<u>**A GIS model for locating climatically sensitive trees in northern Utah**</u>

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Introduction

The objective of this project is to create a GIS model to predict likely locations of climatically sensitive Douglas-fir which can be used to reconstruct flows of the Logan River, Utah. This model will provide dendrochronologists with a tool to help with site selection and sampling strategy. Presently, site selection is conducted by spending several hours looking at topographic maps, aerial and satellite imagery, and driving or hiking to scout potential sample sites. Site selection can be difficult in a distant locations such as across a continent, which usually affords dendrochronologists with one trip in which to locate and sample optimum sites. This is often conducted within a limited, inflexible time span. This process is compounded when the dendrochronologists is unfamiliar with the local terrain and potential species. The model presented here is based upon dendrochronology work conducted within the last year in the Bear River Range and is intended to expedite future searches in the vicinity.

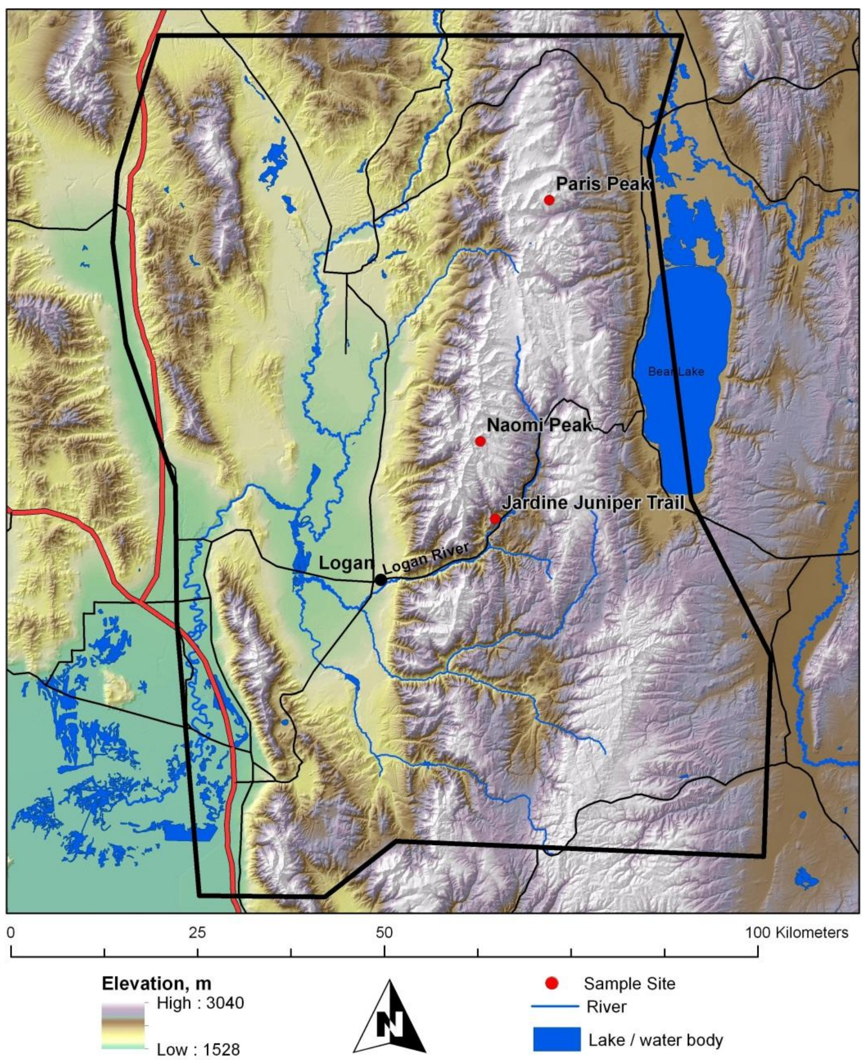

Figure 1. The Bear River Range and the location of sample sites used in this study represented by red dots. The black polygon delineates the area covered by the model presented in this paper.

Background

Study Area

The Logan River watershed is located in the Bear River Range of southeastern Idaho and northern Utah (Figure 1). The river drains 2,288 km^2 and its main tributary is Blacksmith Fork. The highest point in the watershed and Bear River Range is 3,035m Naomi Peak and the lowest elevation is the 1,341m confluence with the Little Bear River.

In the fall of 2010 and summer of 2011, Douglas-fir were sampled at three locations in the Bear River Range (Figure 1). Paris Peak (PAR) is the farthest north site and has a mean elevation of 2845m, while the Naomi Peak (NAO) site has a mean elevation of 2730m. The Jardine Trail (JJT) is the lowest with a mean elevation of 2100m.

Table 1. Elevation data of the sampled sites as determined from the 10m DEM.

SITE	MIN	STD-1	MEAN	STD+1	MAX
PAR	2758	2790	2845	2900	2918
NAO	2572	2644	2730	2817	2917
JJT	2037	2068	2100	2131	2166

Dendrochronology

Dendrochronology is the use of tree rings to reconstruct and date events and processes, such as climate. Unlike some dating methods, dendrochronology produces ages in calendar years. The annual resolution of dendrochronology makes it especially useful in reconstructing high frequency and inter-annual events. This study used annual ring width measurements, which is one of the most widely used techniques (Hughes, 2011; Speer, 2010).

The yearly growth of conifers, such as Douglas-fir, a commonly used species in dendroclimatology, begins in the spring. The amount of growth is influenced by a variety of factors including climate, tree maturity, stand competition, and local disturbances (Fritts, 1976; Hughes, 2011; Speer, 2010). By comparing the growth pattern of many trees in a given site, it is possible to determine the common growth signals, one of which is climate (Fritts, 1976).

When using tree-ring data to reconstruct climate, dendroclimatologists subjectively sample trees growing at the ecological fringe of their habitat. If a tree is stressed for resources, then any increase in the growing conditions results in the tree producing a larger ring (Fritts, 1976). Limited growing conditions are generally described as steep, south facing, rocky slopes (Fritts, 1976; Speer, 2010). Steeper slopes experience relatively quick runoff and the south aspect promotes snowmelt in regions which receive snow. The impact of wildfires and disease are reduced by sampling trees which are isolated from one another. Isolated trees can generally be described as trees whose crowns do not touch. After selecting a site, individual trees are sampled based upon their character. Older, stressed Douglas-fir are characterized by having short, twisted stems with smooth bark and inverted cone shaped crowns. Large lower branches indicate older trees, while dead branches in the crown indicate stress. The standard method for selecting sensitive trees is to consider these criteria in the field before sampling (Fritts, 1976; Speer, 2010; Woodhouse and Lukas in Kjelgren et al., 2011).

Methods

Dendrochonology Data

During the fall of 2010 and summer of 2011, Douglas-fir were sampled at three locations in the Bear River Range using established tree search criteria (Figure 1). The cores were brought to Utah State University and processed using standard laboratory procedures (Stokes and Smiley, 1968; Speer, 2010). The sampled cores were glued onto wooden mounts and secured using string to prevent the cores from twisting. The cores were then sanded using a belt sander and sandpaper of 120, 220, 320 and 400 grit. Individual tree cores were measured using a Velmex slide and digital recorder and crossdated following standard procedures (Stokes and Smiley, 1968; Speer, 2010). The measured ring widths from each core were standardized using the program ARSTAN to remove the ring-width variability unique to each tree. The standardization process involves fitting a mean trendline to the ring width of each tree and dividing the ring width by the value of the trendline in a given year. The type of trendline chosen determines the frequency of signal or noise which is kept or lost and the division produces a growth index for each tree. The program ARSTAN averages the indices of all the trees at a given site and produces three chronology indices: a standard, residual, and ARSTAN (Cook and Holmes, 1999). The standard chronology is the average of all the individual tree indices at a give site. The residual chronology is the standard chronology with the autocorrelation removed. The ARSTAN chronology is the residual with the common autocorrelation added back in and was designed to be the most robust of the three (Cook and Holmes, 1999; Buckley, 2011). Although each chronology is different, the majority of dendroclimatology studies find that the standard and ARSTAN chronologies are usually very similar and the residual the exhibits the most difference, but is still positively correlated with the other two (Lukas in Kjelgren et al., 2011). However, all residual chronologies in this study are inversely correlated with the standard and ARSTAN chronologies. This inverse relationship affected the model calibration.

The correlation between tree-ring data and streamflow was accomplished by regressing the three chronologies from each site with Logan River mean annual flow (Table 2). The period of record of the regression is 1922-2010, the available record of naturalized flows of the Logan River. The standard chronology produced the best results for Paris Peak and the Jardine Trail sites while the residual chronology produced the best results for the Naomi Peak site. Due to the standard chronology's high correlation and its inverse relationship with the residual, only those two chronologies were used for the model calibrations although the ARSTAN was considered.

Table 2. Correlation values of each site with Logan River streamflow.

Site	Standard	Residual	ARSTAN
PAR	0.20	0.11	0.17
NAO	0.17	0.28	0.19
JJT	0.30	0.10	0.28

Acquiring and Processing the GIS Data

The data used to create the model include the GPS determined location of each tree and 10 and 30 meter DEM data acquired from the USGS. The GPS data for each tree were organized in an Excel table where site and tree attribute information were added from field and laboratory notes. The site to Logan River flow correlation values were included in the table. The table was then imported into ArcGIS as an XY event and used to create a point shapefile of tree-ring data.

Both 10 and 30 meter DEM data were acquired from the USGS National Map Viewer 2.0 (2011) with the intent to compare how their resolution affects the model. The DEM data were mosaicked to form a single DEM and the edges clipped by the black polygon shown in Figure 1 to produce a raster of the Bear River and nearby ranges. The "Raster Calculator" tool was used to remove all cells lower than 2000m, the lower elevation limit of Douglas-fir in the Bear River Range. Next, the Aspect and Slope tools were used to create rasters from the elevation DEM.

The elevation, slope and aspect values for each tree were determined using the "Extract Values to Points" tool for both the 10 and 30 meter rasters. The mean, maximum, minimum and standard deviation slope, aspect and elevation values for each site were then determined using the "Zonal Statistics as Table" tool.

Calibrating the Model

The mean, maximum, minimum, and mean +/-1 standard deviation of each topographical variable from the 10 and 30 meter DEM's for each site were regressed with the known site-to-flow correlation values and a best fit trendline determined. The best fit trendlines for the 10 and 30 meter rasters were similar, but the 10m rasters were chosen due to their higher resolution especially on ridgetops where 30m resolution would be less accurate due to the varied slopes, aspect and elevation. Additionally, the topographic variables were regressed with the standard, residual and ARSTAN chronologies for each site to determine which chronology exhibited the greatest correlation (Figures 2, 3, 4). The resulting trendlines were then used to predict the correlation with streamflows for a given slope, aspect or elevation. In this manner, each cell in the slope, elevation and aspect rasters had a predicted correlation to streamflow.

The mean site elevation and site-to-flow correlation values are plotted in Figure 2. The higher correlation with streamflows at lower elevations from of the standard and ARSTAN chronologies is supported by the dendrochronology literature (Fritts, 1976; Speer, 2010; Littell, et al., 2008). However, the residual chronology suggests that higher elevation sites are more suitable. This discrepancy is likely the result of the inverse relationship of the standard and residual chronologies. An initial elevation prediction model was created using the standard trendline. This resulted in a poor prediction of the higher elevation sites and the model predicted that valley bottoms were the best locations to sample. As is common throughout settled areas, almost all of the lower elevation trees were logged by pioneers in the 1800's. Due to these two considerations, the model was adjusted to bias high elevation trees by using the residual chronology trendline:

Elevation index (residual) = 0.0002308*elevation - 0.3521780

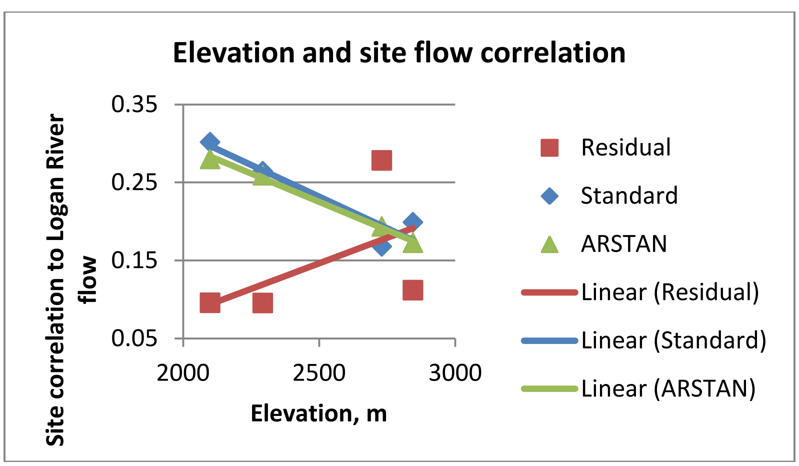

Figure 2. Plot of each site's mean elevation and its correlation with Logan River flow. The elevation values were derived from 10m DEM.

The three chronologies were plotted against the mean of each sample site's slope. The residual chronology exhibits a negative correlation with increasing slope while the ARSTAN and standard are positively correlated with increasing slopes (Figure 3). Due to the desire to bias toward steeper slopes, as established in the dendrochronology literature, the best fit line of the standard chronology data was used. The determined trendline is:

Slope index (standard) = 0.0069184*slope + 0.0491051

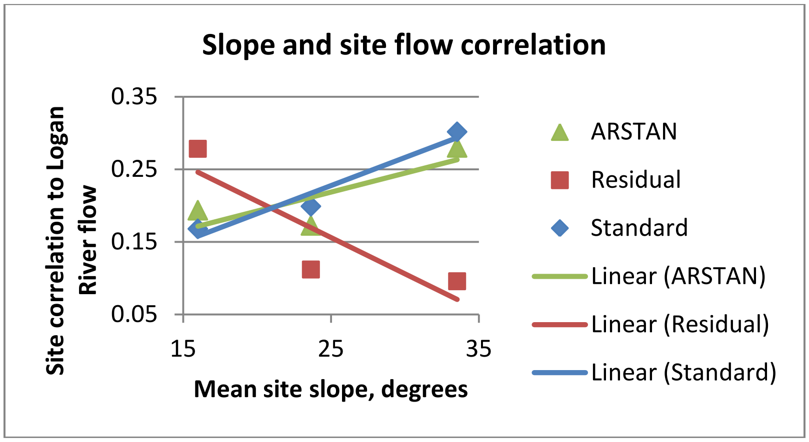

Figure 3. Plot of each site's mean aspect and its correlation with Logan River flow. The slope values were derived from 10m DEM.

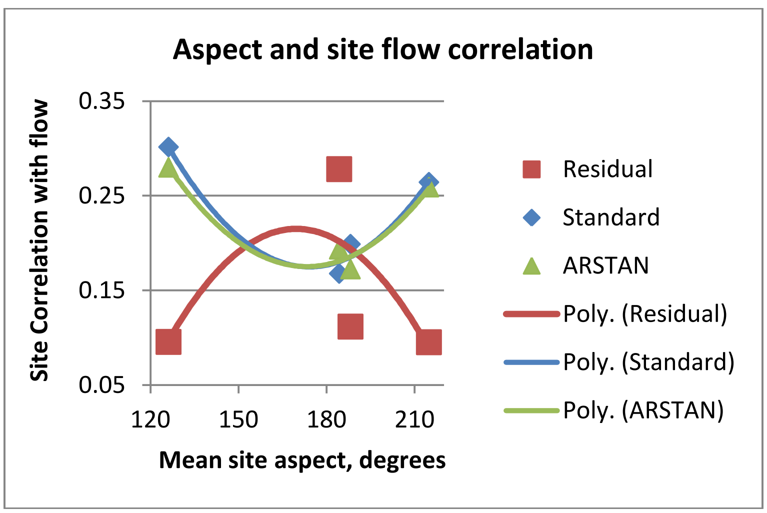

Figure 4. Plot of each site's mean aspect and its correlation with Logan River flow. The aspect values were derived from 10m DEM.

The mean aspect of each site were plotted to determine a trendline similar to the elevation and slope (Figure 4). The plot was made with the assumption that most trees were sampled on south facing slopes in accordance with established methods (Fritts, 1976). In order to accommodate this non-linear relationship, a polynomial was fitted to the data, as shown in Figure 4. The trendlines of the standard and ARSTAN chronologies exhibited a bias toward the lowest and highest aspects while the residual exhibited the most bias on aspects of 160-180°. Due to the desire to bias south facing slopes, the residual trendline was chosen. That trendline is:

Aspect index (residual) = (-0.0000621*aspect^2) + (0.0210911*aspect) - 1.5746173

Creating the model

Several iterations of the model were required to produce meaningful results. Often the changes were errors in the raster calculator equations, but as discussed earlier, different biases were considered. The final model had 3 raster inputs: slope, elevation, and aspect. The raster calculator was used to determine the expected correlation between a tree and streamflow for a given raster cell value using the determined trendlines. The result was three rasters of predicted tree and flow correlation: one for elevation, slope and aspect. The values of the overlying correlation rasters were then added together to create the final model raster of predicted tree and flow correlation. The process is summarized in Figure 5:

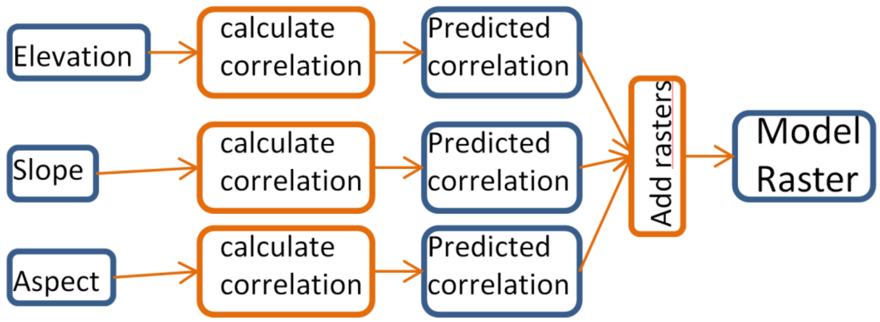

Figure 5. Schematic showing how the final tree prediction model was created. The blue boxes denote rasters while orange denotes the raster calculator tool.

An initial inspection of the model revealed areas of unexpectedly low predicted correlation values in low elevations. After an inspection of the model, it was determined that some of the aspect cells contained negative values. This was corrected by using the raster calculator to nullify all values less than 0 in the predicted aspect correlation raster. The effect of the negative values was determined by creating a raster of only the nullified cells. This raster shows that low elevation and less steep areas, generally in the valley bottoms, were impacted the most. Because these are the least likely areas to locate climatically sensitive trees, no real data was lost in this truncation.

Results

The initial results of the model were first verified qualitatively to determine if more adjustments were necessary. The qualitative assessment emphasized high elevation south facing ridges which should have the highest predicted correlation and low elevation flat areas which should have the lowest predicted correlations. This assessment was enabled by draping the model raster over a hillshade of the study area (Figure 6).

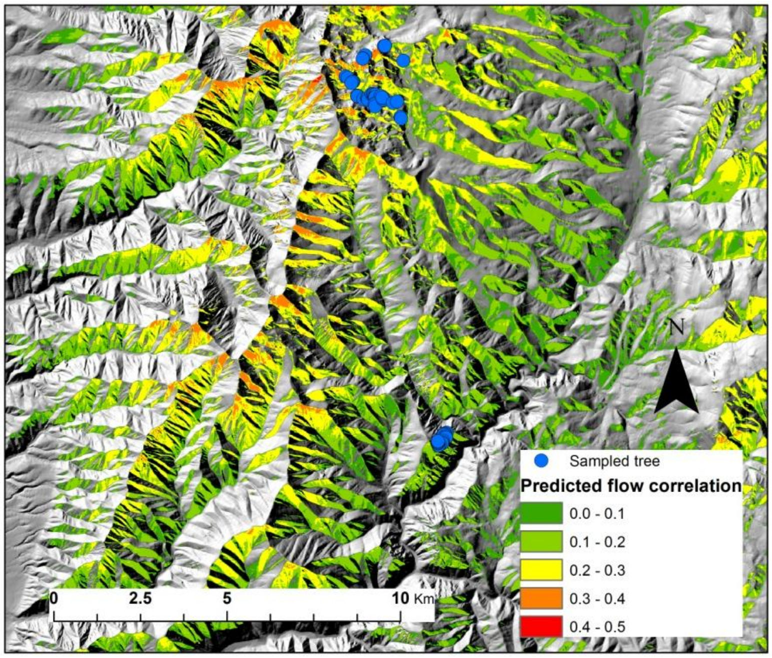

Figure 6. Hillshade of the central Bear River Range with the model raster draped on top. Note that the highest elevation ridges have the greatest predicted correlation to flow. The sharp low elevation limit of the model is due to only using rasters with values above 2000m in elevation.

In addition to assessing the entire Bear River Range, each sample site was visually inspected to examine the distribution of sampled trees and predicted locations. The trees at the highest elevation site, Paris Peak, were predicted well by the model (Figure 7). The exact location of almost each tree was predicted except for trees on slightly north facing slopes. This site is characterized by south facing slopes with few breaks in topography.

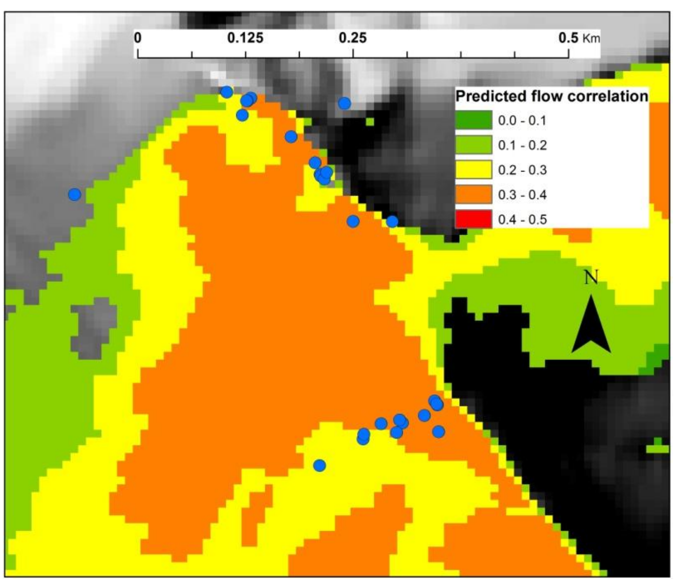

Figure 7. Paris Peak site with trees denoted in blue and correlation values shown as graded colors. Note the model predicted almost all the trees except those on the edge of ridge tops.

The model predicted fewer tree locations at Naomi Peak than at Paris Peak. Figure 8 shows that the model predicted a patchy network of areas which have a relatively high correlations next to areas with low or no correlation. The higher correlation areas are associated with steep, south facing open slopes. Although difficult to discern in the hillshade, the areas of low to no correlation lie in an area composed of hummocky terrain and gullies.

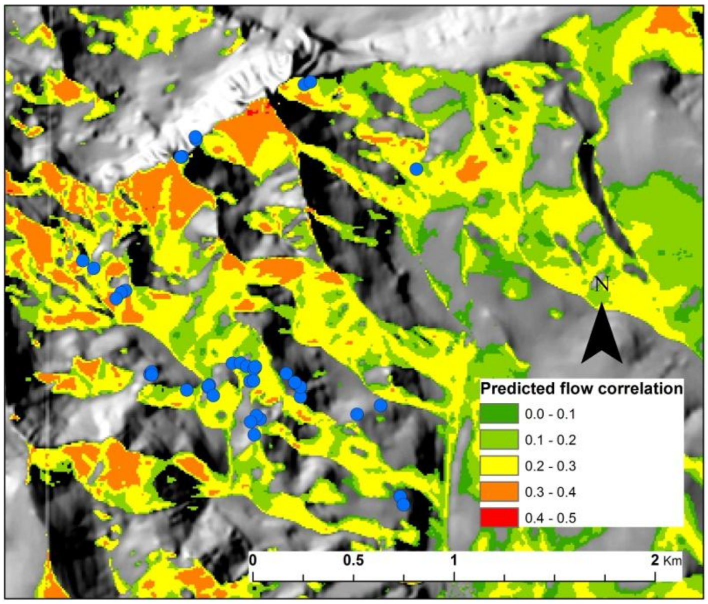

Figure 8. Close up view of the Naomi Peak site with trees denoted in blue and correlation values shown as graded colors. Note the highly varied modeled flow correlation and gaps in the model.

The lowest elevation site, Jardine Trail, was the most difficult site to predict. The trees which were predicted, were predicted with a low correlation (Figure 9). Many trees, especially in the middle of the site and on the ridgeline, were not predicted at all. The site has scattered cliff bands ~8m tall and gullies throughout, but is generally southeast facing and relatively steep.

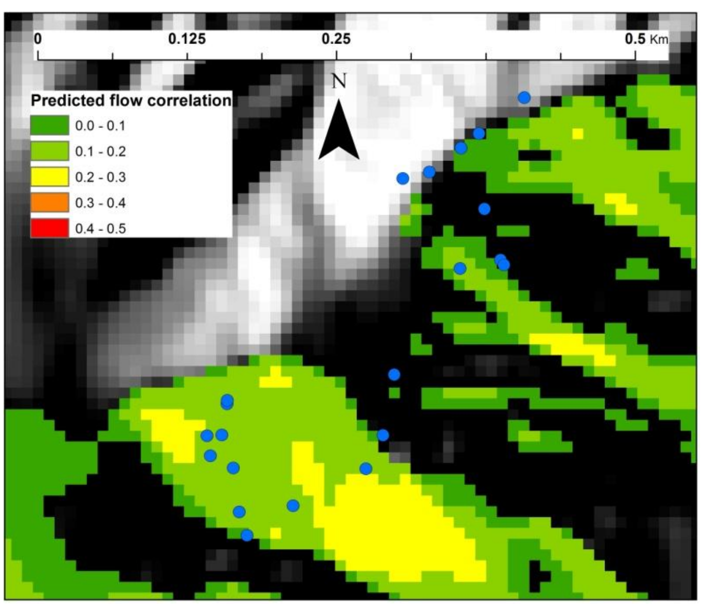

Figure 9. Close up view of the Jardine Trail site with trees denoted in blue and correlation values shown as graded colors. Note the number of trees in predicted locations.

The model was also quantitatively evaluated using the zonal statistics tool to calculate the each site's modeled correlation to streamflow as well as the site minimum and maximum values (Table 3). The results show that the model over predicted Paris Peak by 0.08 and 0.17, compared to the standard and residual chronologies, respectively. The model over predicted Naomi Peak by 0.03 compared to the standard, but underestimated by 0.08 compared to the residual. The Jardine Trail site was under predicted by 0.16 compared to the standard but was only 0.04 above the residual chronology correlation.

Table 3. Table of modeled site correlation with streamflow and actual values from standard and residual chronologies. The modeled site maximum and minimum are also presented.

Site	Max	Mean	Min	Standard	Residual
PAR	0.38	0.28	0.15	0.20	0.11
NAO	0.33	0.20	0.09	0.17	0.28
JJT	0.20	0.14	0.03	0.30	0.10

Discussion

The model exhibits a mixed ability to accurately predict likely locations of climatically sensitive trees. Two of the three sample sites were accurately predicted, but the lowest elevation site, Jardine Trail, was barely predicted by the model, despite having a high correlation to streamflow with the standard chronology. The ability of the model to predict climatically sensitive trees in the Bear River Range can be divided into three main categories: scale, regression calibration, and local factors. The scaling ability will need to be addressed by all potential tree location models, as will regression calibration. However, the local factors are unique to the Bear River Range.

Scalability of the model

Although the model was based on established dendroclimatology site selection criteria, the model suffers from an inability to scale from the site to the tree level, or in this case grid cell. However, the higher elevation sites were accurately predicted due to a higher elevation bias. Dendroclimatologists choose their sites by looking for south facing, steep, rocky slopes with sparsely spaced vegetation. These characteristics are easily quantifiable and can be reliably predicted. The model presented here was able to accurately predict the steep south facing slopes at Naomi and Paris Peaks, but not at the Jardine Trail site. The slopes at the former sites are open and relatively unbroken, while the Jardine Trail site contains rocky outcrops and gullies which result in differing aspect values in close proximity. Correlation values for the cells representing these gullies and outcrops may have been nullified by the truncation of cells with negative correlations produced by the aspect correlation raster. The same effect could explain the patchwork of null values at Naomi Peak. Much of the Naomi Peak site comprises hummocky terrain which includes 5-10m tall knolls. These knolls would have been truncated similar to the gullies and outcrops at the Jardine Trail site. This micro topography affects the model, but is not a significant consideration for dendroclimatologists when choosing which tree to core. Dendroclimatologists choose the individual trees based upon the tree character. Tree character is a qualitative assessment which can only be made in the field and would be virtually impossible to model with GIS. The scaling ability of the model implies that it most suitable when used to highlight large areas, several tens of meters wide, with likely trees. Satellite imagery and aerial photos should be used to confirm that these areas contain sparse vegetation to decide where to sample.

Regression calibration

The regressions used to calibrate the model are based on three sample sites. A regression based upon such sparse data will not produce reliable results due to the significant uncertainty. While each site has several trees, 42 at Naomi Peak, 27 at Paris Peak and 23 at Jardine Trail site, the author was unable to determine an efficient means of standardizing each tree individually for a comparison with streamflow until a couple of days before the project was due. Processing individual tree data and regressing them with streamflow will be the subject of future work. This will produce up to 92 trees to use in the future calibration model, assuming that all trees are significantly correlated to streamflow.

Using the mean topographic values of each site likely resulted in the aspect based raster of chronology to flow correlation having the most error. Although the equation used to calculate tree-to-flow correlation biased south facing slopes, this is not necessarily representative actual aspect data. The aspect of each tree, denoted by site, are displayed in Figure 11. The plot shows that sampled trees occur at nearly all aspects, but some sites exhibit a preferred orientation. Trees at Naomi Peak exhibit the most variation, likely the result of that site's hummocky terrain. Trees were sampled on all sides of knolls, resulting a wide distribution of aspects despite the site being located in a south facing basin. The Jardine Trail site exhibits a strong southeast orientation while Paris Peak a strong west southwest orientation. Both of these sites are located on the sides of a ridge or peak, thus the strong preferential aspects. Mean site values would be generally representative of these sites, but not of the Naomi Peak trees. At Naomi Peak, an aspect of 10° and 350° average to 180°, which is misleading. Additionally, using site averages gives more weight to individual trees in a site with fewer sampled trees than a site with many sampled trees. These issues will be addressed in future models by regressing all trees individually against streamflow and aspect.

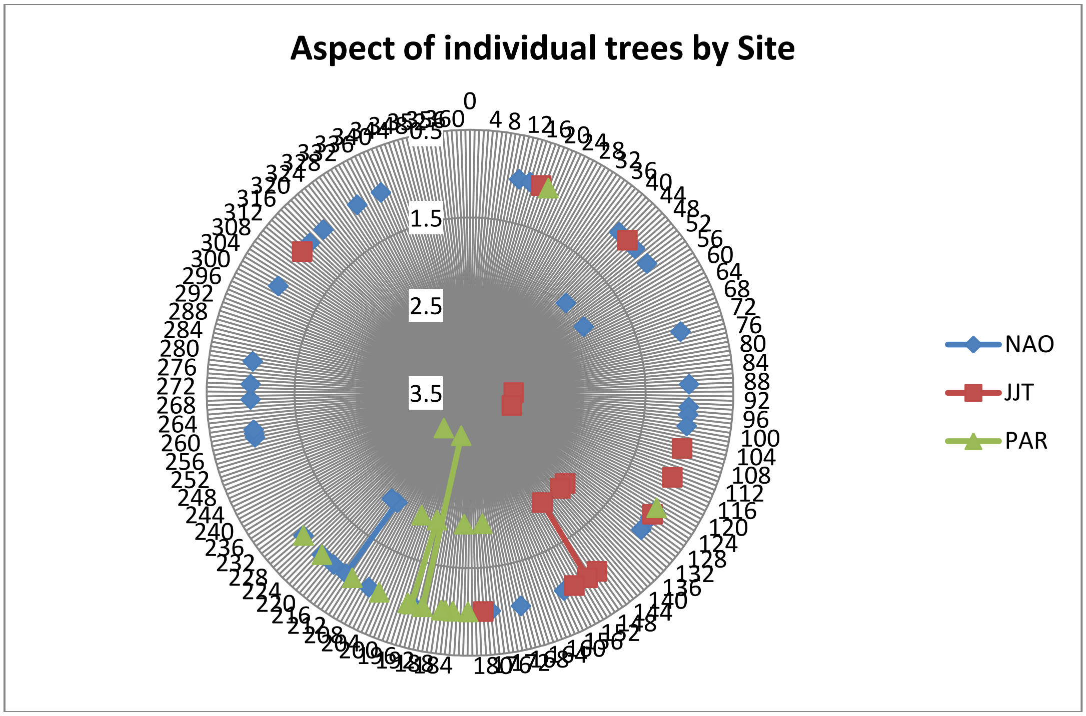

Figure 11. Plot showing the aspect associated with each tree identified by site. Note the difference in preferred aspect of the different sites. The radial scale, number of trees, is inverted for readability.

The calibration data were also limited by the number of sites used. Three other sites not included in this model were sampled in the summer of 2011. However, the data from these sites were not included in the model as the cores from those sites have not been measured and crossdated. After the model was constructed, a sufficient amount of trees at the site located in the farthest southwest corner of the model (Figure 1) were crossdated and measured for use in the model. These new tree data could be used to calibrate future models. As more data are collected, the model accuracy should improve. As the model accuracy improves, it can be used to explore spatial trends in tree growth patterns. For instance, trees on the front of the Bear River Range may exhibit different growth limitations and climate signals than those in the middle of the range as well as comparing trees at different elevations. Ultimately, this will lead to a regional understanding of tree-growth patterns.

Local factors

The detrending and standardization process of dendrochronology produces three indices: a standard, a residual, and an ARSTAN chronology. These chronologies are almost universally positively correlated with one another, except in the Bear River Range (Lukas in Kjelgren et al., 2011). This exceptional phenomenon of the Bear River Range suggests that the model is not suitable for locations outside of northern Utah and southern Idaho. The relief in the Bear River and Wasatch Ranges is much steeper and more pronounced than most places of interest to dendroclimatology studies (Woodhouse and Lukas in Kjelgren et al., 2011). The pronounced relief results in complicated precipitation patterns with a steep precipitation gradient. The majority of precipitation may fall several kilometers away from the mountain front, or in the case of the Wellsville Range, the majority of precipitation falls in what would normally be a rain shadow (Wang in Kjelgren et al., 2011). Areas with less pronounced relief exhibit a more gradual, and predictable, precipitation pattern. The trees in this study are located roughly in the east-west center of the Bear River Range, and in the case of Naomi Peak, receive more snowfall than the rest of the range. The elevation at Paris Peak implies a similar condition. A comparison of the peaks in northern Utah and Colorado shows that northern Utah receives more snow than typical sample sites in Colorado, Arizona, southern to central Utah, and Wyoming (Woodhouse, Gray and Lukas in Kjelgren et al., 2011). The additional snowfall implies that the Dougals-fir used in this study are not as limited by water availability as other studies. Research has shown that higher elevation trees are more influenced by temperature than precipitation (Littell et al., 2008).

A comparison of the minimum April and May temperatures, the onset of peak snowmelt, at nearby Tony Grove, with the Naomi Peak chronologies, exhibit a positive correlation (Table 4). This is most noticeable in the residual chronology. During the warmest month, July, the chronologies are strongly inversely correlated with minimum temperatures. These data suggest that the trees in this study exhibit a mixed temperature and precipitation signal. This mixed signal is difficult to model at a localized scale. This study considered using gridded PRISM precipitation and temperature data as model inputs, but the coarseness of the data and complications of modeling micro-scale precipitation discouraged using these parameters (Wang, Gillies, and Woodhouse in Kjelgren et al., 2011). As climatologists improve their ability to downscale climate models, these data will become more useful for predicting climatically sensitive trees. However, present climate data may be appropriate for other areas of dendrochronological interest which have less pronounced relief than northern Utah.

Table 4. Correlation values between the Naomi Peak chronologies and selected minimum monthly temperatures recorded at nearby Tony Grove SNOTEL. (NWCC, 2011).

Month	Standard	Residual	ARSTAN
April	0.27	0.33	0.27
May	-0.13	0.33	0.13
July	0.49	0.27	0.46

Conclusion

The model did an excellent job predicting trees at higher elevations on even, south facing slopes. Due to a high elevation bias, the model did not accurately predict lower elevation sites. Aspect was also difficult to model due to the variation within a site and the site average values. These limitations will be addressed in future models by using individual tree to flow correlations instead of site averages. Another limitation is that the model requires tree-ring data to calibrate, and is therefore most appropriate for use in areas with pre-existing tree-ring data or where data exists in areas with similar topography and climate. The model may also work better in more typical studies where the Douglas-fir residual chronologies exhibit a strong correlation with the standard and ARSTAN chronologies. Eventually, the model may be used to examine spatial and topographical influences on tree growth. In its present state, the model is best suited to inform the site search process and should be verified by satellite imagery or aerial photographs. Due to the qualitative nature of individual tree selection, sampling requires a field assessment of tree character.

References

Buckley, B., 2011, Utah State Univiersity Dendrochronology workshop, June 2011.

Cook, E. R., Holmes, R. L., 1999, Users Manual for Program ARSTAN, adapted from Tree-Ring Chronologies of Western North America: California, eastern Oregon and northern Great Basin by R. L. Holmes, R. K. Adams, H. C. Fritts, Laboratory of Tree-Ring Research, University of Arizona, Tucson, Arizona, pp. 50-65.

Fritts, H.C., 1976, Tree Rings and Climate, Academic Press, London, 557pp.

Hughes, M. K., 2011, Dendroclimatology in High Resolution Paleoclimatology, *in* Hughes, M. K., T. W. Swetnam, H. F. Diaz, 2011, Dendroclimatology: Progress and Prospects, New York, New York, Springer, p. 17-36.

Littell, J. S., Peterson, D. L., Tjoelker, M., 2008, Douglas-fir growth in mountain ecosystems: water limits tree growth from stand to region, Ecological Society of America, vol. 78, pp. 349-368.

Kjelgren, R., M. Bekker,B. Buckley, R. Gillies, S. Gray, L. Hipps, J. Lukas, T. Rittenour, L. Rupp, S. Wang, C. A. Woodhouse, T. Bardsley, 2011, Utah State University Northern Utah Dendrochronlogy Workshop, March 2011.

National Water and Climate Center, 2011, SNOTEL open access data, Natural Resources Conservation Service online. < http://www.wcc.nrcs.usda.gov/snow>.

Speer, J. H., 2010, *Fundamentals of Tree Ring Research*, University of Arizona Press, Tucson, Arizona, pp. 333.

Stokes, M. A., and. Smiley T.L, 1968, An Introduction to Tree-Ring Dating, University of Arizona Press, Tucson, Arizona, 73 pp.

U. S. Geological Survey, 2011, The National Map Viewer 2.0, online, U. S. Geological survey. http://viewer.nationalmap.gov, accessed November 2011.