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Abstract

Studies of forest meteorology are often conducted at the stand level, but few studies examine temperature heterogeneity within stands. Differences in canopy structure, whether caused by species composition or disturbances, introduce variation in the amount of light reaching the forest floor, which in turn introduces variation in forest floor temperatures. Furthermore, in temperate latitudes, canopy openings cast light on the forest floor in complex patterns depending on the path of the sun throughout one day and throughout the season. We installed two temperature measurement devices in control, gap, and thinning treatments to capture both the time structure and spatial variability of forest floor temperature. We compared air temperatures measured by meteorological stations to spatially continuous ground surface temperatures measured along 760 m of fiber-optic cable. Using the principle of Raman spectra distributed temperature sensing, we inferred temperature at 1 m intervals along the fiber-optic cable every 30 minutes for 42 days in May – June 2010. In regenerating secondary forests with generally intact canopies, temperatures were spatially correlated throughout the day and night. In thinned forests or in gaps, ground surface temperatures were spatially correlated at night, but spatially heterogeneous during the day, suggesting that meter-scale measurements may be required to adequately characterize these environments. Understory plant species richness was 50% lower where higher temperatures were measured. We also modeled light transmission through the overstory with tRAYci and found that understory plant species richness was highest at 10% of above-canopy light and lower at both lower and higher light levels.

Introduction

Most forest ecosystems are characterized by heterogeneous tree composition and structure. Forest tree composition varies with initial species complement, successional stage (Larson et al. 2008), and the relative degree of post-establishment disturbance (Zenner 2005, Lutz and Halpern 2006, Hanson and Lorimer 2007). Both initial tree establishment and subsequent disturbance are spatially heterogeneous processes that result in stand densities that vary at meter to ten-meter scales (Larson and Franklin 2006, Larson and Churchill 2008, 2012). The vertical structure of the forest canopy also varies with successional stage (Franklin et al. 2002, Kane et al. 2010a,b) and exhibits considerable heterogeneity over short distances due to variations in soil, topography, or aspect (Gersonde et al. 2004, Lutz et al. 2010, Minder et al. 2010). Canopy disturbances may result in high ground surface temperatures and high levels of temperature variation compared with undisturbed forests (Gray and Spies 1996, Heithecker and Halpern 2007). Ground surface temperatures can also vary due to cold air pooling and drainage on small spatial scales (Lundquist and Cayan 2007, Lundquist et al. 2008). The combined influences of microtopography and canopy heterogeneity contribute to meteorological conditions that cannot be easily characterized by measurements at a single location (Lookingbill and Urban 2003, Tang and Fang 2006, Rambo and North 2008, Vanwalleghem and Meetemeyer 2009).

Forest trees are hypothesized to limit the understory plant composition through asymmetric competition (Tilman 1982); most usually through limiting light levels on the forest floor (Canham 1988). Forest understory plants are more efficient at harvesting the low levels of light present in closed canopy forests, but are more susceptible to high temperature photoinhibition in open canopy conditions (Gilliam and Roberts 2003). Colonizing species not found in closed-canopy forest may be

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able to withstand higher temperatures or be able to use higher light levels. The interaction among plant physiological traits and competition structures plant communities (Halpern 1988, 1989), but the resulting understory plant species richness at any particular location cannot be easily predicted. The two plant guilds—forest species and colonizing species—may occupy similar locations, leading to higher local levels of species richness. Or they may occur in different locations partitioned by temperature or light levels.

Fiber-optic distributed temperature sensing can be used to measure temperature with higher frequency and with greater spatial resolution than most installations of traditional point sensors. Using the principle of Raman backscattering (Raman and Krishnan 1928), a single fiber-optic cable can provide temperature measurements at approximately every meter of its length (Selker et al. 2006a, b; Tyler et al. 2008; Tyler et al. 2009). We sought to examine whether this high resolution method could provide detailed information about temperatures in forests with intact canopies and forests with recent canopy disturbances. We used an experimental silvicultural treatment of thinning and gap creation. The replicated experimental design (Figure 1) allowed us to examine the effects of temperature and light in a relatively uniform stand (Sprugel et al. 2009). Specifically, we addressed the thematic questions of how temperature varies throughout forests with different canopy structures. We examined how temperature measurements from fiber-optic distributed temperature sensing systems at ground level differ from traditional point-based meteorological measurements, and what the spatial variation in forest-floor temperature implies for the number of temperature measurements required to characterize forest-floor temperature variability. We also examined whether forest-floor temperature and modeled insolation are correlated with understory plant species richness.

Study Area

The Cedar River Municipal Watershed is located approximately 50 km east of Seattle, Washington (47° 21′ N, 121° 38′ W, Figure 1). The study site, 400 m long and 80 m wide, is located at an elevation of 630 – 640 m, on a gentle (< 10°) slope with southwest aspect. The forest is located in the *Tsuga heterophylla* zone (Franklin and Dyrness 1988). The forest was approximately 65 years old in 2010, and was established following clearcut logging in the 20th century. Composition is primarily western hemlock (*Tsuga heterophylla*) and Douglas-fir (*Pseudotsuga menziesii*). Other common species include western redcedar (*Thuja plicata*), Pacific silver fir (*Abies amabilis*), and noble fir (*Abies procera*), with small numbers of red alder (*Alnus rubra*), black cottonwood (*Populus trichocarpa*), and bitter cherry (*Prunus emarginata*) (Sprugel et al. 2009). Mean monthly maximum and minimum temperatures are 20.3 °C and 8.5 °C in July, and 1.9 °C and -3.4 °C in January. Average annual precipitation is 2420 mm (1971–2000 climate normals; PRISM 2011). Although the cover of understory plants is generally low, bryophyte cover is extensive.

Methods

Structural Manipulation

Overall tree density prior to thinning was 1489 stems ha^{-1} with basal area of 73.7 m^2 ha^{-1} (Sprugel et al. 2009). Prior to the thinning, the location, diameter and species of all trees were determined with a combination of a Total Station and Haglöf hypsometers (for details, see Sprugel et al. 2009). The experimental area was divided into twenty 40 m × 40 m experimental units. Preliminary analysis of the overstory structure and understory composition in the 20 experimental units showed that 75% of the forest (fifteen 40 m × 40 m experimental units) could be characterized as uniform based on tree species composition, density, and mean diameter, with the amount of light reaching the forest floor being generally 5% to 10% of the above-canopy light (PACL) (Sprugel et al. 2009). These 15 experimental units were randomly assigned to one of three treatments: gap, thin, or control (Figure 1). The gap treatment involved complete removal of all trees in a circle 20 m in diameter in the center of the experimental unit (an average area of 314 m^2 per gap; 20% of trees, as determined by the pre-treatment stem map, but with post-treatment gap sizes somewhat variable). In the thinning treatment, the largest 40% of trees

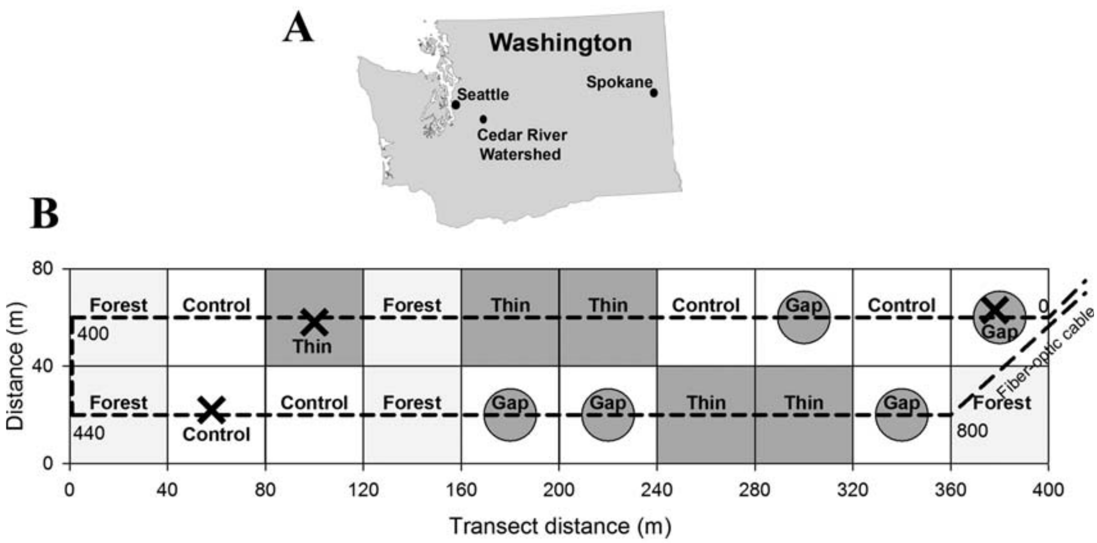

Figure 1. (A) The Cedar River Municipal Watershed is located in western Washington near Seattle. (B) The experimental design at Bear Creek comprises a block of forest 400 m × 80 m. The twenty 40 m × 40 m experimental units were classified into four forest types. Dark gray indicates tree removal, either in gaps or through thinning (see Methods). Both forest and control blocks were untreated. The pre-treatment structure and composition of control, gap, and thin treatments were similar in terms of species composition, basal area, and diameter distribution. The forest blocks were more heterogeneous. The × symbols indicate the location of the three meteorological stations, one in each of the gap, thin, and control blocks. The dotted line indicates the path of the fiber-optic cable. From the instrumentation trailer, the 1000 m fiber-optic cable enters the experimental unit at the upper right (fiber-optic cable length 0 m), traverses across the first row of experimental units (to fiber-optic cable length 400 m) then down to the second row of experimental units (to fiber-optic cable length 440 m) and then to the end of the experimental units. The effective length of the fiber-optic cable (760 m) was less than the full length (1000 m) because of the distance to the instrument trailer, the length of cable used for calibration, and the distance between transects. Vegetation data were recorded along 760 m of the fiber-optic cable, 400 m in the upper transect and 360 m in the lower transect.

(by basal area) were reserved, and the remaining trees were selected in small groups until 30% of the basal area was removed. No trees were removed in the control units. The five experimental units that were not sufficiently similar to be included in the randomized silvicultural treatments were retained as an additional untreated type (the 'forest' experimental unit type). Although there were no treatments in forest blocks, their different overstory and understory justified a separate classification. This forest experimental unit is representative of more heterogeneous (but still closed canopy) regenerating forest, whereas the control represents a more uniform secondary stand structure. In addition to the trees removed to implement the treatment, small yarding corridors were cleared between some of the units so that the logs and slash could be removed. After thinning, the stand was resurveyed to census those trees that were actually removed.

Equipment Installation

One meteorological station was installed in each treatment type. The meteorological stations included a temperature and humidity sensor (Vaisala HMP50-L11) installed approximately 2.5 m above ground level. An instrument height of 1.5 m above level ground is the reference height for instruments in the U.S. Climate Reference Network (NOAA 2002). We installed instrumentation at a slightly higher height to be able to measure temperature at the reference height during winter months when snowpack depth is about 1 m. Temperature accuracy of the HMP50-L11 is ±0.45 °C over the temperature range of 0 °C to 20 °C. Data were logged every 10 minutes (Campbell Scientific CR10X). The fiber-optic cable (BRUsens Temperature +85 °C; Brugg Cable International, Brugg, Switzerland) was installed along two transects in October 2009, running immediately adjacent to the meteorological towers (Figure 1). The fiber-optic cable was run along the ground surface (Figure 1), and held to the ground with landscaping staples. Where the cable would have passed over downed trees or coarse woody debris, the trees and debris were cut where possible so that the cable could be laid on the ground. To the extent possible, debris was placed back in its original position, on top of the cable. A Sensornet Oryx distributed temperature sensing (DTS) system (Sensornet, Elstree, United Kingdom) was installed in an equipment trailer and used to generate light pulses and measure the corresponding reflected spectra. The Oryx compares the ratio of anti-Stokes photons (higher frequency, shorter wavelength) and Stokes photons (lower frequency, longer wavelength) that are absorbed and reemitted as the light pulse comes into contact with the cable wall (Tyler et al. 2009). The ratio of anti-Stokes photons to Stokes photons follows a Boltzmann distribution proportional to the ambient temperature surrounding the fiber-optic cable (Selker et al. 2006b). Immediately after exiting the equipment trailer, the fiber-optic cable ran through two calibration baths, each containing 15 m of coiled fiber-optic cable submerged in a mixture of ice and water at 0 °C. The temperature of each calibration bath was measured with a thermocouple at the same interval as fiber-optic measurements (Tyler et al. 2009). The distributed temperature measuring system collected raw data at 1-m intervals (760 measurements) every 30 minutes, with each measurement averaged for 60 seconds. With post-measurement comparison to simultaneous thermocouple data (below), the distributed temperature measurement system is capable of ±0.1 °C repeatability (Tyler et al. 2009). We measured temperatures between 11 May 2010 and 21 June 2010 (42 days).

Data Reduction

The inferred temperatures from the fiber-optic cable were compared with the thermocouple temperatures in the two calibration baths, and the raw temperature data from the distributed temperature sensing system were adjusted to match the thermocouple data using a linear transformation.

For each treatment, we first examined the time structure of the temperatures recorded by the meteorological station and the fiber-optic cable. We compared temperatures every 30 minutes over the entire 42-day period. The meteorological station temperatures were compared against the fiber-optic cable temperatures where the cable passed the instrument tower (i.e., 2.5 m below the meteorological station temperature sensor). We then examined the spatial structure of temperature using the 760 measurement positions for the fiber-optic cable. In order to see a contrast between shaded portions of the forest floor and portions that were directly illuminated, we selected for comparison a sunny day early in the measurement period when sun angle was low. Using meteorological data from our Cedar River Watershed reference station, located in a clearing about 1 km from the experimental unit, as well as preliminary data from the fiber-optic cable, we selected a single clear and sunny day (14 of the 42 days were sunny—*May*: 12–17, and 19, *June*: 3, 5, 12–14, and 18) to compare the spatial variability of temperature within each treatment type. Sunny days provide the highest level of direct insolation to the forest floor and therefore could represent limiting conditions (Heithecker and Halpern 2007). We calculated the spatial variance of the temperatures from the fiber-optic cable in each of the treatment types as well as the surrounding, more heterogeneous 'forest' blocks using semivariance with lags of 1 m throughout the 40 m of each treatment type. The combination of the 1 m resolution of the fiber-optic cable (taken as a spatial average centered at 0.5 m and every 1 m thereafter) and the maximum semivariance of one-half the transect length in each treatment allowed us to examine semivariance between 1 m and 20 m.

We then compared the distributed temperature readings for the representative sunny day with the modeled forest floor light environment for that day using tRAYci, a spatially explicit light modeling program that calculates light attenuation through a forest canopy (Brunner 1998, 2004). Light models, if accurate, could serve as a proxy for temperature measurements. The tRAYci model considers the sun's transit across the sky and models canopy shape and foliage density from empirical data. The parameters to the tRAYci model were selected based on site data. The output of the tRAYci model is percent of above canopy light (PACL). Modeled light on the forest floor is partitioned into direct light and diffuse light, but there is no explicit modeling of cloudiness. For details of model input parameters, and canopy models, see Sprugel et al. (2009). The tRAYci light model considered trees explicitly removed for the treatments and also those removed for the yarding corridors. The tRAYci model considers both direct and indirect light, and models the hemisphere above each position on the forest floor in 5° × 5° sections. We calculated the spatial correlation of the temperatures and modeled light both at the 1 m quadrat scale and at the treatment scale using ANOVA.

Vegetation

Vegetation quadrats (1 m^2) were placed immediately upslope of the fiber-optic cable along the 760 m of its length in the experimental units. We sampled the understory vegetation (plants ≤ 1.37 m tall) in late-June 2010, and identified plants to species. *Abies amabilis* and *A. procera* were combined to genus, as first year seedlings could not be reliably differentiated. We calculated species richness per 1 m^2 quadrat. Taxa were classified as either forest or colonizer following Halpern (1988, 1989). To analyze the effects of temperature and the total amount of modeled light reaching the forest floor, we used linear quantile regression with $\tau = 0.95$ (Scharf et al. 1998, Cade et al. 1999, McKenzie et al. 2000, Cade and Noon 2003, Yu et al. 2003). Quantile regression allows one variable to be considered limiting, while recognizing that other, unmeasured variables are also important. We used the quantreg package version 4.54 (Koenker 2011) in R (version 2.12.0, R Core Development Team 2010).

Results

The temperatures recorded by the distributed fiber-optic sensing system followed a mostly linear relationship with the meteorological station throughout the 42-day measurement period (Table 1, Figure 2). Temperatures on the forest floor as measured by the distributed temperature measurement system were mostly moderated by their contact with the soil. However, ground surface temperatures in parts of the gap treatment were higher than the meteorological station temperatures (Figure 3). The relationship between temperature measurements was most uniform in the control, most variable in the gap, and intermediate in the thinned (Figure 3). The spatial structure of temperature varied considerably during the experimental period (Figure 4). The effect on temperature of the sun's path across the sky was clearly visible in the tree removal treatments on a clear and sunny day (Figure 5). In the two tree removal treatments (gap and thin), the fiber-optic cable recorded both higher and lower temperatures than the meteorological instruments. Night time temperatures were uniform among treatments for all instrumentation, with the fiber-optic cable reporting higher temperatures than the meteorological station (Figure 3).

The semivariogram analysis showed that points more than 5 m apart in both the gap and the thinning treatments had temperatures that differed by more than 2.6 °C during a sunny day (Figure 6). Temperatures of points within the thinning treatment continued to diverge up to the maximum separation testable by our study layout (19.5 m) (Figure 6). The semivariogram sill for daytime temperatures in the gap treatment was approximately 10 m, and the sill for the thin treatment was > 19.5 m (Figure 6). The more clearly defined sill for the gap than the thin treatment is consistent with the more clearly delineated spatial pattern of disturbance for the gap treatment. At night, temperature variance in all treatment types was very low (Figure 6).

Modeled forest floor light levels varied between 1.5 and 50.8 % of the above-canopy light (PACL). Four quadrats containing entire tree bases were modeled at 0 PACL even though the tree bole did not occupy the entire quadrat. The coefficient of variation of modeled light was 0.67, compared to the coefficient of variation of ground surface temperature, which was 0.20. The correlation at 1 m scale between the tRAYci total light (direct plus diffuse) and early afternoon temperature (14:24) on May 13, 2010 was 0.44 over all treatment types.

TABLE 1. Temperature statistics for thinned and unthinned forests in the Cedar River Watershed between 11 May 2010 and 21 June 2010. Temperatures were measured every 30 minutes at both the meteorological station (2.5 m height) and along the fiber-optic cable. Two values for fiber-optic derived temperatures are shown: the fiber-optic cable point measurement is for the location on the ground immediately below the meteorological station. The fiber-optic cable average reflects the average value for the 40 m of each experimental block. In the 42 day study period, 14 days were sunny—*May*: 12–17, and 19; *June*: 3, 5, 12–14, and 18.

	Temperature (°C)		
Experimental Unit	Mean (Std dev)	Minimum	Maximum
All days			
Control			
Meteorological station	7.75 (3.08)	1.05	16.97
Fiber-optic cable point	7.99 (2.31)	2.42	15.08
Fiber-optic cable average	8.01 (2.31)	2.25	17.34
Gap			
Meteorological station	7.98 (3.60)	0.89	21.89
Fiber-optic cable point	8.20 (2.99)	1.65	25.98
Fiber-optic cable average	8.25 (3.14)	1.55	32.79
Thin			
Meteorological station	7.84 (3.27)	0.92	18.08
Fiber-optic cable	8.32 (2.50)	2.44	18.38
Fiber-optic cable average	8.40 (2.72)	2.11	27.98
Sunny days			
Control			
Meteorological station	9.56 (3.63)	2.87	16.97
Fiber-optic cable point	9.28 (2.45)	4.30	15.08
Fiber-optic cable average	9.30 (2.46)	4.28	17.34
Gap			
Meteorological station	10.09 (4.62)	2.88	21.89
Fiber-optic cable point	9.65 (3.83)	3.82	25.98
Fiber-optic cable average	9.84 (4.05)	3.40	32.79
Thin			
Meteorological station	9.82 (3.92)	2.95	18.08
Fiber-optic cable point	9.69 (2.82)	4.59	18.38
Fiber-optic cable average	9.87 (3.22)	4.24	27.98

The one-way ANOVA test showed that light and temperature differed between treatments ($P < 0.001$ for both), but there was no significant relationship between light and temperature within treatments.

A total of 55 understory taxa occurred in the 760, 1 m^2 quadrats three years post-treatment. Three plants could not be identified and were dropped from analysis. Eight colonist species were found in a total of 35 quadrats. Mean species richness was 4.4 species per quadrat (range 0 to 16). Richness was highest in the forest type (6.4 species per quadrat), lowest in the control (3.6 species per quadrat), and similar in the thin (4.0 species per quadrat) and gap (4.2 species per quadrat) treatments. Quadrats with colonizer species averaged 27.5 PACL compared to 15.7 PACL in quadrats with only forest species. Species richness in the control and forest were different from all other treatments (*t*-test, $P < 0.001$). Thinning and gap creation increased diversity relative to the homogeneous control, even though diversity generally decreased with higher temperatures. Segmented regression at the 95th quantile showed that higher temperatures resulted in lower species richness (Figure 7A). However, the effect of temperature on richness declined as temperature increased. Segmented regression at the 95th quantile showed that species richness was highest at lower levels of modeled light (Figure 7B). However, both the highest and lowest levels of modeled light were associated with lower richness. As modeled by the 95th quantile regression, understory plant

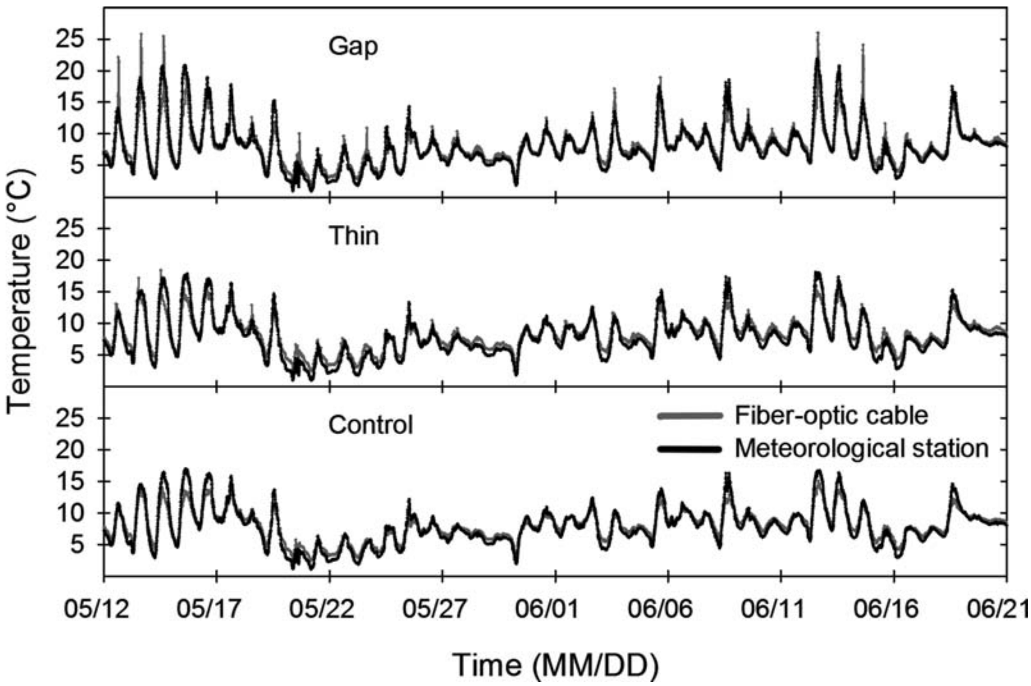

Figure 2. Temperature in gap (top), thin (middle), and control (bottom) treatments between 12 May and 21 June, 2010. The meteorological station recorded temperatures at a height of 2.5 m (black), and the fiber-optic cable recorded temperatures at ground level (gray). When the fiber-optic cable was directly illuminated by the sun, temperatures were higher than those recorded by the meteorological station. Otherwise, the fiber-optic cable recorded more moderated temperatures than the meteorological station, potentially due to the heat capacity of the generally wet ground surface.

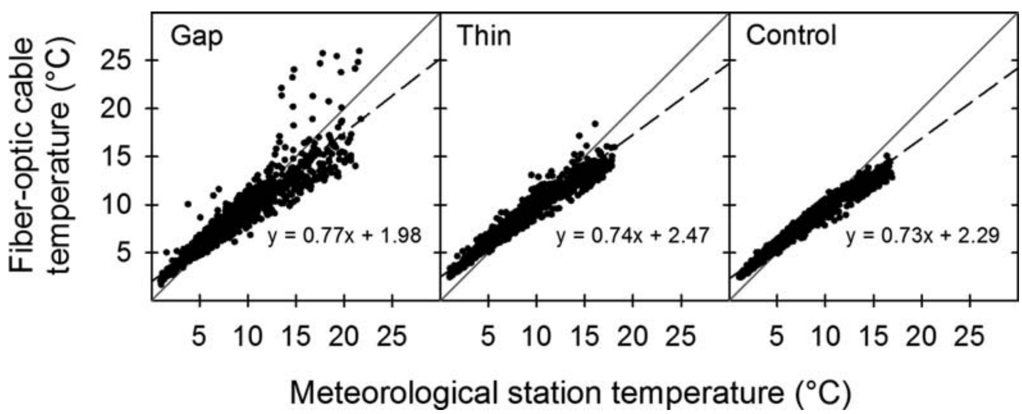

Figure 3. Simultaneous comparison of temperatures measured every 30 minutes with the meteorological station and the point on the fiber optic cable immediately adjacent to the meteorological station between 12 May and 21 June, 2010. The meteorological station recorded temperatures at a height of 2.5 m, and the fiber-optic cable recorded temperatures at ground level. Fiber-optic temperatures were moderated the most in the control treatment (slope = 0.73), followed by the thin (slope = 0.74) and the gap (slope = 0.77). Ground temperatures as measured by the distributed fiber-optic measurement system reached lesser extremes than the 2.5 m air temperature in the control treatment. In the gap and thin treatments, fiber-optic temperatures were generally less extreme than the 2.5 m air temperatures, except for points that lay above the 1:1 line, which are inferred to be those positions on the fiber-optic cable that were directly illuminated by the sun.

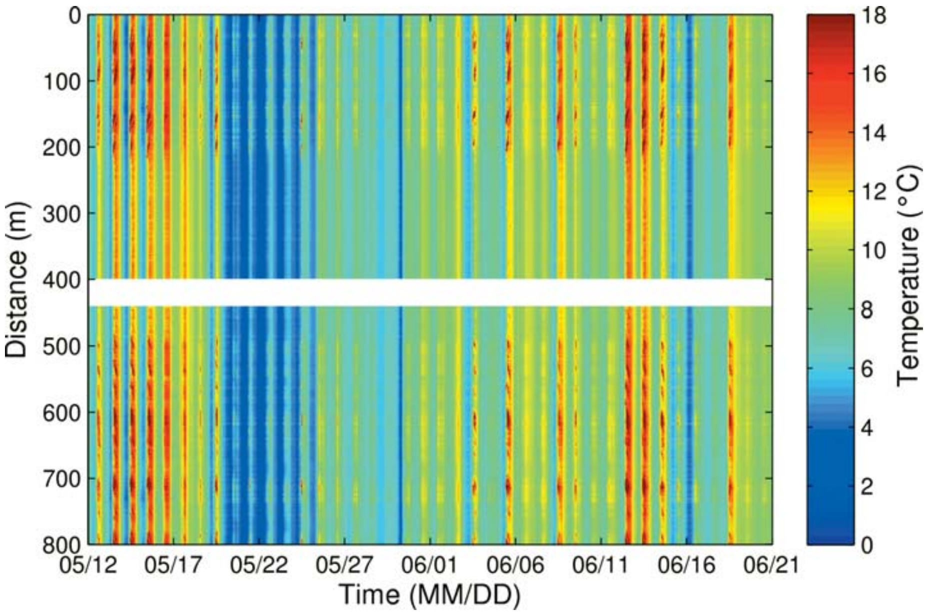

Figure 4. Temperature (°C) as a function of space (y axis, in m of cable) and time (x axis, days) between 12 May and 21 June, 2010. The y axis units match the transect diagram in Figure 1. The first 400 m represents the upper transect. The white space (400 m to 440 m) indicates the transition from the upper transect to the lower transect. And the fiber-optic cable length between 440 m and 800 m represents the lower transect. Clear, sunny days exhibit a greater temperature range and a higher level of spatial heterogeneity than cloudy days.

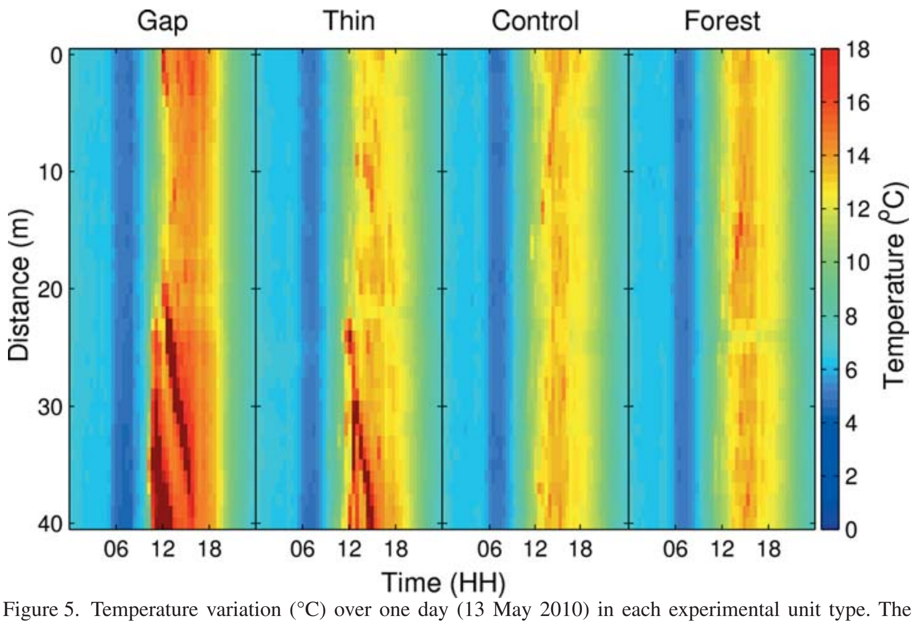

Figure 5. Temperature variation (°C) over one day (13 May 2010) in each experimental unit type. The diagonal pattern of high temperature in the gap and thin treatments shows the interaction of the sun's path with the remaining tree canopy. Horizontal bands of lower temperature extremes (e.g. forest treatment, 8 m) reflect the moderating effect of woody debris on the forest floor. Vertical bands of uniformly lower temperature during the day in all treatments (e.g. 17:00) are inferred to be periods of cloud cover. The four treatment blocks shown correspond to the gap, thin, and control blocks with the meteorological stations (marked in Figure 1). The forest block corresponds to the lower left experimental unit (fiber-optic cable length between 440 m and 480 m; Figure 1).

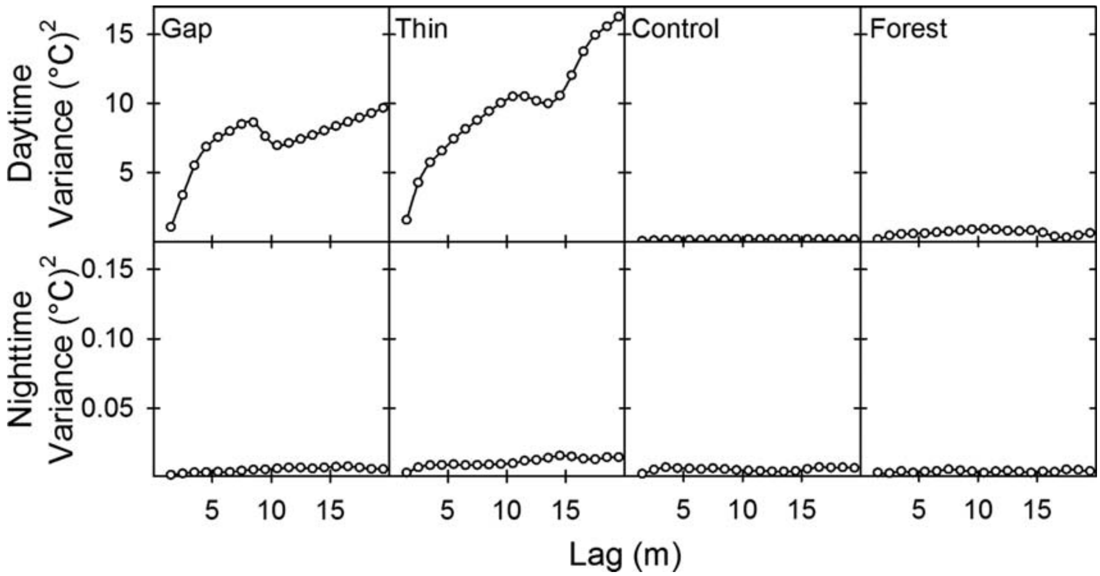

Figure 6. Semivariograms for the gap treatment, thin treatment, control, and forest blocks at 14:24 on 13 May 2010 and at 02:16 the same morning. Temperature is relatively uniform at night, but depends on canopy structure on sunny days.

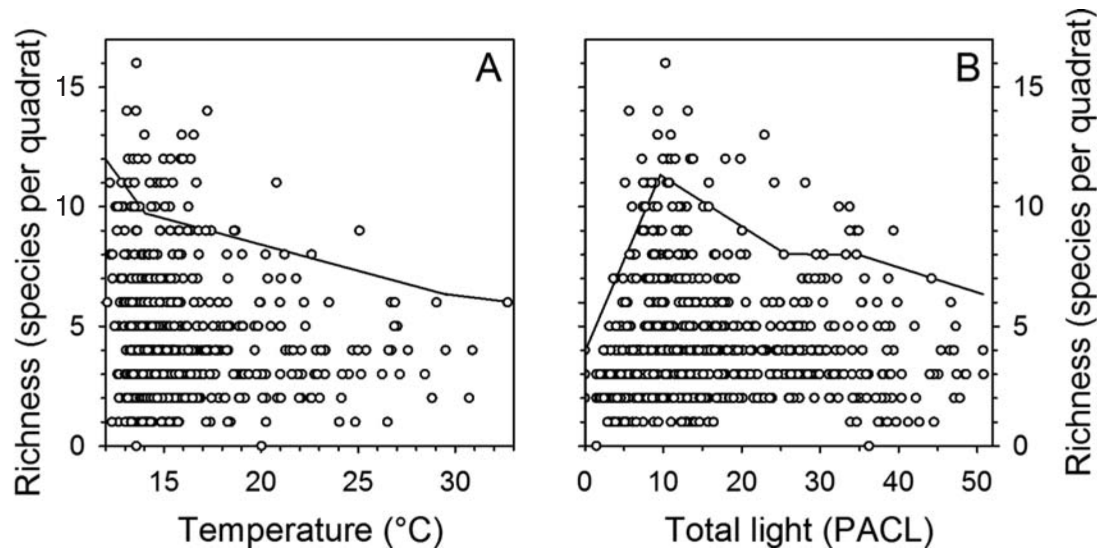

Figure 7. Relationships between species richness and 13 May 2010 temperature measured by the fiber-optic distributed temperature measurement system and forest floor light modeled with tRAYci. Afternoon (14:24) temperature (°C) and richness (species per quadrat) for 760 vegetation quadrats (A). Total modeled light from tRAYci simulation (percent of above-canopy light; PACL) and richness (species per quadrat) for 760 vegetation quadrats (B). Both lines are 95th quantile segmented regressions ($P < 0.001$).

species richness was 12 species per quadrat where the lowest daytime temperatures were measured, compared to 6 species per quadrat where the highest daytime temperatures were measured. The 95th quantile regression showed understory plant species richness highest at 10% of above-canopy light and lower at both lower and higher light levels.

Discussion

The comparison of the simultaneous temperatures recorded by the meteorological station and the distributed fiber-optic temperature sensing system is consistent with the relative positions of the sensors and direct lighting of the forest floor. The control treatment, with very little direct light (Sprugel et al. 2009), showed that the shaded fiber-optic cable on the ground records a similar mean but a lower standard deviation to 2.5 m air temperature. The cable measurement of surface temperature is 75% lower than the 2.5 m air temperature (73% control; 74% thin; 77% gap) when temperatures are above 9 °C (8.5 °C control; 9.5 °C thin; 8.6 °C gap) and correspondingly higher when temperatures are below 9 ° C (Figure 3). However, some cable data points recorded much higher temperatures than the meteorological station. We infer these to be locations that are directly lit by the sun for substantial portions of the day. The low variance in all treatments at night indicates that tree canopies attenuate incoming short-wave radiation much more than incoming long-wave radiation. Therefore, variance of incoming short-wave radiation is only important on sunny days, and if either high temperature or high levels of light are limiting understory plants in the spring, it is only on sunny days. The warmer nighttime ground surface temperatures (Figure 3) may be partially due to the wet forest floor environment. Compared to average years, the La Niña spring of 2010 was wetter and cloudier (436 mm of precipitation in May and June, compared to a 1971 – 2000 climate normal of 268 mm [PRISM 2011]). Combined with the extensive bryophyte cover, the ground surface surrounding the fiber-optic cable was wet during most, if not all, of the measurement period, except for those portions that were directly illuminated for long periods during sunny days. This water would have reduced nighttime ground surface cooling and also reduced daytime heating.

Once forest vegetation has grown into a closed canopy condition, temperature is relatively uniform during the day and night. In second-growth western coniferous forests, more heterogeneous forest (as determined by size structure, density, and species) does exhibit slightly more temperature variance than more uniform forest, but the differences in temperature seem too low to directly affect understory vegetation (Figure 6). Where the canopy has been removed, daytime temperatures have considerable variance in both space and time (Figure 5). While this experiment involved mechanical thinning of the forest, similar canopy gaps are caused by windthrow, snow damage, bark beetles, or pathogenic fungi (Lutz and Halpern 2006, Larson and Churchill 2008, Kane et al. 2011). Daytime temperatures vary on such small spatial scales in these situations that localized meteorological measurements would be needed to adequately characterize the physical environment that plants experience. Meter-scale variation in the light in gaps or thinned areas changes soil moisture (Gray et al. 2002, Griffith et al. 2010), with lower soil moisture decreasing survival of seedlings (Gray and Spies 1996). The high spatial variance of temperature in the gap and thin treatments (Figure 3) cannot be captured by a single meteorological station. The semivariogram (Figure 6) suggests that, in forests of this age and type, temperature measurements should be taken at regular intervals to capture temperatures relevant to vegetation (Figure 7). However, it is important to note that the distributed fiber-optic measurement system is recording a different temperature dynamic than a traditional meteorological station. At heights of 1 m to 3 m, meteorological stations measure air temperature, with the air being relatively well mixed and not subject to influence by meter-scale variation in ground surface moisture content (Lundquist and Cayan 2007). The distributed temperature measurement system records data very close to the actual surface temperature. It may be directly shaded by woody debris, moss, or understory vegetation and therefore may record a moderated temperature. However, these localized ground surface conditions may be more relevant to herbaceous vegetation than 2.5 m air temperature.

The modeled light environment along the cable did not match the measured temperatures as closely as expected. However, the tRAYci model makes several approximations about tree geometry (such as canopy shape and filled volume) that likely vary within individual trees. This within-tree variation could be giving rise to small sun flecks which are not modeled well by tRAYci or any other model that assumes regular canopy geometry. Accordingly, tRAYci modeling could differentiate among treatments, but not at the finer spatial scale within treatments. Importantly, the lack of a within treatment correlation between surface temperatures and modeled surface light in the closed canopy secondary forest suggests that undisturbed tree canopies may be too heterogeneous in geometry to model with simple canopy allometrics – the method used by tRAYci. The study area also has considerable microtopography (pits and mounds), and portions of the fiber-optic cable can be either shaded by the microtopography and woody debris, or alternatively, exposed to the sun at an angle. The generally low correlations between modeled light and surface temperature suggest that *in situ* measurements of environmental parameters are necessary to resolve the forest floor environment at meter scales (see also Sprugel et al. 2009 for limitations of the light model). Other factors, particularly soil moisture, likely influence understory species richness, and these factors likely vary interannually in ways that influence the perennial understory vegetation. The inconsistency between the coefficient of variation of modeled light and surface temperature suggests that modeled light cannot be used as a proxy for temperature.

High temperature and low light are both hypothesized to be limiting factors—higher temperatures increase water stress (Heithecker and Halpern 2007), but low light levels preclude photosynthesis (Boardman 1977). The analysis is complicated in that high light levels, which are beneficial for photosynthesis in the presence of sufficient water (Lutz et al. 2010), are often associated with higher temperatures that forest plants may not tolerate. Higher temperatures are associated with lower levels of overall species richness (Figure 7). However, nighttime temperatures did not differ, nor were they variable, so low temperature levels in May and June cannot explain differences in species richness in these plots (species richness may be limited by low temperatures at other times of the year). Low levels of modeled light (below 10 PACL) were associated with lower levels of species richness (Figure 7). High levels of light, although positively associated with some species (e.g., *Sambucus racemosa* [red elderberry]), were associated with lower levels of species richness, most likely due to higher temperatures and increased evaporation.

Forest environments can be problematic for long term meteorological measurements. In addition to the effects of the weather, and the microtopography of the ground surface, falling branches and uprooted trees can damage equipment on towers. Overcoming the barriers to fiber-optic measurement in forests requires additional logistical planning. Armored cable is heavy and bulky, and its installation in rough terrain is difficult (Figure 8). Fiber-optic cable laid flat on the ground is generally immune to damage from above, but an uprooted tree along the fiber-optic line or falling branches from above could break the cable. However, vertebrate damage probably constitutes the greatest risk to fiber-optic installations. Vertebrate volitional damage (e.g., *Ursus americanus* [American black bear] biting the

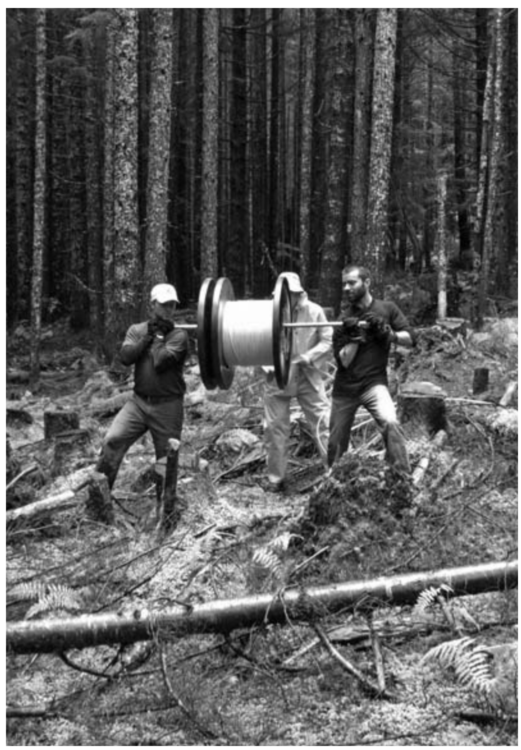

Figure 8. Installing the fiber-optic cable through a gap treatment. Photo: J. A. Lutz.

cable) is common to field installations of plastic items throughout the North American west. Inadvertent damage from elk (*Cervus canadensis*), deer (*Odocoileus* spp.), and bears tripping over the cable may also cause damage. Pinning the cable to the ground with landscaping staples appeared to keep animals from dragging the cable during the ten months the cable was installed, but did not prevent bear damage.

Temperature measurements with fiber-optic cable have the potential to provide more localized meteorological information for vegetation studies. Measurement is centralized, providing an efficient mechanism to collect temperature data once the cable is installed. The high spatial resolution measurements can be used to examine the scale of temperature variation present in a study area so that appropriate supplemental instrumentation can be installed. In this study area, the level of temperature heterogeneity did not require the full fiber-optic cable resolution of 1 m, but the 1-m resolution was necessary to quantify the variance. Understanding the temperature variation on the forest floor can potentially assist in studies of plant propagation and spread, structuring of understory plant communities, and the effects of natural disturbance or treatments.

Conclusions

Fiber-optic cable distributed temperature sensing is a potentially valuable tool for characterizing forest floor surface temperatures. Fiber-optic methods allow ground surface temperature to be characterized at spatial scales matching the size of understory plants. Ground surface temperature and canopy light transmission do limit species richness in regenerating forests, but other physical and biological factors must influence species richness as well.

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