawn water potential using a pressure bomb and sampling foliage at the end of July and at the end of August (at the driest time of the year).

Sampling Summary

In summary, here are the steps for the **pre-treatment sampling effort**:

1. Lay out plots within treatment areas and record locations on map
2. Lay out plot boundaries
3. Record plot characteristics using FIREMON PD form
4. Lay out fuel transects and perform FIREMON FL methods
5. Lay out microplots
    a. Record photoloads
    b. Record fuel depths
    c. Record woody fuel cover by quadrant
    d. Record cover height by species using FIREMON CM form
    e. Take pictures of east, west microplots
6. Tag and measure trees using FIREMON TD form

After the **mastication** treatment, here are the next steps:

1. Remeasure the microplots
    a. Record photoloads
    b. Record fuel depths
    c. Record woody fuel cover by quadrat
    d. Record cover height by species using FIREMON CM form
    e. Take pictures of east, west microplots
2. Collect fuel from the NW quadrant of the North microplot
    a. Store in paper bag or burlap sack
    b. Bring to lab for analysis
3. Measure out a similar loading from fuels outside the plot
4. Replace fuels in NW quadrant
5. Create a series of fuel loadings outside the plots
    a. Photograph the fuelbeds
    b. Collect some fuel for determining moisture content
    c. Bring to lab for analysis
6. Create uniform fuel bed outside the plots in masticated only treatment
7. Remeasure fuels using FIREMON FL form
8. Remeasure trees using FIREMON TD form

After the **burn treatment**, here are the steps to be completed:

9. Remeasure the microplots
    a. Record photoloads

   b. Record fuel depths
   c. Record woody fuel cover by quadrat
   d. Record cover height by species using FIREMON CM form
   e. Take pictures of east, west microplots
10. Collect fuel from the NW quadrant of the North microplot
   a. Store in paper bag or burlap sack
   b. Bring to lab for analysis
11. Perform measurements of synthetic fuelbeds outside the plot
   a. Record photoloads
   b. Photograph the fuelbeds
   c. Collect fuel
   d. Bring to lab for analysis
12. Remeasure fuels using FIREMON FL form
13. Remeasure trees using FIREMON TD form

ANALYSIS

This study is designed to compare the averages of various fuel, ecosystem, and fire attributes across and between treatment areas using the blocks as replication (degrees of freedom) in a multivariate analysis of variance (MANOVA). Most of the statistical analyses are elementary for the many phases of the study because the objective of the study is more descriptive than comparative. However, the sampling design of the study should allow a comprehensive analysis of variance using the treatment areas as the analysis unit.

SAFETY

The field portion of this project may be somewhat dangerous for field crews because we will be sampling in recently cut and burned environments and there will be a high risk of tree fall. And the ground will be covered by slash and organic material so there will be high risk of falling and tripping. 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.

PROJECT SCHEDULE

We would like to start the study by June of 2006 and complete the prototype phase by the end of October. The second phase of the study would then commence during the summer of 2007 and continue till five years after burning, probably till 2013. There will be an additional year of analyses, report writing, manuscript preparation, and review resulting in the project being complete by 2014.

PERSONNEL

Dr. Robert Keane has extensive experience in fuel sampling, vegetation sampling, and large ecological field studies. Dr. Keane will support the project through his expertise in sampling procedures. His is primarily responsible for the field sampling design and analysis of the project and is in charge of the first task.

Helen Y. Smith is an ecologist and has participated in numerous field campaigns. Her role in this project is to coordinate field sampling and conduct initial data analysis.

BUDGET

ITEM	YEAR 1	YEAR 2	TOTAL
National Fire Plan			
Keane salary	Contributed	Contributed	0
Technicians			
2 GS5 Field Techs, 3 years, 4 months per year			
field equipment			
Travel			
Publications			
Project Total			

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. The deliverables include:

- An RMRS General Technical Report describing the characteristics of masticated fuelbeds
- A new masticated fuel sampling method that is included in the FIREMON system
    - Protocol directions with detailed instructions and illustrations
    - Field forms
    - Databases and data entry routines
    - Analysis programs
- A photoload guide for masticated fuels (USDA Forest Service RMRS GTR)
- A RMRS GTR describing the fire behavior in masticated fuels
- A new set of fire behavior fuel models for fire behavior prediction in masticated fuels
- A journal article or RMRS research paper describing the short-term effects of fuels mastication.

TECHNOLOGY TRANSFER

Technology transfer will include:

- The teaching of the masticated fuel sampling technique and photoload technique in the FIREMON training sessions.
- The USFS General Technical Reports describing the photoload technique
- The implementation of the masticated fuels in the BEHAVE and FARSITE fire models
- Publication in various journals
- Presentations of study results at major conferences and symposia

Appendix A
Equipment list and plot forms

Equipment List

Plot setup
- Compass
- Clinometer
- Logger's tape (DBH tape)
- GPS unit
- Heavy gauge wire cut to length
- Flagging
- Tree tags (aluminum and steel)
- Nails (aluminum and steel)
- Hammer
- Pencils, field notebook
- Field sheet
- Rebar or 12 inch spikes
- Wire flagging
- Cloth tapes at least 25 meters long
- Go-no-go gauges
- FIREMON plot sheets – PD, FL, TD, CM
- 8 inch spikes

Microplot
- Microplot frame (1x1m) with graduated marks and string across quadrants
- Measuring probe
- 10 inch spikes
- flagging
- Plot sheets
- Tarp
- Shovel (square nose and spade)
- Scoop
- Burlap sacks, paper bags, large boxes
- Gloves
- Sharpie and labels
-

Gridded depth measures
- 3 x 100+ ft tapes
- 6 chaining pins with mm graduations
- 1 or 2 rulers in mm
- Field data sheet

Photos

- 1 camera
- dry erase board w/ markers
- 1 range pole for center

Burn monitoring
- Weather kit
- Watch with timer
- Camera

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
- Fire behavior –FIREMON FB sheet
- Plot setup sheet to record tape bearings, witness trees, and photo numbers

Plot: Date: Crew:

Measurement	*Microplots*				
	North	**East**	**South**	**West**	**Center**
Photoloads					
1 hour					
10 hour					
100 hour					
Shrub					
Herb					
Fuel Depths (duff/litter/wood)					
1-NW corner					
2-NE corner					
3-SE corner					
4-SWcorner					
5-Grid 1					
6-Grid 2					
7-Grid 3					
8-Grid 4					
9-Grid 5					
10- Grid 6					
11-Grid 7					
12-Grid 8					
13-Grid 9					
Wood cover (%)					
NW Quadrant					
NE Quadrant					
SE Quadrant					
SW Quadrant					
Digital photo number					
Hemi photo number					
LAI estimate					
SEL estimate					

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