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Whitebark Pine (*Pinus albicaulis*), snow and refugia in the Greater Yellowstone Ecosystem

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Abstract Research and management issues related to pine forests, snowpack and refugia are relevant to mountainous ecosystems globally. For this study, we investigated local snowpack longevity as an explanatory variable for whitebark pine performance (survival rate, growth rate and condition). We used Sentinel-2 imagery to monitor local snowpack longevity. This new imagery is spatially and temporally more appropriate than other publicly available satellite imagery, and early results indicate that Sentinel-2 imagery can be successfully used for this purpose. Sites were selected based on a multi-decadal management effort by federal agencies to plant whitebark pine in the Greater Yellowstone Ecosystem. Relative to initial planting records, present-day field sampling affords an opportunity to evaluate whitebark pine performance over time.

Introduction

Yellowstone National Park's Superintendent describes the Greater Yellowstone Ecosystem (GYE) as "the largest remaining, nearly-intact ecosystem in the contiguous United States" (Wenk, 2016). Historically, the GYE has supported a late-season snowpack that supplies water for agricultural and recreation, but this trend has been changing in recent decades (Tercek et al., 2015). Whitebark pine (*Pinus albicaulis*, WBP) is widely recognized as a keystone and foundation species in the high altitude GYE, and over half of the aerial extent of WBP in the U.S. is found there (Hansen et al., 2016). Nearly half of the GYE WBP distribution has exhibited severe mortality in recent years (Macfarlane et al., 2013). Threats to WBP are imminent and of high magnitude, with the species under consideration for protection under the Endangered Species Act (ESA; USFWS, 2011). Additionally, WBP seeds are an important food source for grizzly bears (*Ursus arctos horribilis*; Costello et al., 2014). Until earlier this year, grizzly bears were listed as threatened under the ESA, in large part, due to impact from the loss of WBP.

Seasonal snowpack in forested lands is the primary source of fresh water in western North America (Biederman et al., 2014), but snowpack is declining in the GYE and across the West (Hall et al., 2012; Pederson et al., 2011; Tercek et al., 2015). Healthy forests mitigate spring and summer snowmelt, which leads to more water being available in the late summer and fall months (Musselman et al., 2008). Stakeholders in the GYE are concerned with water, or lack thereof, during this time of the year. For instance, low flows and high water temperatures are contributing factors to major fish kills and subsequent closures on the Yellowstone River (MTFWP, 2016). On a national scale, Trout Unlimited's "primary focus has been and will be to advocate for policies and approaches that make

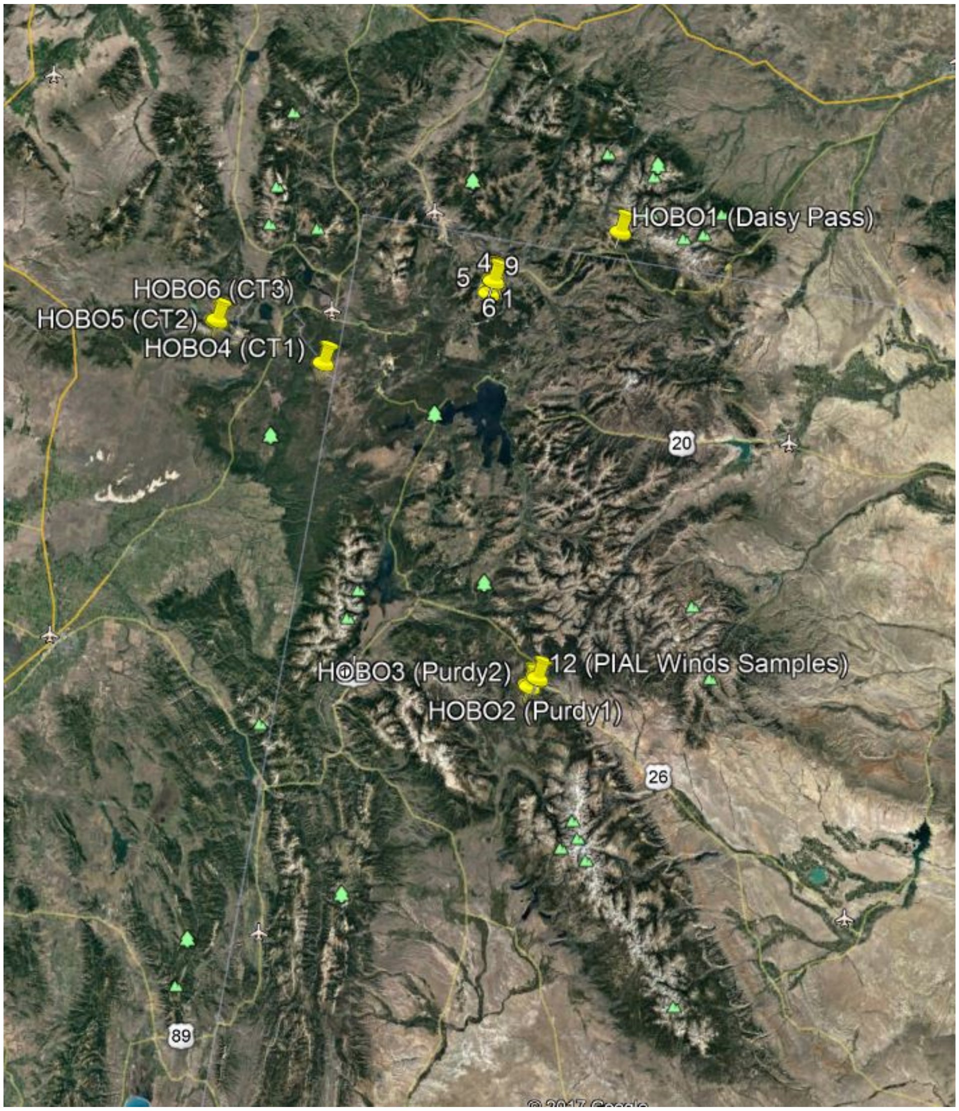

Figure 1. GYE WBP planting units indicated by yellow pins.

communities and landscapes more resilient to the effects of climate change." Declining snowpack and earlier snowmelt are likely affecting water availability for our agricultural systems and leading to an increase in wildfires (Backlund et al., 2008). It is important to note that in addition to Yellowstone River headwaters, there are also significant portions of the Snake and Green River headwaters in the GYE (Tercek et al., 2015).

Climate warming has been associated with loss of taxa that formerly were restricted to high elevations, and research shows that in high altitude and latitude regions the climate is changing more rapidly than elsewhere (IPCC working group, 2014). Climate change likely drives the major threats to WBP (Tomback et al., 2016; Logan et al., 2010), and refugia represent an ecological mechanism by which WBP may remain viable under climate change (Hansen et al., 2016). Climate change refugia are areas relatively buffered from regional contemporary climate change that enable the persistence of species and functions through maintenance of biophysical processes, such as snow retention, soil moisture retention and evapotranspiration (Dobrowski, 2011; Morelli et al., 2016). Identification of past and future refugia is important in the management of anthropogenic climate change impacts, and developing methodologies for their identification and description is a high research priority (Hansen et al., 2016; Keppel et al., 2012). Notably, other terrestrial populations have shown that refugia can support enough individuals to eventually re-colonize earlier areas of loss (Frouz and Kindlmann, 2001), and other researchers believe that GYE WBP refugia exist and correspond to locations that have colder microclimates (Macfarlane et al., 2013).

Greater snowpack longevity (snow refugia) is an abiotic indicator of colder local climate conditions relative to other areas nearby, or locations with greater snow accumulation. This study will identify snow refugia, as well as improve present-day modelling of water availability in mountainous terrain. "If water is the source of life, then life in the GYE is ruled by snow" (Tercek et al., 2015). Notably, uneven snow distribution is absent from current attempts to model the interactions between conifers and their environment (Biederman et al., 2014). Although elevation and aspect strongly influence snowpack longevity, other environmental factors that redistribute or cool snow after it falls bear significant influence on snowpack longevity on a local scale. These factors include the combined effects of wind on cornices and rifts, cold-air pooling and redistribution by avalanches. Environmental models that acknowledge local topographic effects on climate (Dobrowski, 2011) are of interest because of their biological effects. However, understanding of snowpack longevity at local scales is currently lacking.

Researchers acknowledge that there is a significant relationship between snow and WBP presence, but most focus on ecosystem services provided by pine forests such as delaying snowmelt and runoff (Tomback et al., 2016, 2014; Farnes, 1990). Although some GYE WBP are likely water stressed by late summer and fall similar to WBP in other areas of the West (Millar et al., 2012), this has not been well-studied (Shanahan et al., 2016). Significantly, water stressed individuals are likely to be more vulnerable to attacks from mountain pine beetle (Raffa et al., 2013). Since the early 21st century, mountain pine beetle (*Dendroctonus ponderosae*) outbreaks have been the primary cause of mortality of WBP in the GYE (Buotte et al., 2016). Snow may represent a water source during late summer and fall months, therefore reducing water stress and vulnerability to beetle attacks. Although the growing season may be shorter with snow persisting longer, (leading to relatively conservative gains even in high-quality growing seasons), these areas may ameliorate late season water stress, and provide a viable long-term environment for a long-lived species that regularly takes 75 years or more to reach reproductive age.

We have several objectives for this project:

1. Use satellite imagery to study the heterogenous pattern of local snowpack longevity and identify snow refugia
2. Compare historic WBP planting records to summer 2018 field work data in order to assess WBP performance over time and identify WBP refugia
3. Relate local snowpack longevity to WBP performance
4. Relate water balance to WBP performance as an estimate of soil moisture later in the growing season
5. Relate additional biophysical gradients of interest to WBP performance

Methods

Study sites

Our study takes advantage of historic WBP planting sites initially established by the U.S. Forest Service and the National Park Service. In summer and fall 2017, the Greater Yellowstone Coordinating Committee - Whitebark Pine Subcommittee facilitated records transfer of known planting sites that were established prior to 2012. Often, the planting sites are grouped in areas that were disturbed by fire in the year or two prior to planting. These collections of planting sites are called planting units. There are five planting units identified for use in this study with each containing between two and eight planting sites. There are 25 sites in total. The planting units are located near Union Pass in the Wind River Range, Taylor's Peak in the Centennial Range, Big Springs south of West Yellowstone, Mount Washburn on the northern edge of the Yellowstone caldera and Daisy Pass in the Beartooth Range (Figure 1). It is unknown whether these sites fairly characterize the biophysical gradient tolerated by GYE WBP, but additional current efforts by the authors are underway to investigate this uncertainty.

Snow and other explanatory variables

For the purposes of this study, local snowpack longevity is the focal variable for explaining WBP performance. Sentinel-2 satellite imagery will be sampled from the U.S. Geological Survey's Earth Explorer website. Imagery will be imported and analyzed in ArcGIS to determine the timing of transition from winter to spring at each site. We are interested in the period of time where only a portion (25% – 75%) of the site remains snow-covered, thereby revealing the heterogenous pattern of local snowpack longevity. Through this sampling method, we can compare individual tree condition to snowpack longevity, and we can also compare planting unit, site survival and growth rates to snowpack longevity.

Other explanatory variables of interest from the literature, manager's insights and field visits will be collected from field work in summer 2018. Sites will be sampled by hiking transects (3m apart), and are small enough to enable complete site coverage. Other explanatory data collected include: a 1/100th acre survey of nearby vegetation around each WBP in order to investigate potential competitive or mutualistic relationships between species, a general site presence or absence of Clark's Nutcrackers, pocket gophers and domestic cows, hourly temperature data will be collected by on-site HOBO data loggers (Figure 2; deployed to each of the planting units in September 2017 with permission from the associated ranger districts), and estimates of soil texture and rock content will inform an on-site categorical estimate of water holding capacity between 50 and 200mm. Other physical conditions of the sites will be collected from a digital elevation map (DEM; slope, aspect and elevation). In addition, a water balance model developed by one of the authors (D. Thoma) that estimates daily soil moisture, evapotranspiration and water deficit will be used to analyze the relationships between water availability, use and need with WBP performance.

Figure 2. HOBO temperature data logger and housing unit at the Wind River planting unit.

Whitebark pine performance

At each site, we will collect data associated with WBP performance using methodology largely developed by the U.S. Forest Service. We will note the location and number of each living WBP, its height (measured to the nearest inch), and a coarse estimate of its condition (satisfactory or unsatisfactory). Each tree will also be inspected for the presence or absence of blister rust. The survival rate will be determined by dividing the number of living WBP by the number of initially planted pines. Likewise, growth rate will be determined by the change in mean height at each site.

Analysis

A multiple linear regression will be used to examine relationships between the explanatory variables and WBP performance. The Akaike information criterion for finite sample sizes (AICc) will be used for model selection. Statistical software "R" (R Core Team, 2017) will be used for all statistical analyses.

Preliminary Results

Each planting unit was visited in the summer and fall of 2017, and each contained WBP saplings (Figure 3). Qualitative observations of site characteristics were collected, and HOBO temperature loggers were distributed. It appeared that there were discrepancies between the planting maps provided and the presence of WBP in the field. Upon further investigation, managers indicated that it is likely that although a site was selected and mapped, if planters ran out of trees to plant, they simply stopped and did not amend the planting maps to reflect this.

Although MODIS offers a snow cover fraction product to assess the percentage of snow present within a 500m pixel every 8 days, unless multiple pixels are aggregated, there is relatively high error (Arsenault et al., 2014). For this study, the sites of interest are approximately the size of one MODIS pixel or smaller, therefore aggregation of pixels is not relevant. Landsat offers 30m spatial resolution, but an image is only taken every 16 days. The presence and absence of snow during spring melt is dynamic on a much finer temporal resolution. Also, for the purposes of this study, it will likely be advantageous to detect snow at a finer spatial resolution as well. Fortunately, recent advances in satellite imagery yield finer spatial and temporal resolutions than earlier technologies (Figure 4).

According to the European Space Agency (ESA), Sentinel-2 is a "land monitoring constellation of two satellites." At our latitude, the mission provides imagery every 3 – 5 days with a visible spectrum resolution of 10m (bands 2, 3 and 4). The second satellite was launched March 7th, 2017, and became fully functional in mid-June 2017. Our work will likely be the first to utilize this technology to determine microrefugia. As with MODIS and Landsat, Sentinel-2 images are products that are free and open to the global public.

Figure 3. A WBP sapling from the Wind River planting unit.

Conclusions

Early efforts suggest that modern satellite imagery (Sentinel-2) can be used to detect the heterogeneity of snowpack longevity in mountainous landscapes at local scale (10m resolution). Although maps and shapefiles have been made for our study sites, field verification will be necessary in summer 2018. Following collection of biophysical data in the field, imagery will be reviewed and analyzed from summer 2018 that are specific to verified planting locations.

Future Work

Field work to collect biophysical data will be completed by the end of summer 2018. Image analy-

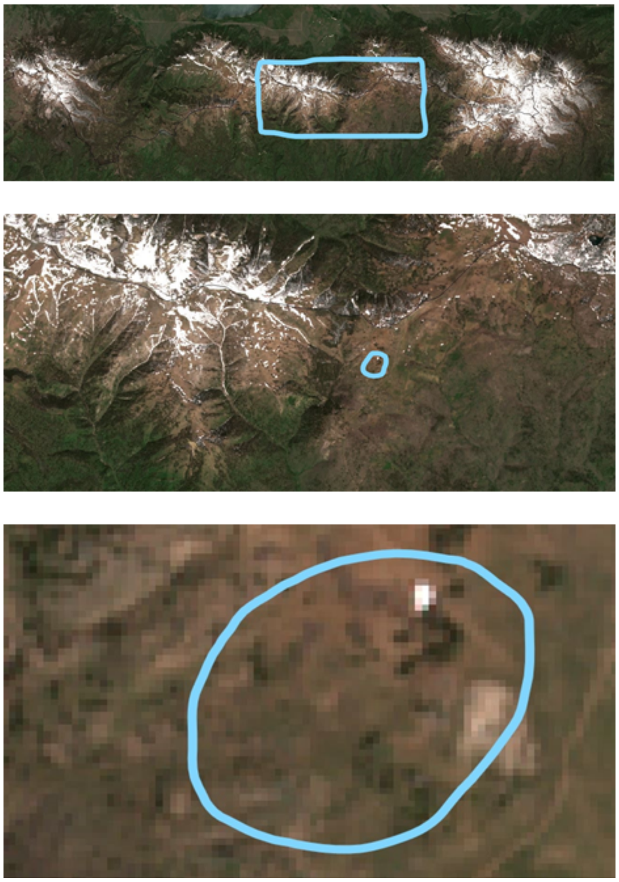

Figure 4. A subset Sentinel-2 image of the Centennial Range from June 2017 with planting unit outlined (top). Additionally subset images of the Centennial planting unit with one planting site outlined (middle and bottom). Snow presence and absence can be clearly seen in the imagery. The unit is approximately 10km, and the site is approximately 500m at its widest.

sis and a final project report will be completed in fall 2018. This project has already cultivated partnerships from multiple entities (NPS, USFS, GYCC and MSU), and represents a unique effort to utilize nascent technological advances for conservation management goals in the GYE. As the project continues to move forward, we will seek opportunities to disseminate our work widely.

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