Climate driven changes in Engelmann spruce stands at timberline in the La Sal Mountains

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INTRODUCTION

Due to global warming spruce-fir forest and associated vegetation may experience elevational displacement and altered species composition at the timberline-treeline ecotone. These forests and their component species are predicted to migrate upslope and thus landscape features such as timberline and treeline may move upslope as well. Prior to this study, baseline data on forest stand structure, plant species distributions, soil temperatures, and soil carbon pools did not exist across these habitats in the La Sal Mountains . This study will provide data that allows land managers, researchers, and conservationists to better assess the degree of change in and the resilience of these high elevation plant communities via repeated measurements to detect specific local change over time.

The study area was in the central high peaks of the La Sal Mountains in Grand and San Juan Counties in southeastern Utah (Fig. 1) and is managed by the USDA Forest Service, Manti-La Sal National Forest, Moab Ranger District. The study area was defined as the ridge just west of Mount Mellenthin (3854 m), below the peak known locally as Mt. Laurel where alpine and spruce-fir forest meet. The LaSal Mountains, created by igneous intrusions forming laccoliths into Permian and Cretaceous sedimentary formations and subsequent erosion of the sedimentary rocks, form the major peaks of Haystack Mountain, Mt. Tomasaki, Mt. Mellenthin, and Mt. Tuckuhnikivatz (Friedman and Huffman, 1997). The most abundant igneous rock is porphyritic diorite, sometimes called trachyte, with phenocrysts of hornblende and plagioclase. Our study site consists of two soils derived from the pophyritic diorite. The soils are Meredith stony loam (20-70% slopes above timberline) and Leighcan cobbly loam (50-70 % slopes below timberline). The Meredith series is classified as a loamy-skeletal, isotic Spodic Humicryepts, while the Leighcan series is a loamy-skeletal, mixed, superactive Typic Dystrocryepts.

Data from this La Sal Mountains site will be added to an existing network of ten high elevation sites which focuses on small, relatively pure Engelmann spruce stands at the top of Southwest Sky Island, Colorado Plateau, and Rocky Mountain peaks. Our design samples a mean annual temperature / latitudinal gradient across the West from the Southern Rocky Mountains in Wyoming to the Sky Islands of southeastern Arizona. We have an established a network of ten sites across this regional gradient and, including the La Sal site, now have data from six of them. A La Sal Mountain timberline site adds a significant geographic component to our network since, at 38°N latitude, it fills the latitudinal gap between the San Juans (37°N) and the main part of the Southern Rocky Mountains (39°N). In a climate change context, timberline-treeline elevation may not change uniformly across the western US over time, and the La Sals would be the westernmost site in our network.

Specific aims of this research were to: 1) collect baseline data to detect climate change effects and to determine stand and biodiversity resilience, 2) collect comparative data along a mean annual temperature/latitudinal gradient to determine possible future trajectories of climate change effects, 3) Detect presence of endemic, exotic, and USFS sensitive plant species near and within insular Engelmann spruce stands at each site.

Methods and Materials

The week of July 18, 2011, we collected tree stem map data with a crew of four people. A 20 m x 250 m belt transect was placed from an alpine meadow patch within the treeline ecotone along a line perpendicular to the topographic contour lines through timberline into the conifer forest (Fig. 6). Placement of this transect was determined from one meter resolution satellite imagery overlain by topographic contour lines within ArcMap™ 10 based on visual timberline/treeline criteria from Körner (1998). These criteria define timberline as the climate-driven upper limit of relatively closed forest and define the treeline ecotone as starting at timberline where the closed forest begins to fragment into large patches and extending upslope to treeline, the general upper limit of small patches of a few arborescent trees (upright, and >3 m height). Krummholz trees, shrubby growth form trees shorter than 3 m (Arno and Hammerly 1984), are located above the treeline ecotone. Thus the treeline ecotone is a mosaic of forest fragments and alpine meadow patches.

For all conifer trees ≥1.4 m height, we recorded their geographic position and elevation in meters as UTM coordinates using NAD 83 projection and height above ellipsoid, respectively, with a Trimble® Geo XH GPS using their TerraSync™ 4.0 software and Zephyr™ external antenna. Offset capabilities within TerraSync allowed us to stand in locations with good GPS reception while measuring the offset (horizontal azimuth, vertical angle, and distance) to individual trees using a laser rangefinder (TruePulse™ 360° B). Tree height, diameter at breast height (dbh), and species were also recorded for each tree. Post processing of the initial spatial data with Trimble® Pathfinder Office using three or more base stations allowed differential correction of each tree position, ± 30-50 cm for most trees. A stem map was created in ArcMap™ 10 using this corrected data.

The centerline of the 20 m x 250 m transect was used to sample soil surface temperatures, soil chemistry, tree regeneration, and vegetation. Spatial location of all sampling points was recorded using the same Trimble® GPS protocols noted above. Soil surface temperature sensors, Maxim™ iButtons Thermochron DS1921G, were placed at 50 m intervals on the mineral soil surface under clumps of perennial herbaceous plants (Fig. 7) or under forest litter to prevent direct solar heating. These iButtons were set to record temperature at one hour intervals (± 0.5° C) from July 19 - September 19, 2011. Air temperatures from the pre-Laurel weather station were downloaded from the MesoWest web site (http://mesowest.utah.edu) maintained by the University of Utah. Data collection for the pre-Laurel weather station was provided by the Friends of the La Sal Avalanche Center. Circular tree regeneration plots with a 5 m radius were located at 20 m intervals along the transect. Counts were recorded for all trees < 1.4 m height by species in 1-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, 80-100 cm, 100-120 cm, and 120-140 cm height classes. Vascular plant species composition was sampled using a 1 m x 1 m sampling frame placed at 20 m intervals along the centerline transect Fig.4). Within each sampling frame, each plant species was identified and recorded as present. Specimens of unknown plants were collected outside the frame and numbered for later identification in the RMRS herbarium.

Soils baseline data include pH, total mineral soil carbon (C) and nitrogen (N), and labile soil organic C (SOC). Mineral soil was randomly collected within 1 m of each sampling point to a depth of 10 cm using a soil probe (Fig.5) or a small trowel due to the very stony nature of the soil, placed in polyethylene bags, then transported back to the laboratory. All samples were stored in insulated containers with ice to reduce activity during transport. Soil pH was determined using a glass electrode immersed in a 1:5 soil/0.01 M CaCl2 solution (Hendershot et al. 1993) using a Orion 550A pH meter (Thermo Fisher Scientific, Inc., Waltham, Massachusetts, USA). Analysis of total C and N in the upper 10 cm of mineral soil was done on uniformly mixed subsamples that had been air-dried and sieved to 2 mm or less. Dried subsamples were ground (< 0.149 mm dia.), then analyzed on a commercially available C/N analyzer (Flash EA 1112, CE Elantech, Lakewood, New Jersey, USA). SOC, the primary element of soil organic matter (SOM), is the most commonly measured indicator of soil decomposability (Wander and Drinkwater, 2000). There are several laboratory methods of measuring the labile fraction of SOC, yet most are time consuming and complex. With this in mind we chose soluble carbon, a relatively fast, non-toxic, and cost effective method of measuring labile SOC. This method utilizes slightly alkaline 2.5 mM KMnO4 to hydrolyze and oxide simple carbohydrates, amino acids, amine/amide sugars, and C-compounds containing hydroxyl, ketone, carboxyl, double-bond linkages and aliphatic compounds (Weil et al., 2003). The intense purple color of the potassium permanganate is neutralized with increased oxidation, which is then quantified using spectrophotometer at 550 nm wavelength.

Statistical analysis was performed using SAS/STAT® 9.2 (2008). Cluster analysis was performed to identify habitat groups by using SAS PROC Cluster with the complete linkage clustering method. Prior to clustering, the Jacaard index (Krebs 1989) was calculated to assign similarity between all pairs of vegetation sampling points. The linear regression model of the tree height - elevation relationship used Proc REG. Graphs were prepared using SAS/ GRAPH® 9.2 (2008).

RESULTS

In July 2011, we mapped the location of all trees ≥ 1.4 m height (n=350) along a 20 m x 250 m belt transect (Fig. 6) which included treeline ecotone and Engelmann spruce-subalpine fir (*Picea engelmannii-Abies bifolia*) forest habitats. These trees had an average height of 6.6 m and an average diameter at breast height (dbh) of 14 cm. The stem map (Fig. 6) shows that the relatively closed forest starts to fragment into more isolated clumps of trees at 3419-3420 m elevation. We defined a 60 m x 20 m block above 3420 m as treeline ecotone for further comparison with two similar sized forested blocks downslope along the same transect. Starting at timberline, 3420 m, tree density in the upslope treeline ecotone block is approximately one half that of the two forested blocks (Table 1). Average dbh was similar between treeline and forested blocks, but for trees ≥ 40 cm dbh, tree height shows a significant downward trend as elevation increases, ($H_0 \neq 0$, $t_{(0.05,1)}=-5.94$, $p<0.001$, $r^2=0.52$). Basal area, total cross-sectional area for all trees ≥5 cm dbh, also decreases with elevation. Density estimates for forest tree regeneration (0-140 cm height) were much lower in the treeline block than in the forested blocks.

Comparisons between Engelmann spruce and subalpine fir among the blocks revealed similar downward trends for basal area with increasing elevation (Table 2), but most of the basal area for all blocks is due to Engelmann spruce. Regeneration density estimates are much lower in the treeline blocks for both species. Subalpine fir shows a downward trend with increasing elevation for tree density, average height, and dbh as well. However, Engelmann spruce has the highest tree density, along with shorter, smaller dbh trees, in the upper forested block compared to the adjacent treeline and lower forested blocks.

The sharp differences between forest and treeline blocks are also reflected in growing season mineral soil surface temperatures (Table 3). We were able to find six of the seven iButtons we deployed in July but only five of those gave useful growing season data. The treeline habitat temperature sensors were placed under herbaceous plants and had average temperatures of 11.8° - 12.0° C, similar to the average growing season temperature of the USFS weather station soil temperature sensor at 11.0° C (Table 3). Both were over 4° C higher than average temperatures for sensors placed under tree litter in the forested blocks. However, July temperatures for the two forested blocks remained above 5° C whereas soil surface temperatures for the treeline ecotone and weather station occasionally dipped below 5° C (Figs. 3, 4, and 5). Hourly temperatures measured on the soil surface at the weather station generally followed the pattern of weather station air temperatures but showed much more variation (Fig. 8). The air temperatures did not go below 5° C until Sept 6, but the soil surface temperatures occasionally dipped below 5° C during the entire measurement period, July 20 - Sept. 18.

Total C of mineral soil (0-10 cm) was quite variable with a mean of 5.7% ±1.0, while total N was highest at the weatherstation and lowest below timberline (Table 3.) The carbon:nitrogen mass ratio (C:N) of the mineral soil (0-10 cm) ranged from highest below timberline to lowest in the treeline ecotone and weatherstation sample points (Table 3). The higher elevation sample points tend to have higher more neutral pH values, while pH decreased with increasing tree density. The amount of labile SOC, a very small portion of the total soil carbon pool, was quite similar among all sampling points (Table 3).

We found a total of 47 herbaceous vascular plant species on the 13 sample points along the 250 m timberline transect (Table 4). Within each block, species richness ranged from 14-28 species. Cluster analysis of herbaceous plant species composition within each one m^2 sampling frame revealed a pattern that matches the habitat blocks determined by tree density. The treeline ecotone and the forested blocks separated into distinct clusters (Fig. 9). Species richness for the treeline habitat was 37, and there were 34 species in the forest habitat. The upper cluster includes species common in alpine meadow habitats such as *Carex elynoides* and *Erigeron grandiflorus*. The lower cluster had species which occur more often in forest habitats such as *Mertensia ciliata* and *Carex rossii*. For plant species that occurred in five or more sampling frames (frequency of occurrence > 0.38), habitat affinities were assigned (Table 4). Seven species were most frequently found in the treeline ecotone habitats but only *C. rossii* most frequently occurred in the forest habitats. Eight additional species showed no habitat affinity.

We did not find any USFWS Threatened or Endangered species during sampling along the timberline transect. Abajo Peak draba (*Draba abajoensis*), a newly described species and March 2010 addition to the USFS sensitive plant species list, was encountered in the forest and treeline ecotone habitats. Its distribution has not been well-documented on the La Sal Mountains. The only exotic plant species in these samples was the common dandelion, *Taraxacum officinale*

(Table 4).

DISCUSSION and CONCLUSIONS

The clear differences in tree density and tree height between the treeline ecotone and forest blocks (Tables 1 & 2) suggest a definitive measurement technique to define timberline location. Using a sample scale of 1000 m^2, timberline is when the mostly closed forest starts to fragment into large patches of trees and the stem density drops by one half. Thus a density measurement quantifies what the eye perceives. This change in tree density is matched by a much larger drop in regeneration size (< 1.4 m height) tree density (Table 1) across timberline, especially in subalpine fir (Table 2). The reduction in average tree height may be a result of a greater number of 1.4 - 2.5 m tree heights as well as shorter dominant trees. Arno and Hamerly (1984) mention the occassional occurrence of relative short Engelmann spruce with very large diameters at timberline. Large patches of meadow vegetation are interspersed within the treeline ecotone, reflecting the shift from closed forest to gradually more open habitats.

Analysis of the 0-10 cm mineral soil layer along the timberline transect at the west end of Mt. Laurel ridge demonstrates how biomass inputs determine soil organic matter decomposability. Tree needles, roots, twigs, and coarse woody debris from forest sampling points contain greater concentrations of recalcitrant organic matter than the treeline and weatherstation points, which reflect the herbaceous cover and greater fine root biomass at these points. The higher pH with elevation (Table 3), along with lower C:N indicates potential for faster decomposition and nutrient cycling. An observable feature reflecting these differences in decomposition is greater surface organic matter within the forest sites. This increase in total carbon mass is correspondent with an increase in litter and the soil C:N ratio which often results in slower mineralization of N, typically the most limiting of plant nutrients. Decomposition and mineralization rates are greatly influenced by N concentrations of litter inputs. As the C:N ratio increases, microorganisms will utilize available soil N during decomposition, which reduces plant available N (Bardgett 2005). The implications for our sites are that treeline and alpine meadow sites have less N limitation compared to the forest sites during the growing season. Our last measure of soil chemistry is the soluble soil C, which did not show a trend, but greatly adds to the larger climate change database. We believe that soluble soil C is the most sensitive indicator of chemical and biological changes to mineral soil over time.

The growing season soil surface temperatures within the closed forest blocks (Table 3) are much lower at 6.7-7.7° C than the more open treeline habitat at 11.8-12° C. This shows the influence of the forest canopy and forest litter in preventing direct solar heating of the forest soil. Treeline ecotone soils receive more direct solar radiation due to reduced canopy height, thinner litter layers, as well as occasional bare patches. Counterintuitive as it may seem, the lower elevation forest soil temperatures are colder than the higher elevation forest ecotone and alpine meadow habitats.

There is a growing body of evidence that on a worldwide scale, treeline may occur at average growing season soil temperatures of 5.4 - 7.4° C (Hoch and Körner 2011). Our results at Mt. Laurel ridge match this fairly well (Table 3). Our temperatures are from the lower edge of treeline ecotone just above timberline rather than Hoch and Körner's (2011) upper treeline edge, and they do not capture the entire growing season. Our treeline ecotone temperatures were also taken in herbaceous plant patches rather than Hoch and Körner's (2011) forest patches. However, the temperatures we have are strikingly similar to the above worldwide pattern. Future measurements in the treeline ecotone will match Hoch and Körner's protocol in order to have a direct comparison.

Hoch and Körner (2011) have also hypothesized that treeline location is governed by temperature since xylem (woody) growth is thought to stop below 4-5° C (Rossi et al. 2008). We have included a 5° C reference line in Figs. 3-5 to indicate that apical meristematic growth and stem tip elongation may be sensitive to the occasional dips below the 5° C line at the weather station and in the treeline ecotone habitat during July. This is a possible explanation for treeline location on Mt. Laurel ridge. Note that within the forest habitat (Fig. 7), July temperatures do not drop below the reference line. The growth limitation treeline location hypothesis is an alternative to more long-standing hypotheses involving stress from frost damage, wind and ice blasting, reproductive failure, and carbon balance. We will continue to test the growth/temperature hypothesis as we analyze the other data sets in our Engelmann spruce network.

FUTURE RESEARCH NEEDS

The most immediate need for research on the Mt. Laurel ridge timberline transect is better soil temperature measurements within the treeline ecotone. We had three iButtons in this block but were only able to retrieve two. Both were in open meadow habitats as determined by our original design of 50 m spacing along the timberline transect. We plan to place iButtons within the forest patches in the treeline ecotone in the future and move upslope to capture soil temperature data from the upper edge of treeline. We predict that the forest patch temperature results will match the closed forest temperature more closely than the open herbaceous patches. This would be by paired samples (n=5) at the same adjacent elevation. In addition, we plan to place more iButton temperature sensors in the alpine meadow above treeline since we have only the weather station soil temperature results to characterize that habitat.

On a longer time scale, we would like to re-sample the tree and vegetation parameters on this site at 5 year intervals in order to detect actual change. We would also like to add compoents to the timberline tranesct to include: soil microbial diversity and biomass, both ecto- and arbuscular mycorrhizal population associations, and Engelmann spruce population age structure/fire history. The Mt. Laurel site has provided an excellent case study on multiple aspects of the treeline/timberline ecotone: soil temperatures, soil carbon pools, tree density and height, plant species richness and composition, and forest stand structure. This study will guide our analysis of data from five other sites in WY, CO, NM, and AZ and allow the integration of data to answer regional scale ecological questions on treeline/timberline definition, cause, and possible future migration.

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Table 1. Stand structure table for the timberline transect at the west end of Mt. Laurel ridge, La Sal Mountains, Utah. Timberline is at 3419-3420 meters elevation, separating a treeline block of 20 m x 60 m from two forest blocks of the same size along the downslope end of the 250 m transect. Density and species composition are for all stems ≥1.4 m in height. Regeneration is stems < 1.4 m in height. Mean height (ht), diameter at breast height (dbh), and basal area are for stems ≥5 cm dbh.

Stand characteristic	treeline block 3420-3441 m el.	forest block 1 3399-3419 m el.	forest block 2 3378-3398 m el.
Density - stems / h	558	1092	1258
Regeneration - stems / h	255	6112	6366
Mean ht m	7.7	8.4	10.8
Mean dbh cm	21	19	22
Basal area m^2 / h	17.761	37.408	53.759

Table 2. Species level stand structure for data from table 1, subalpine fir and Engelmann spruce, on the timberline transect at the west end of Mt. Laurel ridge, La Sal Mountains, Utah. Timberline is at 3419-3420 meters elevation, separating a treeline block of 20 m x 60 m from two forest blocks of the same size along the downslope end of the 250 m transect. Density and species composition are for all stems ≥1.4 m in height. Regeneration is stems < 1.4 m in height. Mean height (ht), diameter at breast height (dbh), and basal area are for stems ≥5 cm dbh.

Stand characteristic	treeline block 2 3420-3441 m el.	forest block 1 3399-3419 m el.	forest block 2 3378-3398 m el.
Density - Fir stems / h	350	583	933
Fir regeneration - stems / h	0	1528	4202
Fir % composition	63	53	74
Fir mean ht m	5.6	7.5	9.1
Fir mean dbh cm	11	14	15
Fir basal area m^2 / h	1.918	9.168	15.134
Density - spruce stems / h	208	508	325
Spruce regeneration - stems / h	254	4584	2164
Spruce % composition	37	47	26
Spruce mean ht m	9.6	9.4	15.8
Spruce mean dbh cm	31	24	43
Spruce basal area m^2 / h	15.842	28.240	38.625

Table 3. Comparison of study site variables by plant habitat blocks along the 250 m timberline transect at the west end of Mt. Laurel ridge, La Sal Mountains, Utah. Habitats are of similar sized blocks and were defined by tree density measurements. Treeline block 1 is an open patch whereas treeline block 2 has both open and forest patches. Soil surface temperatures are the mean of 1470+ readings at one hour intervals within each habitat from July 18 to September 19, 2011. Plant species richness are the total number of occurrences from three 1 m^2 systematic samples along the transect centerline within each habitat. Soil chemistry measurements are from composite samples taken from the 0-10 cm layer of mineral soil.

Study site variables	weather station	treeline block 1	treeline block 2	forest block 1	forest block 2
Elevation m	3557	3442-3456	3420-3441	3399-3419	3378-3398
Soil surface temperature °C	11.0	11.8	12.0	6.7	7.7
Species richness	na	27	28	27	14
Soil nitrogen %	0.63	0.44	0.28	0.41	0.30
Soil carbon %	6.89	5.31	3.88	6.83	6.40
C:N ratio	10.83	13.01	14.26	16.41	21.38
Soluble carbon %	0.0204	0.0197	0.0199	0.0177	0.0196
pH	5.23	5.18	4.79	4.98	4.91

Table 4. Vascular plant species list for the timberline transect at the west end of Mt. Laurel ridge, La Sal mountains, Utah showing frequency of occurrence (freq) and habitat affinity: t = treeline ecotone, f = forest. Species richness = 47.

Family Species	treeline ecotone freq	forest freq	total freq	habitat affinity
Apiaceae				
Cymopterus lemmonii	1.0	0.2	0.6	t
Osmorhiza depauperata	0.3	0.0	0.2	
Asteraceae				
Achillea millefolium	1.0	0.5	0.8	tf
Arnica cordifolia	0.0	0.5	0.2	
Artemisia pattersonii	0.3	0.2	0.2	
Erigeron grandiflorus	0.9	0.2	0.5	t
Hymenoxys hoopesii	0.4	0.3	0.4	tf
Senecio crassulus	0.4	0.7	0.5	tf
Solidago multiradiata	0.7	0.2	0.5	t
Taraxacum officinale	0.3	0.0	0.2	
Boraginaceae				
Mertensia ciliata	0.3	0.5	0.4	tf
Brassicaceae				
Boechera stricta	0.3	0.0	0.2	
Draba abajoensis	0.7	0.7	0.7	tf
Noccaea fendleri	0.9	0.0	0.5	t
Caryophyllaceae				
Eremagone fendleri	0.4	0.2	0.3	
Minuartia obtusiloba	0.1	0.0	0.1	
Crassulaceae				
Sedum lanceolatum	0.4	0.0	0.2	
Cyperaceae				
Carex calciolepis	0.1	0.0	0.1	
Carex elynoides	0.9	0.0	0.5	t
Carex nigricans	0.1	0.2	0.2	
Carex nova	0.1	0.0	0.1	
Carex phaeocephala	0.1	0.2	0.2	
Carex rossii	0.3	0.7	0.5	f
Carex scirpoidea	0.0	0.2	0.1	
Luzula parviflora	0.0	0.1	0.1	
Luzula spicata	0.1	0.0	0.1	
Fabaceae				
Thermopsis rhombifolia	0.1	0.0	0.1	
Trifolium dasyphyllum	0.7	0.2	0.5	t

Trifolium parryi	0.0	0.3	0.2	
Gentianaceae				
Gentiana parryi	0.4	0.2	0.3	
Geraniaceae				
Geranium caespitosum	0.0	0.2	0.1	
Grossulariaceae				
Ribes montigenum	0.0	0.3	0.2	
Poaceae				
Bromus ciliatus	0.6	0.2	0.4	t
Bromus lanatipes	0.1	0.2	0.2	
Elymus trachycaulus	0.3	0.0	0.2	
Poa abbreviata	0.1	0.0	0.1	
Poa glauca glauca	0.6	0.5	0.5	tf
Poa reflexa	0.0	0.5	0.2	
Poa secunda juncifolia	0.0	0.3	0.2	
Polemoniaceae				
Polemonium pulcherrimum	0.0	0.5	0.2	
Primulaceae				
Androsace septentrionalis	0.4	0.2	0.3	
Rosaceae				
Fragaria virginiana	0.1	0.3	0.2	
Geum rossii turbinatum	0.4	0.2	0.3	
Potentilla diversifolia	0.7	0.3	0.5	tf
Potentilla gracilis	0.1	0.0	0.1	
Sibbaldia procumbens	0.4	0.7	0.5	tf
Saxifragaceae				
Saxifraga rhomboidea	0.1	0.0	0.1	

Figure captions

Figure 1. Study area map of the La Sal Mountains in southeastern Utah.

Figure 2. Timberline transect indicated by the white tapeline on Mt. Laurel Ridge, La Sal Mountains. Photo shows treeline ecotone with patches of forest within the herbaceous meadow vegetation.

Figure 3. Temperature sensor (iButton) placement at mineral soil surface; iButton was slid under the *Carex elynoides* plant to the right, above the screwdriver tip.

Figure 4. Vegetation composition sampling frame (1 m x 1 m) centered on the transect centerline. There were 15 species in this sample.

Figure 5. Soil sampling probe with soil collected along the timberline transect.

Figure 6. Stem map of 350 Engelmann spruce - subalpine fir trees along a 20 x 250 m belt transect through the treeline ecotone into the forest below timberline. Coordinates are in meters using a UTM zone 12 projection. The size of the bubbles is proportional to tree height, and elevation increases toward the right side of the graph. The two larger bubbles near Easting 129020 are the location of timberline at 3420 m elevation.

Figure 7. Hourly soil surface temperatures from two sites in the Engelmann spruce - subalpine fir forest blocks on Mt. Laurel ridge from July 20, 2011 to September 18, 2011. Data shown as dots and joined by a line are 15 m higher in elevation than the site represented by square symbols. The vertical reference line at 5° C may represent a conifer growth limitation temperature. The strong temperature drop on August 26 shows the passage of a strong cold front between 3-4 PM.

Figure 8. Hourly soil surface temperatures from the upper and lower edges of the treeline ecotone block on Mt. Laurel ridge from July 20, 2011 to September 18, 2011. Data shown as dots and joined by a line are 18 m higher in elevation than the lower edge shown by squares. The vertical reference line at 5° C may represent a conifer growth limitation temperature. Passage of a cold front on August 26 is less noticeable but actually had a greater temperature drop than in Fig. 7.

Figure 9. Hourly air and soil surface temperatures from the USFS weather station at elevation 3557 m on Mt. Laurel ridge from July 20, 2011 to September 18, 2011. Data shown as dots and joined by a line are air temperatures. Soil surface temperatures are more variable and are shown by square symbols. The vertical reference line at 5° C may represent a conifer growth limitation temperature.

Figure 10. Cluster tree for species composition for 13 sample points along the timberline transect on Mt. Laurel ridge. The upper cluster (observations 1-6) are from the treeline ecotone block and adjacent alpine meadow patch. The lower cluster (observations 7-13) are from the spruce-fir forest blocks.

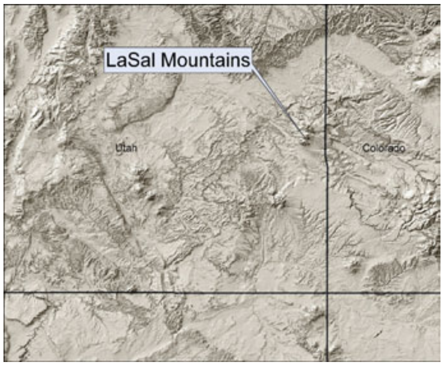


Figure 1. Study area map of the La Sal Mountains in southeastern Utah.

Figure 2. Timberline transect indicated by the white tapeline on Mt. Laurel Ridge, La Sal Mountains. Photo shows treeline ecotone with patches of forest within the herbaceous meadow vegetation.

Figure 3. Temperature sensor (iButton) placement at mineral soil surface; iButton was slid under the *Carex elynoides* plant to the right, above the screwdriver tip.

Figure 4. Vegetation composition sampling frame (1 m x 1 m) centered on the transect centerline. There were 15 species in this sample.

Figure 5. Soil sampling probe with soil collected along the timberline transect.

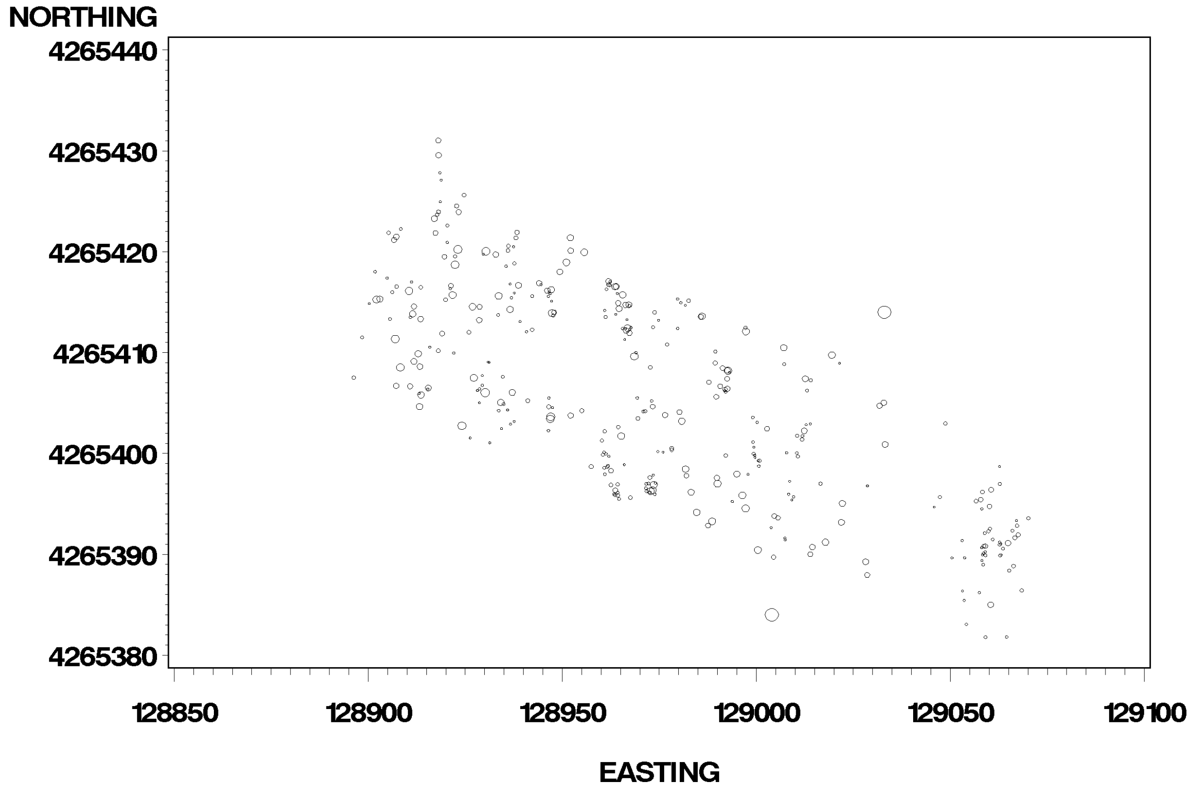


Figure 6. Stem map of 350 Engelmann spruce - subalpine fir trees along a 20 x 250 m belt transect through the treeline ecotone into the forest below timberline. Coordinates are in meters using a UTM zone 12 projection. The size of the bubbles is proportional to tree height, and elevation increases toward the right side of the graph. The two larger bubbles near Easting 129020 are the location of timberline at 3420 m elevation.

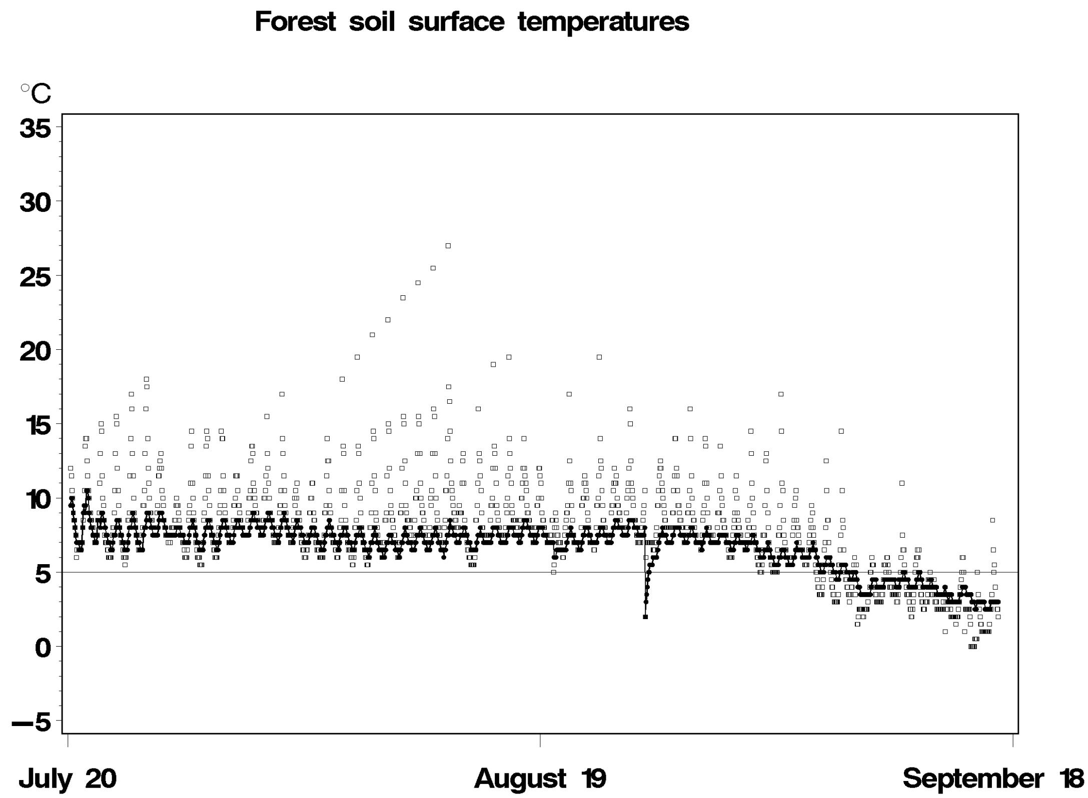
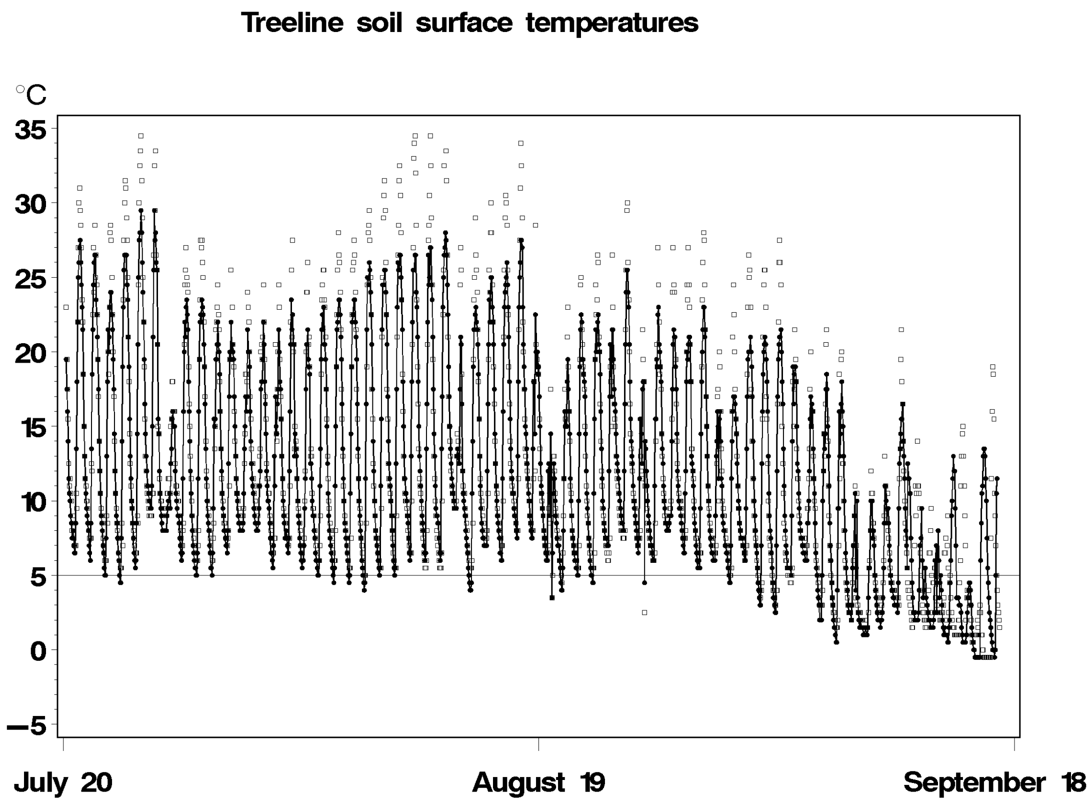


Figure 7. Hourly soil surface temperatures from two sites in the Engelmann spruce - subalpine fir forest blocks on Mt. Laurel ridge from July 20, 2011 to September 18, 2011. Data shown as dots and joined by a line are 15 m higher in elevation than the site represented by square symbols. The vertical reference line at 5° C may represent a conifer growth limitation temperature. The strong temperature drop on August 26 shows the passage of a strong cold front between 3-4 PM.



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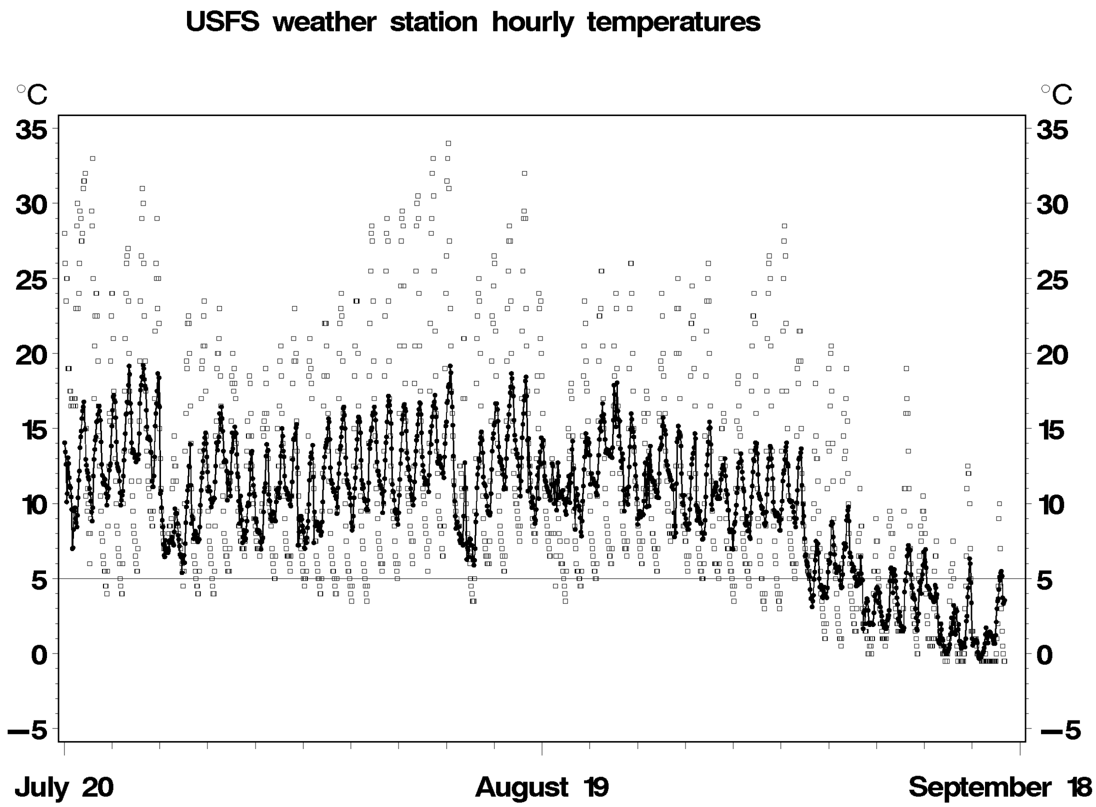

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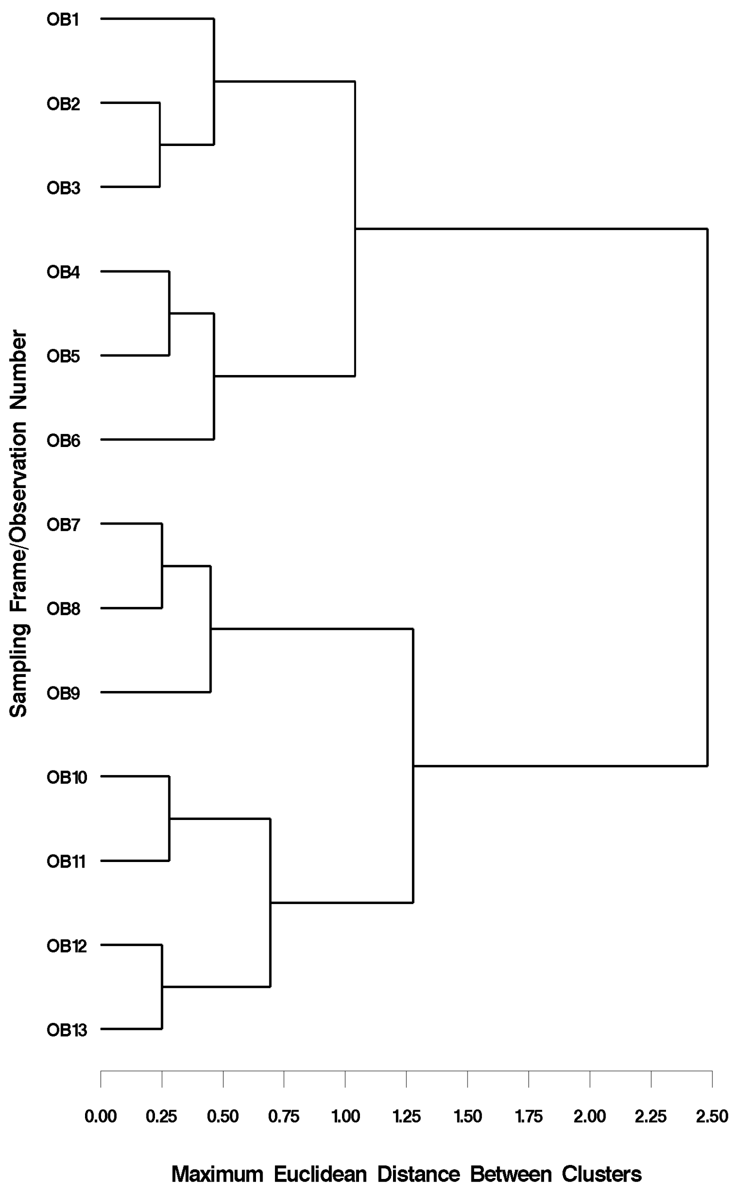

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