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Research Note

Fine woody fuel particle diameters for improved planar intersect fuel loading estimates in Southern Rocky Mountain ponderosa pine forests

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Abstract. Fuel loading estimates from planar intersect sampling protocols for fine dead down woody surface fuels require an approximation of the mean squared diameter (d^2) of 1-h (0–0.63 cm), 10-h (0.63–2.54 cm), and 100-h (2.54–7.62 cm) timelag size classes. The objective of this study is to determine d^2 in ponderosa pine (*Pinus ponderosa*) forests of New Mexico and Colorado, USA in natural, partially harvested, and partially harvested and burned sites to improve fine woody fuel loading estimates. Resulting estimates were generally higher in the 1- and 10-h classes and lower in the 100-h classes when compared with previously published values from other regions. The partially harvested and burned values for 1- and 100-h classes were also significantly lower than in the other stand conditions. Using bootstrap analysis, it was determined that 35 samples would be sufficient to create an accurate estimate of d^2 values.

Additional keywords: fine woody biomass, fuels management, *Pinus ponderosa*, planar intersect, sampling, surface fuels.

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Introduction

Dead down woody fuel loading is an important input to many fire behaviour and effects models, and is an important indicator for the success of fuel hazard reduction treatments (Keane *et al.* 2012). Many sampling techniques have been developed to estimate dead down woody fuel loading in fire management, but the most widely used is the planar intersect method developed by Van Wagner (1968) and operationalised by Brown (1971, 1974). This method is often used in fuel inventories in part because it is relatively simple and quick to implement in the field and is easily taught to fire managers (Sikkink and Keane 2008). Rather than directly measure the fuel load this technique makes use of fuel particle counts of dead down woody biomass within size classes that correspond to the moisture time lag classes used in the National Fire-Danger Rating System: 1-h (0–0.63 cm), 10-h (0.63–2.54 cm), and 100-h (2.54–7.62 cm) fuels (Deeming *et al.* 1972). These counts are multiplied by a slope correction factor and species-specific estimates of particle angles, specific gravity, and mean squared diameters (d^2) for each size class to calculate fuel loading.

However, due to differences in climate, branch growth patterns, and management practices, these estimates vary across broad geographical regions, by species and with stand management history (Brown and Roussopoulos 1974; Sackett 1980). Stand management history including harvest practices, mastication, and prescribed burning can influence diameter distributions by selectively targeting certain sited material for removal, or through the preferential consumption of smaller diameter fuels. Previous studies have shown that improved estimates of particle diameters result in more accurate estimates of fuel loading (Keane and Gray 2013). Regional estimates of d^2 of 1-h, 10-h, and 100-h fuels for common species are available for the Northern Rocky Mountains (Brown and Roussopoulos 1974), the Pacific Northwest (Ryan and Pickford 1978), and the Southwest (Sackett 1980). In addition, Woodall and Monleon (2010) used Forest Inventory and Analysis data to provide national estimates by forest type and Brown (1974) provided a composite value for western tree species with no geographic specificity. These published d^2 values can vary by as much as 60% between regions for the same species. In addition to broad differences across geographic regions and species, d^2 is also affected by natural disturbances and management practices such as fire and harvesting. Most d^2 estimates following active management were taken from clearcuts (Brown 1974), but clearcutting has become a more unpopular practice in dry forests of the southern Rocky Mountains and the Southwest in recent years. It is unclear how different silvicultural systems influence d^2 distributions and estimates, particularly in fine woody fuels.

The goal of this paper is to provide d^2 for dead down woody biomass in ponderosa pine (*Pinus ponderosa*) stands on the eastern side of the continental divide in the Rocky Mountains of Colorado and New Mexico under three common scenarios: natural stands, stands that have been partially harvested to restore a more historic forest structure and composition and stands that have been underburned after a partial harvest. Throughout this manuscript we use the term 'natural' to refer to stands that have not been recently treated, 'slash' to refer to surface fuels in areas that were recently clearcut, 'thinned' to refer to stands that were recently thinned to meet restoration objectives and 'thinned-and-burned' to refer to areas that were mechanically treated and broadcast burned to meet restoration objectives. Currently there are no published values of d^2 for the Southern Rocky Mountains, especially d^2 values that reflect the previously mentioned current silvicultural practices in these systems. The d^2 estimates provided in this study should improve dead down woody fuel loading estimates produced using the planar intersect method in this region. In addition, we perform bootstrap analysis to determine the sample size required to produce reasonably accurate d^2 estimates at a local level. This analysis will inform the decision of whether to use published d^2 values or create locally specific values, a process Van Wagner (1982) theorised would require onerous amounts of extra fieldwork.

Methods

We collected fine dead down woody fuels from 12 ponderosa pine dominated stands on the eastern side of the continental divide across Colorado and New Mexico on the Roosevelt, Pike and San Isabel, Carson, and Cibola National Forests and in Boulder County Open Space. Overstory species composition ranged from 72–100% ponderosa pine by basal area, with other trees species including Douglas-fir (*Pseudotsuga menziesii*), quaking aspen (*Populus tremuloides*), and Rocky Mountain juniper (*Juniperus scopulorum*). Sampled stands ranged in elevation from 2000–2800 m, covering the elevational distribution of ponderosa pine forests in this region (Peet 1981; Dick-Peddie 1993), had slopes from 0–30%, and included all aspects. Because of the wide geographic and elevational range of sites sampled, the values presented here provide improved estimates of fuel loading with the planar intersect method for ponderosa pine dominated forests across New Mexico and Colorado east of the Continental Divide (Fig. 1).

Six sampled stands had natural fuels, as they had not been subject to active management in the preceding 30 years. Three stands had been partially harvested using variable retention thinning to reduce density and increase spatial heterogeneity to within the historic range of variation less than 3 years before sampling and 3 stands had been partially harvested and burned 6–8 years before sampling. Basal area was reduced by 8–68% in each treated area as compared with neighbouring untreated stands. Our treatment sites differ qualitatively from those used in other studies (Brown and Roussopoulos 1974; Bevins 1978; Sackett 1980) in that they were treated to reduce density and improve forest health while the other studies were conducted on stands where treatments emphasised timber harvesting. Harvesting, and particularly clearcutting, tends to remove more and larger trees from the site than forest health treatments do, therefore potentially leaving behind different amounts and distributions of fuels and overstory structures.

At each stand we randomly located a 9-ha plot such that it was completely contained within the treatment unit and had an average slope of less than 5%. Within each quarter of the plot we randomly placed 12 1-m^2 frames for a total of 48 per site and collected all woody fuels less than 7.62 cm in diameter. Because Brown (1974) requires the user to directly measure the diameter of 1000-h fuels and calculate the d^2, they were not included in this study. Following woody fuel collection at each site we sorted all fuel into timelag classes (i.e. 1-h, 10-h, and 100-h fuel classes), with 50 particles randomly selected from each timelag class and measured for endpoint and midpoint diameters. These measurements were used to calculate an arithmetic mean diameter for each particle and a stand-level quadratic mean diameter for each timelag class. From the stand-level quadratic mean diameters of each timelag class the arithmetic mean was calculated and squared to produce our d^2 estimate within each stand condition. Due to initial misclassifications of size class or low fuel loadings, in some cases sample sizes were less or more than 50 on a given site, but always at least 26 in each time lag class, which is sufficient to invoke the central limit theorem and thus provide an unbiased estimate of the mean (Ott and Longnecker 2010). Differences in the mean squared average quadratic diameter among different treatment types were tested using a generalised linear mixed model with treatment as a fixed effect, site as a random effect, and a random residual effect for each site to account for variance heterogeneity between treatments with a critical value (α) of 0.05. The assumed response distribution was lognormal.

We used standard with-replacement bootstrapping techniques (Efron and Tibshirani 1993) to estimate the optimal sample size required to create accurate local estimates of d^2 for each size class and treatment combination. For each fuel size class and treatment combination we created 1000 bootstrapped samples ranging in size from 5–200 samples in increments of 5 and calculated the variance between the mean d^2 of each of the 1000 bootstrap observations at each sample size. For each fuel class and treatment type we visually evaluated changes in the d^2 variance across the range of sample sizes to determine the point where the decrease in variance was minimal compared with the increase in sample size (Jalonen *et al.* 1998). We considered the recommended sample size to be the visually estimated inflection point in the graph (Sikkink and Keane 2008).

Results

d^2 for Southern Rockies ponderosa pine forests

The d^2 of 10-h fuels did not differ significantly between natural, thinned, and thinned-and-burned groups ($P \geq 0.12$), while 1- and 100-h fuels did have significant differences between untreated areas and at least one of the treatment types (Table 1). 1-h d^2 in thinned-and-burned areas was significantly lower than untreated areas ($P < 0.0001$) and thinned areas ($P = 0.0213$). The 100-h d^2 in thinned-and-burned areas was significantly lower than thinned plots ($P = 0.0041$), although thinned-and-burned plots did not differ significantly from natural plots.

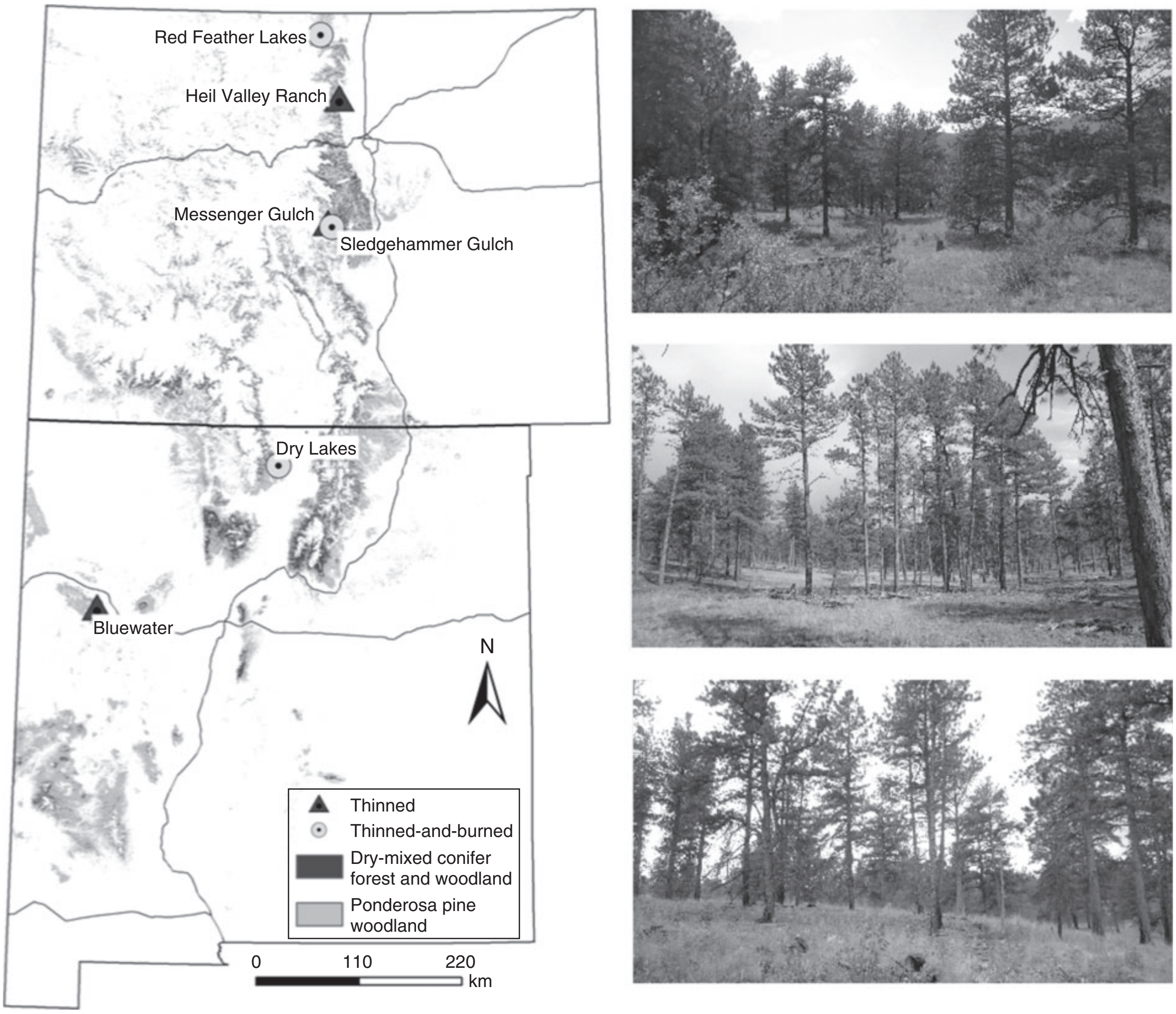

Fig. 1. Six ponderosa pine dominated study locations across the southern Rocky Mountains used in this study. Each location contains an unmanaged site and a treated site. Thinned sites had received mechanical treatments designed to reduce crown fire hazard and restore forest structure. Thinned-and-burned site treatments were designed primarily to reduce fire hazard and consisted of a mechanical treatment followed by a broadcast burn. Images from top to bottom show examples of an untreated site, a thinned site, and a thinned-and-burned site.

Table 1. Comparison of regional d^2 values for ponderosa pine fuels

Regional d^2 estimates of dead down woody fuel classes for ponderosa pine dominated forests. Significant differences within each size class of the Southern Rocky Mountain estimates are indicated by letters ($\alpha = 0.05$). This study's thin estimates correspond to values reported as slash in other publications. Differences between Southern Rocky Mountain estimates and other regional estimates are reported in parentheses. All estimates are given in cm^2

Diameter Class (cm)		Southern Rockies	Brown 1974 (Brown 1974)	Southwest (Sackett 1980)	Pacific Northwest (Ryan and Pickford 1978)	National (Woodall and Monleon 2010)[A]
[0–0.63]	Natural	0.268	0.221 (−18%)	0.244 (−10%)	0.230 (−9%)	0.053 (−80%)
	Thin	0.258	0.160 (−38%)	0.304 (+18%)	–	–
	Thin-and-burn	0.195	–	–	–	–
[0.63–2.54]	Natural	1.746	1.54 (−12%)	1.53 (−13%)	1.69 (−3%)	1.56 (−11%)
	Thin	1.871	2.05 (+10%)	1.59 (−15%)	–	–
	Thin-and-burn	1.821	–	–	–	–
[2.54–7.62]	Natural	15.698	20.13 (+28%)	19.16 (+22%)	–	19.01 (+22%)
	Thin	18.387	18.26 (−7%)	23.03 (+25%)	–	–
	Thin-and-burn	14.778	–	–	–	–

[A]Numbers were estimated using a graphical estimation approach.

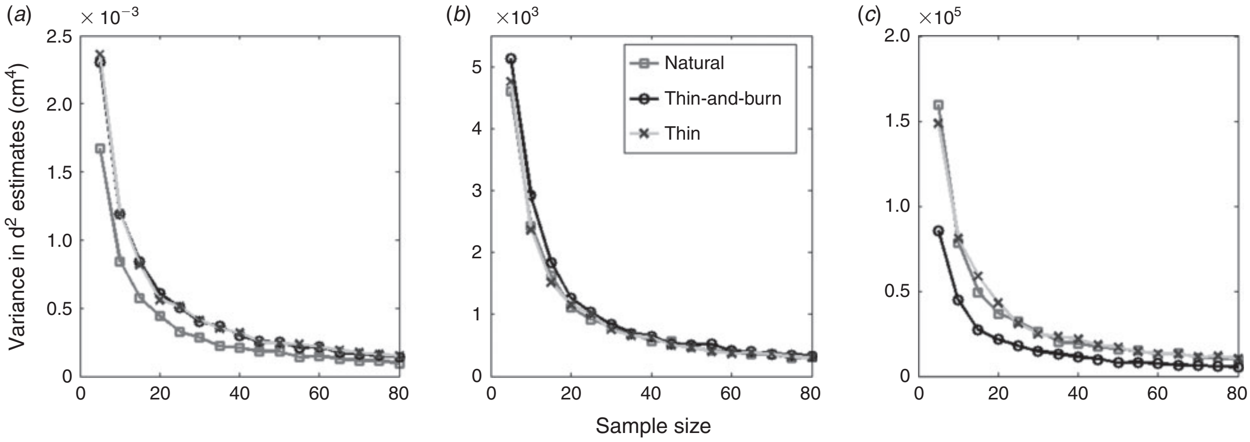

Fig. 2. Effect of sample size on the variance of sample d^2 for (*a*) 1-h fuels (*b*) 10-h fuels and (*c*) 100-h fuels in ponderosa pine dominated forests in the Southern Rocky Mountains.

Required sample size

We found that sample sizes of between 20 and 35 were optimal to determine d^2 for all cases based on the inflection points in our bootstrap analysis (Fig. 2). The inflection point represents the sample size at which the decrease in variance from increasing the sample size is minimal compared with the time and effort required to accomplish the increased sample size (Sikkink and Keane 2008). Based on these findings we would conservatively recommend that at least 35 samples in each size class be collected to develop local d^2 estimates in ponderosa pine forests of the southern Rocky Mountains.

Discussion

Comparing our values to those reported for ponderosa pine from the Southwest (Sackett 1980), the Pacific Nortwest (Ryan and Pickford 1978), national values (Woodall and Monleon 2010), and those reported in Brown (1974) shows that our values generally result in greater estimates of the 1- and 10-h timelag fuel loadings and a lower estimate of 100-h timelag fuel loading (Table 1). These differences may be due to regional differences in climate, branch growth patterns and common harvest or other management practices.

Overall our values show that total woody fuel estimates that use previously published d^2 values may capture the true total fine woody fuel loading in some cases because 1- and 10-h fuel components would be overestimated while 100-h fuels would be underestimated. However, estimates produced using previously published values are likely to result in inaccurate apportionment of fuel loading by size class in ponderosa pine forests of the southern Rocky Mountains. Errors in fuel distribution estimates are likely to be propagated through use in fire effects models and carbon storage estimates.

For any given fuelbed, loading estimates calculated using equations from Brown (1974) are directly proportional to the d^2 values used. For example, using a value 10% higher for d^2 results in a 10% higher estimate of fuel loading. In evaluating fuel treatment effectiveness within southern Rocky Mountain ponderosa pine forests, the d^2 values presented here would thus result in a sizeable increase in post-treatment fuel loading of 1- and 10-h fuels compared with estimates using d^2 values from Brown (1974), assuming all other parameters in the model were held constant (Table 1). The d^2 values presented would also result in a 19% decrease in estimated 100-h loading for thinned-and-burned sites compared with estimates using 100-h slash values from Brown (1974). This suggests that it is worth considering thin-and-burn as a distinct disturbance category when choosing d^2 values in areas where treatments involve broadcast burning.

Our work also shows that contrary to the theorised effort requirements, within these ponderosa pine forests very few samples are needed to create local estimates of d^2. The recommended sample size of 35 can easily be collected and measured in under an hour using basic equipment, and the related calculations can be performed on a standard calculator, requiring no special software or expertise. While current d^2 values seem to capture total fine woody fuel loading, such an exercise would eliminate regional bias from the distribution of fuel loading within particle size classes.

Keane and Gray (2013) found that the accuracies of planar intersect estimated fuel loads increased with better estimates of woody particle diameter measurements. However, there are several additional factors that may also contribute to uncertainty in fuel loading estimates with the planar intersect method. First, as suggested by Keane and Gray (2013) assumptions regarding the shape of woody fuel particles may be oversimplified, diameters may not be static through time, and common measurement techniques may not be appropriate. Second, other parameter estimates beyond the scope of this study, including specific gravity and particle angle, also influence fuel load estimates using the planar intersect method. Finally, the design of many common planar intersect sampling protocols fail to take into account the spatial variability of fuel loading itself (Keane *et al.* 2012). More research is needed to better characterise the broad geographic variability of these parameters, to understand changes over time and to provide a more mechanistic understanding of the drivers of local variability in fuel particle parameters. Improved sampling designs may be necessary to accurately capture this spatial and temporal variability of surface fuels; however, the development of local d^2 estimates, such as done here, could provide a relatively simple approach that acts as a compromise between improving the accuracy of fuel estimates with the planar intersect approach and time and resource limitations for training and sampling using new methods.

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