Multiple disturbance effects on snowmelt and summer microenvironment in a subalpine conifer forest

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ABSTRACT

Forest structures play an essential role in regulating water resources through its influence on snow processes and nutrient cycling. With future climate concerns regarding the availability of water and carbon stocks and anticipated increases in disturbances, it is critical to understand the impact of multiple disturbances in rapid succession. This study assesses the potentially compounding effects of fire individually, in combination with a prior stand-replacing blowdown, and with a logged blowdown on snowmelt timing and summer soil temperature and moisture in a subalpine forest of Colorado. In addition, post-disturbance legacies of the microenvironment (CWD and seedlings) were included to find their potential influences on these variables. Topography was the dominant predictor for snowmelt date, overwhelming the effects of canopy loss on snow processes post-disturbance. However in 2010, the fire melted later than the control and later than the fire + logged + blowdown. Summer soil moisture, coarse woody debris, and seedling density were not significant among treatments. However, temperature profiles through the summer showed significantly warmer temperatures in disturbed than the intact forest. The fire + logged + blowdown had the highest temperatures, however, after excluding topography effects, the fire + blowdown and fire + logged + blowdown behaved similarly, but were significantly warmer than the fire-only disturbance. These results suggest that these compounded disturbances created unique conditions in comparison to the burn. Trends were still significant 9 years following the fire and may have long-term implications for future forest management practices.

INTRODUCTION

Disturbances such as wild fire, salvage-logging, and extreme wind events alter snow accumulation and melt through removal of the forest canopy. If these disturbances occur in rapid succession, unexpected impacts may arise. How do multiple disturbances influence spring snowmelt of subalpine coniferous forests? How will potential differences impact successional processes of the microenvironment? This study evaluates the potential compounding effects of fire and salvage-logging following an extreme blowdown event on soil moisture and temperature due to changes in snow melt timing and potential implications for future regeneration.

A series of large, catastrophic disturbances in a region of Colorado subalpine forest resulted in spatially heterogeneous forest recovery due to the interactions among the disturbances (Rumbaitis-del Rio 2004, 2006, Buma and Wessman 2011). Conifer resilience differed among species, leading to shifts in forest composition and distribution (Buma and Wessman 2012). This study uses this region to assess the potential compounding effects of fire, blowdown, and salvage-logging disturbances on timing of snow melt, subsequent effects on soil temperature and moisture, and consequences for seedling regeneration. Previous studies have assessed the impact of forest canopy removal on snow melt through these events individually, however fewer studies have assessed disturbances in combination.

My hypotheses include the following:

H_1: Differences in disturbance history will result in changes in snowmelt.

H_{1A}: Decreased understory regeneration in fire + blowdown sites (Buma and Wessman, 2012) will result in less shading and therefore earlier meltout date.

H_{1B}: Increased woody debris in fire + blowdown sites will decrease albedo, resulting in earlier meltout date.

H_2: Soil moisture during the summer season will be greater overall in fire + blowdown sites due to more woody debris.

H_3: The greatest summer diurnal variability will be associated with the least understory density.

H_{3A}: Summer soil temperature variability will be similar between fire and fire + logged + blowdown and lower compared to fire + blowdown due to increased understory regeneration.

H_4: Average temperatures will be lowest with greater moisture content.

Snow appearance and disappearance can be recorded through temperature sensors buried slightly below the surface. When snow is present, diurnal temperature oscillations are dampened (Lundquist and Lott 2008), thus, snow disappearance can be deduced when variability over 24 hours > 1°C for 3 consecutive days (Danby and Hik 2007). Using i-button temperature data loggers, I looked at winter and spring soil temperatures between 2007 to 2010 to determine the presence and absence of snow. Summer soil temperatures were also recorded. Soil moisture was assessed using handheld probes to determine if earlier loss of snow correlates with decreased soil moisture throughout the growing season. Finally, coarse woody debris (CWD) and seedlings were surveyed to address the impacts of the previous variables on soil moisture, soil temperature, and coniferous regeneration.

BACKGROUND

Spring and summer ablation (snowmelt) are essential processes for the provision of water to both human populations and ecosystems (Rice et al. 2011). Sixty million people in the Western United States rely on mountain river run-off for regional water supplies (Bales et al. 2006), 75% of which originates from snowmelt (Balk & Elder 2000). Ecosystems also rely on snowmelt for plant growth through its direct effect on soil temperature, soil moisture, and duration of growing season (Litaor et al. 2008). Forest canopies are particularly important in determining the amount of snow accumulated and ablated. Ablation refers to the loss of snow due to snowmelt, evaporation, and sublimination. Loss of canopy through disturbance is likely to increase snow accumulation (Winkler et al. 2005) and melt rates (Boon 2012) due to decreased interception of snowfall by the canopy and increased solar radiation (Pomeroy et al. 2002). This has important implications for humans, as greater melt rates may lead to increased potential for flooding (Schornbus 2011), decreased capacity for dams to hold this release of water (Service 2004), and further implications for water storage. These changes will also strongly influence the microenvironment of subalpine coniferous forests by altering the distribution and duration of snowcover (Varhola et al. 2010), thereby affecting soil moisture and soil temperature throughout the growing season.

Disturbances and the Microenvironment

Disturbances can be defined as discrete events in time that disrupt the ecosystem structure and alter resource availability (Siedl et al. 2011). In subalpine forests of Colorado, fire and blowdown events are natural and essential ecological factors shaping ecosystem development, function, and successional processes (Attiwill 1994, Alexander and Shepperd 1990). In addition, anthropogenic disturbances such as salvage-logging further influence dynamical processes. Whether an ecosystem recovers to its previous structure after disturbance is determined by the ecological resilience of the system (Holling 1973). Multiple disturbances occurring over a short period of time can override this resilience creating non-linear, unexpected consequences (Buma and Wessman 2011) and lead to a shift in ecosystem type (Rumbaitis-del Rio 2006).

Ecological disturbances both shape the microenvironment and are controlled by microenvironmental conditions (Chen et al. 1999). The microenvironment of an ecosystem consists of physical characteristics such as vegetation type and density, soil properties, and ground cover (CWD and bare soil). Although disturbances are often large-scale events their legacies such as CWD and soil impacts are heterogeneous within the landscape, uniquely impacting components of the microenvironment both spatially and temporally (Chen et al 1999). This small-scale variability influences successional processes and the ecosystem's susceptibility to future disturbances (Bigler 2005). For example, increased CWD following a blowdown event was found to increase fire intensity relative to a site that had been previously logged after the blowdown (Buma and Wessman 2011).

The microclimate is largely influenced by the forest structure. The forest canopy functions as a barrier against harsh environmental elements such as incoming solar radiation and wind regulating temperatures and moisture of the microclimate (Zheng et al. 2000, Burles and Boon 2011). Burles and Boon (2011) found a reduction in wind variability by 96% and reduction in magnitude of sensible and latent heat fluxes at the surface up to 200% in control versus burned sites. Post-disturbance legacies such as

CWD can also influence the microclimate of the ecosystem through shading which moderates light and temperatures, thus moisture, and offers protection from harsh winds potentially reducing physiological stress to seedlings (Rumbaitis-del Rio 2004).

Figure 1 Coarse woody debris promotes seedling establishment

Because the understory microenvironment is highly sensitive to changes in light intensity, disturbances to the overstory can have large effects on plant regeneration, distribution, biodiversity, and abundance (Chen et. al 1999). Secondary succession following disturbances is dependent on the tolerance of coniferous species to shade and moisture. Post-disturbance succession releases previously suppressed shade tolerant species in the understory for reestablishment (Buma and Wessman 2012). Following blowdown events, salvage-logging is often implemented to reduce fire fuel loads and prevent spruce beetle outbreaks. Logging may act as a compound disturbance interrupting normal ecosystem processes often through the removal of CWD. Findings have shown that CWD can create differences in soil temperatures by 1.6°C up to 7°C (Hoelzle et al. 2003, Gruber and Hoelzle 2008, Harris 1996, and Harris et al. 1998). These alterations of the microenvironment and microclimate may alter the successional trajectory changing from coniferous forest to a subalpine meadow (Rumbaitis-del Rio 2006).

The subalpine forests of the Colorado Rocky Mountains are classified as Engelmann spruce-subalpine fir dominated forests with lodgepole as a subdominant component. Both spruce and fir are shade-tolerant species, while lodgepole grows best in full sunlight (Germino and Smith 1999). Spruce seedlings have a low tolerance to high temperatures, particularly large diurnal fluctuations, and drought. A large contributor to the mortality of spruce in the first year has been attributed to drought (Alexander and Shepperd 1990). Noble and Alexander (1977) examined conditions favorable to spruce germination and survival in Frasier Experimental Forest in the central Rocky Mountains of Colorado. They found maximum surface temperatures less than 30°C to favor regeneration and shading to be significant for both germination and survival. In addition, drought was cited as the greatest factor influencing mortality. Lodgepole seedlings are much less specific in temperature and moisture preferences and are able to survive temperatures greater than 60°C even in the first 2 to 4 weeks of age (Lotan and Critchfield 1990). Many disturbances which remove the canopy often present favorable opportunities for lodgepole due to high temperature tolerance, preference for full sunlight, and serotineous cones which require fire to release seeds.

Previous studies have been conducted within Routt National Forest regarding regeneration. Rumbaitis-del Rio (2004) found that subsurface soil temperatures often exceeded 32°C during the growing season (pre-fire) following logging. The higher initial seedling growth in non-harvested sites was most closely correlated to the biomass of coarse woody debris demonstrating the importance of CWD on moderating temperature and light availability.

However, Buma and Wessman (2011) found higher regeneration in high severity fire + blowdown areas that were salvage-logged due to the removal of CWD. Pine regeneration was greater than both spruce and fir and negatively correlated to the density of pre-fire downed trees (increased regeneration in previously logged sites likely due to decreased burn times and fire severity). Engelmann spruce regeneration was higher in the presence of aspen and forbs with successful aspen recruitment occurring with high moisture levels. Aspen also decrease light intensity for shade-tolerant spruce, thereby, enhancing the likelihood of spruce regeneration.

Snow cover and subsequent ablation are the most important factor controlling plant growth due to their direct effect on soil temperature, soil moisture, and duration of growing season (Litaor et al. 2008). As ablation rates increase in disturbed sites, soil moisture has the potential to be reduced earlier in the growing season influencing ecological processes such as regeneration (Litaor et al. 2008).

Disturbance Type and Snow Processes

Forest canopies play a critical role in the duration and distribution of snow cover (Varhola et al. 2010) directly through the interception of precipitation and indirectly through shading which influences net radiation (Breshears et al. 1999). Disturbances such as beetle kill, wild fire, salvage logging (clearcutting), and extreme wind events generally observe increased snow accumulation relative to forested sites and alter the initial timing and rate of winter runoff (Winkler et al. 2005 and Boon 2009, Varhola et al. 2010)

An analysis of 33 studies conducted by Varhola et al. (2010) found forest cover to account for 57% of changes in snow accumulation and 72% of ablation. Increases in snow accumulation of 5-70% has been observed following disturbances (Winkler et al. 2010) with increased melt rates between 30-300% (Boon 2012) due to reduced snow interception and increased energy at the surface following canopy removal. Forest canopies also reduce the variability of accumulation and ablation from year to year (Winkler 2011).

Many studies have assessed the impact of logging individually on snow processes. Winkler et al. (2005) compared two juvenile stands, unthinned and thinned (cut to 3 m height), to a clearcut forest following logging over a three year time period. Snow accumulation, commonly measured as April 1 snow water equivalent (SWE), was similar between juvenile stands but up to 40% greater in the clearcut. However, snowmelt began earlier and disappeared sooner in the thinned stand than both clearcut and unthinned stands, suggesting the importance of ground cover and understory succession following disturbances.

Snow accumulation and melt after high severity burns have been found to resemble clearcut snow patterns with earlier melt dates and greater accumulation than intact forests (Burles and Boon 2011) but also behave significantly different from eachother. A 5 year study of a subalpine forest in British Columbia compared snow accumulation in a burned stand with a mature forest and a clearcut (Winkler 2011). On average, SWE was greatest in the clearcut followed by the burn then the forest. Significant differences between the burn and the clearcut were found for 4 of the 5 years. The greatest differences between the disturbed sites and the forest occurred in the year of highest SWE while the largest difference between clearcut and burn was measured during the year of lowest SWE (Winkler 2011). Average ablation rates were slightly higher in the severe burn than the clearcut but only significant 2 of the 5 years.

Factors Influencing Snow Accumulation and Ablation

Snowmelt is primarily driven by net available energy which is modified by forest density (Varhola et al. 2010). Forest canopies have a large impact on the snow ablation energy balance:

$$Q_m = K + L + H + LE + G.$$

where Q_m is the available energy for ablation, K + L is the sum of net radiation (shortwave and long wave radiation, respectively), while the turbulent fluxes consist of H, LE, and G (sensible, latent heat, and ground heat fluxes) (Boon 2009).

Shortwave radiation is the predominant factor in this equation and generally increases at the snow surface with reduced canopy cover (Boon 2009, Woo and Giesbrecht 2000). In dense forests, snowmelt is controlled by shortwave and longwave radiation emitted by vegetation (Boon 2011, Winkler et al 2005). Although canopies emit more longwave radiation than disturbed sites, they reduce the net energy at the snowsurface through absorption and reflection of shortwave radiation (Boon 2009). In less dense canopies, longwave radiation becomes negligible. Here, wind speeds increase turbulent heat fluxes with sensible heat flux becoming particularly important in determining ablation in addition to net shortwave radiation (Boon 2009).

Other factors influencing snow accumulation and ablation in relationship with forest cover include snowfall magnitude (storm size) (canopy geometry (leaf orientation), topography, spatial distribution of trees and disturbance size, and wind speed (Golding and Swanson 1978, Pomeroy et al. 2002, Boon 2009). Weather conditions and variability from year to year including cloud cover and ambient air temperatures are also important in determining snow processes.

Boon (2009) found a threshold in snow accumulation with snowfall magnitude; branches are limited in the amount of snow they can intercept and when snowfall exceeds a certain amount, forest cover becomes decreasingly important. Microscale properties such as leaf orientation and tree distribution are also important in controlling snow interception (Varhola et al. 2010). The spatial size of the disturbance interacts with both wind speed and net radiation. Varhola et al. (2010) found intermediate-sized clearcuts to accumulate the most due to shading from nearby trees and decreased wind erosion in comparison to larger disturbances areas.

Topographic variables alter solar radiation, air temperatures, and snowfall magnitude. Elevation influences melt rates with higher temperatures at lower elevations leading to faster melting (D'Eon 2004). In addition, SWE (amount of water contained in the snow) increases at higher elevations (Toews and Gluns 1986). Aspect and slope influence solar radiation, with south and west-facing areas in the Northern Hemisphere melting faster than north and east-facing areas (Murray and Buttle 2003) and increased ablation on steeper slopes due to lower incidence angles (Ecological Climatology).

MATERIALS AND METHODS

Study Site

In 1997, a severe windstorm blew down 10,000 ha of subalpine forest within Routt National Forest of northwestern Colorado (Baker et al. 2002). In response, the U.S. Forest Service salvage-logged 935 ha of the blowdown from 1998-2011(Rumbaitis-del Rio 2006). Five years after the blowdown lightning ignited fires that burned a significant portion of the previously disturbed areas on August 17, 2002 (Rumbaitis-del Rio 2006). A map of the study area with plots can be found in Figure 2.

The canopy of this mature, subalpine forest is dominated by subalpine fir (*Abies lasiocarpa),* Englemann spruce (*Picea engelmannii*), lodgepole pine (*Pinus contorta*) and quaking aspen (*Populus termuloides*). Soils are classified as loamy skeletal typic Cryochrepts and typic Dystrocryepts (U.S.D.A Forest Service 1999) and formed from Precambrian granites, gneiss, and glacial deposits (Snyder et al. 1987). Annual mean temperature is 3.9°C with a mean maximum of 13.2°C and mean minimum of -5.5°C (Western Regional Climate Center 2013). Total mean annual snowfall is 166.6" with nearly 60% of this falling in the winter (98.9"), 25% in the spring (39.8"), and 17% (27.9") in the fall. Probability of temperature below 0°C (freezing) for the spring is 60% as of July 1.

This study is based on data collected from 2007 through 2010 and is part of ongoing research conducted within Carol Wessman's lab. Four treatments were studied including green, intact forest (control-CU), fire only (F), fire + blowdown (FB), and fire + salvage logged + blowdown (FLB)(total n=19). Plot elevations range from 2465 m to 3050 m, with FB plots consistently at higher elevations due to the nature of disturbances. Plots were 15X15m.

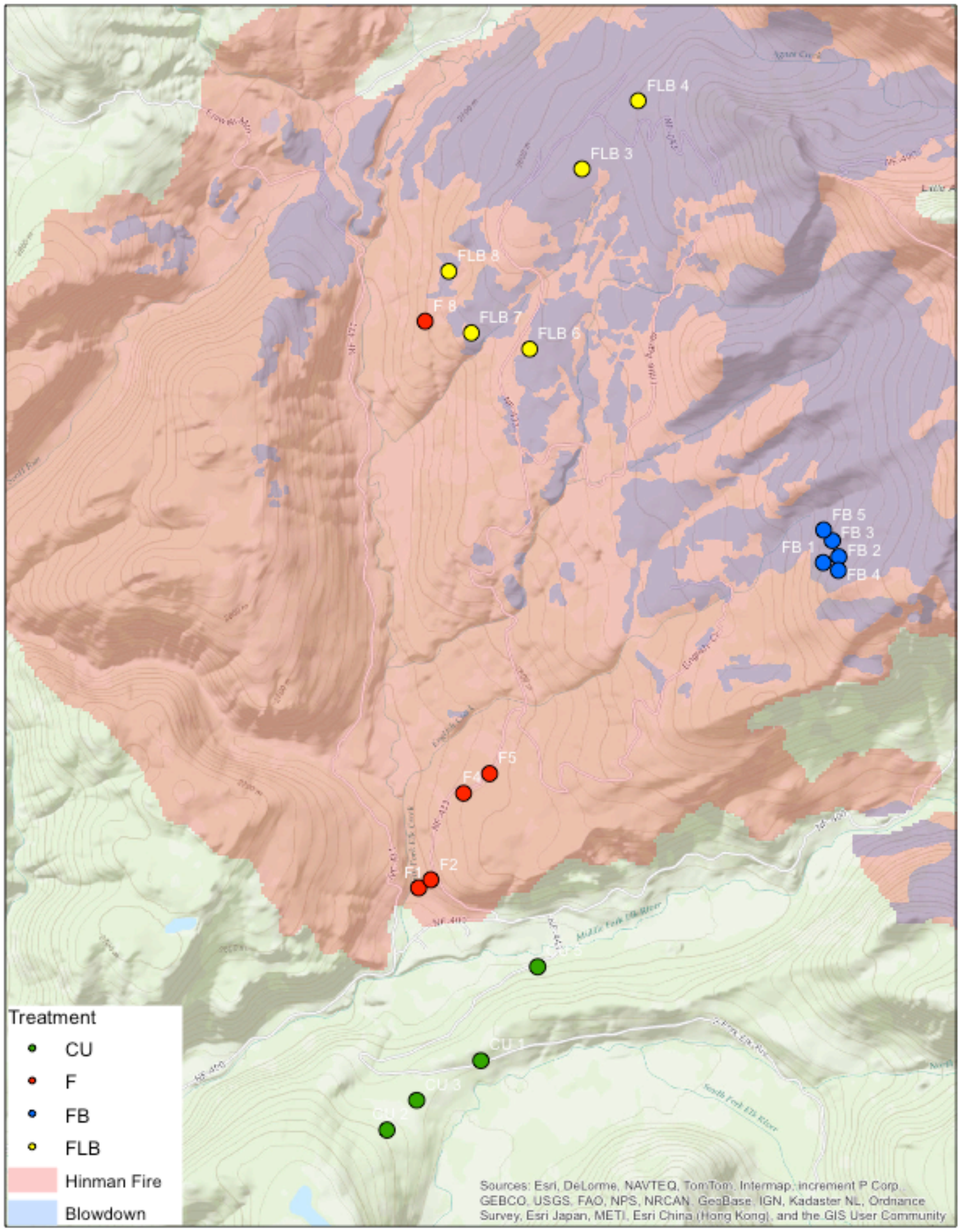

Figure 2. Map of study area in Routt National Forest, northwestern Colorado. Portions are shaded to represent the windstorm in 1997 and Hinman Fire in 2002. Plot locations are marked with colors indicating treatment category. CU (control, n=4), F (fire, n=5), FB (fire + blowdown, n=5), and FLB (fire + logged + blowdown ,n=5).

Figure 3 Control (CU)

Figure 4 Fire-only (F)

Figure 5 Fire + Blowdown (FB)

Figure 6 Fire + Logged + Blowdown (FLB)

Methods

Winter measurements

Study plot characteristics and climate can be found in Table 1. An inexpensive method to monitor snowcover is through the use of Maxim iButton temperature sensors (Maxim Integrated Products, Sunnyvale, CA). During the winter, snow cover often increases near surface temperatures in comparison to the overlying air and dampens soil temperature variability by creating an insulating layer below the snowpack (Danby and Hik 2007, Lewkowicz 2008, Gubler et al. 2011). Once the surface layer above the loggers is exposed diurnal variance resumes. Thus, the first occurrence of the absence of snow (meltout date) was assumed to be the third day when diurnal temperature variance exceeded 1°C (Danby and Hik 2007).

The manufacturer states the accuracy of these loggers to be ±0.5°C, however, Gubler et al. (2011) found greater accuracy (±0.125°C). Through comparisons to observed snowpack measurements (Lewkowicz 2008) these iButtons have demonstrated they are an effective, inexpensive, and less time-intensive alternative to meteorological stations and snow depth probes. As a multiyear, ground-based study with numerous plots, this method was a favorable alternative to deduce snow cover.

Soil temperature at 5 cm was recorded for each treatment with 3 iButtons placed in open ("sun") areas without overstory. Temperature data from twenty-four plots were recorded between the winter years of 2007 to 2011 to compare the meltout date among treatments: 4 within green, intact forest (control-CU), 5 fire only (F), 5 fire + blowdown (FB), and 5 fire + salvage logged + fire (FLB). For each plot, daily mean, mean maximum, mean minimum, and mean range were calculated through the spring at 3-hour intervals.

Summer Measurements

Soil temperatures were obtained utilizing the same iButton temperature method but at 1-hour intervals during the summers of 2007-2010. Six iButtons were placed at each plot 3 in the sun and 3 in the shade of CWD.

Volumetric water content (VWC) was measured at 36 grid-points using a hand-held Hydrosense probe (CD620 Display, CS620 Water Content Sensor Campbell Scientific Inc, Logan, UT). In 2008 and 2009, VWC was measured in late June, August, and September.

During the summers of 2007 to 2009, all conifer seedlings were counted at each plot and analyzed by density per hectare. Seedlings were identified by morphological characteristics. Logged (FLB) sites were planted by the US Forest Service in 2005 and 2006.

Downed woody debris measurements were counted in 2006 based on the planar intersect technique by recording CWD with diameters 3 cm or greater (Brown 1971, Brown and Roussopoulos 1974). Limitations of the study only allowed for CWD to be counted for 1 year. For the purpose of this study, the assumption was made that CWD with diameters greater than 3 cm decayed at a slow enough rate that it was essentially a constant over a 4-year time period. In addition, shade iButtons were remissioned each year in the spring and replaced under existing CWD to account for any possible small-scale variations.

Statistical Analysis

R statistical analysis software (version 2.15.2) was utilized for all tests. Meltout date was determined when temperature range exceeded 1°C for 3 consecutive days. Aspect was transformed to a radiation index (TRASP) where 0=NNE typically wetter soils, and 1=SSW, typically drier soils.

A one-way between-treatments analysis of covariance (ANCOVA) was conducted compare the influence of topographic variables on meltout date and summer temperatures. Tukey's post-hoc test for multiple comparisons was used to identify whether differences of meltout date and summer temperatures existed between treatments after accounting for topographic variables. Statistical significance for all tests was determined using α=0.05. In 2010, temperature data was only recorded for disturbed sites excluding control.

Pearson correlation matrices were calculated for 2007, 2008, and 2009, followed by ANOVAs to elicit significant relationships between microenvironment variables. Volume of coarse woody debris (Mg/ha) with a diameter of +3cm was calculated using the Brown's Line equation. Soil moisture levels were calculated as the mean of the 3 periods taken over summers 2008 and 2009 as a relative soil moisture index (Kueppers and Harte 2005). Soil temperatures above 30°C are unfavorable to spruce regeneration (Noble and Alexander 1977). Temperature influences on seedling establishment were analyzed as the proportion of extreme days were calculated for total, sun, and shade buttons when temperature exceeded 30°C over the summer sampling season (2007: mid June to early September; 2008, 2009, 2010: late June to mid September).

Plot	Elevation (m)	Slope (%)	Aspect	CWD (Mg/ha)	Soil Moisture (%)		Seedling density (stem/ha)			Julian Meltout Date				Total proportion of extreme days			
					2008	2009	2007	2008	2009	2007	2008	2009	2010	2007	2008	2009	2010
CU1	2569	11.6	S	22	9.5					107	141	128		0	0	0	
CU2	2602	8.8	NE	28	23.3	24			2222	133	154	141	152	0	0	0	
CU3	2566	2.4	NE	23	16.9	20			2000	134	162		156	0	0	0	
CU5	2475	15.8	NW	1	13.5	12			1956	123	158	138	129	0	0	0	
F1	2466	6.9	W	79	10.1		133	89	175	98	140	127	141	0	0	0	0
F2	2497	13.8	SW	61	8.1	11	800	933	2844	111	143	129	141	0	0	0	0
F4	2568	9.1	NW	15	8.7	9	1111	1200	1644	120	151	135	148	0	0	16	0
F5	2575	4.7	NW	46	11.9	12	1067	1778	3511	120	151	136	148	0	0	10	0
F8	2707	12.8	W	50	17.6		400	622	450	122	154	138	152	0	5	24	9
FB1	2994	15.0	NW	215	10.4		178	44	2450	160	178	163	169	0	0	0	0
FB2	3018	19.2	NW	85	11.6		0	0	300	150	173	161	167	19	20	35	7
FB3	3001	12.6	S	32	8.9	9	0	0	356	156	179	165	161	5	29	43	8
FB4	3048	19.4	NW	127	11.9	7	44	44	311		177	169	172	0	0	5	0
FB5	2988	16.7	NW	36	11.4	10	0	0	667	163	178	165	165	0	0	0	2
FLB3	2865	3.5	S	24	13.0	19	0	356	1422	140	168		159	0	6	0	0
FLB4	2908	9.4	W	68	12.3		0	0	625	140	166	142	156	0	8	40	7
FLB6	2790	5.2	W	39	12.6	12	0	1867	5244	134	162	142	156	0	31	19	12
FLB7	2748	2.8	SW	8	9.9	12	1022	1644	5733	132	156	136	153	0	23	36	26
FLB8	2728	7.7	W	34			311	489		133	160			27	33		

Table 1 Study plot characteristics with meltout date and proportion of extreme days.

RESULTS

Meltout Date

Graphs of mean temperatures leading to meltout date can be found for all years in Figures 7 through 10. In 2007, 2008, and 2009 no significant treatment effects were found after accounting for topographic variables. CU and F consistently melted out first followed by FLB then FB. Post-hoc analysis in 2010 found significant differences between F and CU ($p=0.046$) and F and FLB ($p=0.033$). Marginal significance was also found between FB and FLB ($p=0.063$). ANCOVA found elevation had a significant impact on meltout date in each year ($p<0.001$, $F_{2008}=179.692$, $F_{2010}=2623.53$ and $p<0.01$, $F_{2007}=417.326$, $F_{2009}=145.778$, $df=1$). Slope was also significant for all years ($p<0.01$, $F_{2008}=43.082$, $F_{2009}=120.467$, $F_{2010}=274.94$ and $p<0.05$, $F_{2007}=55.34$, $df=1$). Trasp was only significant for three of the years ($p<0.01$, $F_{2010}=190.53$ and $p<0.05$, $F_{2007}=58.115$, $F_{2008}=17.453$, $df=1$).

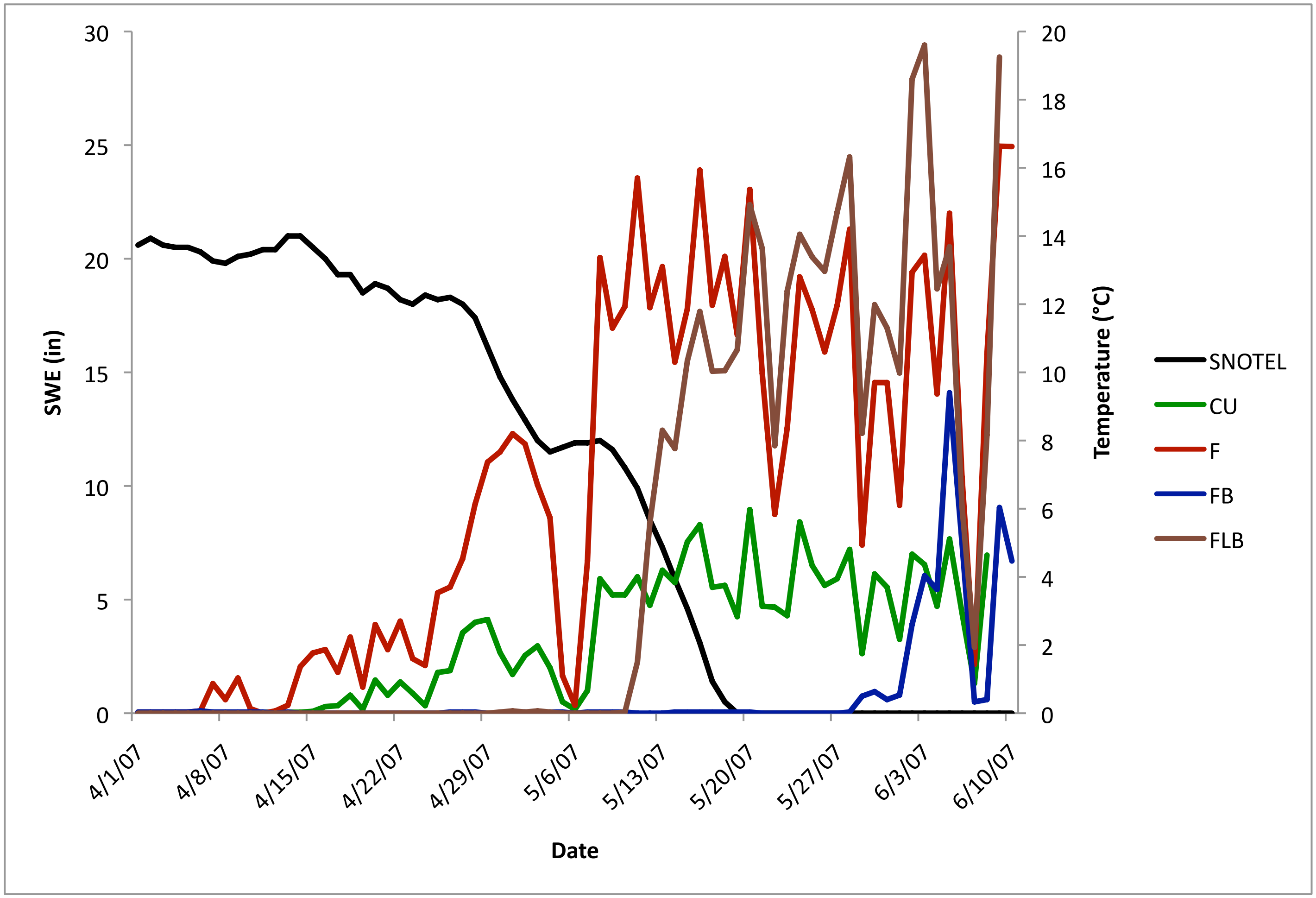

Figure 7 Snowmelt timing for 2007. Snow water equivalent (SWE) observed at Lost Dog Snotel site. Mean diurnal variability of treatments on secondary y-axis. CU (control n=4), F (fire n=5), FB (fire + blowdown n=4), FLB (fire + logged + blowdown n=5). Meltout date was determined when diurnal variability exceeded 1°C.

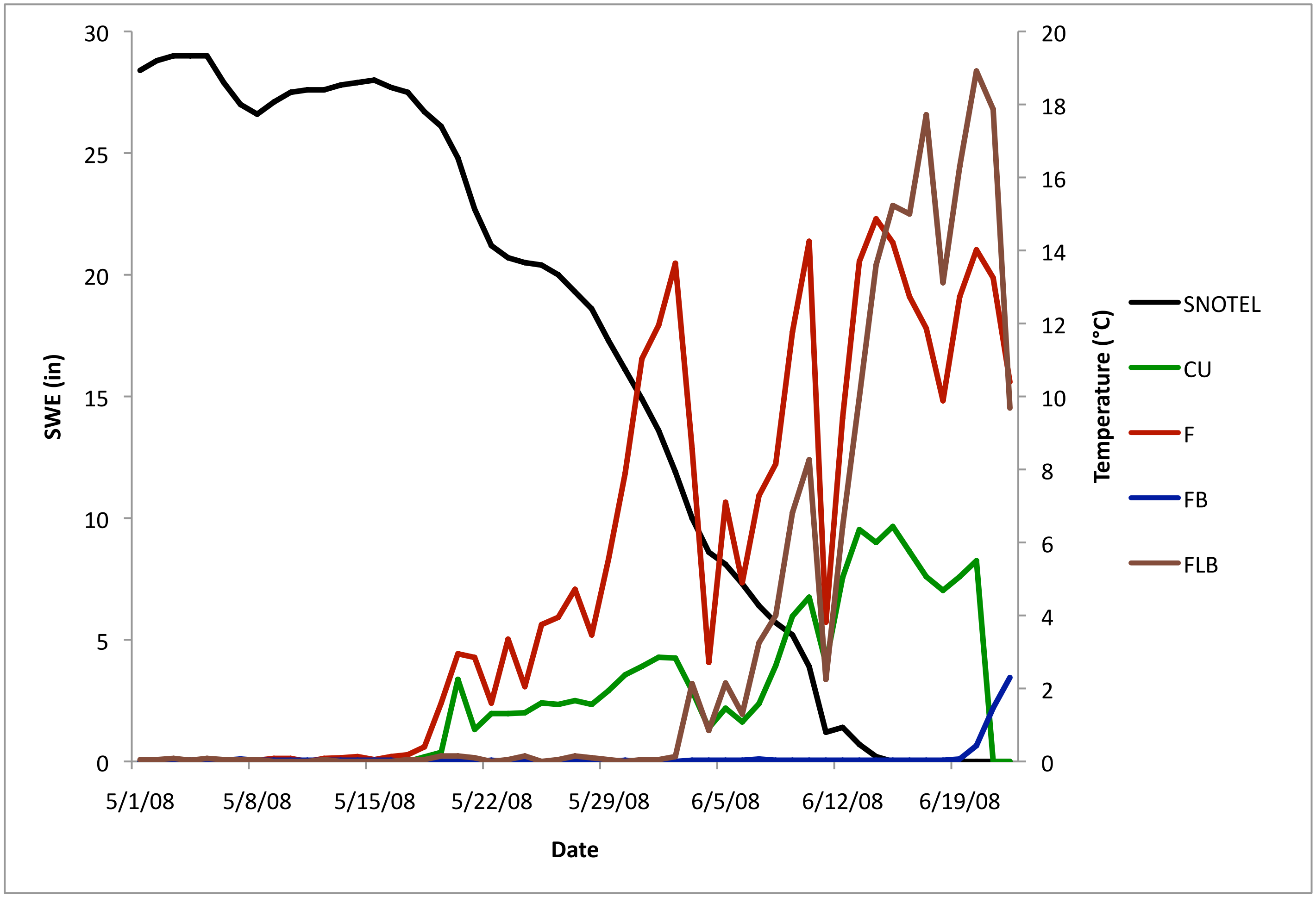

Figure 8 Snowmelt timing for 2008. Snow water equivalent (SWE) observed at Lost Dog Snotel site. Mean diurnal variability of treatments on secondary y-axis. CU (control n=4), F (fire n=5), FB (fire + blowdown n=5), FLB (fire + logged + blowdown n=5). Meltout date was determined when diurnal variability exceeded 1°C.

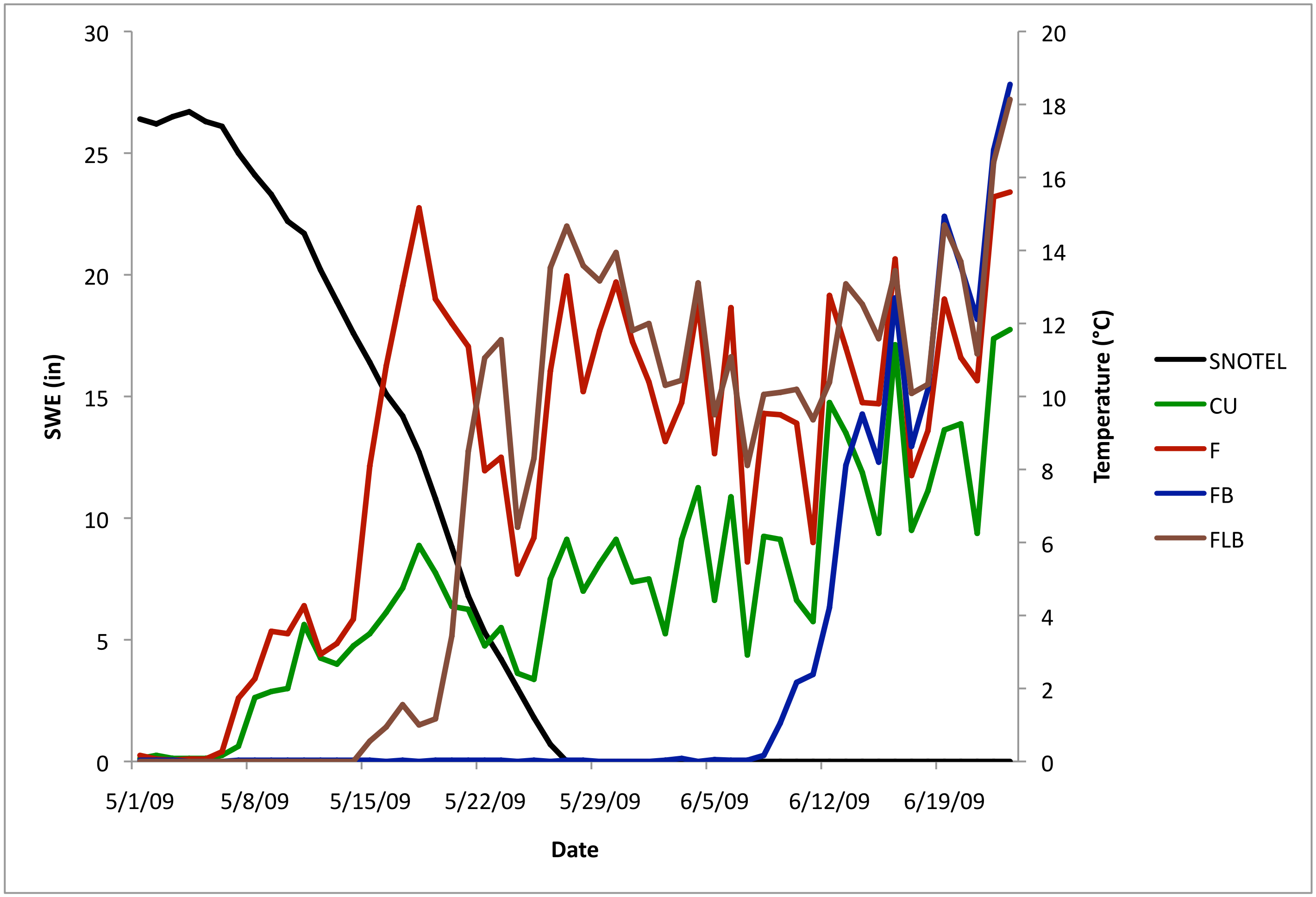

Figure 9 Snowmelt timing for 2009. Snow water equivalent (SWE) observed at Lost Dog Snotel site. Mean diurnal variability of treatments on secondary y-axis. CU (control n=3), F (fire n=5), FB (fire + blowdown n=5), FLB (fire + logged + blowdown n=3). Meltout date was determined when diurnal variability exceeded 1°C.

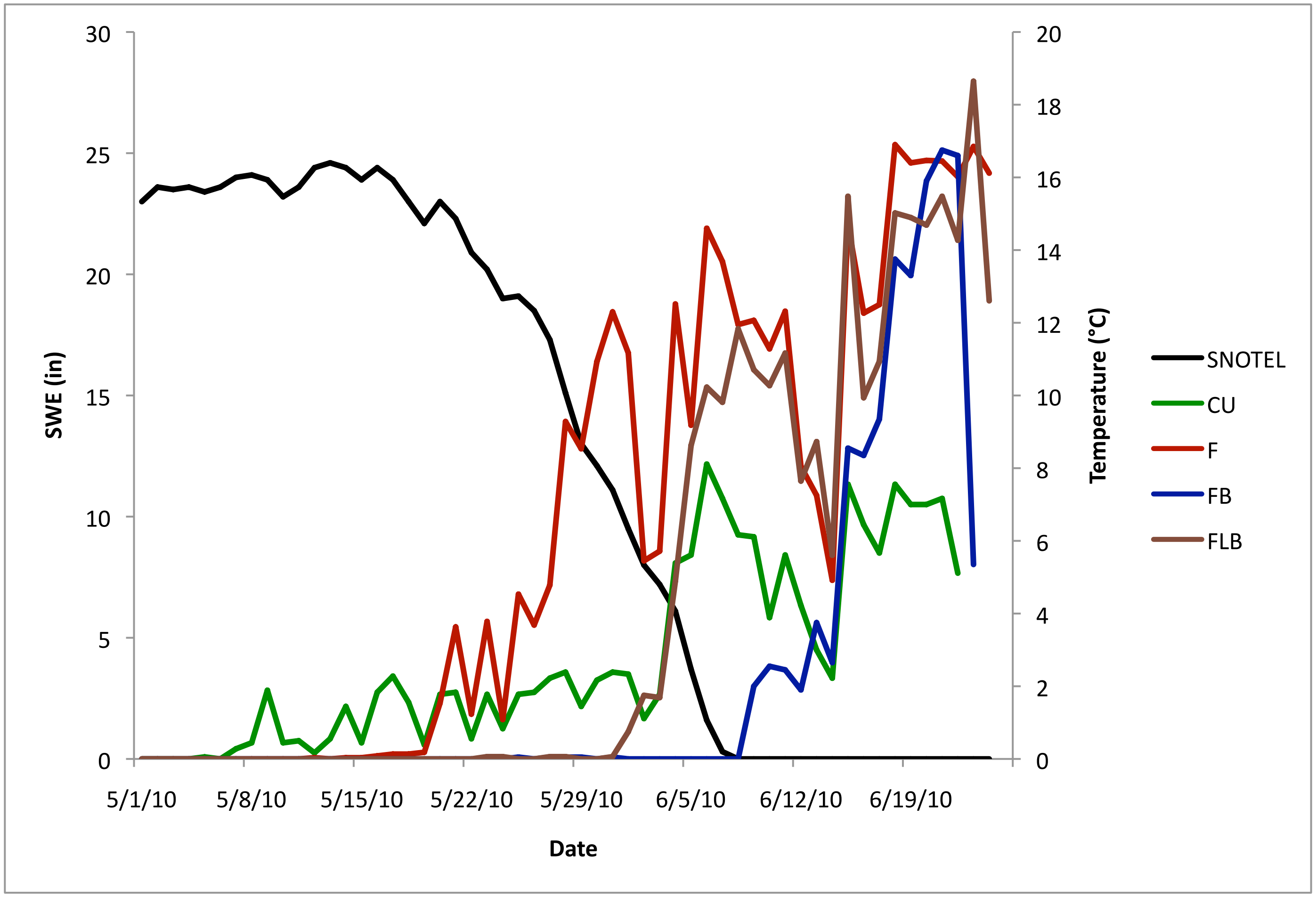

Figure 10 Snowmelt timing for 2010. Snow water equivalent (SWE) observed at Lost Dog Snotel site. Mean diurnal variability of treatments on secondary y-axis. CU (control n=3), F (fire n=5), FB (fire + blowdown n=5), FLB (fire + logged + blowdown n=4). Meltout date was determined when diurnal variability exceeded 1°C.

Summer Temperatures

Summer Means

ANCOVA F ratios for summer daily means, maximums, minimums and ranges of sun + shade iButtons averaged across the summer are found in Table 4 for all years. When significant treatment effects were found for Tukey's post-hoc analyses but were not noted, p=0.000. Temperature means for total iButtons are found in Table 2. In all years, highest mean temperatures were found in disturbed plots where FLB > F > FB > CU (excluding 2010 where no CU temperatures were recorded). Tukey's analyses after accounting for topography found no significance between FB and FLB plots for all years. In 2007, 2008, and 2009, significant differences in means of all iButtons were found between disturbed plots and controls (p=0.000). F treatments were also significantly different from FB and FLB for these years. In 2010, treatment effects were only found between F and FB (p=0.044).

Mean temperatures in the sun were 3°C to 5°C less in CU than disturbed sites. In 2007, sun means were significant for all treatments (p=0.000) except FLB and F. In both 2008 and 2009, Tukey's showed significant treatment effects in the sun for all but FLB and FB. However in 2010, no significant differences of sun mean temperatures were found between any treatments.

No significant differences between treatments were found for mean temperatures in the shade for 2010, while FLB was significantly warmer than F in 2007 and 2008. In 2009, significant differences were found for shade mean temperatures between F and the other disturbed treatments (FB and FLB). No significant difference was observed between FB and FLB.

Summer Soil Temperature												
	Average (°C)				Maximum (°C)				Minimum (°C)			
Treatment	2007	2008	2009	2010	2007	2008	2009	2010	2007	2008	2009	2010
CU	12.3 ±1.6	10.9±1.5	11.5±0.8		15.1±1.9	13.7±1.9	14.1±1.0		10.2±1.7	8.9±1.6	9.5±0.9	
F	16.0±1.9	14.5±2.4	14.4±1.5	13.5±2.1	22.3±2.9	19.6±3.0	20.0±2.0	18.1±2.1	11.4±1.8	10.5±2.3	10.3±1.5	10.0±2.2
FB	15.0±2.5	13.0±3.0	13.0±1.8	13.1±2.5	21.2±3.4	18.2±3.7	17.9±2.1	17.2±2.7	10.3±2.4	9.1±2.7	9.2±1.7	9.8±2.5
FLB	16.3±2.4	15.4±3.1	14.4±1.9	14.2±2.1	22.9±3.3	21.9±4.0	21.6±2.7	19.7±2.3	11.2±2.1	10.3±2.9	9.0±2.0	9.8±2.4

Table 2 Summer mean, maximum and minimum temperatures for sun + shade iButtons averaged within treatments. Recorded 2007: mid-June to early September. Recorded 2008, 209, 2010: late June to mid-September. Standard deviation indicated by ±.

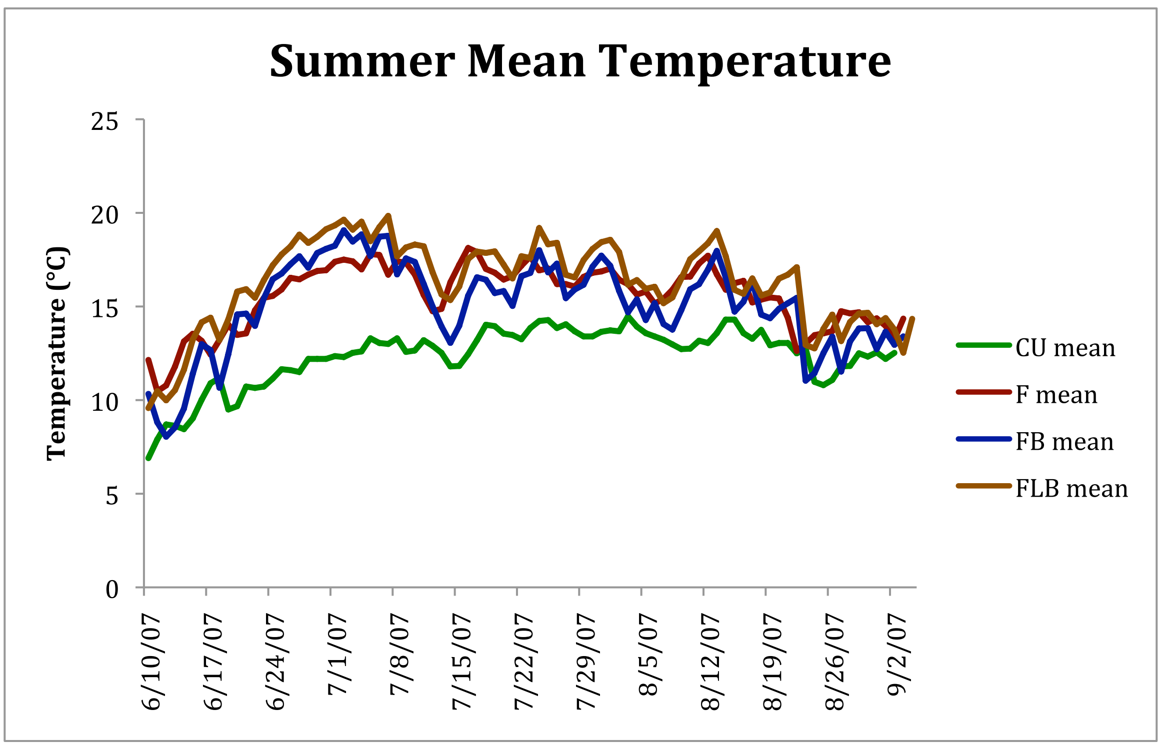

Figure 11 Summer mean temperatures for 2007 averaged within treatments for sun + shade iButtons. Although not included in figures, 2008, 2009, and 2010 exhibited similar trends with CU (control) significantly cooler than the disturbed. Summer maximums and minimums also exhibited the same trends .

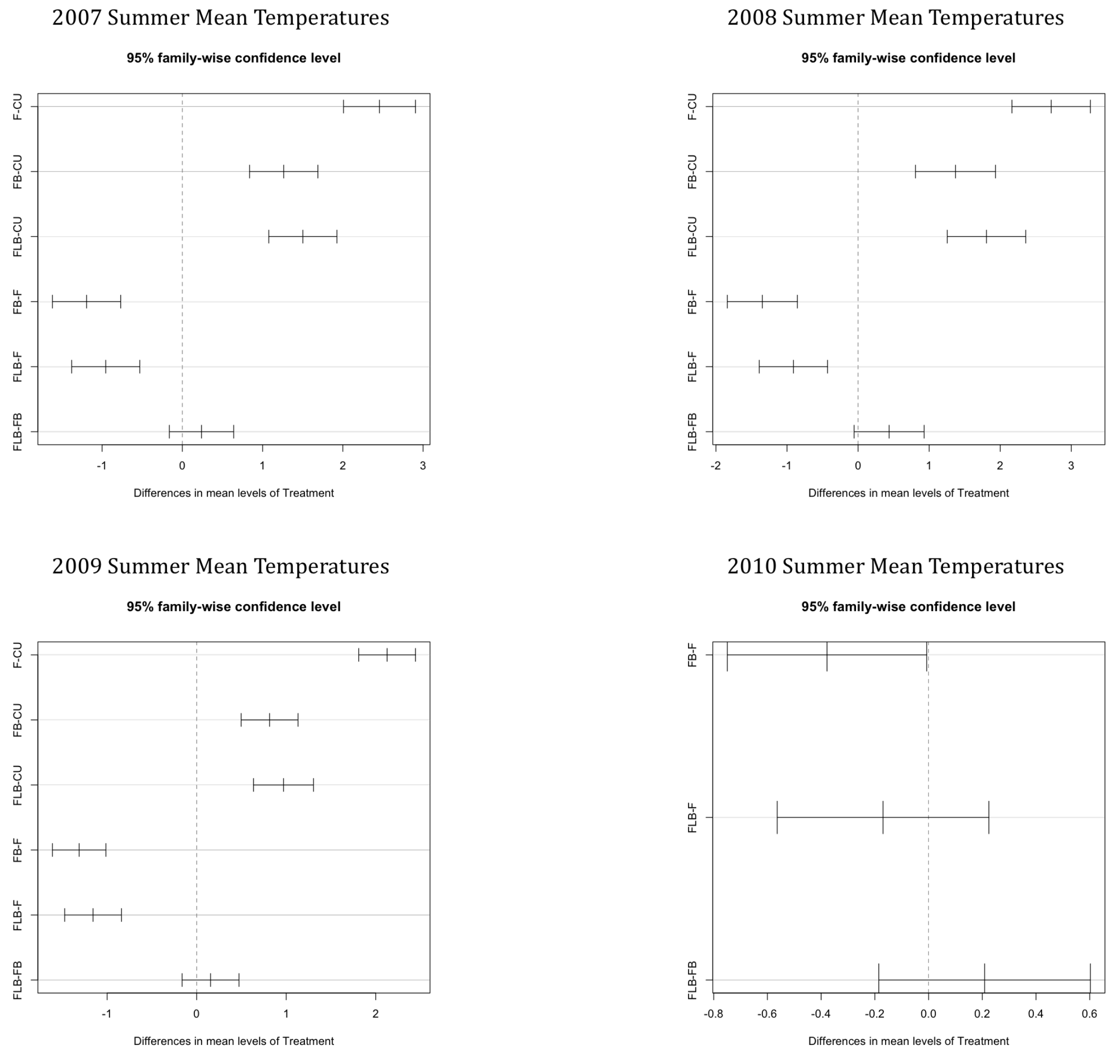

Figure 12 Pairwise comparison of daily summer mean temperatures for sun + shade iButtons . after Tukey's post-hoc test. Bars overlapping zero indicate no significant difference was found between treatments.

Summer Maximums

F ratios of ANCOVA results including the influence of topographic variables for summer maximums can be found in Table 5. See table 2 for summer maximum temperatures of sun + shade iButtons. Temperature maximums for all iButtons were greatest in FLB, followed by F, FB, then CU. Pair-wise comparisons showed significant differences between all treatments in 2008 and 2009 for maximum temperatures (p=0.000). In 2007, CU maximums were statistically different from all disturbed sites (p=0.000). Both FB and FLB differed from F (p=0.000) while no treatment effects were found between FB and FLB. In 2010, FB summer maximum temperatures of all iButtons were significantly different from F and FLB, while F and FLB behaved similarly.

Maximum temperatures were approximately 10°C greater in the sun for disturbed sites than CU. Significant differences were found for sun maximums between all disturbed sites and CU (p=0.000). In addition, significance was found between all treatments in 2007 and 2009. In 2008, FLB and FB were the only treatments where no significance in sun maximums were found, while in 2010 insignificance was only found in FLB and F. Shade maximum temperatures had the same significant treatment effects as sun maximums in all years.

Alexander and Shepperd (1990) suggested that surface temperatures greater than 30°C were detrimental to spruce regeneration. The number of days were counted by plot that exceeded this value in each summer in the sun, shade, and the sum of both then averaged across the four years (table 1). Shade buttons never exceeded 30°C. No statistical significance was found between treatments, however, great variability existed within treatments. CU maximum temperatures by plot never exceeded 30°C. FLB had the most proportion of extreme days with 67 days averaged across the 4 years, followed by FB with 43 days. Fire had less than 10 days greater than 30°C for 2007, 2008, and 2009, but 50 days in 2010.

Summer Minimums

Summer minimum temperatures can be found in table 2 and ANCOVA results in table 6. Minimums among all iButtons had less treatment effects than seen in mean and maximum temperatures. In 2007, no significance in minimums of all iButtons were found between any of the disturbed plots. Statistical significance was only found between CU and F (p=0.001) and CU and FLB (p=0.007). Again in 2008, significant differences were found between CU and F (p=0.000) and CU and FLB (p=0.008). In addition treatment effects were found for minimum temperatures between both F and FB (p=0.000) and F and FLB (p=0.012). Minimum temperatures for all treatments in 2009 ranged between 9.5°C and 10.3°C, however, significant differences were still found between F and CU (p=0.009), F and FLB (p=0.000), and FLB and FB (p=0.000). No significance was found for treatments in 2010.

Statistical significance for minimum temperatures measured in the sun were minimal. No significant differences were found in 2007 or 2010 for any treatments. Post-hoc analyses only found significance for sun minimums in 2008 for F and CU (p=0.023) and F and FB (p=0.008). In 2009, FLB was statistically different from all other treatments.

However, within the shade more significant differences of minimum temperatures were found than in the sun. These were also more variable from year to year. In 2007, shade minimum temperatures were statistically significant between CU and F (p=0.000), CU and FLB (p=0.000), FLB and FB (p=0.015), and FB and F(p=0.017). In 2008, significant treatment effects were found for all shade except FB and FLB. In 2009, shade minimums were statistically different between CU and F, CU and FB, and F and FLB (p=0.000). FLB differed from both F and FB in 2010, while no significant differences were found between F and FB for shade minimums.

Summer Ranges

ANCOVA results for iButton ranges can be found in table 4, 5, and 6. Diurnal variability for all disturbed sites was two-fold greater than CU ranges for all iButtons. Post-hoc analyses found statistical significance between CU and disturbances relative to diurnal variability for all years. In 2007 and 2009, ranges between all treatments were significant in the sun. In 2008, FLB and FB were the only treatments without significance for sun ranges while in 2010, significant differences for sun diurnal variability only existed between FLB and FB ($p=0.000$) and FLB and F($p=0.002$). Significance in the shade was found between all treatments in all years ($p=0.000$), excluding 2009 where FB and CU were not.

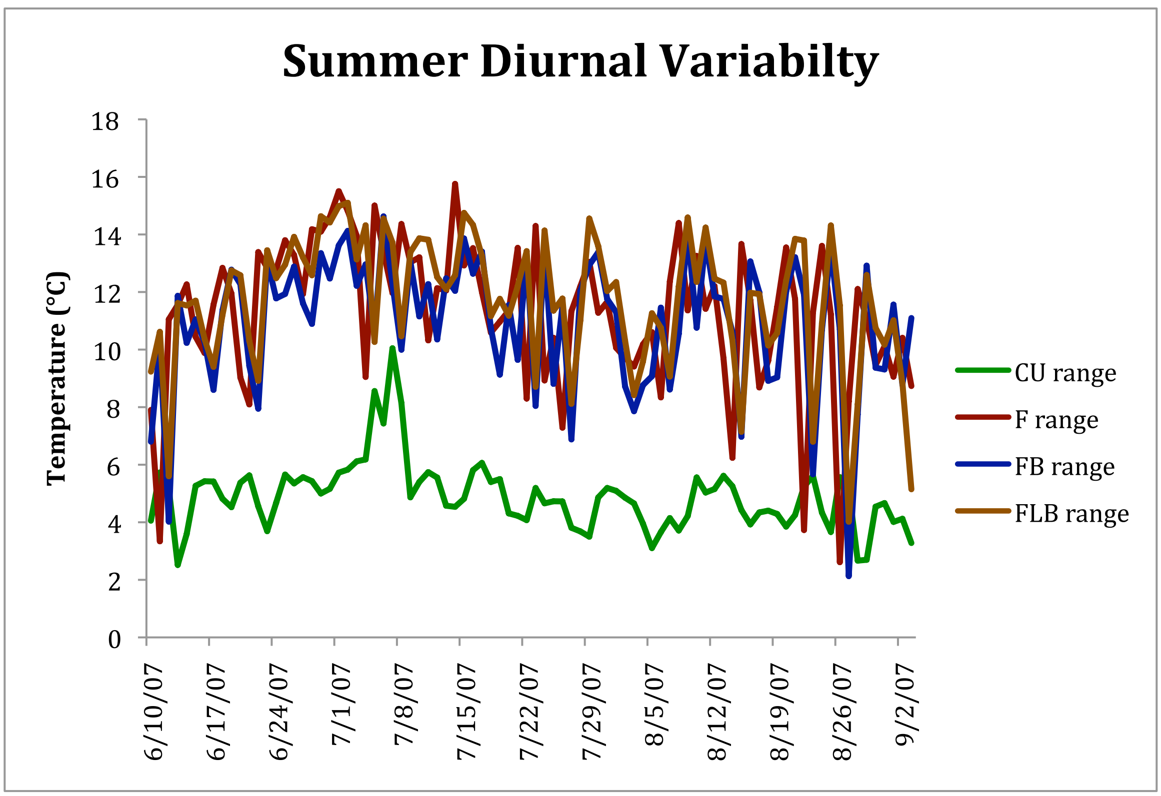

Figure 13 Summer diurnal temperatures for sun + shade iButtons. Ranges in 2008, 2009, and 2010 exhibited similar trends with CU (control) ranges less than disturbed treatments.

Source of Variation	2007 df	2008 df	2009 df	2010 df
Slope	1	1	1	1
Elevation	1	1	1	1
Aspect	1	1	1	1
Treatment	3	3	3	2
Slope:Treatment	3	3	3	2
Elevation:Treatment	3	3	3	2
Aspect:Treatment	3	3	3	2

Table 3 Degrees of freedom for analysis of covariance for total, sun, and shade temperatures in tables 4, 5, and 6. No data was collected for CU(control) in 2010.

	Total Means				Total Maximums				Total Minimums				Total Range			
	2007	2008	2009	2010	2007	2008	2009	2010	2007	2008	2009	2010	2007	2008	2009	2010
Source of Variation	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
Slope	22.98	146.00	64.12	29.83	0.60	47.23	42.78	117.34	20.97	14.29	12.00	0.00	6.29*	86.43	22.53	185.91
Elevation	141.55	66.42	86.22	5.18*	200.87	283.52	496.64	25.01	0.13	0.45	58.37	1.65	306.82	25.05	920.82	60.41
Aspect	206.55	112.76	282.48	19.68	495.25	585.07	408.73	0.11	30.44	58.05	30.36	48.55	525.85	8.74	340.77	74.30
Treatment	87.82	79.29	155.74	31.01	183.70	162.51	354.57	92.48	9.80	21.66	20.32	17.19	208.77	195.08	437.11	110.46
Slope:Treatment	22.58	6.18	11.35	9.69	20.65	3.70*	6.59	21.06	3.74*	8.85	10.60	1.30	22.22	646.44	7.23	19.39
Elevation:Treatment	41.08	41.18	21.91	60.49	62.29	40.44	30.72	103.15	6.86	26.46	3.96*	21.60	61.14	567.99	30.69	52.70
Aspect:Treatment	37.62	40.22	83.43	62.49	53.46	57.34	179.81	126.56	4.43	4.55*	11.37	15.89	55.88	30.98	192.38	88.30
Residuals	1539	1481	1539	1191		1566	1539	1191	1539	1566	1539	1191	1539	1566	1539	1191

Table 4. Analysis of covariance for sun +shade summer temperatures with F-values determining significnce of topography. Statistical significance found for those not shaded p<0.001, asterisk (*) p<0.05. Shaded are not significant.

	Sun Means				Sun Maximums				Sun Minimums				Sun Ranges			
	2007	2008	2009	2010	2007	2008	2009	2010	2007	2008	2009	2010	2007	2008	2009	2010
Source of Variation	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
Slope	0.48	128.75	11.71	24.83	15.56	180.98	0.54	119.72	29.26	42.20	50.24	0.28	54.47	133.93	14.04	160.93
Elevation	203.93	133.86	288.71	18.10	331.11	382.25	1107.10	89.74	0.37	0.11	68.79	5.03*	414.70	626.46	1676.83	159.14
Aspect	400.82	196.98	282.96	112.65	773.73	295.36	388.85	113.02	32.26	48.01	78.81	75.48	751.65	253.94	238.60	15.35
Treatment	91.14	74.89	75.50	14.97	159.97	77.99	264.76	33.52	3.68*	19.02	23.40	9.37	189.10	98.23	348.48	29.77
Slope:Treatment	32.61	8.40	13.45	3.10*	53.37	27.61	33.28	1.29	6.86	7.64	10.93	3.70*	52.26	24.45	41.86	3.57*
Elevation:Treatment	61.97	43.26	39.74	147.18	80.47	23.66	80.37	214.24	9.60	23.02	11.94	59.49	67.86	4.98*	72.95	93.56
Aspect:Treatment	35.37	33.15	78.78	35.33	43.47	89.47	231.07	123.67	6.64	1.62	14.03	0.40	47.68	128.78	321.97	157.45
Residuals	1539	1481	1539	1191	1539	1556	1539	1191	1539	1480	1539	1191	1539	1480	1539	1191

Table 5 Analysis of covariance for sun summer temperatures with F-values determining significance of topography. Statistical significance found for those not shaded p<0.001, asterisk (*) p<0.05. Shaded are not significant.

	Shade Means				Shade Maximums				Shade Minimums				Shade Ranges			
	2007	2008	2009	2010	2007	2008	2009	2010	2007	2008	2009	2010	2007	2008	2009	2010
Source of Variation	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
Slope	100.17	54.30	86.92	87.72	123.17	83.13	125.44	179.75	8.93*	3.67	0.02	9.48*	133.14	124.46	165.00	209.17
Elevation	57.74	28.58	0.15	13.40	51.60	149.16	11.23	81.99	0.24	4.82*	48.12	1.22	98.43	435.89	92.42	204.35
Aspect	74.41	154.06	163.35	0.37	159.62	274.47	347.59	9.71	28.77	31.92	2.91	1.60	124.31	308.65	406.07	38.15
Treatment	72.13	100.08	106.59	24.71	166.93	144.09	279.98	61.53	25.87	29.17	44.43	35.55	168.19	160.64	415.17	157.53
Slope:Treatment	38.45	18.74	75.85	34.22	45.98	8.65	12.95	25.71	5.70	19.48	78.80	22.45	58.81	2.74	49.90	20.78
Elevation:Treatment	27.71	17.86	5.66	16.95	44.05	0.37	32.54	34.86	5.88	21.37	2.14	5.46*	43.53	29.39	54.54	28.27
Aspect:Treatment	38.44	27.80	126.36	109.46	56.02	56.21	68.35	123.16	10.34	21.54	54.57	70.86	45.84	83.00	12.79	29.68
Residuals	1539	1547	1539	1191	1539	1546	1539	1191	1539	1546	1539	1191	1539	1546	1539	1191

Table 6 Analysis of covariance for shade summer temperatures with F-values determining significance of topography. Statistical significance of those not shaded p<0.001, asterisk (*) p<0.05. Shaded are not significant.

Summer Microenvironment Variables

To determine if treatment effects were present, ANOVAs were conducted for mean summer moisture and coarse woody debris. In 2008 and 2009, no treatment effects were found for soil moisture. Differences between treatments for CWD were also absent.

Pearson correlations show relationships between microenvironment variables for 2007 in Table 7, 2008 in Table 8, and 2009 in Table 9. It is important to note that the influence of the microenvironment was not assessed in this study to determine favorable conditions for regeneration due to planting of seedlings in fire + logged + blowdown, rather, the potential influences of seedling density on meltout date, soil moisture, and soil temperature. Seedling density was extremely low in FB for all years (see Figure 14). A significant inverse relationship was found in 2008 with seedling density influencing meltout date. Seedling density in this year was nearly equivalent between F and FLB. A significant relationship was found between seedling density and temperature mean and max in 2008.

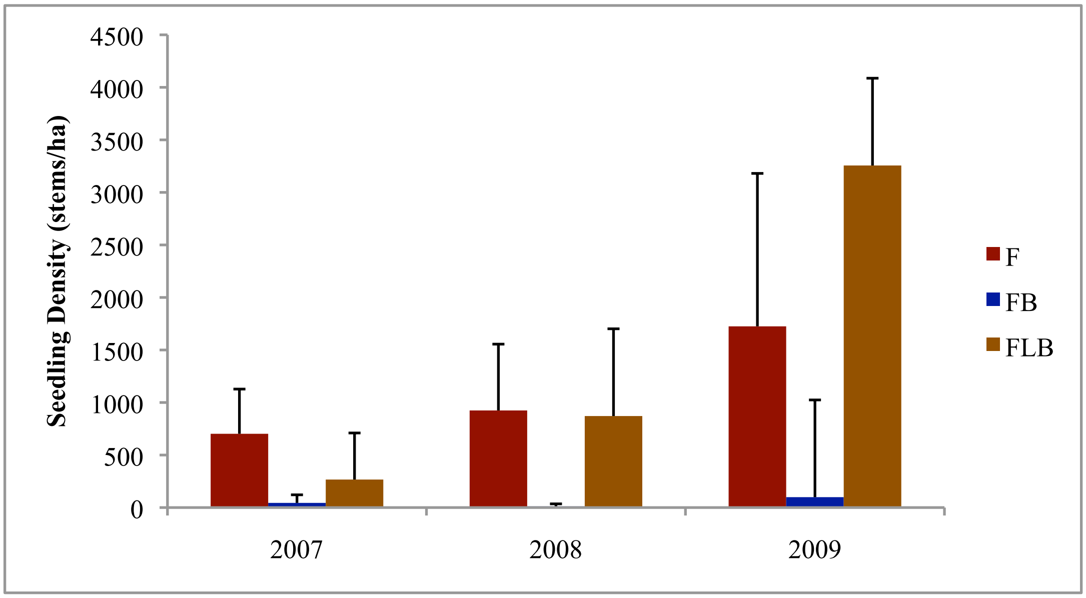

Figure 14 Seedling density counted in 2007, 2008, 2009 of lodgepole pine, Engelmann spruce, and subalpine-fir with standard deviation bars.

In general, soil moisture was greatest in June, drying through the summer, and converging by September (see Figure 15 and 16). Soil moisture content was greatest in CU for both 2008 and 2009. FLB had the greatest soil moisture content of the disturbed sites. In June and August of 2008, soil moisture was greater in FB than F, while this was reversed in 2009. Soil moisture was only inversely related to topographic variables; moisture averaged over the three observations through the summer was not influenced by meltout date. There was a decrease in temperature with greater moisture levels although not significant. CWD did not influence soil moisture.

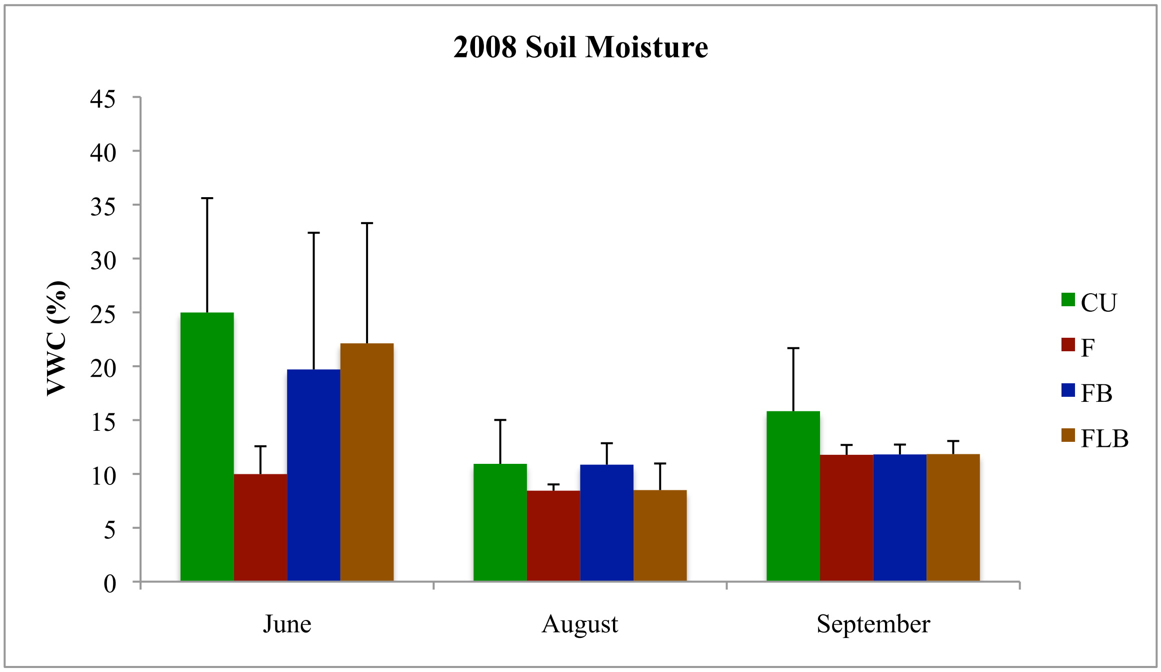

Figure 15 Soil moisture measured with hydrosense probes in 2008 averaged within treatments with standard deviation bars. No significant treatment effects were found.

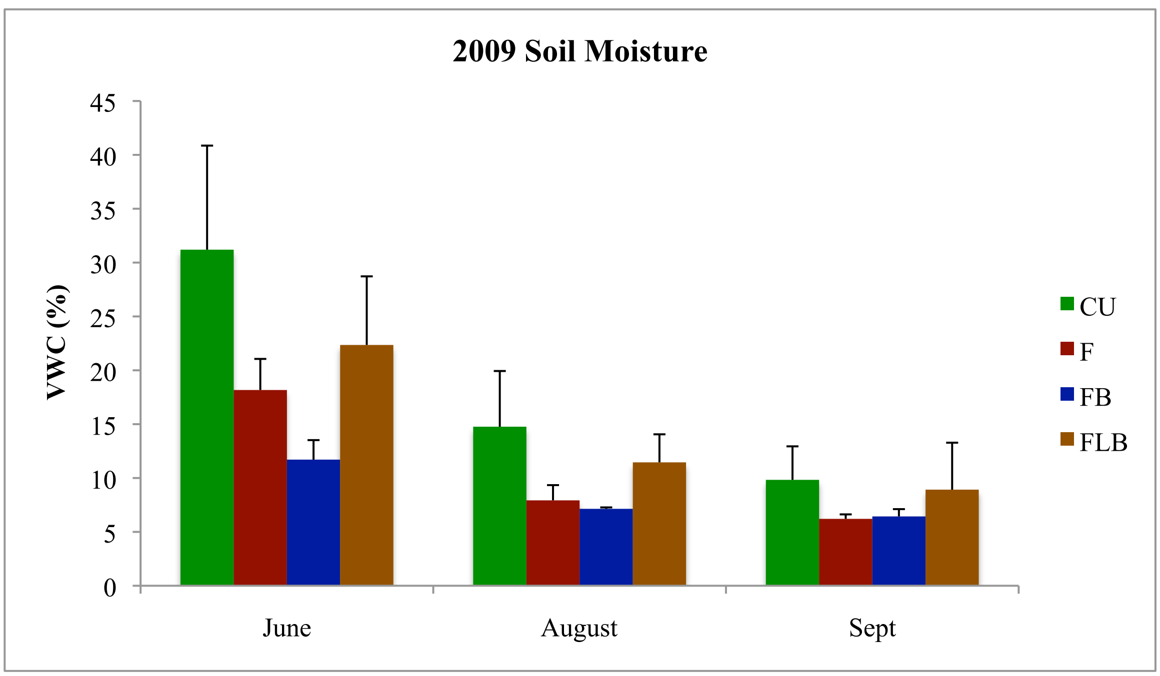

Figure 16 Soil moisture measured with hydrosense probe in 2009 averaged within treatments with standard deviation bars. No significant treatment effects were found.

CWD was greatest in FB sites and least in FLB for the disturbed treatments (see Figure 17). CWD marginally influenced meltout date in 2008 and 2009, however, it was also positively related to elevation and slope which were both highest and greatest in FB sites which consistently had the latest meltout date.

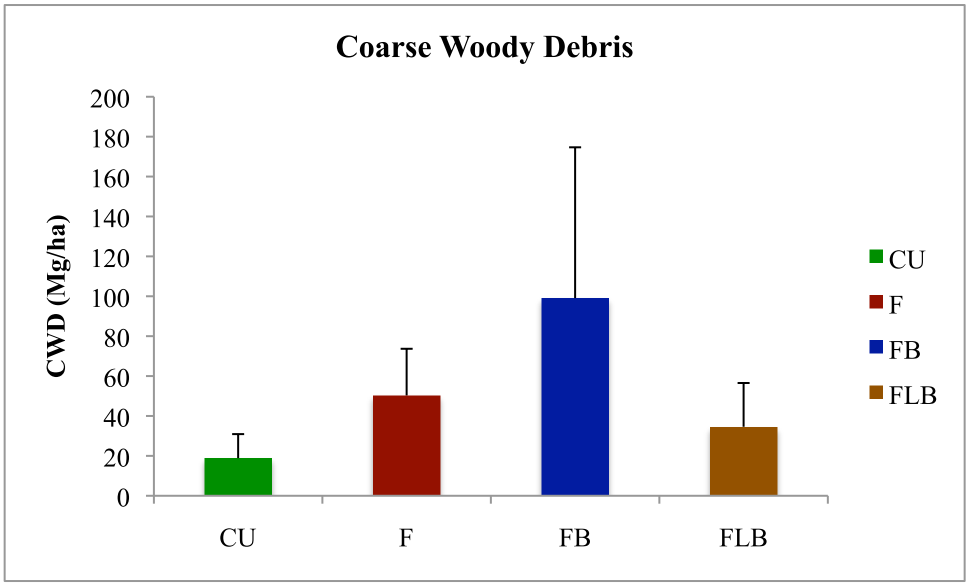

Figure 17 Coarse woody debris surveyed in 2006 averaged within treatments with standard deviation bars.

2007	*Elevation (m)*	*Slope (%)*	*Trasp*	*Meltout Date (Julian)*	*Seedling Density (#/ha)*	*CWD (Mg/ha)*	*Total Mean (°C)*	*Total Max (°C)*	*Total Min (°C)*	*Total PED (#days> 30°C)*	*Sun PED (#days> 30°C)*
Elevation	1										
Slope	**0.42**	1									
Trasp	-0.02	-0.20	1								
Meltout Date	**0.89**	0.38	-0.42	1							
Seedling Density	**-0.67**	-0.38	-0.01	**-0.52**	1						
CWD	**0.48**	**0.45**	-0.16	0.44	-0.32	1					
Total Mean	0.20	-0.09	**0.57**	-0.13	0.31	-0.11	1				
Total Max	0.29	-0.01	**0.55**	-0.07	0.19	-0.01	0.98	1			
Total Min	-0.19	-0.27	**0.52**	-0.38	**0.46**	-0.35	0.76	0.62	1		
Total PED	0.22	0.15	0.07	0.16	-0.17	0.00	0.48	0.54	0.16	1	
Sun PED	0.26	0.12	0.38	-0.06	-0.11	-0.09	0.75	0.77	0.45	0.69	1

Table 7 Correlation matrix of summer variables with *r values* for 2007 with 95% confidence level. Red bolded values are statistically significant (p<0.05) after ANOVA. Black bolded values are marginally significant (p<0.1) after ANOVA.

2008	*Elevation (m)*	*Slope (%)*	*Trasp*	*Meltout Date (Julian)*	*VWC (%)*	*Seedling Density (#/ha)*	*CWD (Mg/ha)*	*Total Mean (°C)*	*Total Max (°C)*	*Total Min (°C)*	*Total PED (#days> 30°C)*	*Sun PED (#days> 30°C)*
Elevation	1											
Slope	**0.42**	1										
Trasp	-0.02	-0.20	1									
Meltout Date	**0.90**	0.40	-0.26	1								
VWC	-0.14	-0.16	**-0.53**	0.00	1							
Seedling density	**-0.55**	**-0.63**	0.13	**-0.53**	-0.03	1						
CWD	**0.48**	**0.45**	-0.16	**0.39**	-0.17	**-0.45**	1					
Total Mean	0.11	**-0.45**	**0.54**	-0.06	-0.23	**0.49**	-0.27	1				
Total Max	0.22	-0.42	**0.53**	0.04	-0.30	**0.52**	-0.20	0.97	1			
Total Min	-0.20	-0.37	0.47	-0.35	-0.01	0.32	-0.31	0.83	0.68	1		
Total PED	0.36	-0.19	0.44	0.27	-0.19	0.19	-0.19	0.67	0.71	0.40	1	
Sun PED	0.33	-0.27	0.42	0.28	-0.15	0.19	-0.22	0.67	0.71	0.40	1	1

Table 8 Correlation matrix of summer variables with *r values* for 2008 with 95% confidence level. Red bolded values are statistically significant (p<0.05) after ANOVA. Black bolded values are marginally significant (p<0.1) after ANOVA.

2009	*Elevation (m)*	*Slope (%)*	*Trasp*	*Meltout Date (Julian)*	*VWC (%)*	*Seedling Density (#/ha)*	*CWD (Mg/ha)*	*Total Mean (°C)*	*Total Max (°C)*	*Total Min (°C)*	*Total PED (#days> 30°C)*	*Sun PED (#days> 30°C)*
Elevation	1											
Slope	**0.42**	1										
Trasp	-0.01	-0.19	1									
Meltout Date	**0.91**	**0.63**	-0.38	1								
VWC	-0.37	**-0.56**	-0.34	-0.39	1							
Seedling Density	-0.27	**-0.54**	0.15	-0.38	0.11	1						
CWD	**0.48**	**0.44**	-0.15	**0.49**	-0.38	-0.21	1					
Total Mean	0.14	-0.22	**0.52**	-0.16	-0.41	0.02	-0.25	1				
Total Max	0.29	-0.20	**0.47**	-0.04	-0.44	0.05	-0.18	0.96	1			
Total Min	**-0.47**	-0.14	0.34	**-0.52**	-0.04	-0.15	-0.26	0.47	0.22	1		
Total PED	**0.42**	-0.01	0.29	0.19	-0.41	0.01	-0.11	0.72	0.75	0.14	1	
Sun PED	**0.42**	-0.01	0.28	0.19	-0.41	0.01	-0.12	0.72	0.74	0.12	1	1

Table 9 Correlation matrix of summer variables with *r values* for 2009 with 95% confidence level. Red bolded values are statistically significant (p<0.05) after ANOVA. Black bolded values are marginally significant (p<0.1) after ANOVA.

DISCUSSION

This study assessed the following questions: 1) How will changes in canopy cover and compound disturbance legacies influence snowmelt? 2) What are the effects of snowmelt timing on soil moisture through the summer? 3) Will reduced soil moisture in disturbed treatments lead to higher temperatures? 4) How will these interacting properties influence regeneration post-disturbance? Disturbances remove the canopy cover altering the energy balance and influencing snow accumulation, ablation, soil temperature and moisture. Generally, disturbances lead to more snow accumulated through loss of interception by the canopy but earlier snowmelt due to increased solar radiation. However, the influences of topography can have an overwhelming effect on snowmelt.

Results of this study suggest that topography is the best predictor influencing snowmelt. The timing of snowmelt was consistently later in the season with increasing elevation which is supported by previous findings (Varhola et al. 2010, Rice et al 2011). Both intact forest and fire treatments were located at the lowest elevations, corresponding to the earliest melt for all years with treatment ranges between 1 to 10 days of eachother. Fire + blowdown sites were located at the highest elevations with the latest melt in all years, approximately 30 days after control and fire sites, similar to a study conducted in the Merced and Tuolomne River basins (Rice et al. 2011) which found meltout to be 2-3 weeks later for each increase in 300 m of elevation between a band of 1800 to 3900 m.

In 2010, significant differences in meltout date were present between fire and control with fire melting later than the control. This finding does not agree with previous studies which have found loss of canopy to remove snow more rapidly following severe fires in comparison to intact forests (Burles and Boon 2011). Snowmelt date in the burned stand was also significantly different melting later than the fire + logged + blowdown possibly due to changes in coarse woody debris and seedling growth (discussed later). Although fire stands behave more similarly to clearcuts than live forests, these findings also agree with those in British Columbia which found the rate of snow ablation to continue to increase in burn sites several years post-fire relative to clearcuts due to further loss of the canopy and falling of burned stems (Winkler 2011). Although significant differences in meltout date between treatments were only observed in 2010, a common pattern emerges with the rate of warming after snowmelt increasing faster and to greater temperatures in the summer in the disturbed plots.

Among all years, variability of meltout date within treatments was greatest within CU plots. This is important for human water management as greater variability in snowmelt will reduce the likelihood of flooding, as well as, decrease the risk of fire due to dry soils.

On average for all treatments, meltout date occurred earliest in 2007. Observations are consistent with data from a nearby SNOTEL station which also reported 2007 as the earliest meltout year and year with the least accumulated SWE during the study period. In 2007, variability between meltout dates by treatment was also the greatest. Both our study site and SNOTEL found average snowmelt to occur latest in 2008.

Soil moisture relationships in this study seem to be unique when compared with other research. Unlike previous studies evaluating the effects of snowmelt on soil moisture through the summer, neither of the years sampled here found significance between meltout date and VWC (Litaor et al. 2008). Moreover, no significance was found between treatments for soil moisture. In contrast to studies that found logging post-fire to increase soil temperatures and consequently reduce soil moisture (Ginzburg and Steinberger 2012), soil moisture was greater in the logged treatment following fire than the unlogged sites. It is important to note that other studies, focus on impacts of logging following fire, not before, suggesting that it is not the logging-fire combination per se, but the sequence of the events (Kemp and Wessman, unpublished). This study's results suggest a unique impact of compound disturbances leading to "ecological surprises" (Paine et al. 1998). Prior to the 2002 fire, logged soils in the region had reduced depth in the organic horizon from the control and blowdown areas (a typical logging impact), and did show lower soil moisture, although not significantly different from the other treatments (Rumbaitis-del Rio 2006). However, CWD was significantly lower in the logged sites and, thus, during the fire experienced shorter burn times compared to the blowdown and control sites (Buma and Wessman 2011). Consequently, the sequence of logging before the fire appears to have reduced the impacts of the combined disturbances.

Typically, conditions are sunnier and warmer in open areas than under the shaded forest canopy (Baliksy and Burton 1995, Boggs and McNulty 2010). Mean summer soil temperatures were significantly cooler in control sites all summers ranging from 10.9°C to 12.3°C relative to the disturbed stands which ranged from 13°C to 16.3°C. Significant differences in mean and maximum temperatures were also seen between disturbances which demonstrates the importance of the microenvironment for thermal regulation. Vegetation in the understory can protect the surface from solar radiation. Balisky and Burton (1995) found significantly warmer soil temperatures with no cover in comparison to a sparsely covered surface, with less variability in temperature occurring as understory vegetation became more dense. Fire-only areas differed from the other disturbed sites, however, the fire + blowdown and fire + logged + blowdown treatments had similar mean temperatures after accounting for topography. This suggests compounding disturbances influence the microenvironment more similarly than the singular disturbance. Future studies should include measurements of the understory to evaluate this component of the microenvironment and its effect on soil temperature.

Further effects of the microenvironment can be seen with the location at which temperature measurements were taken. Maximum temperatures for both open and shaded locations were largely different among all treatments. However, minimum temperatures for iButtons placed in the open were only slightly different between treatments, while shade minimums were significantly affected by disturbance history, although this extent varied largely from year to year. This suggests that canopy cover largely effects maximum soil temperatures regardless of location measured while minimum temperatures are less influenced by the overstory and more by the local weather conditions of the day.

Due to the planting of seedlings in the logged sites of lodgepole, this study focused on the influences of seedlings on the microenvironment (i.e. meltout date, temperature and moisture content) rather than the influence of the microenvironment on seedling density. To this point, seedlings were inversely correlated with meltout date. Although seedlings were not measured in 2010, their densities in fire and fire + logged + blowdown were becoming more similar the previous year. As seedling density converged this may suggest that other microenvironmental factors including understory composition became increasingly important. Seedling density was only correlated to mean and maximum temperature in 2008 while other years showed no relationship. The largest proportion of extreme days (> 30°C, temperatures unfavorable to spruce regeneration (Alexander and Noble 1995)), was found on the fire + logged + blowdown treatment. Not surprisingly, this treatment was the only to not see the re-establishment of spruce by the end of the study period.

Limitations

Although topography was controlled for by the best means possible, due to the characteristics of the disturbances with blowdown at higher elevations and logging located for human accessibility, topographic variables between treatments still significantly influenced most statistical analyses and likely diminished the presence of treatment effects.

The relatively small sample size reduced the degrees of freedom, limiting the ability to conduct multiple analyses and likely reducing potentially significant treatment effects.However, even with the relatively small sample size, the trends in the data were logical and expressed conditions observed across the region (Wessman and others, personal observations).

Previous studies support the use of iButtons to determine the presence of snow. This study defined “meltout date” as the third consecutive day when temperature variability exceeded 1°C. However, control plots warmed much more slowly than disturbed and this method could possibly have mislabeled the proper date for those sites. In addition, snowcover is spatially variable; iButtons might not capture this heterogeneity. In recognition of this restriction, this study was designed to characterize the endmembers (open and shaded) and capture the larger envelope of variation. A refined analysis of spatial structure of the plot area would be useful to extrapolate the endmember data to the plot.

CONCLUSION

The initial increase in snowmelt caused by the removal of the canopy through fire, blowdown, and salvage-logging may be overwhelmed by topographical influences. However in 2010, the fire melted later than the control and later than the fire + logged + blowdown. Soil moisture through the summer was not impacted by the initial timing of melt nor did it influence soil temperatures. Although no significant differences were found for these variables, even 5-years post-disturbance, temperature effects were still significantly warmer in disturbed plots than the intact forest. In addition, the compounding effects of the blowdown and salvage-logging resulted in significantly warmer temperatures than in the fire-only treatment.

Disturbances are natural drivers in structuring forest ecosystems, however, the frequency, intensity, and size of these disturbances are influenced through weather and climate (Dale et al. 2000). Increased severity of fire disturbances has been seen within recent years (Miller et al. 2009, Dillon et al. 2011, Holden et al. 2007). Climate change scenarios expect favorable fire conditions to increase in the future years suggesting the importance of understanding the interactions of multiple disturbances for future management plans.

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Appendix

CU	Control (intact forest)
F	Fire
FB	Fire + Blowdown
FLB	Fire + Logging + Blowdown
CWD	Coarse Woody Debris
PED	Proportion of Extreme Days
SWE	Snow Water Equivalent
TRASP	Aspect (topography)
VWC	Volumetric Water Content