Evaluating Potential Correlation Between Water Deficit and Mountain Pine Beetle Infestation in Whitebark Pine

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Abstract

The lands of the greater Yellowstone area contain ever growing swatches of brown. Many of these dead zones are the result of the current outbreak of mountain pine beetles. One particularly hard hit species of pine is the White Bark Pine: 90% of its population in the greater Yellowstone area has been killed in the last 20 years. Preserving whitebark pine is vital as they are an ecologically important keystone species that prevents erosion by providing structure for snowpack and soil at treeline. Pines that are facing a lower relative water deficit have a higher chance of surviving mountain pine beetle attacks. This project investigated tools that land managers could use to identify areas to plant whitebark pine that offer the highest chances of survival. These areas were identified by considering changes in relative deficit, and other microclimatic conditions including precipitation and solar gain as influenced by local elevation, aspect and day length. I found that relative water deficit is likely not a factor influencing the mortality of white bark pine in Glacier National Park as very few areas within the trees' habitat experience significant amounts of water deficit.

I. Introduction

White bark pine is an ecologically important keystone species: the seeds of their cones provide vital nutrients to many animals living at high altitudes including Clark's nutcrackers – a small bird that plays a key role in spreading the seeds of pine trees. Additionally, these trees create a stable environment for other trees and plants to grow by consolidating soil and preventing erosion. However, changes in climate are causing these trees to be killed in startling quantities (Keane & Arno, 1993). Currently, whitebark pine are a candidate species for federal listing under the Endangered Species Act. Their habitat is rapidly shrinking, and they're being faced with an onslaught of mountain pine beetles that conservation managers have limited resources to combat.

Because of this, it is important to identify locations where replanting has a very high chance of long term survivability for the trees. Recent research of the factors that influence a tree's ability to survive beetle attacks has found that trees that face less drought stress are more capable of fending off beetle attacks. This may be because trees facing a shortage of water are less capable of producing protective chemicals for resin production which are critical to mounting an effective biological defense (Arango-Velez et al., 2011). To aid land managers in their efforts to help this species persist, I have calculated the point by point relative water deficit of a section of Glacier National Park in order to locate these areas.

II. Methods

I. Area of Study

I chose to perform my analysis on a section of Glacier National Park. Glacier National Park is a large area in North Western Montana. This park has a large amount of alpine terrain with its highest peaks reaching over 3000 meters in elevation. These high altitude areas are conducive to growth of whitebark pine – and groves of the trees can be found throughout the park. The park's climate is highly variable, but USGS researchers have noted a a warming trend in recent years. Average annual rainfall ranges from 23 inches in the driest areas of the park, to 30 inches in the most wet. Until recently, forest fires within the park were suppressed, which has contributed to the trend of whitebark pine being replaced by subalpine pines.

My research focused on a roughly 30 by 50 kilometer rectangle contained in the park's boundaries containing an acceptable representation of the park's varied climates. A subsection of the park was used instead of the park in its entirety in order to decrease the processing requirements of running the model (discussed in greater depth in the limitations section).

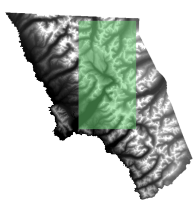

Figure 1: *The DEM of Glacier National Park with the area of study overlaid in green.*

II. Data

A digital elevation model (DEM) was created from mosaicked USGS 10-meter DEM data, clipped to the boundaries of the national park. This model was then upscaled to a 1 kilometer resolution. The DEM was necessary for the calculation of slope and aspect values. Elevations from the model were also input into ClimateWNA (Wang, Hamann, & Murdock, 2012) for the calculation of small scale temperature and precipitation estimates.

The water model is capable of incorporating soil data: specifically the water holding capacity of the top 150 cm of soil. But, in order to further reduce the complexity of the modeling task, water holding capacity was assumed to be a constant 100 mm throughout the area of study.

Due to the hardware constraints involved in collecting statistics for localized weather, climate data is not available at high resolutions. PRISM monthly climate data is available in 2.5 by 2.5 arc minute sections. To increase the resolution of this, data the program ClimateWNA was used to extract and downscale the PRISM climate data. ClimateWNA was then used to calculate monthly climate variables for specific locations in the area of study at centroids of a 1 kilometer grid.

Monthly solar radiation values were calculated for points on the same 1 kilometer grid using ArcMap's solar gain tool with its default values.

III. Analysis

I calculated the water balance of my area of study with a modified implementation of Thornthwaite's water balance model (Thornthwaite, 1948) (Lutz, van Wagtendonk, & Franklin, 2010), which analyzes the allocation of water among the components of a system. The model begins by calculating the melt factor F_m

$$\begin{aligned} T_a \leq 0^\circ C &: F_m = 0 \\ 0^\circ C < T_a < 6^\circ C &: F_m = 0.167 * T_a \\ T_a \geq 6^{circ} C &: F_m = 1 \end{aligned}$$

with T_a being defined as the mean monthly temperature in degrees celsius. The melt factor represents the rate at which a given cell will lose snow, and is used to determine the fraction of snow storage that will melt in a month. From here I calculated estimates for rain and snowfall amounts using the known monthly precipitation values.

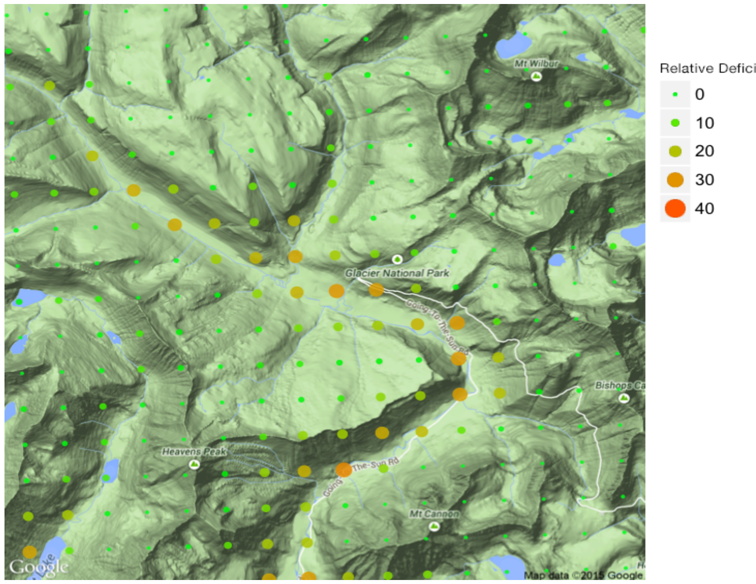

Figure 2: *Mapping of the computed grid's relative deficit values.*

$$RAIN_m = F_m * P_m$$
$$SNOW_m = (1 - F_m) * P_m$$

Snowpack $PACK_m$, and melt water $MELT_m$ input was calculated beginning in August with a snowpack of 0, then calculated for the following 29 months in order to generate a base snowpack to work from. The last 12 months calculated were used for the final result.

$$PACK_m = (1 - F_m)^2 * P_m + (1 - F_m) * PACK_{m-1}$$
$$MELT_m = F_m(SNOW_m + PACK_{m-1})$$

Snowpack and melt water values are used to determine the amount of water available to a centroid, as well as how much water it is expected to lose for any given month. Next, the calculated solar gain data was used to generate potential evapotranspiration (PET).

$$PET_m = 29.8 * days * dayLength * \frac{VSP(T_a)}{T_a + 273.2}$$

In this water model, monthly PET is calculated using the Hammon equation (Hamon, 1963). The $dayLength$ value used in this calculation is determined using the Gavin method (Forsythe, Rykiel, Stahl, Wu, & Schoolfield, 1995), which uses a latitude and day of the year to calculate a day length accurate to 1 minute. VSP is the vapor saturation pressure at a given T_a. Finally, with the monthly PET values, the soil water balance can be calculated. Similar to the snowpack calculation, the soil water balance is run for 30 months, starting with fully saturated soil in May, and only the last 12 months of the simulation are used. The soil water balance is necessary to determine the amount of actual evapotranspiration (AET) occuring.

$$WAT_m \geq PET_m : SOIL_m = WAT_m - PET_m + SOIL_{m-1}$$
$$WAT_m < PET_m : SOIL_m = SOIL_{m-1} - FRAC_m$$
$$SOIL_m > SOIL_{max} : LOSS_m = SOIL_{m-1} * (1 - exp(-\frac{PET_m - WAT_m}{SOIL_{max}}))$$

$SOIL_{max}$ was set to a constant 100 mm. Monthly change in soil moisture is a given month minus the following month.

$$SOILCH_m = SOIL_m - SOIL_{m+1}$$

A revised PET_m can be calculated such that:

$$PETmod_m > WAT_m \wedge T_a > 5 : PET_m = WAT_m + SOILCH_m$$

The AET is chosen $AET = minimum(PETmod, PET)$. From here, the monthly water deficit can be easily calculated as

$$DEFICIT_m = PET_m - AET_m$$

AET and Deficit values were written to a CSV file containing monthly values for each, as well as the UTM coordinates associated with the values. Using R's ggplot2 and ggmap (Kahle & Wickham, 2013) libraries, I was able to further analyze the water balance model's results.

III. Results

I found a strong inverse correlation between elevation and deficit (see III). In the area I examined, my analysis found no points with a deficit greater than 50 mm. Further, there were no points with a deficit greater than 10 mm above an elevation of 2250 m. Therefore, based on this analysis it seems likely that the loss of whitebark pine in Glacier National Park is not strongly driven by mountain pine beetles, and may instead be the result of other factors such as white pine blister rust (WPBR).

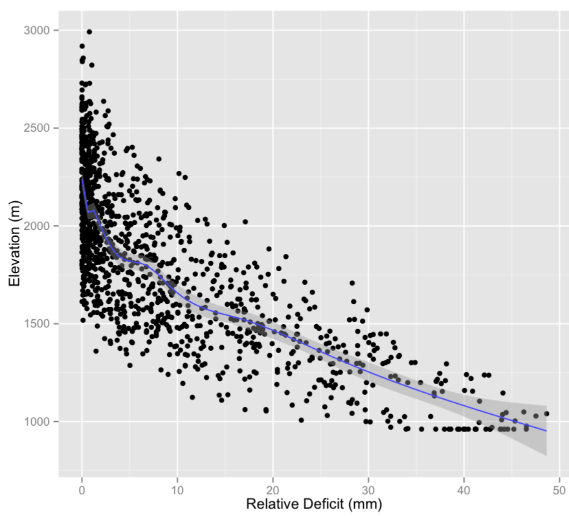

Figure 3: *Comparision of elevation to relative water deficit.*

IV. Discussion

Although the results of this analysis do not support the hypothesis that water deficit is a driving factor in the decline of Glacier National Parks's whitebark pine, the map of water deficit may still be a useful tool for managers, for example, in conjunction with fire management. Actual evapotranspiration and relative deficit data is not generally available at this resolution, and can provide additional information to park managers.

Typically dry weather is unfavorable for the spread of WPBR: it can spread most effectively in cool, humid air (Maloy, 1997). For the most part, Glacier National Park's climate fits this description. The park receives, on average, 30 in of precipitation, and is cold for a large amount of the year. These factors combined with my calculated deficit values strongly support the conclusion that a majority of the dying white bark pine in Glacier National Park are being affected by WPBR, not mountain pine beetles. If correct, this information could inform management efforts by selecting for trees that are more resistant to WPBR.

The deficit values were calculated using 30 year norm climate data which shows a clear long term warming trend. However, because of this long time span, it is not possible to account for important annual variations in climate. These shorter term fluctuations can have a large impact on vegetation: plants adapted to cool and wet conditions will experience stress on warmer years. The calculated deficit values show a significant increase during the warmer summer months, signifying that a warmer year would have a noticeable impact on deficit values.

V. Limitations

This research was conducted over the span of a month and a half. This time constraint made it necessary to limit the research's scope. The water holding capacity of the soil a tree is growing in is a significant factor in how long the tree can sustain itself without water input. My calculations assumed the water holding capacity of the soils in the area of study were constant, which would have resulted in soils with a below ideal water holding capacity to be inaccurately favored. The resolution of my calculations was also not ideal. Similar research was performed using 90 m centroids – a resolution more than 10 times more accurate than mine. But, running the model with millions more points would have taken too much time per run to be feasible for me to use. I would have also liked to calculate the heat load in R based off of the slope and aspect derived from the DEM, instead of relying on ArcMap's solar gain tool.

VI. Conclusion

The climate is noticeably warming: higher elevations are experiencing increasingly warmer temperatures. These changes are exposing whitebark pine to increasing numbers of threats. It is vital that these threats be identified and addressed early on, or these trees will likely become exptirpated. As it stands, the species is in danger of extinction in two to three generations (Fish & Service, 2011). While I was unable to confirm my hypothesis, the deficit information resulting from my calculations provides interesting insights into Glacier National Park's ecosystems that deserve further exploration. A higher resolution analysis that incorporates soil water holding information would be a necessary next step towards gathering further insights. Water balance is also a powerful tool for examining vegetation distributions. Future research could incorporate existing vegetation mappings in order to provide a baseline for drawing conclusions.

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