Proceedings for the 5th International Fire Behavior and Fuels Conference
April 11-15, 2016, Portland, Oregon, USA
Published by the International Association of Wildland Fire, Missoula, Montana, USA

New frontiers in fuel sampling: Techniques for measuring surface fuel loadings for fire management in the US

Robert E. Keane
USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, 5775 Highway 10 West, Missoula, Montana 59808. Phone: 406-329-4760, FAX: 406-329-4877.
Email: rkeane@fs.fed.us

Introduction

Measuring fuel properties in the field is the most accurate and consistent method for fire managers and researchers to collect the inputs needed for fuel description, and fire behavior and effects simulation (Keane 2015). Quantification of fuel properties is accomplished by field sampling; measuring fuel characteristics *in situ* to estimate fuel properties. And since there is a great diversity of fuel components, coupled with a large number of fuel characteristics, there are numerous sampling approaches and designs to estimate fuel properties at the particle, component, and fuelbed scale. Here, field sampling is a general term used to describe the wide range of approaches for measuring only one specific fuel property – loading or mass per unit area.

Operational sampling facilitates the planning, design, and eventual implementation of a fire management application. Often, management oriented sampling designs do not require the same degree of accuracy as research sampling, so they are often less intensive, not as costly, and easier to implement (Lutes et al. 2006). Management sampling efforts are designed to be applied across large areas by technicians with little to high levels of training in fuel sampling. This presentation is a summary of the latest surface fuel sampling technologies for management applications by both indirect and direct methods for all fuel components including litter, duff, fine woody debris (FWD; woody particles < 25 cm diameter) and coarse woody debris (CWD; woody particles greater than 25 cm diameter).

Indirect Fuel Sampling

These methods involve quantifying fuel loadings using techniques that don't directly involve measuring the fuel property, but rather, use other sources to quantify loadings. This usually involves subjectively assigning loadings by comparing with existing data (association), inspecting fuel conditions and visually comparing to reference conditions (visual), or correlating with remotely sensed imagery.

Associative Techniques

The most common associative technique involves **using existing data or information**, often collected by someone else from somewhere else, to estimate loading values for the area of concern or project area. Fuel loading data collected for another area, for example, may be associated to the area in question if the two areas are deemed similar, perhaps based on vegetation composition, disturbance histories, and biophysical site conditions. Catchpole and Wheeler (1992) call this approach the comparative yield method and mention it could be improved by using statistics, photos, and expertise to aid in the data assignment. The problem with this technique is that each site and project area is ecologically unique and the extrapolation of loadings from one site to another might ignore those important but subtle factors that influenced component loadings, such as differences in basal area, tree density, disturbance history, topographic setting, and stand structure. Another commonly used associative technique is to **assign fuel loadings to a sample area based on the sampled area's vegetation characteristics**. Many fuel classifications were built by summarizing plot-based fuel component loadings across categories in vegetation and related classifications such as structural stage, cover type, and potential vegetation type (Keane 2015).

Another associative method is **using mapped loading values** from readily available digital geospatial products as fuel loading estimates. The LANDFIRE National Project, for example, mapped four fuel classifications across the United States (Reeves et al. 2009) and many have used the loading values from these classifications to quantify loadings for a specific project area. This method, while inexpensive, quick, and easy, is not recommended until existing fuel maps are much improved. Locally created fuel maps may have sufficient quality, but regional and national maps should only be used for fuel analyses at broad scales, not at the project level. Depending on the resolution, fuel maps could still be useful for stratifying the sample area (or target population) into subunits to make sampling efforts more efficient.

Visual Techniques

Visual techniques involve assessing the loading of fuel components from ocular estimates. This level of resolution and accuracy may be acceptable for some fuel applications, such as describing fuels to other professionals. However, it is rare that anyone can accurately estimate loadings of all fuel components by eye, especially for FWD, duff, and litter.

Perhaps the most popular comparative visual technique is the **photo series**. Surface fuel loadings are ocularly estimated using a set of photos that present stand conditions for various vegetation types and site conditions. Photos were taken of representative fuel types in a particular geographical region, and then fuel component loadings were measured for the photo footprint and the summary of those loadings is reported next to the photo in the photo series publication. These photo series publications are taken to the field and the observed conditions in the field are visually matched to the best photo and the loading computed for the photographed stand are used for the loadings of the matched stand. Despite its huge popularity, the photo series has yet to be comprehensively evaluated across many vegetation types or environmental conditions. Sikkink and Keane (2008) found loading estimated using photo series approaches were often inaccurate and difficult to repeat across observers, albeit there were some limitations in the training of the crews. While photo series may give loading estimates to the resolution needed for management decisions, future uses of loading estimates, such as predicting smoke emissions and carbon inventories, may demand a more accurate and repeatable method of loading estimate.

The **new photoload method** uses calibrated, downward-looking photographs of known fuel loads for woody, shrub, and herbaceous fuels to compare with conditions in the field (Keane and Dickinson 2007a, b). These ocular estimates can then be adjusted for diameter, rot level, and fuelbed height. There are different photoload methods for logs, FWD, shrubs, and herbaceous material, but there are no photoload methods for measuring duff and litter loading. The photoload technique differs from photo series in that assessments are made by comparing field fuel conditions to smaller scale downward-pointing photographs of graduated fuel loadings. Photoload methods are much faster and easier than fixed-area and planar intercept techniques with comparable accuracies (Sikkink and Keane 2008), and they can be used in multi-stage sampling strategies where a fraction of the total plots are also destructively sampled and correlated to photoload samples to develop a means for correcting all photoload estimates (Keane et al. 2012b). However, Keane and Gray (2013) found the photoload technique requires extensive training to be used effectively; inexperienced users often could not consistently and accurately estimate high fuel loads.

Fuel classifications can also be used as a sampling method. In this technique, a fuel classification class is visually identified in the field, and the loadings assigned for that class are used as the sampled loadings. Fuel classifications that use vegetation to classify fuelbeds are probably the most uncertain, while classifications that contain dichotomous keys for identifying classes based on fuelbed properties, such as the FLM classification (Lutes et al. 2009b), are best for fuel assessment because they can be used by inexperienced crews to estimate fuel loadings with moderate accuracies (Keane et al. 2013).

Another visual method uses **fuel hazard assessments** across different fuel strata to obtain loading estimates for various components in the fuelbed. Originally developed by Gould et al. (2008) for Australia, this method involves making hazard assessments for the overstory and intermediate canopy layers, and then elevated, high, and low surface fuel layers. Each layer is given a score based on fuelbed attributes including percent canopy cover, presence of stringy bark, and suspended dead material. These scores are summarized and correlated to actual fuel loadings using statistical models (Gould et al. 2011).

One last visual technique involves using **cover-volume** methods to calculate loadings from visually estimated canopy cover and height. In this technique, canopy cover is estimated by eye for those components with small and variable fuel particles that are grouped together into one component, such as shrubs, herbs, and trees, and an estimate of measured or estimated height is also made in a fixed area sample unit for those components. Some fuel sampling packages, such as FIREMON (Lutes et al. 2006), describe how to estimate canopy cover and how to visually estimate height. Volumes of the assessed components (volume includes air pockets) are then calculated by multiplying the proportion cover (% cover divided by 100) by height (m) and sampling area (m^2). Loadings are then estimated by multiplying volume (m^{-3}) by bulk density estimates (kg m^{-3}) for the sample unit. Bulk densities for litter, duff, shrub, and herb components can be found in the literature (Brown 1981; Keane et al. 2012b) or estimated from a small proportion of the plots using destructive sampling.

Imagery Techniques

Imagery techniques involve using advanced statistical analysis to correlate fuel loadings to the digital signatures in the digital imagery. A potentially useful imagery technique is the quantification of fuel loads using image processing techniques or software. Years ago, Fahnestock (1971) calculated loading for several fuel components using a dot grid projected on color photographs of a cross-section of bayberry shrub fuel layer. Today there are sophisticated image processing approaches that use computer software. The stereoscopic vision technique (SVT), for example, involves taking stereoscopic photos of the fuelbed in the field then inputting the digital photos into computer-image recognition software to identify woody fuels and then compute loading volume (Arcos et al. 1998; Sandberg et al. 2001).

Another emerging technology is the use of ground based lidar to estimate fuel loads for some fuelbeds (Loudermilk et al. 2009). Here, a terrestrial scanning lidar (TSL) unit is mounted on a truck or some other vehicle to obtain scan distances for ground fuels at sub-cm scales. The lidar signal can then be related to loading by constructing statistical models where destructively sampled loadings for various components are correlated to the lidar imagery scan distances. It is sometimes difficult to differentiate between fuel components using TSL in heterogeneous fuelbeds but still possible. This technique may only be possible for research purposes in the near future because the TSL instrument is rather expensive (>$40,000), demands a high level of expertise to use and analyze, and it is also difficult to transport and use in complex terrain.

Direct Methods

These methods involve directly sampling or measuring characteristics of fuel particles to calculate loading. This usually involves direct contact with the fuel, such as measuring dimensions of particles using calipers, estimating depths of duff and litter using rulers, or collecting particles for drying and weighing in the lab.

Planar Intercept

Planar intercept (PI) techniques are the most commonly used sampling methods for sampling downed woody fuels for both management and research (Catchpole and Wheeler 1992; Dibble and Rees 2005) and both inventory and monitoring projects (Waddell 2001; Busing et al. 2000). PI sampling involves counting woody fuel particles by diameter size classes, or by directly measuring individual particle diameters, as they intercept a vertical sampling plane that is of a fixed length and height (Brown 1970, Brown 1974). These intercepts are then converted to loadings using standard formulae (Brown 1974). Advantages of the PI method are that it is easy to use and easy to teach (Lutes et al. 2009a; Lutes et al. 2006). Novice field technicians can be taught this method in a short time (1 hr) to achieve moderately repeatable measurements. The method can also be easily modified to adjust for local conditions, available expertise, and sampling conflicts, such as long plot times, scattered woody fuels, or slash. The sampling plane can be any size, shape, or orientation in space and samples can be taken anywhere within the limits set for the plane (Brown 1971). It also requires few specialized equipment; often a plastic ruler and cloth tape are the only gear needed.

However, there are some problems to the PI method. First, it only can be used for estimating downed dead woody loading; loadings for other fuel components, such as canopy fuels, litter, and duff, must be estimated with entirely different methods. This is problematic because the sampling unit for PI (transect) does not always scale to the fixed area plot methods used for other components or other forest and range inventories (Keane and Gray 2013). CWD transects, for example, are usually too long to fit within the area of standard plot sizes. PI sampling designs are also difficult to merge with other sampling designs because the PI was designed to sample entire stands, not fixed-area plots. PI methods also require a large number of transects under highly variable fuel conditions, which may be time- and cost-prohibitive for operational sampling efforts. Keane and Gray (2013) found that over 200 m of transect were needed on a 0.05 ha plot to sample FWD within 20% of the mean. Moreover, some feel that it is difficult to repeat particle intercept counts with any degree of reliability (Sikkink and Keane 2008).

Fixed area plots

In contrast to unequal probability strategies, such as, PI, fixed area plots (FAP) are based on equal probability sampling methods and have been adapted from vegetation composition and structure studies to sample fuels (Mueller-Dombois and Ellenberg 1974). In FAP sampling, a plot of any geometric shape, often round or square, is used as a sampling unit and all fuels within the plot boundary are measured using any number of fuel measurement methods including destructive collection, volumetric measurements, vertical depths of duff and litter layers, and particle counts by size class) (Keane et al. 2012b) . FAPs can be any size, and often the best sampling efforts scale the size of the FAP to the fuel being measured (e.g., small plots for FWD, large plots for CWD). Because FAP approaches require significant investments of time and money, they are more commonly used to answer research questions rather than to monitor or inventory fuels for management planning. However, new methods have been designed to use FAP in operational sampling projects (Keane and Gray 2013)

The FAP method may be a more ecologically appropriate method for obtaining accurate fuel loading estimates for many surface fuel components. FAP techniques tend to give a better representation of the actual variation observed in the field for surface fuel components (Keane and Gray 2013). FAP sizes and number can be adjusted to reduce sampling times but may result in reduced precision of fuel loading estimates. FAP size can also be adjusted to account for the spatial scaling of loading by fuel size. Larger fuels (CWD), for example, can be sampled with larger plots to fully account for spatial distributions in sample estimates. Moreover, FAP sampling is easily adapted or merged with other protocols commonly used to sample other fuel components or other ecosystem attributes. And last, it may be more practical to sample fuels using FAP methods because many fuel components can be linked together in the same sampling unit. The main limitation of the FAP sampling method is that there has yet to be a set of standardized operational FAP protocols for surface fuel sampling. Many fuels professional are unfamiliar with the FAP technique and don’t have the knowledge and expertise to create their own FAP methods.

Distance sampling

Another new method is perpendicular distance sampling (PDS) which samples logs using probability proportional to volume concepts (Gove et al. 2012; Ducey et al. 2013; Williams and Gove 2003). With PDS, the total volume of the logs on a landscape can be estimated from counts of logs at various sample points. Loading can then be estimated by multiplying volume by particle density (kg m-3) estimates. PDS is named because a log is selected to the sample if a line from a sample point intersects the central axis of the log at a right angle and the length of this line is less than some limiting distance that changes along log length in a manner that is based on the sampling design. There are many variants of PDS including the distance-limited protocol for PDS, which uses a fixed distance from the perpendicular line to estimate volume then loading (Ducey et al. 2013). Transect relascope, point relascope, and prism sweep sampling use angle gauge theory to expand on the PDS and line-transect method for sampling coarse woody debris (Stahl 1998; Gove et al. 2005; Bebber and Thomas 2003). This method is most effective for measuring CWD (Gove et al. 2012), but Ducey et al. (2008) demonstrated PDS can be used to estimate other ecological attributes, perhaps finding a future use in FWD loading estimation.

Cover and volume sampling

An alternative to the above direct methods is applying the abundant methods that directly measure canopy cover in vegetation sampling efforts to fuel sampling, as opposed to visually estimating canopy cover as presented above. Canopy cover is directly measured using a suite of methods, techniques, and protocols for ecological inventories and research efforts (Krebs 1999; Mueller-Dombois and Ellenberg 1974), and some of these may potentially be applied to measuring fuel loading. Point sampling, for example, involves using a vertically placed rod of a small diameter to determine the particle that it contacts, and the number of contacts per particle type (i.e. fuel component) is then used to estimate cover. If applied to fuel sampling, the number of contacts can be correlated with the destructive sampling estimates of biomass. Measures of the height of each contact can be augmented with number of contacts to associate both cover and average height with loading (Catchpole and Wheeler 1992). The problem with cover methods for estimating loadings is that canopy cover, regardless of how it's measured, may be poorly correlated with fuel loadings (Catchpole and Wheeler 1992). Many of these cover methods provide repeatable estimates with low bias compared to visual techniques, but the use of cover methods to assess all fuel component loadings would not be recommended.

The volume method involves sampling the dimensions of a fuel particle or component to compute volume then multiplying volume by particle density or bulk density to get loading. An advantage of the volume method is that it can be used at particle, component, and fuelbed scale. Fuel component volume can indirectly calculated using the proportion measured cover (% cover divided by 100) and multiplying it by height (m), sampling area (m^2), and bulk density (kg m^{-3}). Hood and Wu (2006) used the cover-volume approach to calculate loadings of masticated fuelbeds. Fuel component or particle dimensions can also be measure to directly estimate volume. Litter loading, for example, can be estimated by (1) measuring litter depths within a 1 m^2 microplot, (2) computing an average depth (m), (3) multiplying by sample unit FAP area (1 m^2) to calculate volume, and (4) calculating loading by multiplying volume (m^3) by bulk density (kg m^{-3}) and dividing by area of microplot (m^2). Volume can also be used to estimate mass of a fuel particle by (1) measuring particle dimensions (length, width, and depth), (2) estimating a volume by multiplying length, width, and depth, and then (3) multiplying particle volume by particle density to get dry weight. Loading is then calculated by summing all particle dry weights over sample unit (FAP) area.

Destructive sampling

Destructive sampling involves removing fuel by clipping, collecting, drying, and weighing the material. An alternative is to (1) collect and weigh the wet fuel in the field; (2) subsample that fuel to dry and weigh to estimate a moisture content, and then (3) use the subsampled moisture content to adjust the wet field weight to dry weight. Destructive sampling can be scaled for any sampling design or objective. Fuel particles can be collected individually, as a group (shrub or tree), or on fixed area plots. Destructive sampling almost always involves subsampling a fuel component or fuelbed so statistical methods are often required to summarize subsampled estimates to describe the sampling area. Often, destructive sampling is used to create predictive biomass equations for a fuel component, such as a tree or shrub. This predictive equation can then be applied to inventory data to compute loading. Most destructive sampling is for research rather than operational management inventory and monitoring.

Integrated surface fuel sampling

Sampling projects are rarely designed using only one sampling approach or technique. The diversity of surface fuel components coupled with the constraints of limited resources always result in a project-level sampling designs that compromise statistical rigor to ensure success by integrating the above techniques and approaches. Conventional standardized surface fuel sampling protocols nearly always recommend using planar intercept techniques for woody fuel loading and volume approaches for litter, duff, shrub and herb (Lutes et al. 2006). The photoload approach has been augmented with planar intercept, fixed area log sampling, and volume estimates for duff and litter (Keane et al. 2012b). Catchpole and Wheeler (1992) mention a sampling technique called “double sampling” where destructive techniques are used on a subsample of fixed area plots to calibrate loading estimates from visual techniques. Keane et al. (2012b) used double sampling for another reason -- to adjust visual estimates using statistical regression. This melding of approaches, techniques, and intensities may aid in successful sampling designs, but the resultant loading estimates have different error distributions, variability, and usefulness for each fuel component.

References

Arcos A, Alvarado E, Sandberg DV Volume estimation of large woody debris with a stereoscopic vision technique. In: Proceedings: 13th Conference on Fire and Forest Meteorology, Lorne, Australia, 1998. International Association of Wildland Fire., pp 439-447

Bebber DP, Thomas SC (2003) Prism sweeps for coarse woody debris. Canadian Journal of Forest Research 33:1737-1743

Brown JK (1971) A planar intersect method for sampling fuel volume and surface area. Forest Science 17 (1):96-102

Brown JK (1974) Handbook for inventorying downed woody material. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report GTR-INT-16 Ogden, UT, USA 34 pp.

Brown JK (1978) Weight and density of crowns of Rocky Mountain conifers. United States Department of Agriculture, Forest Service Intermountain Forest and Range Experiment Station, Research Paper INT-197 Ogden, UT USA 56 pp.

Brown JK (1981) Bulk densities of nonuniform surface fuels and their application to fire modeling. Forest Science 27:667-683

Brown JK, Bevins CD (1986) Surface fuel loadings and predicted fire behavior for vegetation types in the northern Rocky Mountains. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Research Paper INT-358 Ogden, UT USA 9 pp.

Brown JK, Oberheu RD, Johnston CM (1982) Handbook for inventoring surface fuels and biomass in the Interior West. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-129 Ogden, UT, USA 48 pp.

Busing R, Rimar K, Stolte KW, Stohlgren TJ, Waddell K (2000) Forest health monitoring. Vegetation pilot field methods guide.Vegetation diversity and structure down woody debris fuel loading. USDA Forest Service, National Forest Health Monitoring Program, Washington, D.C., USA 54 pp.

Catchpole WR, Wheeler CJ (1992) Estimating plant biomass: A review of techniques. Australian Journal of Ecology 17 (2):121-131.

Dibble AC, Rees CA (2005) Does the Lack of Reference Ecosystems Limit Our Science? A Case Study in Nonnnative Invasive Plants as Forest Fuels. Journal of Forestry 103 (7):329-338

Ducey MJ, Williams MS, Gove JH, Roberge S, Kenning RS (2013) Distance-limited perpendicular distance sampling for coarse woody debris: theory and field results. Forestry 86 (1):119-128.

Ducey MJ, Williams MS, Gove JH, Valentine HT (2008) Simultaneous unbiased estimates of multiple downed wood attributes in perpendicular distance sampling. Canadian Journal of Forest Research 38 (7):2044-2051

Fahnestock GR (1971) Weight of brushy forest fire fuels from photographs.Forest Science 17 (1):119-124

Fischer WC (1981) Photo guide for appraising downed woody fuels in Montana forests: Interior ponderosa pine, ponderosa pine-larch-Douglas-fir, larch-Douglas-fir, and Interior Douglas-fir cover types. USDA Forest Service, Intermountain Research Station, General Technical Report INT-197 Ogden, UT USA 133 pp.

Gould JS, Lachlan McCaw W, Phillip Cheney N (2011) Quantifying fine fuel dynamics and structure in dry eucalypt forest (Eucalyptus marginata) in Western Australia for fire management. Forest Ecology and Management 262 (3):531-546.

Gould JS, McCaw W, Cheney N, Ellis P, Matthews S (2008) Field Guide: Fire in Dry Eucalypt Forest: Fuel Assessment and Fire Behaviour Prediction in Dry Eucalypt Forest. CSIRO PUBLISHING, Canberra, ACT Australia 33 pp. ISBN: 0643102760

Gove JH, Ducey MJ, Valentine HT, Williams MS (2012) A distance limited method for sampling downed coarse woody debris. Forest Ecology and Management 282 (0):53-62.

Gove JH, Ducey MJ, Valentine HT, Williams MS (2013) A comprehensive comparison of perpendicular distance sampling methods for sampling downed coarse woody debris. Forestry 86 (1):129-143.

Gove JH, Williams MS, Stahl G, Ducey MJ (2005) Critical point relascope sampling for unbiased volume estimation of downed coarse woody debris. Forestry 78 (4):417-431

Hood S, Wu R (2006) Estimating fuel bed loadings in masticated areas. In: Andrews PL, Butler BW (eds) Fuels Management—How to Measure Success, Portland, Oregon USA, 2006. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Proceedings RMRS-P-41 pp 333-345

Keane RE (2015) 'Wildland fuel fundamentals and applications.' (Springer: New York)

Keane RE, Dickinson LJ (2007a) Development and evaluation of the photoload sampling technique. USDA Forest Service Rocky Mountain Research Station, Research Paper RMRS-RP-61CD Fort Collins, CO USA 44 pp.

Keane RE, Dickinson LJ (2007b) The Photoload sampling technique: estimating surface fuel loadings using downward looking photographs. USDA Forest Service Rocky Mountain Research Station, General Technical Report RMRS-GTR-190 Fort Collins, CO USA 44 pp.

Keane RE, Gray K (2013) Comparing three sampling techniques for estimating fine woody down dead biomass. International Journal of Wildland Fire 22 (8):1093-1107.

Keane RE, Gray K, Bacciu V (2012b) Spatial variability of wildland fuel characteristics in northern Rocky Mountain ecosystems. USDA Forest Service Rocky Mountain Research Station, Research Paper RMRS-RP-98 Fort Collins, Colorado USA. 58 pp.

Keane RE, Herynk JM, Toney C, Urbanski SP, Lutes DC, Ottmar RD (2013) Evaluating the performance and mapping of three fuel classification systems using Forest Inventory and Analysis surface fuel measurements. Forest Ecology and Management 305:248-263.

Krebs CJ (1999) Ecological Methodology. Second edn. Benjamin Cummings, New York, NY, USA

Loudermilk EL, Hiers JK, O'Brien JJ, Mitchell RJ, Singhania A, Fernandez JC, Cropper WP, Slatton KC (2009) Ground-based LIDAR: a novel approach to quantify fine-scale fuelbed characteristics. International Journal of Wildland Fire 18 (6):676-685. doi:http://dx.doi.org/10.1071/WF07138

Lutes DC, Benson NC, Keifer M, Caratti JF, Streetman SA (2009a) FFI: a software tool for ecological monitoring*. International Journal of Wildland Fire 18 (3):310-314.

Lutes DC, Keane RE, Caratti JF (2009b) A surface fuels classification for estimating fire effects. International Journal of Wildland Fire 18:802-814

Lutes DC, Keane RE, Caratti JF, Key CH, Benson NC, Sutherland S, Gangi LJ (2006) FIREMON: Fire effects monitoring and inventory system. USDA Forest Service Rocky Mountain Research Station, General Technical Report RMRS-GTR-164-CD Fort Collins, CO USA 222 pp.

Mueller-Dombois D, Ellenberg H (1974) Aims and methods of vegetation ecology. John Wiley and Sons, New York, New York., USA 234 pp.

Reeves MC, Ryan KC, Rollins MC, Thompson TG (2009) Spatial fuel data products of the LANDFIRE project. International Journal of Wildland Fire 18:250-267

Reinhardt E, Scott J, Gray K, Keane R (2006b) Estimating canopy fuel characteristics in five conifer stands in the western United States using tree and stand measurements. Canadian Journal of Forest Research 36 (11):2803-2814.

Sandberg DV, Ottmar RD, Cushon GH (2001) Characterizing fuels in the 21st century. International Journal of Wildland Fire 10:381-387

Sikkink PG, Keane RE (2008) A comparison of five sampling techniques to estimate surface fuel loading in montane forests. International Journal of Wildland Fire 17 (3):363-379.

Stahl G (1998) Transect relascope sampling - A method for the quantification of coarse woody debris. Forest Science 44:58-63

Waddell KL (2001) Sampling coarse woody debris for multiple attributes in extensive resource inventories. Ecological Indicators 1:139-153

Williams MS, Gove JH (2003) Perpendicular distance sampling: an alternative method for sampling downed coarse woody debris. Canadian Journal of Forestry Research 33:1564-1579