Final Report

Developing Fuels Treatments for Balancing Fuel Reduction, Soil Exposure, and Potential for Erosion in the Tahoe Basin (P019)

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Executive Summary

Following is a brief description of the research and key findings. Further detail may be found in two Master Theses which follow the summary. With clarity of Lake Tahoe the dominant concern in the Basin, protecting soil resources and reducing erosion currently dictate how many forest and fuel management activities are carried out. Concurrently, reduction of wildfire hazards looms large in land management decisions over the recent past, particularly following major wildfires in 2007. Balancing these two often opposing concerns is a major challenge for land managers and policymakers in the Lake Tahoe Basin. While fuels treatments may meet soil erosion and fire behavior reduction objectives in the short term, these same treatments may exacerbate the same issues in the long-term in the event of a wildfire. Both the amount and continuity of organic material on the forest floor may result in high fire severity and more homogenous burns. The excess litter and woody fuel that is now on the forest floor and the greater continuity of this organic material may indeed protect the soil, but when this material burns, either through wildfire or prescribed fire, the result is a burn that is much more continuous than historical fires were likely to be (for example, the Angora Fire of 2007), leaving the system more prone to erosion.

Research is urgently needed to understand how best to balance erosion and fire hazard reduction objectives using forest and fuel management activities in the Lake Tahoe Basin.

Background and Problem Statement

Prior to Euroamerican settlement, low to moderate severity fires burned through forests in the Lake Tahoe Basin at an average return interval of 11 years (Taylor 2004). After fire, litter and other fine fuels necessary to sustain surface fire require time to accumulate to the point where they propagate fire. Because of the spatial heterogeneity of Basin forests, litter accumulation can be quite variable. Historically, the mixture of areas with and without sufficient fuels to carry fire led to patchy burn patterns (Knapp and Keeley 2006), but the way fire now burns may be fundamentally different. In forests that have experienced many decades of fire suppression, forest densification, and fuel accumulation, most areas currently contain sufficient fine fuels to carry fire. This increased connectivity (Miller and Urban 2000) has implications for how much fuel is consumed, the amount of mineral soil exposed, and with wildfires – the total fire size.

All of these factors can influence erosion and sedimentation rates. Understanding relationships between fuels management, erosion and sedimentation is of central importance for ecosystem health of the Lake Tahoe Basin. The clarity of Lake Tahoe has declined dramatically in 40 years of measurement. Research suggests that the origins of this decline are linked to watershed sources of suspended sediment and total phosphorus (Jassby et al. 1994). A documented shift towards earlier snowmelt and increased rainfall relative to snowfall in the mountainous west (Knowles et al. 2006, Westerling et al. 2006) is likely to increase the probability of high-severity fire and the erosivity of precipitation (Beeson et al. 2001).

Burn patchiness may have played an important role historically, with unburned islands at multiple scales creating barriers to erosion. Research suggests that there may be thresholds of bare mineral soil exposure that when exceeded result in exponential increases in sediment yield (Campbell et al. 1977, Johansen et al. 2001). Compiling data across multiple studies in different ecosystems, Johansen et al. (2001) determined that the relationship between sediment yield and bare soil is non-linear; sedimentation rates were low at low to moderate levels of soil exposure, but once a threshold of approximately 60-70% of the ground surface was exposed, erosion increased exponentially. They proposed that as the percentage of area exposed increases, the connectedness of burned patches increases, reducing sediment capture and infiltration.

As shown by the Angora Fire, the Little Washoe Fire, and other recent fires within and outside of the Basin, it is clear that the amount and continuity of surface fuel currently found in many contemporary forests leads to undesirable outcomes when burned in a wildfire. Wildfires occurring in the driest conditions of summer and early fall frequently burn a high proportion of the available fuel and cover a large proportion of the ground surface. In addition, high surface fuel loads increase the probability of torching and crown fire (Agee and Skinner 2005, Ritchie et al. 2007). Treating/ removing surface fuel through prescribed burning would reduce the probability of such high severity fire. However, the Tahoe Basin has unique constraints to fire management because of erosion concerns with soil exposure, the extensive wildland-urban interface, and air quality issues. Where prescribed fire is not an option, mechanical treatments may be used instead, but how much fuel/ organic matter is it necessary to leave on the forest floor and in what spatial arrangement should it be left to minimize the threat of erosion while also reducing the chance of forest loss in a wildfire? Where prescribed fire is an option for reducing these fuel loads, is it possible to develop burning prescriptions that lead to patchy burns with enough unburned islands to capture sediments but also consume enough fuel to reduce the probability of high fire severity?

It is well known that fuel consumption is strongly associated with fuel moisture at the time of burning (Van Wagner 1972, Hille and Stephens 2005), with consumption constrained at higher fuel moisture values because of the high specific heat of water (Frandsen 1987). Knapp et al. (2005) found that early season burns conducted under higher fuel moisture conditions were patchier and left more than twice as much ground unburned compared to late season burns (27% vs. 12%, respectively). This burn patchiness, in surface fuels similar to those found in the Tahoe Basin, occurred at many spatial scales, ranging from centimeters to 10's of meters (Rocca 2004; Fig. 1).

Burn patchiness may be explained by fuel moisture variation across the forest floor and influenced by shading and rainfall interception by the forest canopy (Miyanishi and Johnson 2002, Hille and Stephens 2005). With prescribed burning, managers can time ignition for particular fuel moisture levels and thus control the amount of spatial patchiness in burn pattern. Prescribed burns conducted when duff is still relatively moist can lead to burn patterns with patchiness closer to historical norms (Knapp et al. 2005).

Perhaps nowhere else is this conflict between fuel reduction objectives and erosion control objectives clearer than in the Tahoe Basin. Threat of high severity wildfire is minimized by reducing surface fuel loads; however, this exposure of bare mineral soil may lead to erosion and sedimentation concerns. Research linking the amount and arrangement of surface fuels to erosion and sedimentation and determining erosion thresholds will help managers design mechanical and prescribed fire treatments that balance fire hazard reduction objectives with ecological and hydrological realities unique to the Tahoe Basin. Furthermore, research on fuel moisture and how it influences prescribed fire burn pattern in different litter types under contemporary conditions of high fuel loading and high fuel continuity may allow burn prescriptions to be developed that better meet both fire hazard reduction and water quality goals.

Goals and Objectives:

The goal of this research was to understand erosion thresholds in order to determine the optimal levels of surface fuel retention with mechanical mastication and prescribed fire treatments that maximize fire hazard/ fire severity reduction goals while minimizing the threat of erosion and sedimentation. We sought to understand current static conditions and seasonal changes in fuel moisture in order to link fuel moisture with timing of prescribed fire, and the pattern of the resulting burn. Finally we compared our field erosion measurements against predictions made using a popular modeling tool, the Watershed Erosion Prediction Project (WEPP) in order to support the use of this tool in the Lake Tahoe basin.

We evaluated 1) how much organic material is required on the forest floor to buffer against erosion and quantified specific erosion thresholds for the Basin's soils by using on-site overland-flow simulation, 2) the role of spatial arrangement of organic material (evenly dispersed vs. patchy) on erosion rates, 3) the degree to which WEPP model predictions matched measured field erosion values, 4) on the composition, bulk density, mineral content, depth, and loads of forest floor fuels fuel moisture heterogeneity and 5) spatial and temporal variability in forest floor moisture.

1) Effect of patchiness on measured rill erosion from Lake Tahoe forest sites with masticated fuels treatments

Drastic differences in sediment yield were observed between fuels treatments that exposed large patches of bare soil and those that retained fuels on the soil surface. Masticated treatments characterized by even distributions of surface fuel and limited patches of exposed soil mitigated severe erosion by trapping sediment and increasing infiltration. In prescribed fire plots, heterogeneous patches of unburned or less severely burned islands of surface fuel were present to mitigate erosion in a similar manner. Reduction in erosion was especially pronounced if fire burned < 54% of the plot area. Thus, in the most macroscopic sense, two very different surface fuel treatments observed in this study were found to share a common result – as areas of exposed mineral soil increased, the amount of erosion due to snowmelt runoff increased by orders of magnitude. By exploring the details of this overall finding, land managers in the Lake Tahoe Basin and elsewhere can pursue strategies that balance erosion control with wildland fuel reduction objectives.

For masticated sites, greater amounts of sediment yield were measured in treatments that lacked surface cover than those that contained it, with increasing amounts of erosion observed in treatments characterized by large areas of bare soil exposure (Figure 1). Average erosion was 97% greater when all of the masticated fuels were removed down to bare soil than in treatments where 25-50% of the masticated material was retained in patches. This finding indicates that small patches of surface fuel and duff possess great potential to mitigate severe erosion. Results also reveal how the fluctuations in sediment yield observed between the masticated treatments of this study can be attributed to differences in the amount and connectivity of surface fuel and duff measured within each plot. For example, in 0%, 25%, 50%, and 75% “patchy removal” plots, mean depth to bare mineral soil within undisturbed litter and duff layers were thick (15.01 cm) and mean sediment yields were low (0.01 kg). As the amount of fuel and duff increased within each treatment, rill development decreased, infiltration increased, and sediment delivery was impeded, illustrating a highly negative correlation between erosion and surface cover. In most cases across sites, severe erosion was only measured when 100% of plot areas were exposed down to bare soil.

While increased amounts of residual surface fuels following mechanical mastication are known to reduce erosion by promoting high rates of infiltration and limiting soil detachment from erosive forces due to overland flow, they may also produce negative consequences following wildland fire. Excessive post-treatment fuel loads can lead to high levels of soil heating due to smoldering and substantial mortality of residual trees due to crown scorch. This study indicated that distributing fuel at 50% of current levels, or retaining fuels on 25% of plot area would be sufficient to control erosion while still breaking up fuel continuity and limiting the possibility of soil heating and crown scorch.

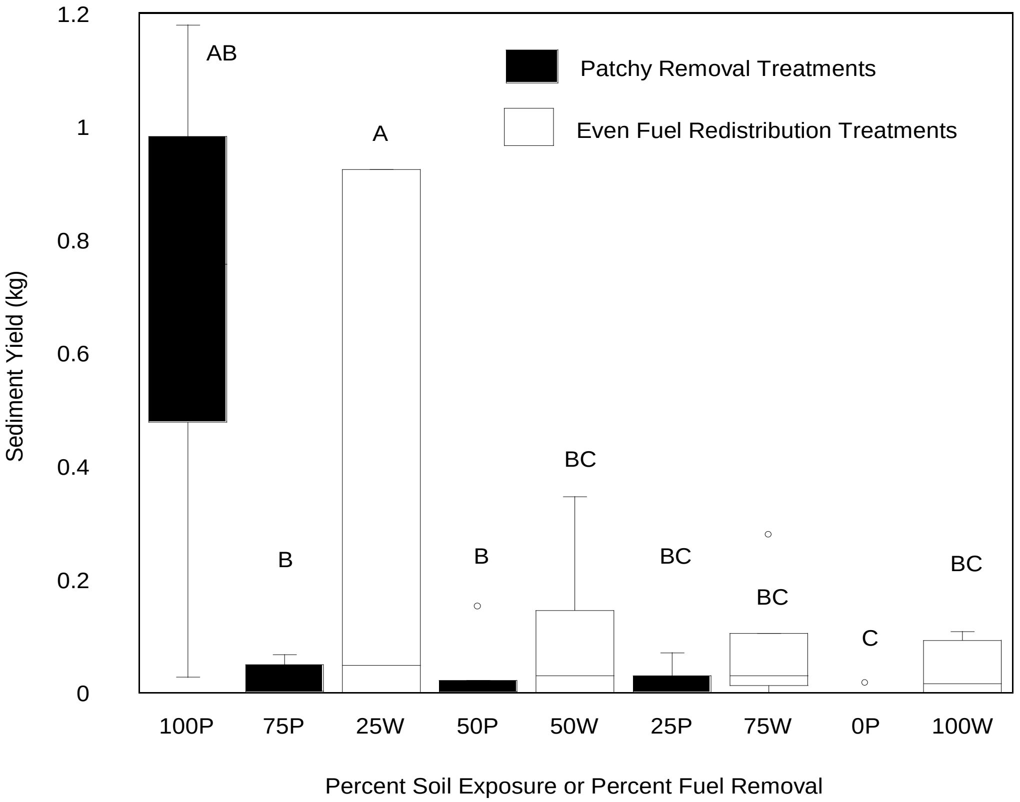

Figure 1. Sediment yields from all P: "patchy removal" and W: "even fuel redistribution" treatments on masticated sites in the Lake Tahoe Basin, California and Nevada. Different letters are significantly different at p ≤ 0.05 (Tukey-Kramer)

2) Effect of patchiness on measured rill erosion from Lake Tahoe forest sites with prescribed fire treatments

Area of plot surface exposed to prescribed fire was a significant predictor of sediment yield (ANOVA, $p < 0.001$). A distinct threshold was observed with severe erosion potential occurring when the burned area within each plot exceeded 54% (Figure 2, piecewise regression). Highest sediment yields were generally found on bare volcanic soils. Results for decomposed granitic sites showed high runoff infiltration but were extremely susceptible to large-scale erosion events when groundcover was lacking (100% burned area). The results support our hypothesis that prescribed burn treatments that are able to create spatial patchiness, by burning during higher moisture conditions, will be effective in reducing fire risk without increasing erosion potential. Furthermore, those treatments, by reducing the risk of severe fire occurrence, help avoid the risk of resulting severe post-fire erosion.

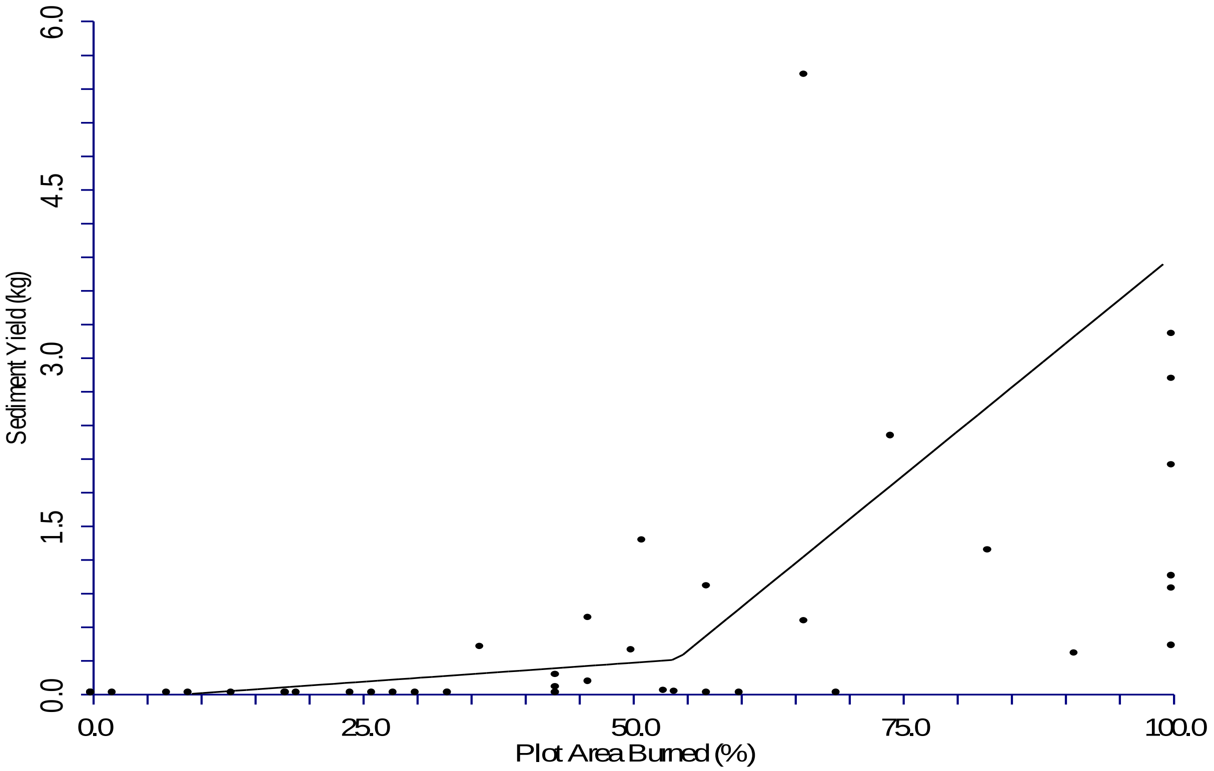

Figure 2 Percentage of plot area burned vs. sediment yield (kg) with prescribed fire sites of the Lake Tahoe Basin, California and Nevada. Data fit with piecewise polynomial regression (R^2 = 0.32).

3) Comparison of WEPP model predictions and field measurements.

The WEPP model results replicated the general trend of the field erosion data for prescribed burn treatments, showing a threshold of burn severity above which erosion rates increased dramatically (Figure 3). However the WEPP model put the threshold higher than was observed in the 2 x 5 meter field erosion plots. Additionally, the model showed low levels of erosion occurring at low levels of burn severity where the field experimentation did not record any runoff or erosion from the plots. Erosion estimates for severely burned sites (100% of plot area burned) were much higher in WEPP than observed in field measurements. WEPP predicted sediment yield had a stronger relationship (R^2 = 0.89) with burn severity than did observed sediment yield (R^2 = 0.31).

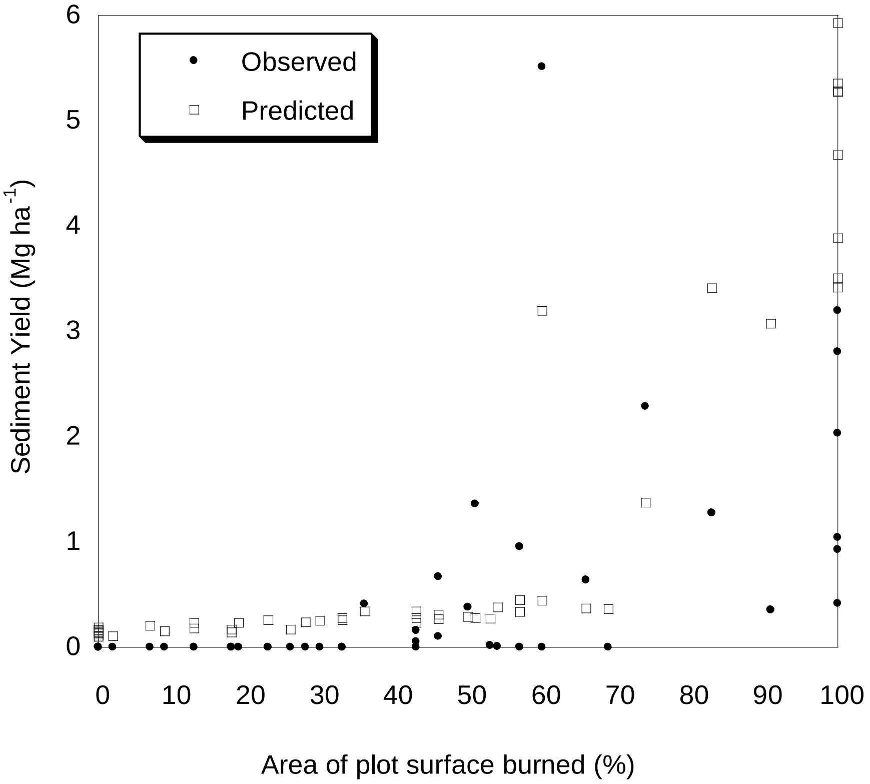

Figure 3 Observed and WEPP predicted sediment yields (Mg ha^{-1}) vs. the area burned (%) in prescribed fire sites in the Lake Tahoe Basin, California and Nevada.

4) Static conditions of forest floor

In spite of the mechanistic links to fire effects, little information is available on the composition, bulk density, mineral content, depth, and loads of forest floor fuels. We collected fuels from deep, well-developed forest floors in four long-unburned Jeffrey pine -white fir stands in the Lake Tahoe Basin (Figure 4). To isolate the effects of spatial location, we measured forest floor (litter, fermentation, and humus, where present) loading, depth, bulk density, and mineral ash content at the base of each tree, beneath the crown drip line, and beyond the crown in open “gaps”.

Figure 4 Location of the forest floor fuel sampling sites in the Tahoe Basin.

We found substantial variability between the two conifers' forest floor fuels: composition of Jeffrey pine litter was dominated by pine needles and cones (84.2 and 10.0 % by mass, respectively) while white fir forest floor fuels were composed of pine needles, fir needles, and cone fragments (47.4, 25.0, and 14.9%, respectively; Table 1).

Table 1. Mean percent composition (by mass) of forest floor litter between species and spatial position in relation to distance from trees in four long-unburned forests of the Lake Tahoe Basin.

		n	% Composition						P
			Pine Leaves	Fir Leaves	Cone Matter	Bark	Reproductive Structures	Other Leaves	
Species	*P. jeffreyi*	54	84.2	0.4	10.0	2.3	3.1	0.1	< 0.001
	A. concolor	54	47.4	25.0	14.9	8.3	4.2	0.2	
Location	Tree Base	36	56.7	4.6	16.1	17.8	4.9	0.1	< 0.001
	Crown Drip Line	36	79.0	2.3	11.3	3.9	3.5	0.1	
	Open Gaps	36	81.8	4.6	9.7	1.0	2.7	0.2	

Litter varied spatially, with accumulations near tree stems significantly different ($P < 0.001$) from those found at drip line or in open gaps (Table 2).

Table 2. Mean bulk density (kg m-3) and 95% confidence intervals (95% C.I.) for forest floor horizons in long-unburned Jeffrey pine and white fir forests throughout the Lake Tahoe Basin, USA.

			Bulk Density kg m^{-3} (95% C.I.)					
		n	Litter		Fermentation		Humus	
Position	Tree Base	214	26.7^{bA}	(22.2, 32.2)	120.2^{bC}	(110.7, 130.5)	93.5^{aB}	(74.9, 116.6)
	Crown Drip Line	196	21.1^{aA}	(17.9, 24.9)	99.3^{aB}	(88.0, 112.0)	125.9^{bC}	(100.3, 157.9)
	Open Gap	179	23.7^{abA}	(19.8, 28.3)	98.9^{aB}	(87.3, 112.1)	168.9^{bC}	(135.8, 210.2)
Site	Pioneer	135	14.7^{a}	(12.1, 17.9)	84.2^{a}	(75.5, 93.9)	95.3^{a}	(72.1, 125.7)
	Secret	159	19.8^{ab}	(17.6, 22.2)	95.3^{a}	(82.6, 109.8)	133.2^{a}	(97.2, 182.3)
	Bobwhite	156	24.9^{ab}	(20.9, 29.6)	128.4^{a}	(113.9, 144.7)	158.3^{a}	(122.5, 204.4)
	Baldy	139	42.6^{b}	(34.5, 52.6)	121.1^{a}	(107.6, 136.3)	109.0^{a}	(85.4, 139.0)

Superscripted lowercase letters (a, b, c) represent significant differences vertically.

Superscripted uppercase letters (A, B, C) represent significant differences horizontally.

Forest floor accumulations were deep, with substantial loadings in the four sampled stands (Figure 5). Forest floor was "mounded" near tree stems, with the majority of the depth (and mass) comprised on fermentation fuels. Humus was present across spatial positions, but was less common with increasing distance from trees. Ash contents varied between trees (fir > pine) and with depth (humus > fermentation > litter). Forest floor bulk density and depths did not vary between the two conifers.

Figure 5 Forest floor fuels in fire-excluded stands the Tahoe Basin are heavy, with severe implications for fire behavior and effects.

Results highlight the substantial spatial variation in forest floor fuels in fire-excluded Tahoe Basin forests. Future work that links these characteristics to fire effects is sorely needed.

5) dynamic moisture content of forest floor

In many coniferous forests, forest floor fuels have been linked to variation in important consequences of fire, including mineral soil heating, tree mortality, and erosion. Moisture content of forest floor duff is a primary predictor of fire behavior and effects. To better understand spatial and temporal variability in forest floor moisture, we collected fuels from each forest floor horizon, cones, and woody fuels in four long-unburned Jeffrey pine - white fir stands in the Lake Tahoe Basin (Figure 4). To isolate the effects of spatial position, fuel moisture was measured at the base of each tree, beneath the crown drip line, and beyond the crown in open gaps across a fire season. We compared spatial moisture dynamics at the m^2, ha, and Basin scales and temporal dynamics at the day (one 24-h sampling period), month, and annual scales (one site was measured in 2009 and 2010).

Forest floor moisture followed predicable patterns across the Tahoe Basin. Litter, woody fuels, and cones consistently had the lowest moisture contents of the sampled fuels. These low moisture contents allow these fuels to ignite and sustain fire throughout much of the fire season. Underlying duff, particularly the fermentation horizons, were consistently wetter, but they dried below threshold consumption values early in both fire seasons.

Duff moisture varied spatially within stands, whereas moisture in litter, cones, and woody fuels did not. Open gaps and at the crown drip lines were consistently drier than near the tree base, except late in the fire season. All duff moisture values declined through the fire season, with rapid losses early in the season and a gentle decline after early July until snowfall (Figure 6).

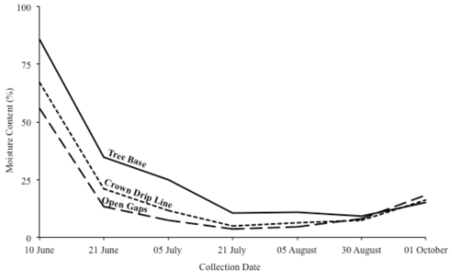

Figure 6 Spatial duff moisture variation in Tahoe Basin pine-fir stands.

The implications of early drying duff are that fuel consumption will be substantial in fires after these dates until snows or intermittent rains dampen these horizons. The options for prescribed burning to reduce, but not eliminate duff, are narrow, with windows either in the early season or during the evening when fuels have sufficient moisture or spatially patchy moisture to reduce consumption.

The variability in field results underscore the importance of measuring duff moisture content, as well as 10-h woody fuel moisture. A better understanding of the complexity of forest fuels will help land managers manage fire in Tahoe Basin forests and inform the understanding of fuels dynamics in other temperate coniferous forests.

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