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Predictions of Ponderosa Pine Resiliency to Climate Change in the Cebolla Canyon Watershed, New Mexico

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by

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DEDICATION

I dedicate this to all my friends and family because I am so fortunate to have your steady support in my life. And to my mom and dad in particular who taught me to think critically, creatively, and compassionately. You both let me forge my own path.

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ABSTRACT

This project was designed to understand the potential impacts of climate change on soil moisture and the resiliency of ponderosa pine in the forested region of the Cebolla Canyon watershed (Cebolla), located in eastern New Mexico. Much of the watershed is administered as public domain land by the U.S. Bureau of Land Management (BLM). This project aims to help BLM managers understand how climate change is projected to impact ponderosa pine seedling establishment and mature ponderosa pine productivity in Cebolla.

Current and potential future soil moisture regimes in Cebolla were simulated on three hills using HYDRUS-1D. The soil moisture regimes were compared to those of a ponderosa pine forest (PPF) reference site and a pinyon-juniper woodland (PJW) reference site where measured soil moisture data was available. Soil moisture for all sites was interpreted relative to its θ_{crit}, a site specific soil moisture value that depends on soil properties and the minimum soil-water potential at which ponderosa pine can extract water from the soil. The projection for seedling establishment was measured by the shallow soil moisture which was lower than θ_{crit} more often in Cebolla than the PPF site, indicating that Cebolla soils are drier than ideal for seedlings. Mature ponderosa pine productivity was measured by the deeper soil moisture regime which had over 900 consecutive days out of 1825 below θ_{crit} and became progressively drier as temperatures were increased. The results suggest that ponderosa pine resiliency is low. There are indications that current thinning treatments have sustained ponderosa pine, but the impact of thinning treatments in the future remains uncertain and small changes in θ_{crit} significantly alter the projection of ponderosa pine resiliency. Therefore, a monitoring program is recommended to obtain measured meteorological, soil moisture, and soil water potential data in Cebolla. These data would improve the BLM's understanding of soil moisture changes and projections for ponderosa pine resiliency as the climate changes.

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1 INTRODUCTION

In a changing climate (Gutzler, 2005; IPCC, 2013), forward-looking, scientifically based management decisions are desired by forest managers in order to sustain resources, wildlife habitat, and watershed conditions in the long-term. Forest managers routinely perform thinning operations in order to reduce the risk of high intensity fires and competition among tree species so that the existing ecosystem can thrive. While land managers have an interest in ensuring the sustainability of resources where possible, there is uncertainty surrounding the resiliency of forest ecosystems to climate change. As a result, management agencies face uncertainty regarding how to manage forest resources as the climate continues to change. They need more knowledge about the resiliency of vegetation and about the impacts of their current treatments on watersheds.

Studies show that as the climate changes in the southwestern US, regions that were once ideal to support certain species may become too hot and dry to continue supporting those species, leading to type conversion (Haffey, 2014; Turnbull et al., 2010; Kurc and Small, 2007; Allen and Breshears, 2002; Allen and Breshears, 1998). It is important to note that type conversions due to climate changes have occurred continuously throughout Earth's vegetated history. Only recently have we become interested in understanding how and why these changes occur because we now understand that ecosystems provide us with vital ecosystem services, like water supply. As a result, management agencies aim to understand and prevent actions that induce degradation and they aim to promote actions that lead to healthy ecosystems. The Bureau of Land Management (BLM) is required to manage the land such that the quality of scientific, scenic, ecological, and environmental standards is protected—this includes the consideration of any climate changes that may impair the attainment of these objectives.

By understanding the resiliency of certain species, the land can be managed within its limits and the limited financial resources available for management can be used efficiently. In some areas, supporting productive ecosystems could mean recognizing an inevitable transition to a different ecosystem rather than supporting the ecosystem that currently exists.

Identifying the areas where it might be better to adapt management practices to a transitioning ecosystem and areas where the ecosystem is resilient enough to thrive given current land management, was the goal of this project. Since soil moisture is a limiting factor in ecosystem productivity (Turnbull et al., 2010), this project investigated the resiliency of ponderosa pine to climate change in a semi-arid climate by determining its current and predicting its future soil moisture regimes.

The results of this project will be used to assist the BLM in their management efforts in the forested area of the Cebolla Canyon watershed. The scope is to understand current and future potential soil moisture dynamics and their impacts on pine ecology at the hillslope scale. We seek to answer the following questions:

1. What are the current soil moisture regimes in Cebolla Canyon? On which hillslopes are soil moisture conditions suitable to support ponderosa pine growth?
2. How might climate change alter the short term, upper soil moisture (for seedling establishment) and the long term, deeper soil moisture regimes (for drought resistance) in Cebolla Canyon?

2 BACKGROUND

The area of interest is the Cebolla Canyon Watershed. It is located 25 miles south of Grants, New Mexico (**Figure 1**) and is managed by the Bureau of Land Management (BLM). Approximately one third of the watershed area is a federally designated wilderness area. The watershed occupies the transition zone (or ecotone) between a ponderosa pine forest and a pinyon-juniper woodland.

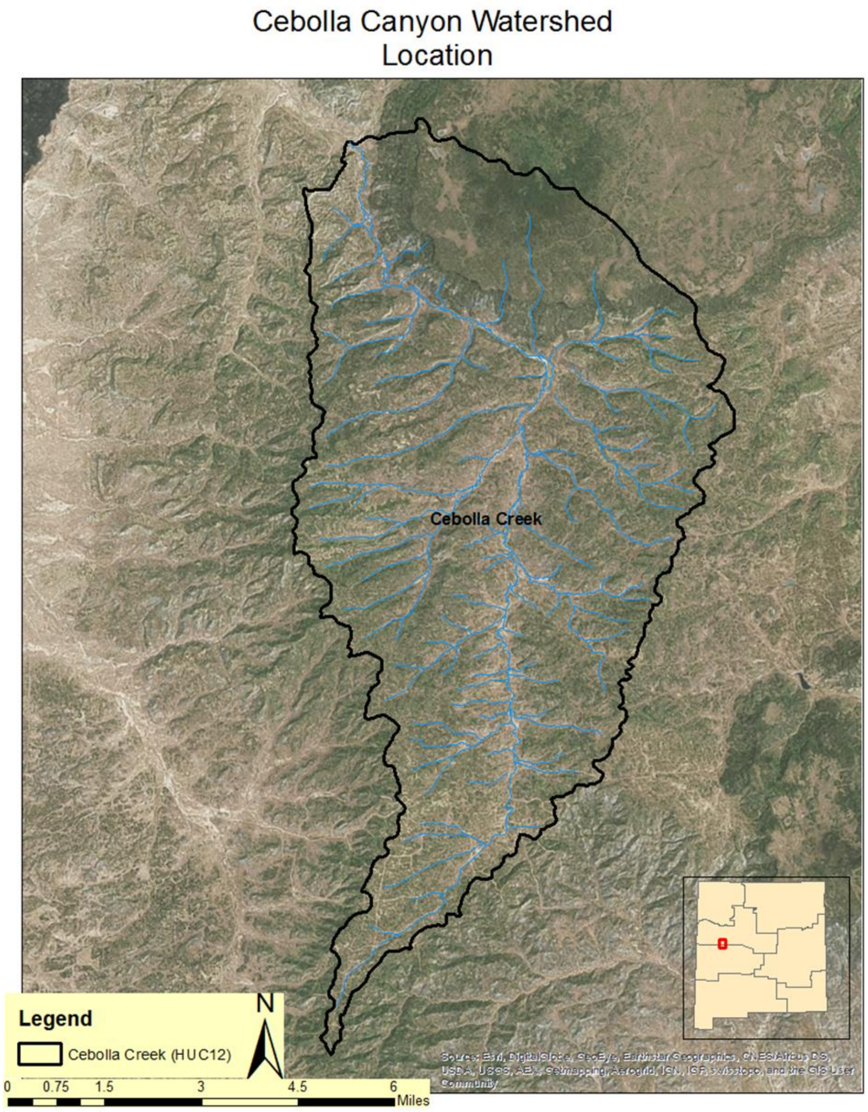


***Figure 1**: Cebolla Canyon Watershed Location Map*

2.1 Site Descriptions

To understand how the soil moisture in the Cebolla Canyon Watershed (Cebolla) relates to ponderosa pine resiliency, the soil moisture in Cebolla was compared to that of a ponderosa pine forest reference site (PPF) and a pinyon-juniper woodland reference site (PJW) where soil moisture was measured on site in each ecosystem.

2.1.1 Cebolla Canyon Watershed, NM

The Cebolla Canyon watershed occupies 35,633 acres (or approximately 56 square miles), and approximately one third of the area is a federally designated wilderness area. The elevation ranges from 2206-2673 meters (7237-8769 feet) (**Figure 2**) which puts it at the lower end of the ponderosa pine zone for the Southern Rocky Mountain region (Allen *et al*., 2002; Oliver and Ryker, 1990). Current land management practices include forest thinning, prescribed fire, chemical treatments, grazing, and historically included logging and timber harvesting.

In addition to ponderosa pine and pinyon-juniper, various shrubs and grasses are also present including Arizona fescue, mountain muhly, spike muhly, western wheatgrass, gambel oak, blue grama, and gray horsebrush (Parham, 1993). Field observations also reveal noticable differences in the vegetation on north and south aspects. Vegetation coverage is noticeably less on southern aspects where few ponderosa pine are observed except in the valleys at the bottom.

The major soils, as defined by Soil Survey Geographic Database (SSURGO), are mapped as associations and complexes. The three major soils found in Cebolla are soil mapping unit (SMU) NM591 (occupies ~50% of the watershed), SMU NM515 (occupies ~25% of the watershed), and SMU NM525 (occupies drainages, <10 % of the watershed) (**Figure 3**). The soils range from 16 to 60 inches deep. SMU 515 is suitable for pinon-juniper, SMU591 is suitable for ponderosa pine growth, and SMU 525 is located in valleys and drainages. Some important soil properties for each of the three major mapping units are shown in **Table 1**(from the soil survey and Parham, 1993).

The geology of the region includes basaltic and andesitic Miocene flows, sandstone and Mancos Shale (sandstone, shale, conglomerate, limestone), Mesozoic Tres Hermonos Formation (sandstone) and Mesozoic Crevasse Canyon Formation of fine grained mixed clastic and coal bearing units. The study area is located southeast of the El Malpais basaltic lava flow.

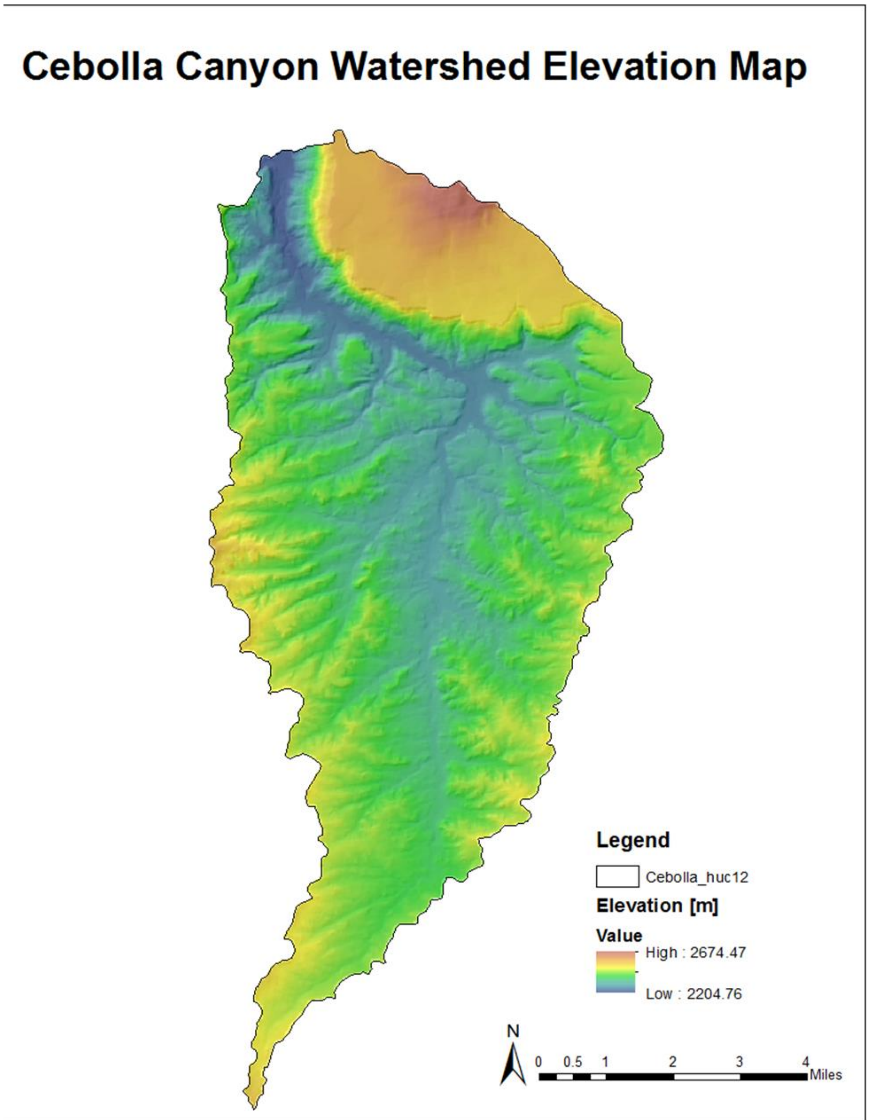


***Figure 2**: Cebolla Canyon Watershed Elevation Map*

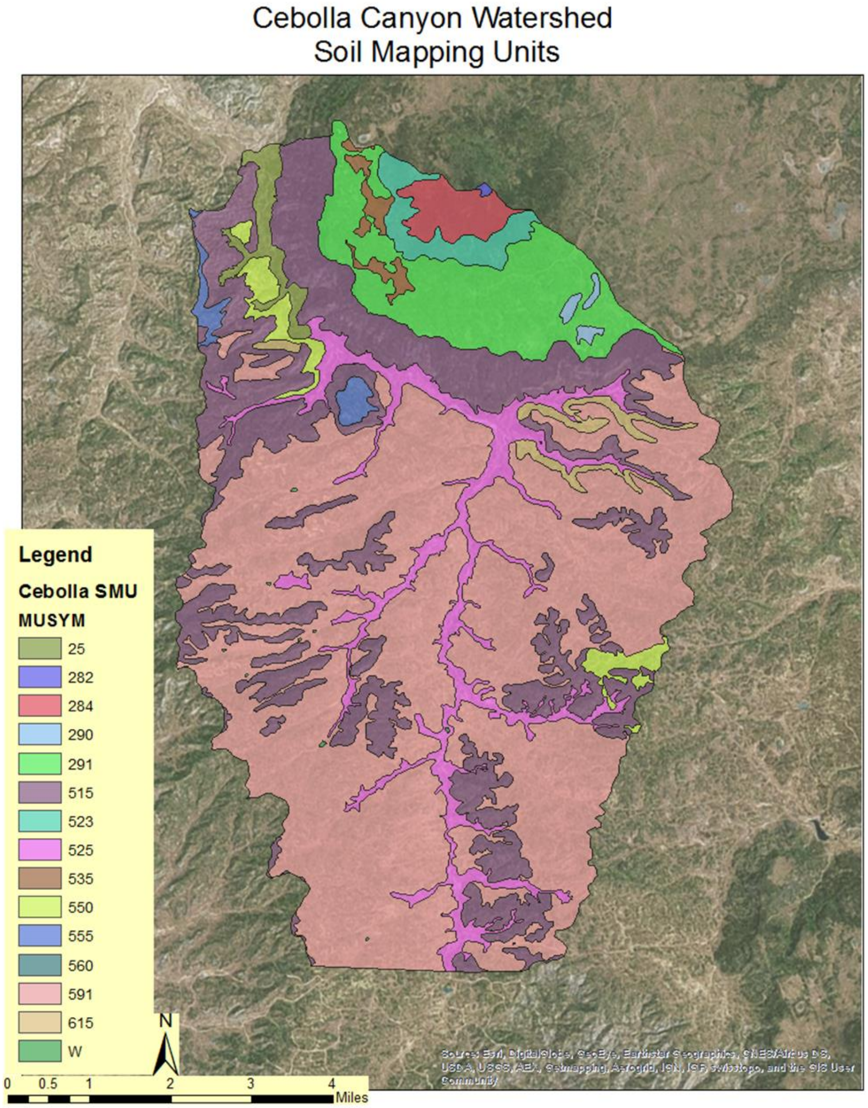


Figure 3*: Cebolla Canyon Watershed Soils Map*

Soil Mapping unit	NM 591	NM591	NM515	NM515	NM515	NM525	NM525
Major soil	**Valnor (45%)**	**Techado (40%)**	**Rock Outcrop (45%)**	**Vessila (20%)**	**Mion (20%)**	**Catman (45%)**	**Silkie (40%)**
Soil Depth	38 inches	16 inches	NA	15 inches	11 inches	60 inches	60 inches
Soil Texture	Clay loam	Clay Loam	NA	Sandy loam	Loam	Clay loam	Clay loam
Erosion hazard	Slight	Moderate	NA	Severe	Severe	Moderate	Moderate
Wind Throw Hazard	Slight	Severe	NA	Severe	Severe	Slight	Slight
Available Water Capacity	Moderate (14-21%)	Low (13-16%)	NA	Low	Very Low	High	Very High
Permeability	Slow (0.06-0.2 in/hr)	Slow(0.06-0.2 in/hr)	NA	Moderate (0.6-2.0 in/hr)	Very Slow (<0.06 in/hr)	Very Slow (<0.06 in/hr)	Very Slow (<0.06 in/hr)
Slope found on	2-7%	5-25%	NA	3-55% (North slopes)	3-55% (South Slopes	1-5%	3-10%

Table 1*: Soil Mapping Unit Details*

2.1.3 Ponderosa Pine Forest (PPF) reference site: Valles Caldera, NM

The PPF is located in the Valles Caldera National Preserve in northern central New Mexico (**Figure 4**). The site has an eddy covariance flux tower which measure climate and ecosystem scale exchange of carbon, water and energy fluxes. The tower is located at 35.862360 N, -106.597430 W at an elevation of 2200 meters (~7200 feet). The tower is maintained by Dr. Marcy Litvak of the UNM Biology Department since October 2006. Soil moisture is recorded at 5, 20, and 50 cm. Soils in the upper 50 cm, according to the soil survey, consist of silt loam (0-38 cm) overlying a gravelly loam (38-50 cm) (Soil Survey Staff, NRCS). The soil is moderately well drained with an average K_{sat} = 1 cm/hr in the most limiting soil unit in the profile (Soil Survey Staff, NRCS). The parent material is derived from rhyolite (Soil Survey Staff, NRCS).

2.1.4 Pinyon Juniper Woodland (PJW) reference site: Mountainair, NM

The PJW site is located south of Mountainair, NM in central New Mexico (**Figure 4**). The flux tower here is located at 34.438450 N, -106.237694 W at an elevation of 2100 meters (~6900 feet). This tower is also maintained by Dr. Marcy Litvak. The soil survey indicates that the PJW flux tower is located on a map unit that is bedrock. Since the site is not actually on bedrock, the next closest soil unit, located on the west side of the hill, was used. It is a stony loam (0-23 cm) and a cobbly clay loam (23-50 cm) derived from limestone (Soil Survey Staff, NRCS). The most limiting soil unit has an average K_{sat} = 0.33 cm/hr (Soil Survey Staff, NRCS).

***Figure 4**: Location Map of Study Sites*

2.2 Ponderosa Pine Ecology

Ponderosa pine is widespread throughout the western United States. New Mexico generally falls within the Southern Rocky Mountain region for ponderosa pine growth. Suitable elevations for growth tend to range from 1830—3050m (6000-10000 ft) (Allen *et al.*, 2002; Oliver and Ryker, 1990). Average annual temperatures range between 5-10 °C (41-50 °F) and 17-21 °C (62-70°F) for July and August (Oliver and Ryker, 1990). Soil moisture requirements are related to soil texture and depth. Ponderosa pine prefers sandstone derived, course textured, well drained soils over clay or fine textured soils. It is intolerant to compacted or poorly drained soils and has adapted to grow in moisture-limited regions on a wide variety of soils derived from basalt, andesite, granite, pumice, sandstone, shale, schist, limestone and quartzite (Oliver and Ryker, 1990).

It adapted to survive low intensity fires by adapting insulating bark (Graham and Jain, 2005). Due to these adaptations, seedlings do not regenerate well in unburned, organic soil (Graham and Jain, 2005) and they prefer ample sunlight (low or sparse over-story). For the first two months, they require daily minimum temperatures above -5 °C (23 °F) (Oliver and Ryker, 1990). Studies show that air temperatures between 15-23 °C (59-73 °F) and a soil temperature of 23 °C (73 °F) lead to the most productive seedlings (Oliver and Ryker, 1990). Ponderosa pine seedlings have adapted to grow tap roots because seeds do not germinate until the soil is continuously warm and moist, usually mid-summer and deeper in the soil profile (Oliver and Ryker, 1990). Mature ponderosa pine tends to access moisture from below 30 cm (~12 inches) in the soil profile (Breshears and Barnes, 1999).

2.3 Pinyon-Juniper Ecology

Pinyon-Juniper woodlands (PJW) are also widespread across the western United States. Pinyon and juniper typically occur together and are adapted for arid to semiarid environments where moisture and nutrients are limited (Neilson, 2009). In New Mexico PJW occur between 1520-2130 meters (5000-7000 feet) in elevation where mean annual temperatures are between 4.4-16.1˚C (40-61 ˚F) and mean annual precipitation is between 18-63 cm (7-25 inches) (Neilson, 2009; Kricher, 1998; Ronco 1990). Juniper extends to lower elevations and has a progressively higher population relative to pinyon at lower elevations, while pinyon extends to higher elevations within the given range and its relative population increases as the elevation increases (Neilson, 2009; Pieper, 2008).

Pinyon is expected to be the dominant species near the PJW-PPF ecotone. In central New Mexico oneseed juniper (*J. monosperma*) is the most common juniper variety while Rocky Mountain pine (*P. edulis*) is the most common pine (Pieper, 2008). They tend to occur on alkaline soils that are well drained, shallow and rocky, however, they can also occur on deeper moister soils (Neilson, 2009). Barth (1980) found that they have adapted to concentrate moisture and organic material beneath their canopies to create higher fertility. Similar to ponderosa pine, pinyon grows best in open canopy areas where there is ample sunlight with optimum temperatures at about 21 ˚C (70 ˚F), but often seedlings are observed growing near mature trees (Pieper, 2008).

2.4 Soil Moisture

Soil moisture is the total amount of water within a soil. It can be defined as the ratio of the volume of water in soil pores to the total volume of soil (V_w/V_s)—this definition is known as volumetric water content (θ). It varies diurnally, especially after a rainstorm or snow melt, and it varies more at the soil surface than deeper in the soil profile. Since we are interested in long term trends in soil moisture, daily averages were used.

Soil moisture is an important variable because vegetation depends on it to survive. While the influence of soil moisture on vegetation growth is clear, accounting for soil moisture is complex because it is affected by many variables that vary in space and time. Soil properties, vegetation, hillslope parameters and processes, climate and land management practices (such as thinning) all affect soil moisture regimes.

2.5 Components of Forest Hydrology

Soil moisture in a forested region is dependent, in part, on how precipitation partitions between the following hydrologic components: interception by tree canopies and litter, stemflow, throughfall, infiltration, surface runoff, evaporation or sublimation, and evapotranspiration (ET) (Owens *et al*. 2006). Of these seven components studies show that the percentage of canopy cover and vegetation type are the most significant factors that determine how much precipitation will reach the soil surface (Owens *et al.* 2006; Ffolliot *et al.* 2012). Owens *et al*. (2006) found that on average juniper canopies intercept 35% of rainfall and another 5% is intercepted by litter. The study reported average results for single trees.

Storm intensity is also a significant factor that affects interception. The smaller the storm, the higher the percentage of intercepted rainfall (Owens *et al*. 2006). Owens *et al.* (2006) found that 60% of low intensity rainfall (defined as less than 13 mm per 19 hour period) was intercepted by the tree canopy compared to 20% that was intercepted during high intensity rainfall (defined as >70 mm per 15 hour period) (Owens *et al.* 2006).

Rainfall that is not intercepted contributes either to direct throughfall (as opposed to indirect throughfall which falls after having been in the tree canopy) or stemflow. In juniper forests about 55% of rainfall reached the ground as direct throughfall (Owens *et al.*, 2006), however, that does not imply that 55% of rainfall contributes to soil moisture. Infiltration rates depend on the physical characteristics of the soil and, thus, can vary spatially and temporally (Ffolliot *et al.*, 2012). It is important, therefore, to have an accurate account of soil distribution and of soil properties.

Infiltration rates are also affected by vegetation type and distribution because trees are efficient at extracting soil moisture. Sub-canopy infiltration rates tend to be higher than either beneath understory vegetation or bare soil (Ffolliot *et al.*, 2012). In regions of high infiltration soil moisture is typically lower unless there is a significant and continuous flux of water into those regions. By using available soil moisture, root systems increase infiltration, soil permeability, and soil reinforcement (Chang, 2003). Additionally, organic material (litter and duff layers) on the soil surface can increase infiltration by protecting the soil surface from compaction, sealing, crusting, and evaporation, as well as by slowing runoff and allowing water to infiltrate (Chang, 2003; Ffolliot *et al.*, 2012).

Water that is not infiltrated upon first contact with the soil surface will lead to depression storage (ponding) and may runoff into a stream or infiltrate at another location on the hillslope. Litter further complicates where water will infiltrate because plants act as barriers to overland flow both delaying the onset of runoff after a storm (Ffolliot *et al.*, 2012; Turnbull *et al.*, 2010) and leading to infiltration at those “barrier” locations.

In general, forested watersheds have less runoff, longer runoff time, and lower water yield than non-forested watersheds (Chang, 2002). It seems reasonable that as trees are thinned, overland runoff will increase; however, understory vegetation that has grown post-thinning could alter flow paths and increase infiltration and transpiration rates. The result is less runoff than expected (Turnbull *et al.*, 2010). One study found that in a pinyon-juniper dominated watershed where slash was thinned and burned, streamflow increased for the first two years and then decreased the following two years as transpiration from newly grown grasses ensued (Ffolliot *et al.*, 2012).

2.6 Hillslope Parameters, Energy Balances, and Soil Moisture

Hillslope parameters include the topographic variables elevation, slope angle, aspect, and curvature. They are primarily responsible for creating “microclimates” and affecting where water flows or collects, how much water is received, and how much is evaporated. Hillslope processes are those such as erosion and mass movements which form the hillslope and the observed topographic variables. Hillslope processes are important but assumed constant this study. Soil genesis is also an important hillslope process, but is too complex for the scope of this project.

Elevation is a primary driver for microclimate differences on a hillslope. In general, as elevation increases, precipitation increases while temperature decreases. While lapse rates vary throughout the atmosphere, in air that is not saturated a dry lapse rate of 9.8 °C/km (5.5 °F/1000 ft) can be generally applied. Given the dry lapse rate and that elevations in Cebolla range ~1500 feet, we expect a temperature difference of ~8 °F between the upper and lower elevations. Since average annual temperatures range between 5-10 °C (41-50 °F) and 16-21 °C (62-70 °F) for July and August, it is likely that an increase of 2.2 °C (4 °F) over the next century (IPCC, 2014) could impact ponderosa pine productivity, resulting in higher average temperatures than typically seen in a PPF. Some models predict temperature increases in New Mexico as high as 3.3-6.7 ˚C (12° F) (Gutzler, 2005).

Aspect significantly affects soil moisture regimes because it determines how much solar radiation is received on a hillslope. Due to the earth’s inclination, equatorward slopes receive more solar radiation than pole-ward slopes (the fraction depends on latitude and season). As a result, in the northern hemisphere, south-facing slopes tend to be warmer with higher ET rates and either sparse vegetation or different vegetation altogether compared to northern facing slopes, all other factors (slope and elevation) remaining equal.

2.7 Drought Resistance

Drought has been associated with long term tree mortality in many areas. In New Mexico during the 1950's drought, when temperatures where abnormally warm and precipitation was below average, ponderosa pine mortality was observed at the lower elevations on both the Pajarito Plateau and the Frijolito Mesa in the Bandelier Wilderness (Allen and Breshears, 2002; Allen and Breshears 1998). Fifty years after the drought, very few ponderosa pine trees rebounded in those lower elevations despite favorable climatic conditions in both areas (Allen and Breshears, 2002; Allen and Breshears 1998). Predicting when and where drought related mortality will occur is an important aspect of determining resiliency to drought.

McDowell *et al*., 2008 published a review of the mechanisms that lead to widespread drought caused mortality in tree populations. They simplified previously observed mechanisms into three categories: hydraulic failure, carbon starvation, and insect/biotic infection (McDowell *et al.*, 2008). Hydraulic failure occurs due to cavitation of either the rhizosphere, the area of soil near the roots, and/or the xylem, which transports water through the tree (McDowell *et al.*, 2008). Cavitation effectively slows water movement throughout the tree. If water movement is slow enough the tree's tissue dies. Hydraulic failure occurs when a tree is depleted of water before it is depleted of carbon, i.e. when soil water potentials reach Ψ_{cav} where 100% cavitation occurs (McDowell *et al.*, 2008). Carbon starvation occurs when the tree closes stomata (the cells used for photosynthesis) to avoid hydraulic failure (McDowell *et al.*, 2008). The affect is triggered when the leaf water potential reaches a species specific minimum (Ψ_{leaf}) and if water potentials are at Ψ_{leaf} for long enough, the tree will die of carbon starvation (McDowell *et al.*, 2008).

According to McDowell *et al.*, 2008, the mechanism that leads to mortality depends, in part, on whether the tree is isohydric or anisohydric. Isohydric species maintain a constant leaf water potential as soil water potential decreases, thus, reducing the likelihood that they will reach Ψ_{cav} where 100% cavitation occurs. Isohydric species also limit the range of soil-water potentials that they can uptake water at a maximum rate (McDowell *et al.*, 2008). Anisohydric species allow leaf water potentials to decrease as soil-water potential decreases so that the species continues to uptake water and photosynthesize until Ψ_{cav} is reached (McDowell *et al.*, 2008). As a result, McDowell *et al.*, 2008 predict that isohydric species, such as pinyon and ponderosa pine, are more likely to die of carbon starvation and subsequent insect attack than from hydraulic failure unless the drought is severe enough and the soil is dry enough to lead to cavitation in the rhizosphere. They predict that anisohydric species, such as juniper, are more likely to die of hydraulic failure (McDowell *et al.*, 2008).

Some have challenged the basis of these hypothesis as phenomenological and relying on minimal evidence (Sala *et al.*, 2010). However, studies have consistently identified species specific Ψ_{crit} values—the minimum or critical, water potential when a species stops production or cavitates (Breshears *et al.*, 2009; McDowell *et al.* 2008; Maherali et al., 2004; Pockman et al., 2000). Importantly, Breshears *et al.* 2009 showed that widespread pinyon-juniper mortality was observed when below Ψ_{crit} for 10 consecutive months.

Unlike the 1950's drought which lasted about a decade, today's southwestern climate is predicted to become warmer and drier for the foreseeable future (Gutzler, 2005; IPCC 2013). The ecotone shifts that have persisted on Pajarito Plateau and Frijolito Mesa highlight the importance of understanding where mortality due to drought may occur. Changing climatic conditions in the southwest could very well result in unfavorable conditions for sustaining ponderosa pine in the Cebolla Canyon watershed. Obtaining an understanding of ponderosa resiliency is, therefore, necessary for understanding how to manage it. This study is to inform BLM managers on the possibility of ponderosa pine resiliency to climate change in the Cebolla Canyon Watershed by using the information presented so far combined with field data and HYDRUS modelling.

In this study, "resiliency" is defined in terms of the tree's ability to persist as soil moisture regimes change and applies to either seedling establishment or mature ponderosa pine. The term "soil moisture regime" is defined as the spatial and temporal characteristics of soil moisture on a hillslope.

3 METHODS

To understand ponderosa pine resiliency in Cebolla, the relationship between soil moisture and pine ecology at the hillslope scale was investigated. Given the time frame for this project and the persistent monsoon that occurred during El Nino of the summer of the 2015 study period, extensive field and climate data were unrealistic to obtain. Since Cebolla is an ecotone between PPF and PJW, soil moisture and climate data was used from two known “end member” ecological zones, a PPF and PJW. The soil moisture regimes of Cebolla were compared to those at each of the end member sites to assess the relative wet or dry state of the soil both currently and as the climate changes.

Flux tower data obtained and shared by Dr. Marcy Litvak from the PPF site in the Valles Caldera National Preserve and from the PJW located south of Mountainair, NM was used for the end member sites. HYDRUS-1D, a numerical hydrologic model was used to simulate soil moisture in the vadose zone for each of the selected hillslopes in Cebolla. Input parameters included soil texture and associated soil hydraulic properties, climate data from the North American Regional Reanalysis (NARR) dataset, and basic information about ponderosa pine physiology.

3.1 Site Selection

Within Cebolla, three hillslopes were chosen as study areas, termed Hill 1, Hill 2, and Hill 3. The hillslopes were chosen to cover as much of the 467 m elevation range as possible. Since there are few untreated sites, among the treated areas, only those that have been thinned were considered, rather than burned or chemically treated areas.

Hill 1 represents the highest elevation ranges in the watershed where conditions could remain relatively cooler and wetter, if the climate becomes hotter and drier. Its elevation ranges from 2389 to 2424 m. According to the soil survey, its soil is primarily clay loam. It was thinned in November of 2011 and the slash was scattered on the ground. Hill 2 represents the middle elevation range in Cebolla ranging from 2341 to 7385 m. Its soil is also primarily clay loam, according to the soil survey. It was thinned in 2012 and the slash was scattered on the ground. Hill 3 represents the lower elevation Cebolla ranging from 2314 to 2324 m. On Hill 3 the soils are sandy loam on the north aspect and loam on the south aspect, according to the soil survey predictions. It was thinned in 2010 and the slash was scattered. **Table 2** shows information for each site.

Within each hillslope study area, four sites were chosen of size 25 x 25 feet; there were 12 study sites in total at Cebolla. The four locations on each hillslope were chosen near the bottom and the top of each north and south facing slope. The top and the bottom of a slope was differentiated based on slope morphology, vegetation abundance, and soil surface features such as rock fragments or outcrops. The location of each site was chosen to be representative of the vegetation in the area.

3.2 Field Methods

Soil samples were collected from the middle of each 25 ft. x 25 ft. site. A hand auger was used to collect soil from the first ten inches of the soil profile. The entire soil sample was placed in a two-gallon plastic zip-locked bag, then another two-gallon zip-locked bag, and was then stored in a black bag inside a cooler to reduce evaporation until the samples could be analyzed.

3.3 Laboratory Methods

To determine the soil texture, both sieve and hydrometer tests were performed on all twelve soil samples. ASTM standard D422: *Standard Test Method for Particle Analysis of Soils* was used as a reference for both analyses, as was *Soil Mechanics Lab Manual* by B.M. Das. The sieve analysis was used to determine the percent by mass of particle sizes greater than 75µm (sand and pebble sizes) and the hydrometer analysis was used to determine percent by mass of particle sizes between 75µm and 2 µm (silt sized particles). The percent less than 2 µm (clay sized particles) was then deduced from the percent of sand and the percent of silt so that the three totaled 100%.

3.3.1 Sieve Analysis

The sieve analysis is designed to determine the mass of particle sizes greater than 75µm. A set of sieves with different mesh sizes is used and the mass retained on each sieve helps to differentiate between particle sizes. The smallest mesh size is 75µm and particles that passed through that sieve were retained in the pan for hydrometer analysis.

For each soil sample, 500g of the sample was measured and then dried in an oven at 110°C for 12 hours to remove water from the pore spaces and to prevent particles from sticking together. The sample was then pulverized in order to crush conglomerates of finer particles for a more accurate sieve analysis. However, it was observed that many of the finer particles were still aggregated, falsely appearing to be larger sized particles. In an effort to break the finer sized particles apart, the sample was washed in a #200 sieve (75 μm) which would retain sand and pebble sized particles. The sample was only partly washed in order to retain some of the fines for the hydrometer analysis.

After washing the sample, it was, again, dried at 110°C for 12 hours and reweighed. The difference between the mass after the first drying and the mass after the second drying was recorded and amounted to the mass of particles < 75 μm (silt and clay sized particles, or "fines") that fell through the sieve when the sample was washed.

The sample was pulverized again, poured into the sieve set (ASTM standard sizes 4, 10, 20, 40, 60, 100, 140, 200), and shaken using a mechanical shaker for 10 minutes. At the end of ten minutes, the sieves were removed from the shaker. The mass of the sample that was retained on each sieve was weighed and recorded. The fines, were retained for the hydrometer test.

3.2.2 Hydrometer Test

The hydrometer test was used to determine the percent by mass of silt and clay. The test is designed to differentiate between silt and clay sized particles by dispersing individual particles and recording the time they take to fall to the bottom of the cylinder. The hydrometer is calibrated to float at a certain density and sinks as particles fall to the bottom of the cylinder. Measurements are taken at numerous times. At each time the position of the hydrometer is recorded, from which the velocity of the settled particles is determined. Stoke's Law (**Eqn. 1**) is then used to determine the maximum particle size remaining in suspension at a given time, as well as the percent by mass of the particles that remain in suspension.

For each sample, 50 g of the remaining fines was weighed and used for the hydrometer test. The fines were soaked for 12 hours in 250 mL of a 4% solution of $NaPO_3$ (Sodium Phosphate), a dispersing agent. At the end of the 12 hour soaking period, the fines were mixed in a dispersion cup and poured into a 1000 mL graduated cylinder. The cylinder was filled with distilled water to the 1000 mL mark and was turned up and down for one minute to mix the sediment. After the cylinder was set down, the hydrometer was placed in and readings were recorded at 15 seconds, 30 seconds, 1, 2, 4, 8, 16, and 30 minutes, and at 1, 2, 4, 8, 12, and 24 hours until the particle size in the suspended sediment was < 2 μm which indicated that the remaining particles were clay sized. The hydrometer was taken out between readings after four minutes.

$$v = \frac{\gamma_s - \gamma_w}{18\eta} D^2 \qquad \text{[Stokes Law]} \qquad \textbf{Eqn. 1}$$

In Stokes Law, v is the settling velocity [cm/s], γ_s is the specific weight of the soil [g/cm^3], γ_w is the specific weight of water [g/cm^3], η is the viscosity of water [g-s/cm^2], and D is the diameter of the particle [cm].

3.3 Climate Data Processing

Five years of climate data from January 1, 2009 – December 31, 2013 was accessed from the National Centers for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR) dataset. Precipitation, temperature, relative humidity, wind speed, and net radiation were downloaded. The data was originally in the form of NetCDF files and was processed and formatted using the R programming language (R) so it could be entered into HYDRUS. The R package RNetCDF (Pavel, 2015) was used to unpack the NARR data.

The NARR data is reanalyzed climate data. It is simulated by assimilating millions of sources of climate data from observations (weather stations) and model generated climate data into one comprehensive climate model (Dee, 2015). It is considered comprehensive because the reanalyzed model can be used to fill in gaps between observation points i.e. climate parameters can be determined at every grid point, compared to observational data which is limited in its coverage and comprehensiveness. The NARR data is on a 32 km by 32 km grid (~20 mi x 20 mi).

For each of the five climate parameters (precipitation, temperature, relative humidity, wind, net radiation) 3-hourly time steps were chosen and averaged to daily time steps. The code used to process the NARR data is shown in **Appendix A**.

3.4 Flux Tower Data

The PPF and PJW sites each have flux towers that record continuous data at 30-minute intervals. The five years from January 1, 2009- December 31, 2013 was used for temperature, precipitation, relative humidity, wind speed, net solar radiation, soil moisture, and soil temperature. At the PPF site soil moisture and temperature were recorded at depths of 5, 20, and 50 cm. At the PJW site measurements were taken at 5, 10 and 30 cm depth.

R was used to average the 30-minute data to daily intervals. Daily data was used because soil moisture records indicate that the probes are very sensitive to temperature fluctuations and are more accurate when averaged over the whole day. Soil moisture and soil temperature measurements were made in multiple pits at each site, so the average value of all the pits was used for each depth.

3.5 HYDRUS

3.5.1 HYDRUS Basics

HYDRUS-1D is a numeric model that was developed to help characterize water movement in porous media. It combines hydrologic, topographic, vegetation, and soil parameters via mass and energy balances to model flow (Simunek *et al*., 2013). It is capable of simulating saturated and unsaturated conditions.

The primary equation it solves is the Richard’s equation for uniform water flow (**Eqn. 2**):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K\left(\frac{\partial h}{\partial x} + cos\alpha\right)\right] - S \qquad \textbf{Eqn. 2}$$

Where $\frac{\partial\theta}{\partial t}$ is the change in volumetric water content θ [cm^3/cm^3] with respect to time, $\frac{\partial}{\partial x}$ is the partial derivative with respect to the direction x (in this case, soil depth), K is the hydraulic conductivity [cm/s], $\frac{\partial h}{\partial x}$ is the partial derivative of the pressure head [cm] with respect to x, cosα is the cosine of the angle between the vertical axis and the axis of the soil profile, and S is a sink term that can be used for root water uptake.

The root water uptake equation (without compensation) is defined by the Feddes *et al.* 1987 model (**Eqn. 3**):

$$S(h) = \alpha(h)S_p \qquad \textbf{Eqn. 3}$$

Where α(h) is the root-water uptake water stress response function at h [dimensionless] and S_p is the potential water uptake rate [T^{-1}]. Root-water uptake is zero at saturation and approaches zero at the water retention of the soil (Simunek *et al*., 2013).

The van Genuchten-Mualem model was chosen to calculate the volumetric water content (soil moisture) and the Penman-Monteith equation was used to calculate the meteorological boundary condition at the surface.

3.5.2 HYDRUS Calibration Methods

To understand how the soil moisture regime in Cebolla compares to a PPF and a PJW and if it is closer to one or the other, two models were used to simulate each hillslope in Cebolla. One simulated a PJW and the other simulated a PPF. The two types of simulations are designated by *.PJ (for PJW simulation) or *.PP (for a PPF simulation). For example, a PJW simulated on Hill 1 is H1.PJ and a PPF simulated on Hill 1 is H1.PP. The idea behind simulating both ecosystems in Cebolla is that actual conditions will be somewhere between the two and projections for how well each ecosystem might survive in Cebolla can be made.

To achieve each simulation there were two phases, calibration and testing with NARR data. In the calibration phase each measured site was simulated with measured meteorological data to ensure that the HYDRUS model adequately reproduces soil moisture; these calibrations are named

PJW.measured and PPF.measured. Next, the measured sites were simulated using NARR data because NARR data is used to simulate hillslopes in Cebolla; these simulations are named PJW.narr and PPF.narr and are used as “benchmarks” to compare the Cebolla simulations to for the reasons explained below.

The processes used to simulate soil moisture in HYDRUS were water flow, heat transport, and root water uptake. Since New Mexico’s climate is bimodal, exhibiting a precipitation peak in the spring from snow melt and a peak in the summer from monsoon rains, snow hydrology was also enabled.

Measured values of precipitation, temperature, relative humidity, and wind speed were used to calibrate the HYDRUS model at the PPF and PJW sites. The record of measured net radiation had numerous missing values so NARR data was used instead. Soil texture was estimated from the Web Soil Survey through the NRCS website. The same soil texture was assumed for the entire soil profile (0-30 cm for PJW and 0-50 cm for PPF) for simplicity. The average values of percent sand, silt, and clay over the appropriate depth were obtained. Regarding the slope, HYDRUS requires the decline from the vertical axis which was calculated based on the elevation gain and length of the hillslopes obtained using Google Earth. The HYDRUS simulation was run at a daily time step for 1825 days from January 1, 2009 to December 31, 2013. Daily variations of transpiration were generated by HYDRUS as well as sinusoidal variations of precipitation. The Penman-Montheith equation was used to calculate potential evapotranspiration (PET) and the van Genuchten-Mualem soil hydraulic model was used.

The simulation for PJW had the following soil parameters: 38.2% sand, 37.4% silt, 24.4%, K_s=100cm/day (0-5cm), K_s =8 cm/day (5-30 cm). The soil particle fractions were entered into Rosetta Lite v 1.1, HYDRUS’s internal calculator to obtain estimates of the soil hydraulic parameters required to run HYDRUS.

Feddes root water uptake model was used. The parameters required were the value of the pressure head [cm] below which roots: (1) begin to extract water from the, (2) extract water at the maximum rate, (3) can no longer extract water at the maximum rate for an upper evaporation rate, (4) for a lower evaporation rate, and (5) can no longer extract water (the wilting point). The root water uptake parameters were estimated by comparing the gross primary productivity (GPP) to the soil water content graph (**Figures 13-16**). The soil water retention curve for the site was then used to determine the soil water potential at which productivity peaks and when it stops. The parameter values for PJW were -60 cm, -610 cm, -4000 cm, -6100 cm, and -20400 cm for conditions 1-5 respectively.

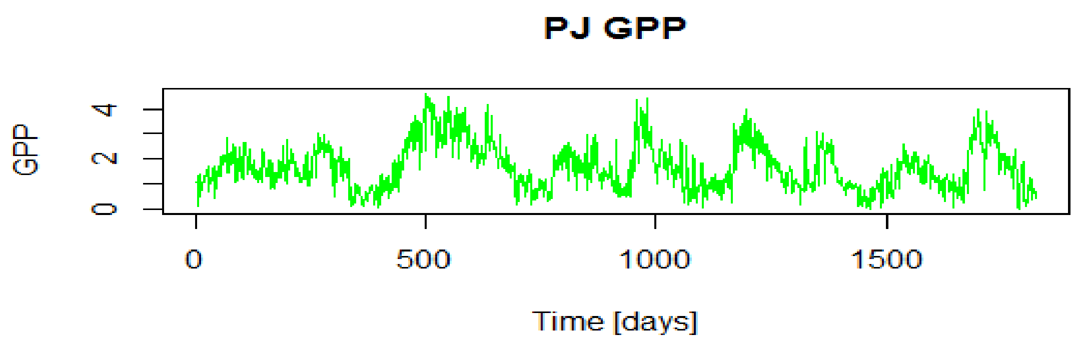


Figure 5*: PJW Gross Primary Production*

GPP of the PJW site for the five year period from Jan.1, 2009-Dec.31, 2013 shows annual cyclic variation

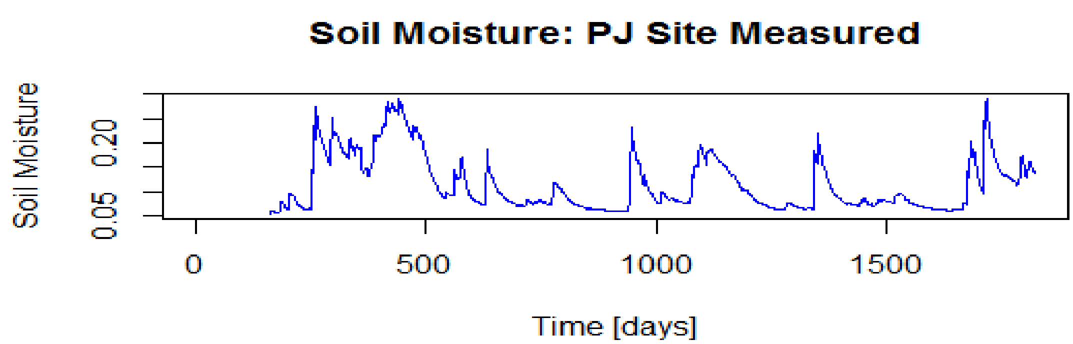


Figure 6*: PJW Measured Soil Moisture*

Measured soil moisture at the PJW site for the five year period from Jan.1, 2009-Dec.31, 2013 shows bimodal variation that approximately corresponds to GPP

The upper boundary condition was set to “atmospheric boundary condition with surface layer” with runoff initiated above h=0 water height on the surface. The lower boundary condition was set to free drainage. Heat transport parameters were estimated internally by HYDRUS according to the work of Chung and Horton and upper and lower boundary conditions were based on temperature. Snow parameters were left at the default values. Variable boundary conditions included precipitation and soil temperature at the top and bottom of the soil profile; averages for each day were used from measured data. Another boundary condition was hCritA, the minimum pressure head [cm] allowed at the soil surface. If the pressure head at the soil surface is higher than hCritA, then the actual evaporation equals the potential evaporation. hCritA is calculated by **Eqn 3**:

$$h_A = \frac{RT}{Mg} \ln H_r \qquad \textbf{Eqn. 3}$$

Where H_r is the relative humidity, h [m] is the pressure head at the soil surface, M is the molecular weight of water (0.018015 kg/mol), R is the universal gas constant (8.314 J/mol K), and T is the absolute temperature [K] (Simunek *et al*., 2013).

Meteorological parameters were net radiation, and the given leaf area index (LAI) of 1.73 for PJW (Grier *et al.*, 1992). The soil profile was discretized into 101 nodes where the spacing at the top was 0.25 cm and increased up to 0.5 cm at the bottom. The root distribution decreased from 0.40 to 0.05 through the 30 cm depth. The root densities were estimated lower than those determined by other studies for ponderosa pine (Guan *et al*., 2010; Newman *et al*., 2010) under the assumption that PJW root densities would be lower than ponderosa pine.

For the PPF site, the soil parameters used to calibrate the HYDRUS model were: 30.8% sand, 50.4% silt, 18.8% clay, K_s=100 cm/day (0-5 cm) and K_s= 17 cm/day (5-50 cm). The PPF site was calibrated for 0-50 cm since measurements at that site were taken at 5, 20, 50 cm. Root water uptake parameters were: -10.2, -500, -1000, -5000, -10200 for PO, POpt, P2H, P2L, P3 respectively (**Figures 15-16**). The root density decreased from 0.50 to 0.05 from surface to 50 cm (Guan *et al*., 2010; Newman *et al*., 2010).

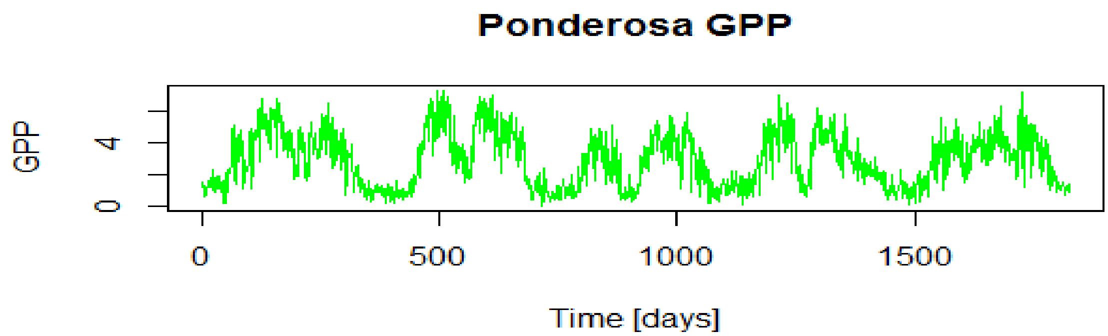


***Figure 7**: PPF Gross Primary Productivity*

GPP of the PPF site for the five year period from Jan.1, 2009-Dec.31, 2013 shows annual cyclic variation

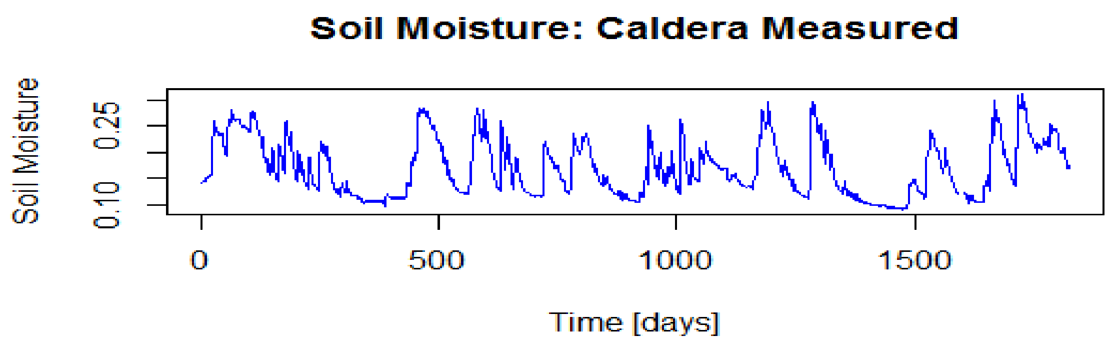


***Figure 8**: PPF site Measured Soil Moisture*

Measured soil moisture at the PPF site for the five year period from Jan.1, 2009-Dec.31, 2013 shows bimodal variation that corresponds fairly close to GPP cycles

Three tests were used to determine how well the HYDRUS model simulated the soil observed moisture:

1. Nash-Sutcliffe Efficiency test (NSE)—measures the predictive accuracy of a hydrologic model (**Eqn. 4**). A value of E=1 indicates a perfect match between the predicted and observed values. E=0 indicates that the model predictions are as accurate as the mean of the observed data and E<0 indicates the observed mean is a better predictor than the model. Moriasi *et al.* 2007 determined that the most accurate hydrologic models have NSE > 0.5

$$E = 1 - \frac{\sum_{t=1}^{T}(Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T}(Q_o^t - \overline{Q_o})^2}$$ **Eqn. 4**

2. Root Mean Squared Error—measures the error of the model predictions relative to the observed values. It yields the standard deviation of the prediction error, Moriasi *et al.* 2007 determined that the most accurate models will have an RMSE that is half of the standard deviation of the observed values. For example, the standard deviation of the PJW site is 0.056, so an RMSE < 0.028 is ideal.

$$RMSE = \sqrt{\overline{(Simulated - Observed)^2}}$$ **Eqn. 5**

3. Percent Bias (Bias)—measures the accuracy of the model predictions by calculating the percent difference between the simulated and the observed values (**Eqn. 6**). A percent bias =0 is a perfect match, Bias > 1 indicates that the model is over predicting, and Bias < 1 indicates that the model is under predicting. According to Moriasi *et al.* 2007 the most accurate models have Bias < 10.

$$Percent\ Bias = 100\frac{\sum(simulated - observed)}{\sum(observed)}$$ **Eqn. 6**

The accuracy of each simulation was tested against the observed for accuracy at 5cm, 10cm, and 30cm depths, those depths and for the average of the entire depth.

3.5.3 HYDRUS Simulation Analysis Methods

In order to quantitatively assess how wet or dry a soil moisture regime is, all simulations were analyzed relative to Ψ_{crit}, the soil water potential below which productivity stops. Studies show that sites that remain below Ψ_{crit} for 10 consecutive months (305 days) are correlated with large scale tree mortality (Breshears *et al.*, 2009; McDowell *et al.* 2008). The simulations in Cebolla are compared to PJW.narr and PPF.narr based on frequency above Ψ_{crit} and to whether or not a site has any instance of 305 consecutive days below Ψ_{crit}.

First, Ψ_{crit} for each site was determined. Ponderosa pine and pinyon pine each have different Ψ_{crit} values. The water retention curves for each measured site shows Ψ_{crit} approximately equal to -2.0 MPa for PJW and -1.0 MPa for PPF. These numbers are in agreement with those published in other studies (Breshears *et al.*, 2009; McDowell *et al.*, 2008; Domec *et al.*, 2004; Lajtha and Barnes, 1991). Each Ψ_{crit} corresponds to a θ_{crit}, the volumetric soil moisture content below which the plant cannot access moisture, for each site, depending on the soil texture. For the PJW site, Ψ_{crit} corresponds to θ_{crit} = 0.07, and for the PPF site θ_{crit} = 0.12. For each site in Cebolla, θ_{crit} was approximated using the retention curves generated in HYDRUS. The results are shown in **Table 5**.

PJW Model		**Ponderosa Model**	
Site	$\boldsymbol{\theta_{crit}}$	**Site**	$\boldsymbol{\theta_{crit}}$
PJW actual	0.07	**PPF actual**	0.12
PJW.narr**	0.1	**PPF.narr****	0.095
H1.PJ	0.056	**H1.PP**	0.065
H2.PJ	0.051	**H2.PP**	0.057
H3.PJ	0.048	**H3.PP**	0.055

Table 2*: Critical Soil Moisture Values for All Sites*

**θ_{crit} for the measured sites was 0.12 (PPF) and 0.07 (PJW) based on data collected from each site and reflects the actual soil texture at each site. Since each *.narr site was simulated in HYDRUS using soil texture data from the Soil Survey, θ_{crit} was obtained from the soil water retention curves generated by HYDRUS. Thus, the soil texture entered to HYDRUS differs from the actual soil at each site and explains why the actual θ_{crit} is different than that of *.narr.

3.5.4 HYDRUS Predictions for Climate Change Scenarios

Climate change in the southwestern United States is expected to result in higher temperatures, while precipitation remains approximately the same (Gutzler, 2005; IPCC, 2013). Temperature increases, without changes in relative humidity, will cause the vapor pressure deficit to increase, leading to higher evaporation from the soil and higher transpiration rates from vegetation. Vegetation will have higher moisture needs, as a result, but less moisture will be in the soil due to evaporation and overall higher demand for water. For such cases, an increase in the frequency that soil moisture is below θ_{crit} is predicted, as well as an increase in the maximum consecutive days below θ_{crit}. To understand how the ecosystem in Cebolla might respond to a warmer climate, temperature increases of 2, 4, and 6 °C were simulated for the three hillslopes in Cebolla.

	Hill 1				Hill 2				Hill 3			
Site Name	Hill 1 North Bottom	Hill 1 North Top	Hill 1 South Top	Hill 1 South Bottom	Hill 2 North Bottom	Hill 2 North Top	Hill 2 South Top	Hill 2 South Bottom	Hill 3 North Bottom	Hill 3 North Top	Hill 3 South Top	Hill 3 South Bottom
Site Acronym	H1NB	H1NT	H1ST	H1SB	H2NB	H2NT	H2ST	H2SB	H3NB	H3NT	H3ST	H3SB
Elevation (ft)	2389	2424	2424	2410	2342	2385	2385	2367	2314	2324	2324	2321
Slope (gradient)	0.1823	0.1823	0.195	0.195	0.153	0.153	0.148	0.148	0.153	0.153	0.059	0.059
Soil Texture in top 14” (from Soil Survey)	Clay Loam to Clay	Clay Loam to Clay	Clay Loam to Clay	Clay Loam to Clay	Clay Loam to Clay	Clay Loam to Clay	Clay Loam to Clay	Clay Loam to Clay	Clay loam	Clay loam	Clay loam	Clay loam
Vegetation	Ponderosa Pine Pinyon Juniper Gamble Oak	Ponderosa Pine Pinyon Juniper Gamble Oak	Ponderosa Pine Pinyon Juniper Gamble Oak	Ponderosa Pine Pinyon Juniper Gamble Oak	Ponderosa Pine Pinyon Juniper Gamble Oak	Ponderosa Pine Pinyon Juniper Gamble Oak	Ponderosa Pine Pinyon Juniper Gamble Oak	Ponderosa Pine Pinyon Juniper Gamble Oak	Ponderosa Pine Pinyon Juniper Gamble Oak	Ponderosa Pine Pinyon Juniper Gamble Oak	Ponderosa Pine Pinyon Juniper Gamble Oak	Ponderosa Pine Pinyon Juniper Gamble Oak
Treatment	Thinned, slash left	Thinned, slash left	Thinned, slash left	Thinned, slash left	Thinned, slash left	Thinned, slash left	Thinned, slash left	Thinned, slash left	Thinned, slash left	Thinned, slash left	Thinned, slash left	Thinned, slash left
Treatment Date	November 2014	November 2014	November 2014	November 2014	2012	2012	2012	2012	2010	2010	2010	2010

Table 3*: Cebolla Hillslope Site Characteristics*

4 RESULTS

4.1 Soil Texture

The soil texture of each sample was determined using the US Department of Agriculture (USDA) soil classification system which classifies soils based on the percent of sand, silt, and clay sized particles in the soil. The USDA soil classification triangle was used to determine the texture of each sample. See **Figures 5-7** to view the position of each sample in the triangle. **Table 3** shows the percent of particle sizes as determined by the sieve and hydrometer analyses.

Classifying the soil texture was complicated by the fraction of pebble sized particles. Half of the samples had less than 10% pebbles, but five samples had more than 20% pebbles by mass. In sample H3NT, a few medium pebbles (>25mm) accounted for 7% of the total mass and fine pebbles (>4 mm) accounted for 51% of the total mass of the sample. The other samples had fine pebbles (>4 mm) that accounted for all of the pebble mass. Samples from Hill 3 in particular had the two highest pebble fractions with fine pebbles accounting for 58% and 38% of samples H3NT and H3ST respectively.

In order to classify the soils based on the USDA system, only the relative fractions of sand, silt, and clay were taken into account, the pebble fraction was ignored (**Table 4**). However, since the presence of pebbles influences the hydraulic properties of a soil, particularly the hydraulic conductivity (K_{sat}), the fraction of pebbles was considered when specifying hydraulic soil parameters in HYDRUS.

Of the twelve soil samples, seven were classified as sandy loam, three were loamy sand, and one was loam. Among the samples, the difference in textures was due to differences in sand and silt since clay is less than 10% in each sample. The percentage of sand sized particles ranges from 51% to 78%, the percentage of silt sized particles ranges from 21% to 41%, and the percentage of clay sized particles ranges from 1% to 9%.

Regarding the relationship between soil texture and aspect or slope position, there is no apparent pattern. Sand sized particles are highest at H1ST, H2NB, and H3NB and lowest at H1SB, H2NT, and H3ST.

The texture all twelve samples was different than the soil survey predicted. Looking strictly at the top 10 inches of each soil, Hill 1 and Hill 2 were predicted by the soil survey to be on the border between clay and clay loam and Hill 3 was predicted to be clay loam. **Table 4** shows the soil classification based on the samples analyzed here and the soil survey prediction (for the top 10 inches), for comparison.

The samples analyzed were coarser than the soil survey predictions. However, during the analysis it was difficult to completely pulverize some samples and break apart the finer sediment, thus, it is likely that the sand fraction is too high and that the silt or clay fractions might actually be higher. It is difficult to say how much lower the sand fraction might be and whether silt or clay or both would be higher. Nonetheless, the analyses illustrate that caution must be taken when relying on the soil survey.

Since soil texture varies spatially, it is possible that the soil survey predictions are more accurate in some areas than in others, such as where soils are deeper or where there is more vegetation. The soils could also be changing rapidly due to high erosion rates. It is unknown how fast soils change in the Cebolla region after treatments. The changes might be different for different treatments and changes might occur at different rates.

	Hill 1				Hill 2				Hill 3			
Site	H1NB	H1NT	H1ST	H1SB	H2NB	H2NT	H2ST	H2SB	H3NB	H3NT	H3ST	H3SB
% Pebble	5.87	4.56	9.24	7.11	23.03	13.55	24.85	9.93	1.60	58.86	38.68	27.62
% Sand	58.23	58.82	63.75	46.98	59.53	44.43	54.77	61.18	71.34	28.30	39.90	46.25
% Silt	29.15	31.77	23.04	37.73	15.93	33.87	18.95	24.12	24.03	12.07	20.74	24.01
% Clay	6.53	4.34	2.38	7.11	1.3	8.04	1.2	4.64	2.62	0.57	1.38	1.81
Total	99.79	99.49	98.4	99.76	99.77	99.89	99.77	99.88	99.59	99.80	100.70	99.68
NRCS Soil Survey Texture Determination	Clay to Clay Loam	Clay to Clay Loam	Clay to Clay Loam	Clay to Clay Loam	Clay to Clay Loam	Clay to Clay Loam	Clay to Clay Loam	Clay to Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam

Table 4*: Soil Texture Analysis Resutls*

	Hill 1				Hill 2				Hill 3			
Site	H1NB	H1NT	H1ST	H1SB	H2NB	H2NT	H2ST	H2SB	H3NB	H3NT	H3ST	H3SB
Total Sand silt Clay	93.91	94.93	89.17	91.82	76.76	86.34	74.92	89.94	97.99	40.94	62.02	72.07
% Sand	62.01	61.96	71.49	51.17	77.55	51.46	73.10	68.02	72.80	69.13	64.33	64.17
% Silt	31.04	33.47	25.84	41.09	20.75	39.23	25.29	26.82	24.52	29.48	33.44	33.31
% Clay	6.95	4.57	2.67	7.74	1.69	9.31	1.60	5.16	2.67	1.39	2.23	2.51
USDA Soil Classification	sandy loam	sandy loam	sandy loam	Loam	Loamy Sand	Loam	Loamy sand	sandy loam	Loamy sand	sandy loam	sandy loam	sandy loam
NRCS Soil Survey Texture Determination	Clay to Clay Loam	Clay to Clay Loam	Clay to Clay Loam	Clay to Clay Loam	Clay to Clay Loam	Clay to Clay Loam	Clay to Clay Loam	Clay to Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam

Table 5*: Soil Texture Analysis Results Sand, Silt, Clay Only and Comparison to NRCS Soil Survey Prediction*

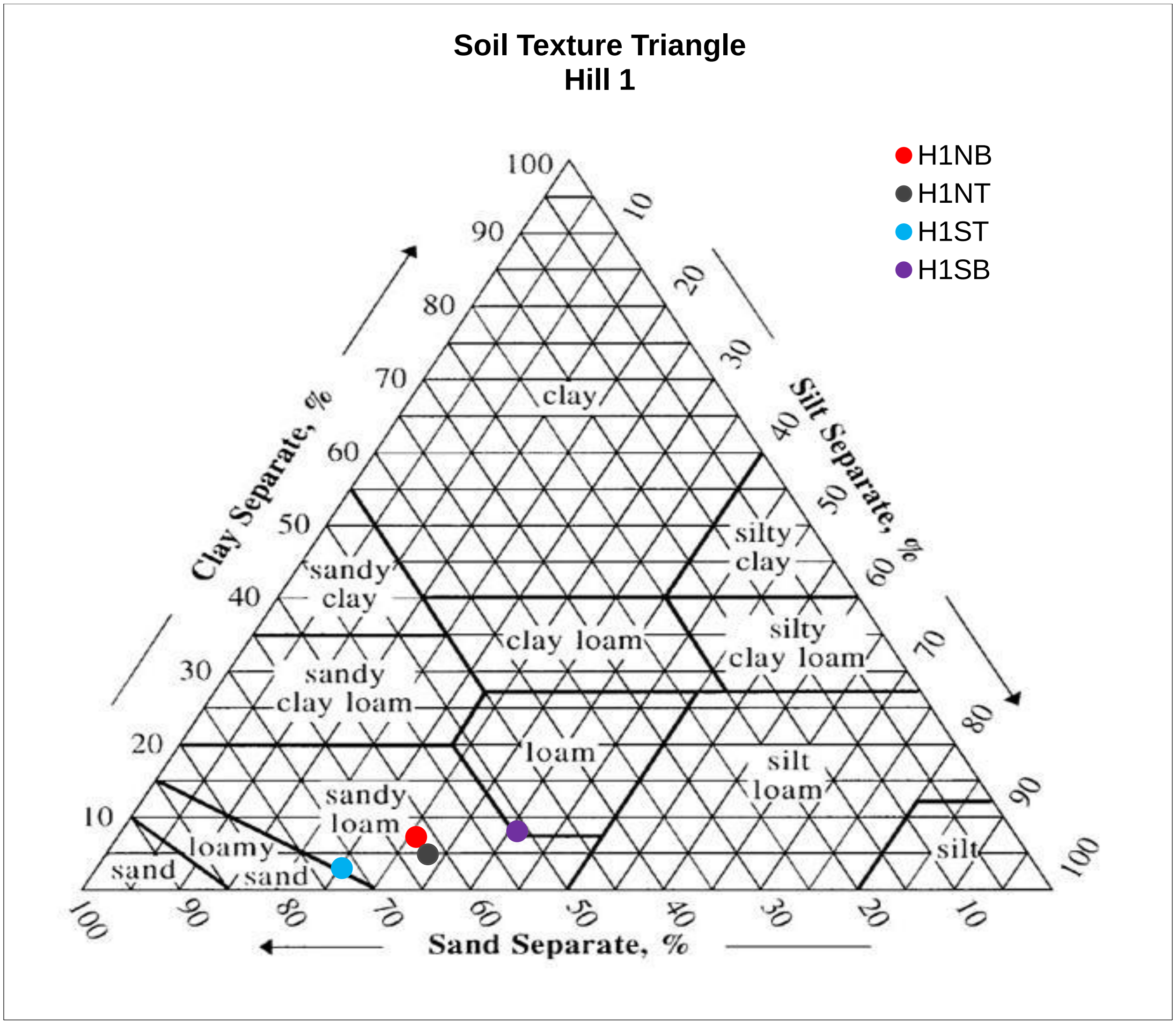


***Figure 9**: Soil Texture Classification of Hill 1 Samples.*

The classification is based on the USDA standards of percent sand, silt and clay (plot courtesy of NRCS soil texture calculator)

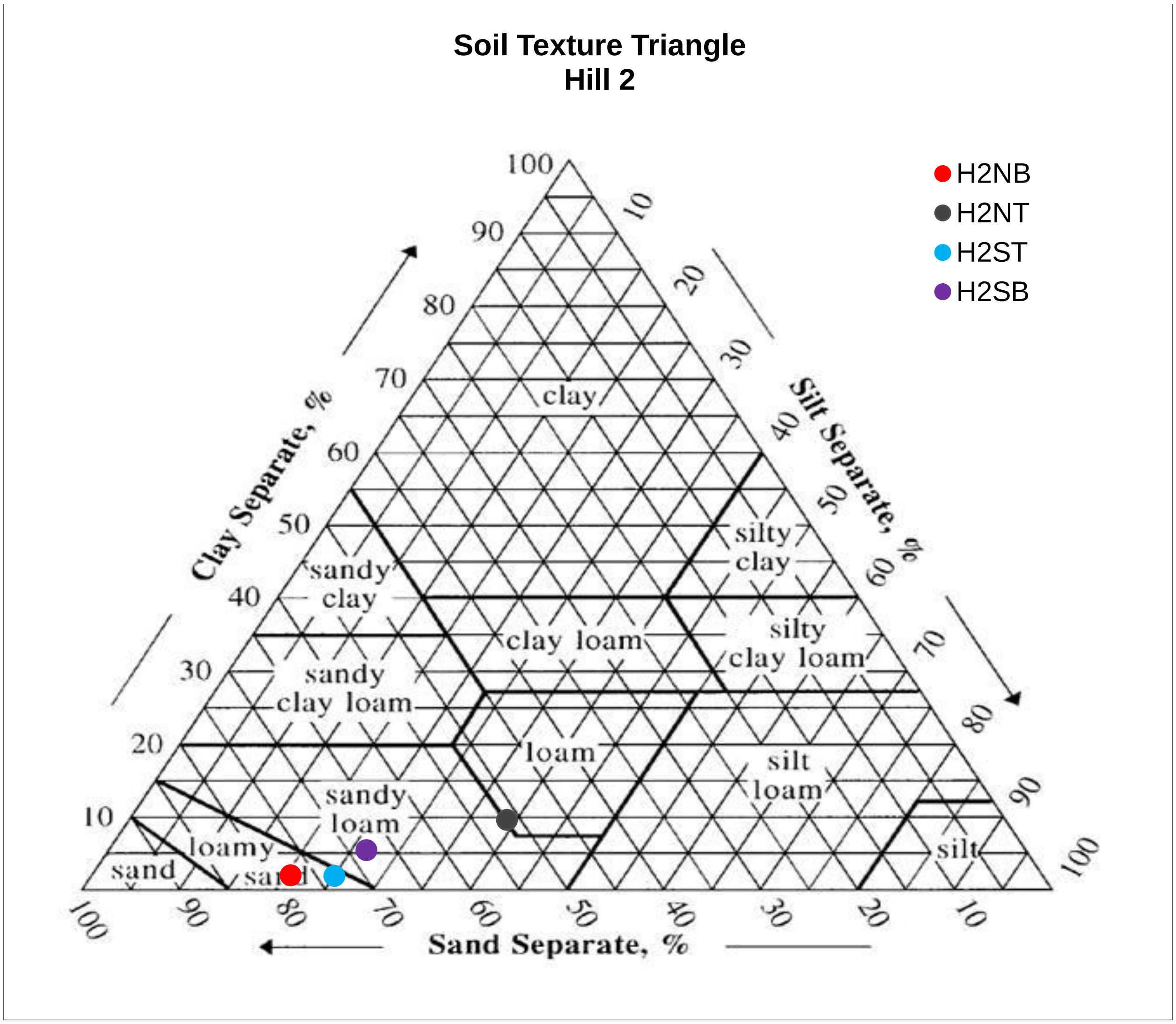


Figure 10*: Soil Texture Classification of Hill 2 Samples*

The classification is based on the USDA standards of percent sand, silt and clay (plot courtesy of NRCS soil texture calculator)

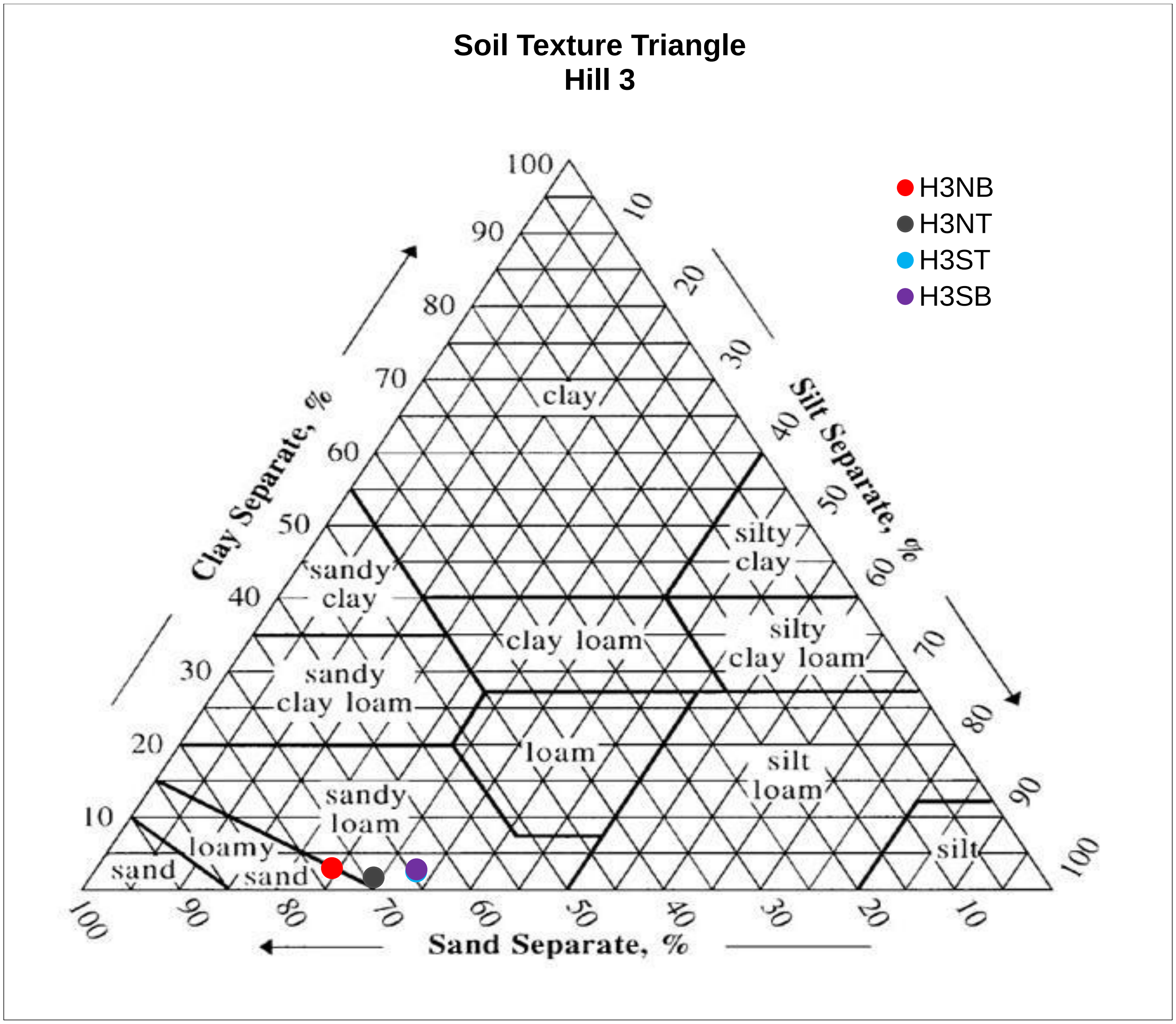


Figure 11*: Soil Texture Classification of Hill 3 Samples*

The classification is based on the USDA standards of percent sand, silt and clay (plot courtesy of NRCS soil texture calculator)

4.2 Climate Data Comparison to Flux Tower Data

NARR data was used because within the timeframe and scope of this project it was not possible to measure climate data in Cebolla. In general, the NARR data closely matched the data measured at the PPF and the PJW sites, so it is assumed that NARR data will match climate data at Cebolla just as closely. Precipitation was the most notable exception, but the difference is expected given that the scale of NARR data is 35 km^2 and precipitation is a highly localized, spatially variable event. **Figures 8-12** show the comparison of NARR data to the data measured at the PPF and at the PJW.

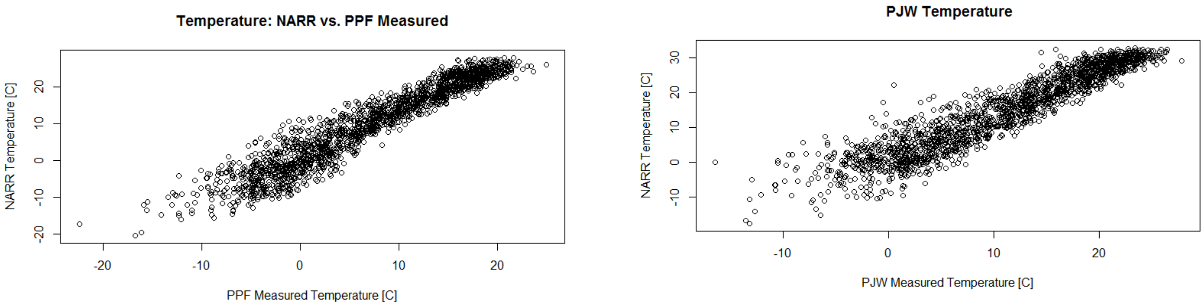


Figure 12*: Daily Average Temperature NARR vs. Measured data*

The correlation between daily average temperature NARR data and measured data for the PPF site (left) and the PJW site (right) is close

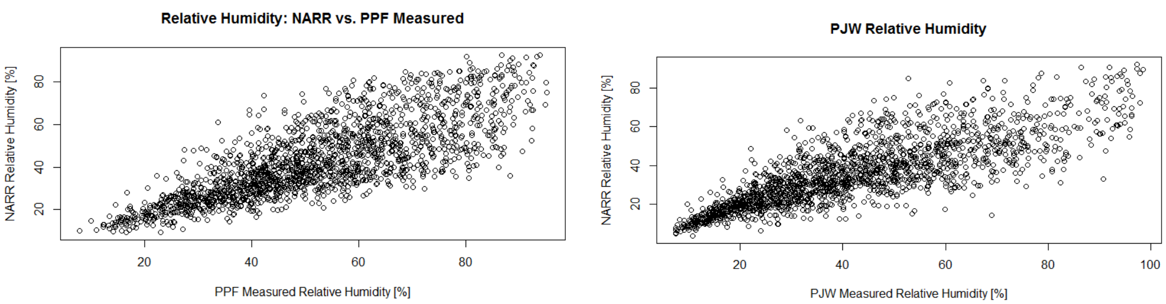


Figure 13*: Daily Average Relative Humidity NARR vs. Measured Data*

The correlation between daily average relative humidity NARR data and measured data for the PPF site (left) and the PJW site (right) is fairly close, but better at lower temperatures

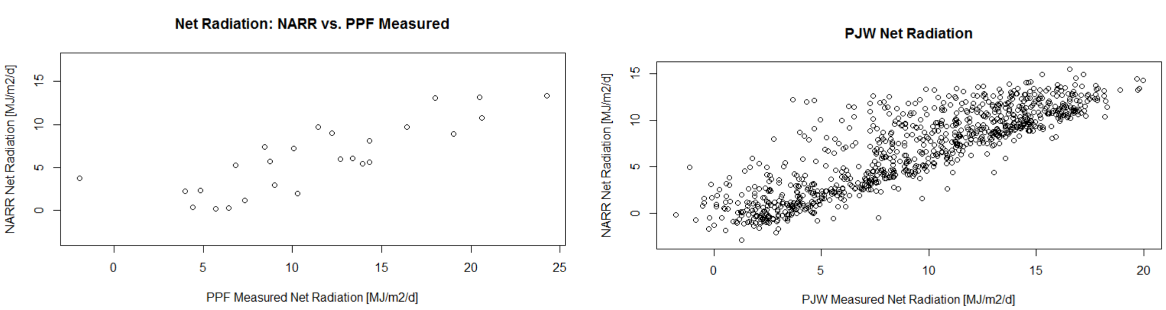


Figure 14*: Daily Average Net Radiation NARR vs. Measured Data*

The correlation between daily average net radiation NARR data and measured data for the PPF site (left) and the PJW site (right). NARR data consistently under-predicts net radiation compared to measured

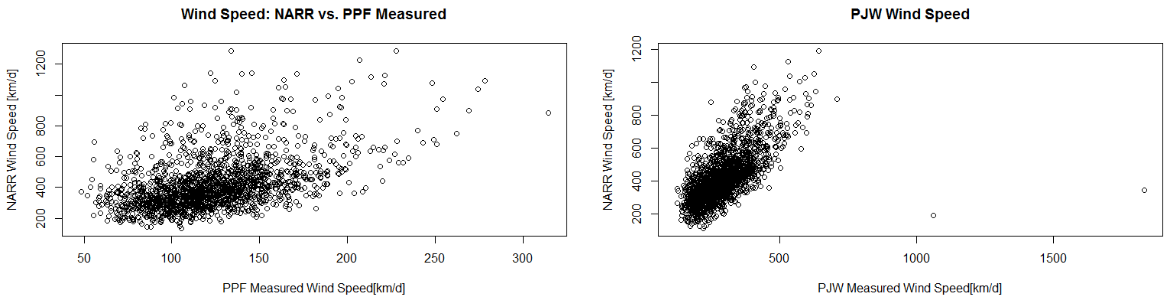


Figure 15*: Daily Average Wind Speed NARR vs. Measured Data*

The correlation between daily average wind speed NARR data and measured data for the PPF site (left) and the PJW site (right). NARR data tends to over-predict net radiation compared to measured

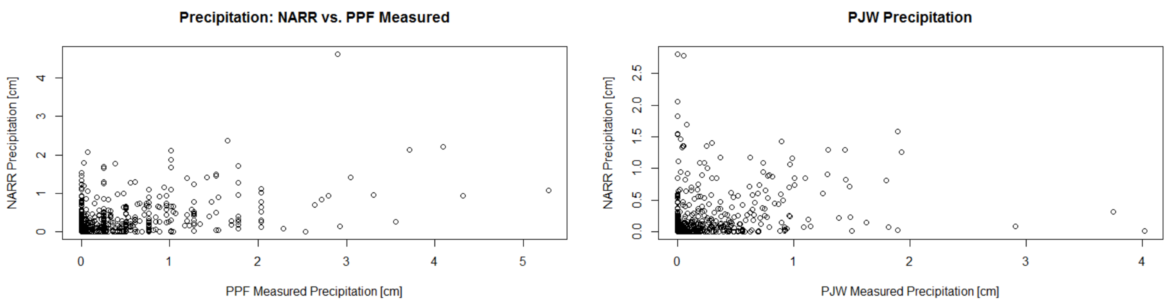


Figure 16*: Daily Average Precipitation NARR vs. Measured Data*

The correlation between daily average precipitation NARR data and measured data for the PPF site (left) and the PJW site (right). There is very little to no correlation between the two datasets.

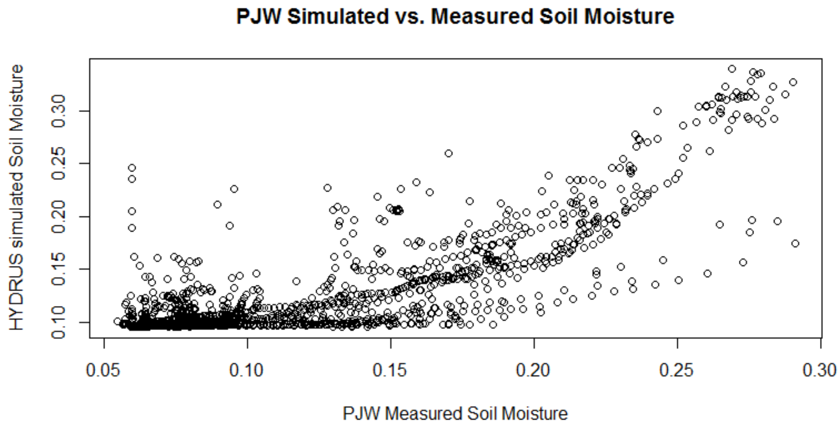
4.3 HYDRUS Simulation

To achieve each simulation there were two phases, calibration and testing with NARR data. In the calibration phase each measured site was simulated with measured meteorological data to ensure that the HYDRUS model adequately reproduces soil moisture; these calibrations are named PJW.measured and PPF.measured. Next, the measured sites were simulated using NARR data because NARR data is used to simulate hillslopes in Cebolla; these simulations are named PJW.narr and PPF.narr and are used as “benchmarks” to compare the Cebolla simulations to for the reasons explained below.

4.3.1 Calibration

For PJW.measured the average soil profile NSE = 0.63, RMSE = 0.034, Bias = 7.7%. The model’s accuracy to predict the average soil moisture is adequate and it over predicts the soil moisture by 7.7%. The RMSE is larger than desired, however, it is less than the standard deviation of the observed data (**Figure 17-18**).

For the PPF site, the observed soil moisture was measured at 5cm, 20cm, and 50cm and was averaged over 50 cm. The average NSE= -0.14, RMSE= 0.056, and Bias = -18 for PPF.measured (**Figure 17**). The statistical tests for the PPF site indicate that the parameters used are not predicting the soil moisture well. It appears that it could be due to groundwater flux because at 50 cm NSE = -3.19 and Bias = -41.8%, values that indicate a very poor predictive power and a highly under-predictive model. Assuming there is no groundwater input at Cebolla, the PPF model should be as accurate a predictor as the PJW.



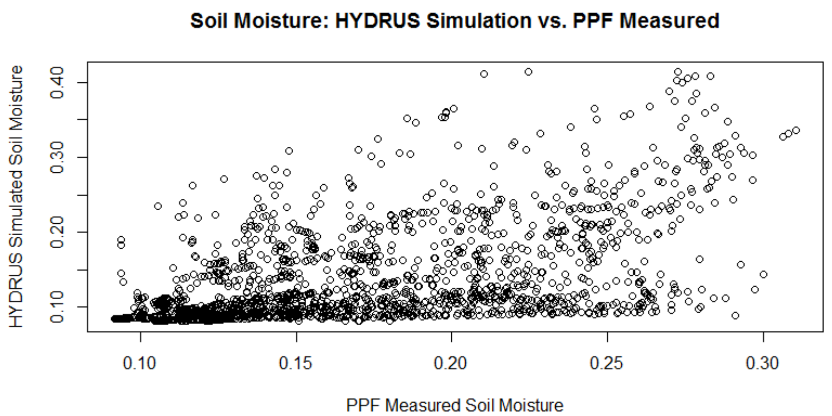


Figure 17*: Simulated Soil Moisture vs. Measured Soil Moisture*

The correlation between the HYDRUS simulated average soil moisture and the measured average soil moisture for the PJW site (top) and the PPF site (bottom). Both simulations used measured meteorological data to determine the best HYDRUS reproduction of measured soil moisture before entering NARR data. HYDRUS shows a good correlation to the measured PJW soil moisture, but under-predicts at the lower values and over-predicts at higher soil moisture values. For the PPF site, HYDRUS under-predicted most values, likely due to an unknown groundwater source.

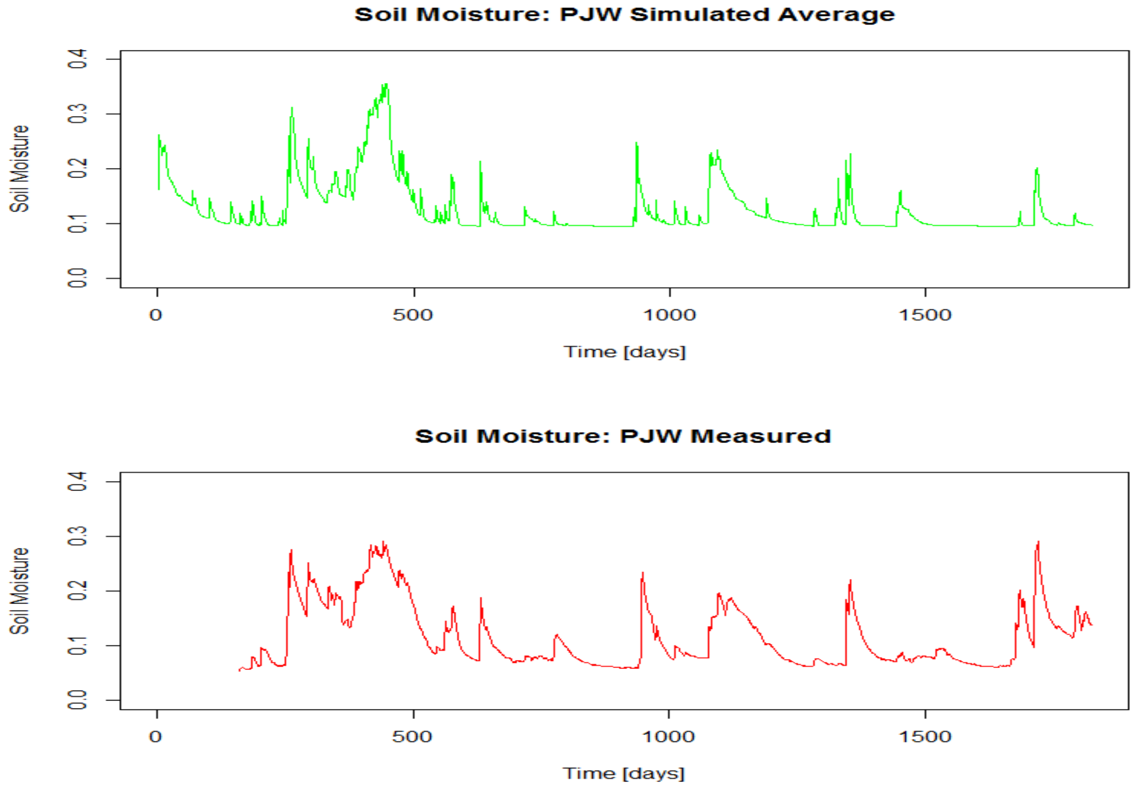


***Figure 18**: Simulated and Measured Average Soil Moisture (PJW)*

The variation in the average soil moisture (volumetric soil moisture) over the five year period between Jan. 1, 2009-Dec. 31, 2010 for the HYDRUS simulated soil moisture (top) and for the measured data (bottom) for the PJW site. The first 150 days of the measured data were missing.

The model was most sensitive to soil texture and hydraulic properties, precipitation, and root water uptake parameters. When more negative root water parameter values were used, the soil moisture curves had noticeably less intense spikes after precipitation events and in some cases no spikes at all where measured data showed spikes. Conversely, when higher root water uptake parameters were used, the soil moisture curve, overall, was higher than the measured data.

4.3.2 Testing with NARR Data

Using NARR data resulted in an underestimation of soil moisture at both sites (**Figure 19-20**). For PJW.narr, NSE = 0.23, RMSE =0.049, and Bias = -5.7. For PPF.narr, NSE =-1.27, RMSE = 0.079, and Bias = -37.1. The underestimation is expected since NARR data overall predicts drier conditions than observed and, especially since it under-predicts precipitation. Thus, the soil moisture predicted for Cebolla will likely be lower than actual. For that reason, the simulations at Cebolla are compared relative to PJW.narr and PPF.narr rather than PJW.measured and PPF.measured. The assumption is that when simulated with NARR data, the sites will under-predict actual conditions within the same margin of error. So when the simulations that use NARR data are compared to each other, the relative differences will be accurate.

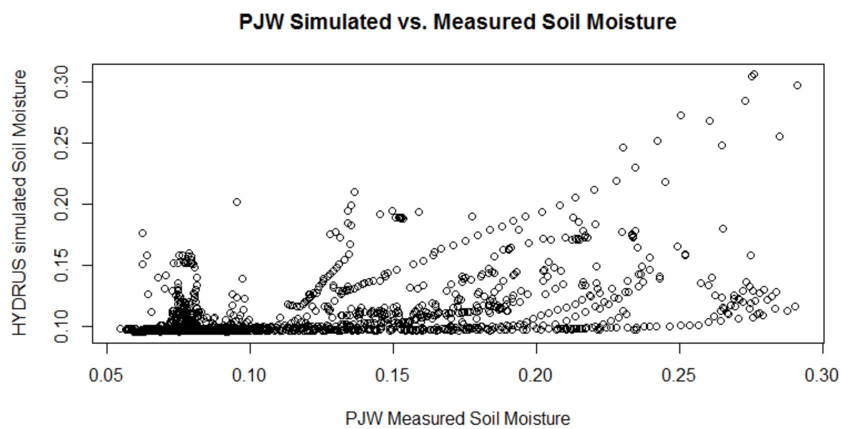


***Figure 19**: HYDRUS calibration using NARR data vs. Measured (PJW)*

The correlation between HYDRUS simulated soil moisture using NARR data vs the measured data at the PJW site. Using NARR data results in a model that under-predicts soil moisture relative to the measured.

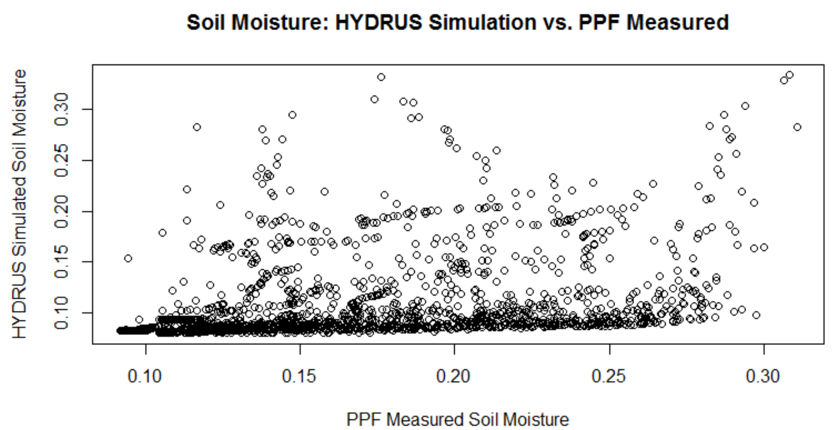


***Figure 20**: HYDRUS calibration using NARR data vs. Measured (PPF)*

The correlation between HYDRUS simulated soil moisture using NARR data vs the measured soil moisture at the PPF site. Using NARR data results in a model that under-predicts soil moisture.

4.4 HYDRUS Predictions for Current Conditions in Cebolla

Graphing the frequency that each site is above and below θ_{crit} (**Figure 21**) for the average soil profile reveals that currently, both of the measured sites are above θ_{crit} 79% of the time. And PJW.narr and PPF.narr are above θ_{crit} 41% and 43% of the time, respectively. Using 41% and 43% as benchmarks for typical PJW and PPF ecosystems reveals that all Cebolla hillslopes that were simulated as a PPF are below θ_{crit} 10-14% more often than the PPF.narr benchmark. When current simulated as a PJW, all hillslopes are above the PJW.narr benchmark. Two hillslopes, H1.PJ and H2.PJ are above θ_{crit} 100% of the time. The results confirm that current conditions in Cebolla are drier than a typical PPF and wetter than a typical PJW.

It is important to note that there are no instances when the soil moisture on any hillslope is less than θ_{crit} for more than 305 consecutive days. For all hillslopes and for both *.PJ and *.PP simulations, the maximum number of consecutive days that soil moisture is below θ_{crit} is very close to or below the benchmark. Interestingly, 108 was the maximum number of consecutive days below θ_{crit} for both measured sites, and they both have intervals above θ_{crit} that are at least twice that number. Having longer intervals above θ_{crit} than below might be an important part of recovering from drought. All of the simulated hillslopes in Cebolla have a longer intervals when the soil moisture is below θ_{crit} than when it is above θ_{crit}, indicating that the hillslopes in Cebolla might have less time to recover from drought than either of the endmember ecosystems.

The results of the current, average soil moisture show that hillslopes in Cebolla are below θ_{crit} more often than a typical PPF, but the intervals of time that each spent below θ_{crit} is about the same as its benchmark. The difference is that the intervals of time spent above θ_{crit} are shorter. The shorter intervals of time spent above θ_{crit} could ultimately influence the amount of moisture that is stored in the soil and might indicate progressively less resistance to long periods of dry periods (defined as time spent less than θ_{crit}) or drought.

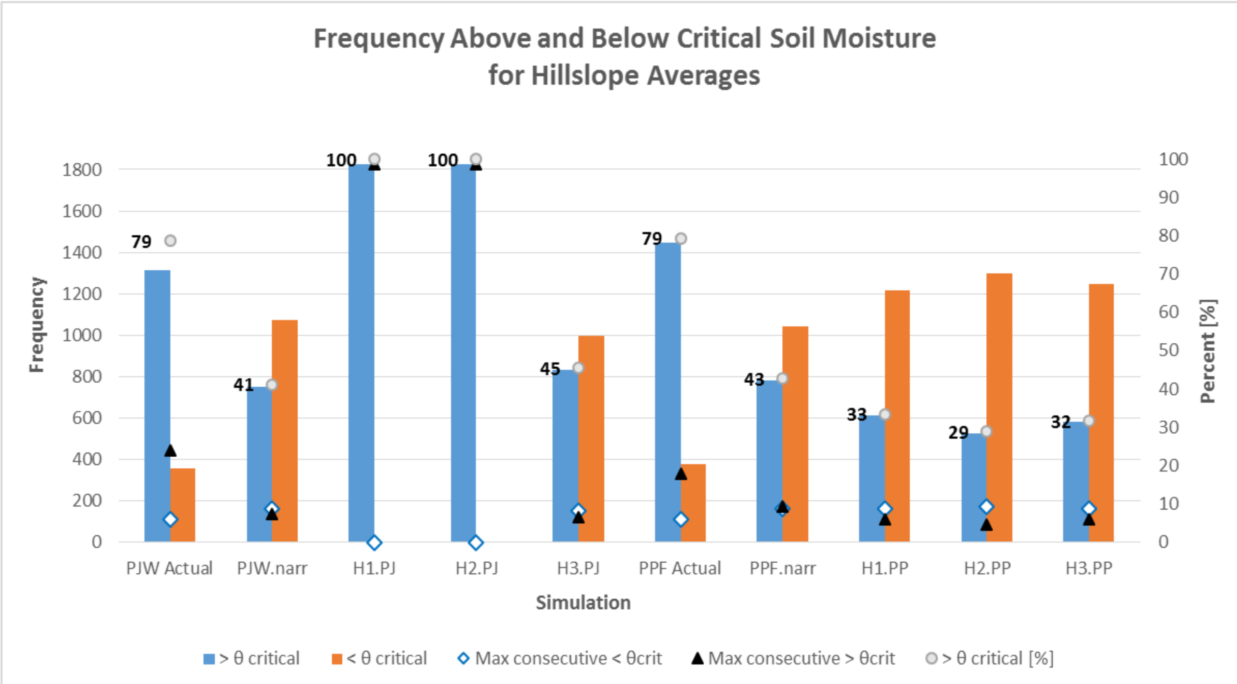


***Figure 21**: Current Average Soil Moisture in Cebolla Relative to θ_{crit}*

PJW Actual and PPF Actual are the soil moisture values that were measured at each site. PJW.narr and PPF.narr are the HYDRUS calibrations for each measured site and represent "benchmark" values that if met by the Cebolla simulations, closely match the typical soil moisture regime for that ecosystem. Bars show the frequency in days above and below θ_{crit}. Gray circles show the percent of days above θ_{crit} with the percent written in black numbers. Open diamonds and closed triangles represent the maximum number of consecutive days below and above θ_{crit}, respectively. Overall, current soil moisture is below the benchmark of typical PPF.

The shallow soil moisture regime (5 cm) appears wetter, overall, than the average soil moisture regime (**Figure 22**). The *.PJ simulations were all are above θ_{crit} more often than the benchmark; H1.PJ and H2.PJ are above θ_{crit} 98-100% of the time and H3.PJ is above θ_{crit} 8% more often than the benchmark.

There are no instances of 305 consecutive days when the soil moisture is less than θ_{crit}. The hillslopes in Cebolla have shorter dry periods than their respective benchmark ecosystems as evidenced by the maximum number of consecutive days that soil moisture is below θ_{crit}, but the maximum number of days when soil moisture is greater than θ_{crit} are all lower than the benchmark for the *.PP simulation. So the *.PP simulations still have relatively longer dry periods than wet periods in the shallow soil moisture regime. Overall, simulations indication that current, shallow soil moisture in Cebolla may be adequate for ponderosa pine seedling establishment, however, a long or intense drought could be difficult for seedlings, especially, on hills 2 and 3 which are driest.

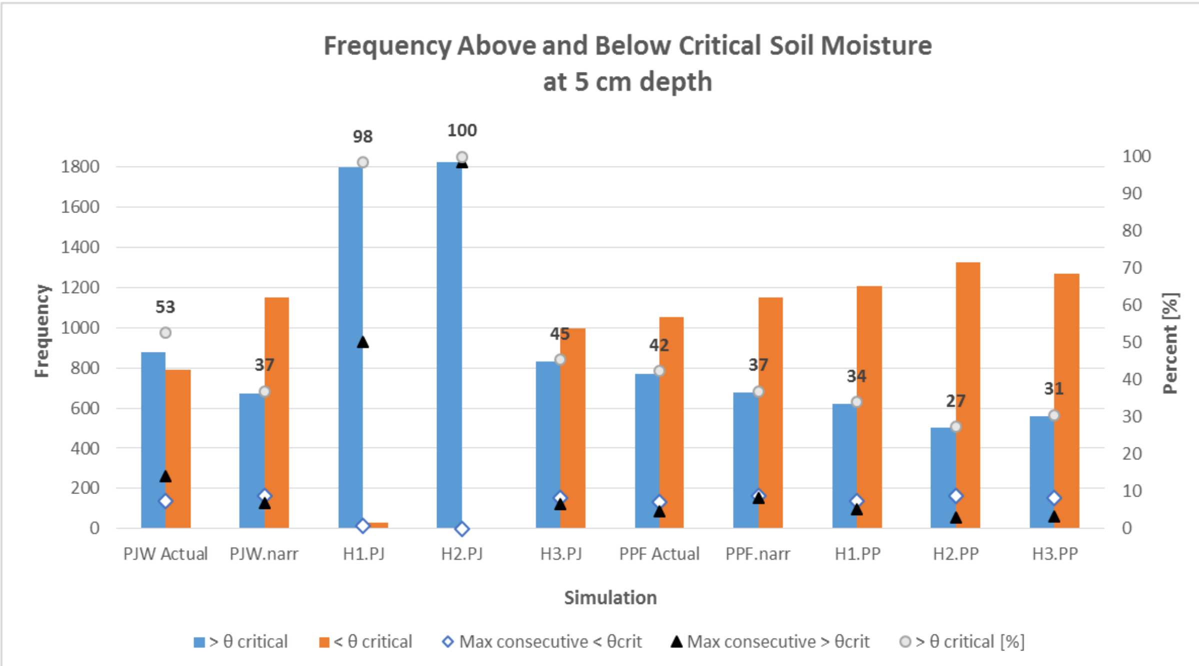


***Figure 22**: Current Soil Moisture at 5cm in Cebolla Relative to θ_{crit}*

Assessing the deeper soil moisture regime (30 cm for PJW and 50 cm for PPF) is an important consideration for the potential resilience to drier conditions. **Figure 23** shows that the *.PJ simulations are all above θ_{crit} more often than the benchmark PJW.narr simulation. Thus, the current deep soil moisture regime is wetter than a typical PJW (H1.PJ and H2.PJ are above θ_{crit} 100% of the time). The *.PP simulations are all below θ_{crit} more 11-17% more often than the PPF.narr benchmark. Both of the measured (actual) sites are above θ_{crit} 100% of the time which might be a necessary characteristic for short or long term drought resistance, especially since trees typically access moisture from below 30 cm.

Each *.PP simulation has over 1000 consecutive days or more when the soil moisture is less than θ_{crit}, indicating that, currently, the trees do not have enough moisture from deeper in the soil profile to withstand drier conditions. Contrastingly, all of the *.PJ simulations have zero days when the soil moisture is less than θ_{crit}. The high number of days below θ_{crit} is partially because the NARR data under-predicts precipitation. Actual soil moisture in Cebolla is probably not quite that dry.

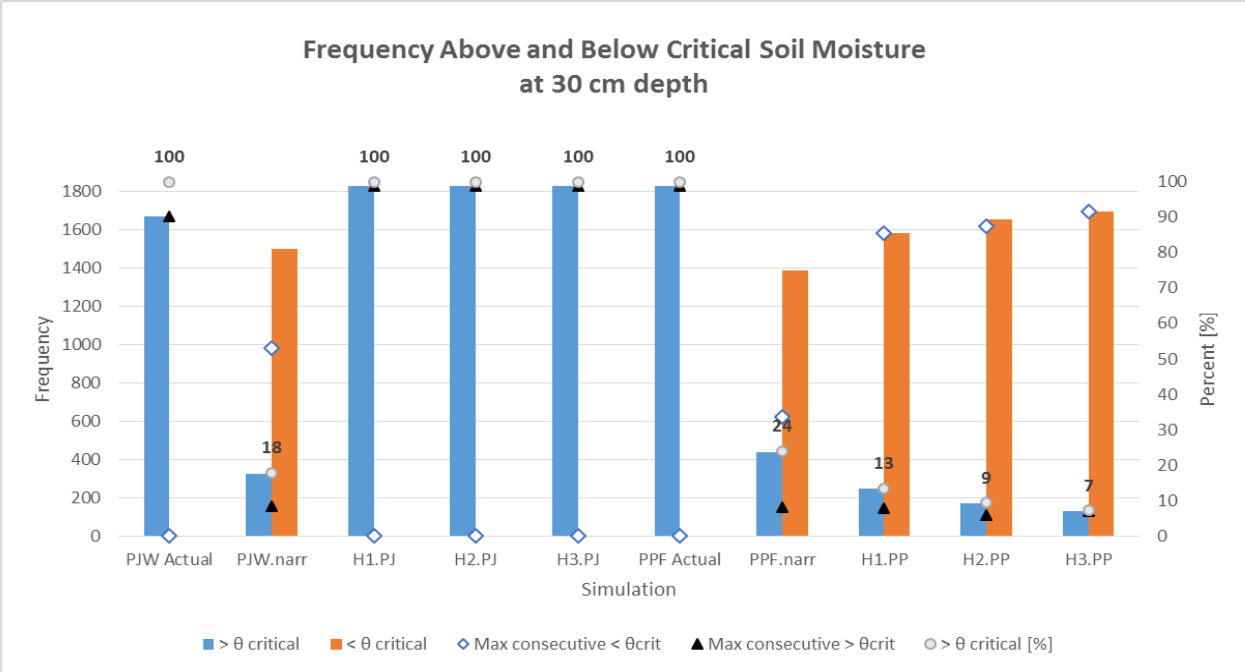


***Figure 23**: Current Soil Moisture at 30 cm in Cebolla Relative to θ_{crit}*

The deeper soil moisture regime at PJW actual and PFF actual is above θ_{crit} 100% of the time. The soil moisture in Cebolla is greater than a typical PJW site when simulated as a PJW and it is less than a typical PPF when simulated as a PPF. As a PPF, there are over 1000 consecutive days below θ_{crit}

The simulation results for the average, shallow, and deep soil moisture show that the soil moisture regimes in Cebolla are drier than those for a typical PPF and wetter than a typical PJW. While not surprising, the results do confirm that the soil moisture regime is between that of a PPF and a PJW. The average soil moisture and the shallow soil moisture regimes, while drier than a typical PPF are not critically dry and suggest that ponderosa pine can survive, though a PJW may establish and outcompete in drought situations. The deep soil moisture regime is critically dry for a PPF and the simulations indicate that ponderosa pine might not survive a long drought if the upper soil moisture became critically dry too.

Depth	PJW Model				Ponderosa Model			
	Site	305 Consecutive Days < θ_{crit}?	Max Consecutive Days < θ_{crit}	Max Consecutive Days > θ_{crit}	Site	305 Consecutive Days < θ_{crit}?	Max Consecutive Days < θ_{crit}	Max Consecutive Days > θ_{crit}
Average of all depths	PJW actual	No	108	443	PPF actual	No	108	329
	PJW.narr	No	161	137	PPF.narr	No	162	170
	H1.PJ	No	0	1825	H1.PP	No	162	112
	H2.PJ	No	0	1825	H2.PP	No	170	85
	H3.PJ	No	154	123	H3.PP	No	164	108
5 cm	PJW actual	No	138	259	PPF actual	No	135	89
	PJW.narr	No	161	126	PPF.narr	No	162	151
	H1.PJ	No	14	984	H1.PP	No	140	95
	H2.PJ	No	0	1825	H2.PP	No	162	56
	H3.PJ	No	154	122	H3.PP	No	154	60
30 or 50 cm	PJW actual	No	0	1666	PPF actual	No	0	1825
	PJW.narr	Yes	979	155	PPF.narr	Yes	624	1579
	H1.PJ	No	0	1825	H1.PP	Yes	1579	145
	H2.PJ	No	0	1825	H2.PP	No	1617	107
	H3.PJ	No	0	1825	H3.PP	Yes	1693	132

Table 6: *Consecutive Days Above and Below θ_{crit} for Current Average Soil Moisture in Cebolla*

4.5 HYDRUS Predictions for Climate Change Scenarios

4.5.1 Average Soil Moisture

Compared to the benchmarks, as the temperature increased so did the frequency that soil moisture was below θ_{crit}. The only exception was the H1.PJ simulations which had 100% of days above θ_{crit} in every temperature scenario. The maximum number of consecutive days below θ_{crit} remained within a few days of the benchmarks. And the maximum number of days above θ_{crit} remained nearly the same for *.PP simulations, H1.PJ, and H3.PJ, but was erratic for H2.PJ. There were no instances of more than 305 consecutive days under θ_{crit} for any simulation. The results are shown in **Figures 24-26** and in **Table 7** and are in agreement with predictions.

The average moisture regime is wetter than a typical PJW, currently, and is projected to stay wetter (on Hill 1) or decrease to closely match the soil moisture of a typical PJW for +2 °C and +4 °C scenarios (on Hill 2 and Hill 3). At +6C, the soil moisture is projected to decrease distinctly on all hillslopes. For a PPF, current soil moisture is drier than a typical PPF and is projected to become ~20% drier as the temperature increases. However, since the maximum number of consecutive days below θ_{crit} is 183, the average soil moisture over 50 cm might be adequate to sustain ponderosa pine with careful management even if temperatures increase 6C. The pros and cons of such management to keep ponderosa pine will need to be weighed, significant erosion may occur as a result, for instance (see discussion).

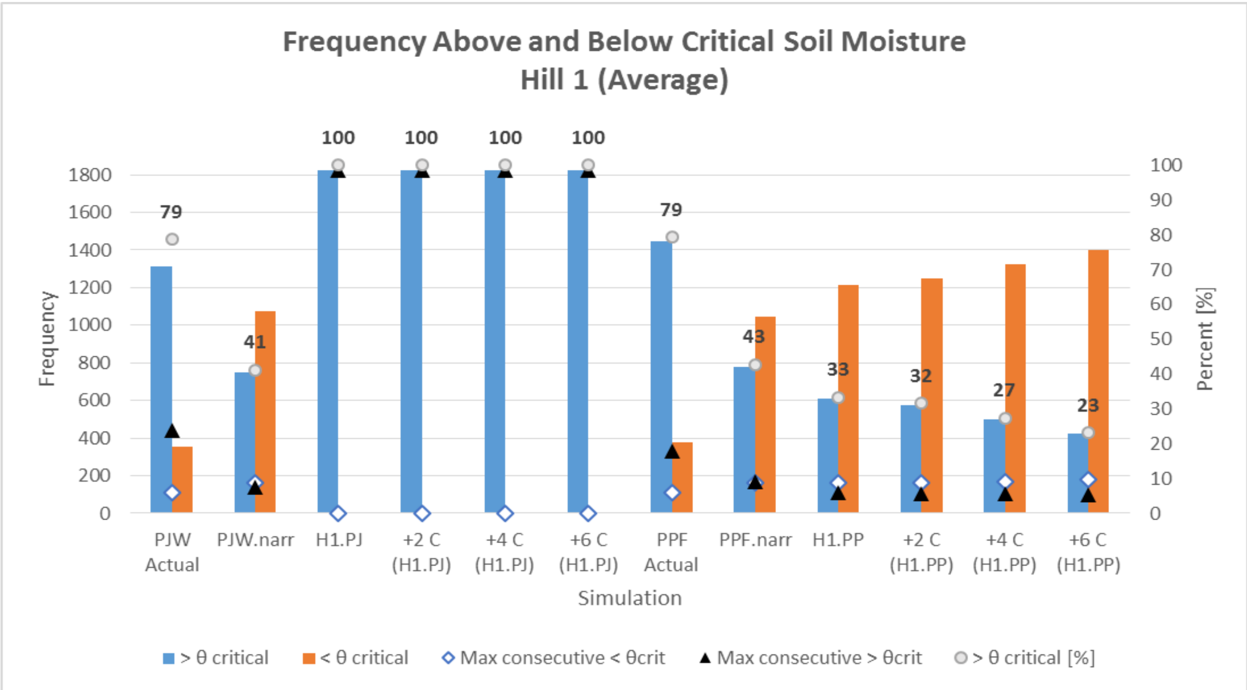


***Figure 24**: Hill 1 Average Soil Moisture for Increasing Temperatures*

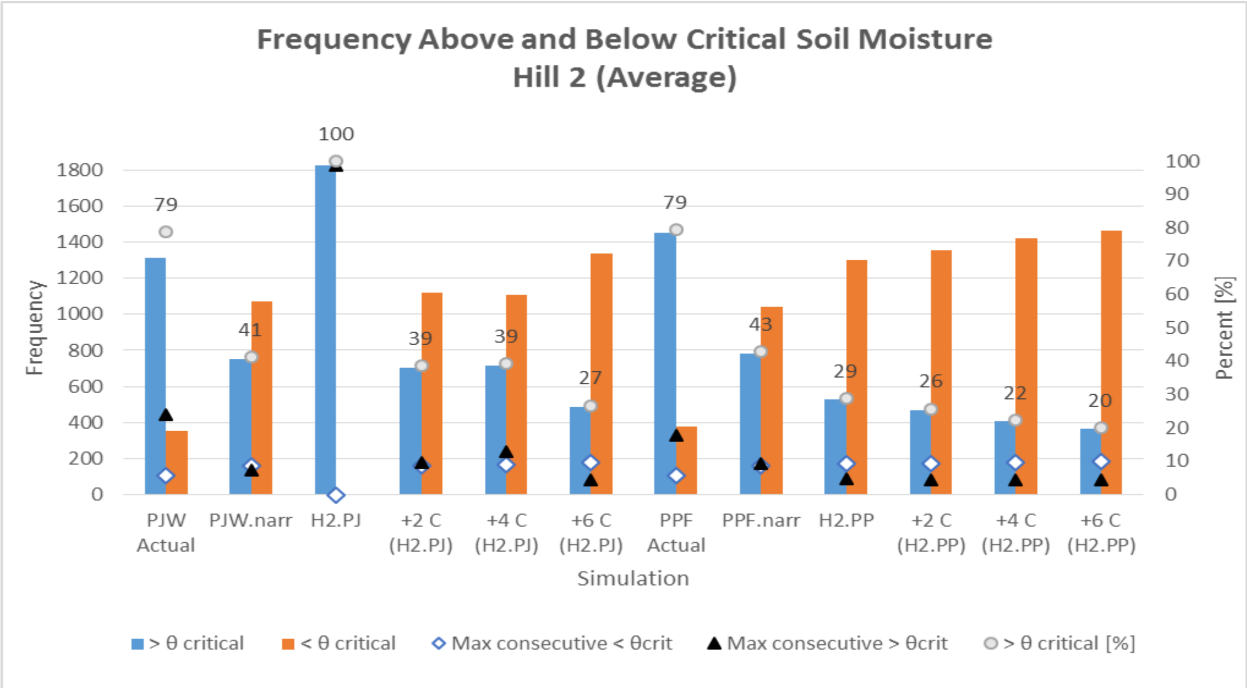


***Figure 25**: Hill 2 Average Soil Moisture for Temperature Increases*

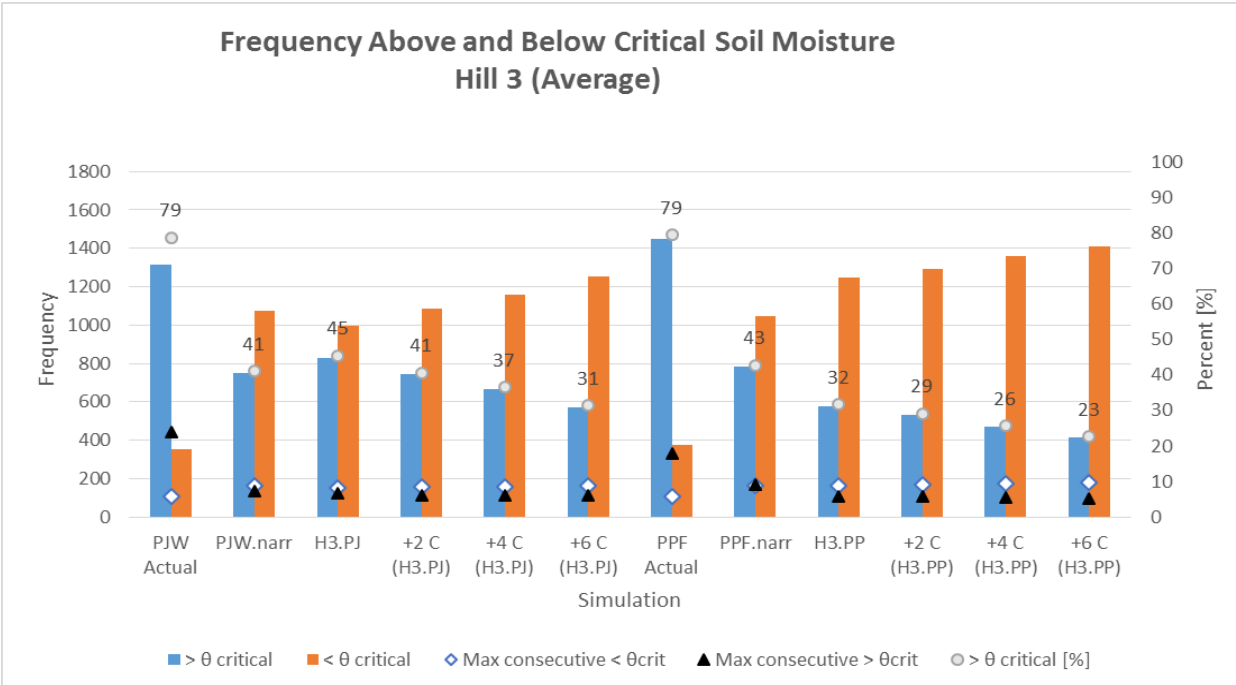


***Figure 26**: Hill 3 Average Soil Moisture for Temperature Increases*

Temperature	PJW Model				Ponderosa Model			
	Site	**305 Consecutive Days < θ_{crit}?**	**Max Consecutive Days < θ_{crit}**	**Max Consecutive Days > θ_{crit}**	**Site**	**305 Consecutive Days < θ_{crit}?**	**Max Consecutive Days < θ_{crit}**	**Max Consecutive Days > θ_{crit}**
Current	PJW actual	No	108	443	PPF actual	No	108	329
	PJW.narr	No	161	137	PPF.narr	No	162	170
	H1.PJ	No	0	1825	H1.PP	No	162	112
	H2.PJ	No	0	1825	H2.PP	No	170	85
	H3.PJ	No	154	123	H3.PP	No	164	108
+2 °C	H1.PJ	No	0	1825	H1.PP	No	163	107
	H2.PJ	No	161	176	H2.PP	No	172	82
	H3.PJ	No	155	115	H3.PP	No	170	105
+4 °C	H1.PJ	No	0	1825	H1.PP	No	170	104
	H2.PJ	No	169	239	H2.PP	No	179	80
	H3.PJ	No	157	112	H3.PP	No	174	100
+6 °C	H1.PJ	No	0	1825	H1.PP	No	178	97
	H2.PJ	No	179	79	H2.PP	No	183	79
	H3.PJ	No	165	112	H3.PP	No	179	94

***Table 7**: Consecutive Days Above and Below θ_{crit} for Temperature Changes*

4.5.2 Shallow Soil Moisture Regime

The shallow soil moisture regime (5 cm) was differentiated in order to predict how seedling establishment and survivability might be influenced by climate changes in Cebolla. The trends in the shallow soil moisture regime resemble those of the average and the frequency above and below θ_{crit} are close as well (**Figures 27-29** and **Table 8**). The frequency of days greater than θ_{crit} decreases as the temperature increases for all simulations. Similarly, the maximum number of consecutive days greater than θ_{crit} decreases as the temperature increases. There are no instances of more than 305 consecutive days when soil moisture is below θ_{crit}. The *.PP simulations are all lower than the benchmark while the *.PJ simulations show some variability, but they are all below the benchmark by +2°C except H1.PJ which remains above the benchmark through +6 °C. The shallow soil moisture simulations have shorter intervals of days above θ_{crit} compared to both the benchmark and the average soil moisture.

Notably, PJW Actual and PPF Actual show a decrease in the frequency above θ_{crit} by more than 25% compared to the average soil moisture. The decrease is because water moves into and out of the first 5 cm of soil much more rapidly than deeper in the soil due to the exchange of energy from the atmosphere. The shallow soil moisture regime is sensitive to atmospheric conditions, especially precipitation as it shows large spikes in soil moisture after precipitation.

The shallow soil moisture regime shows the same decreasing trend in the number of days above θ_{crit} as the average. Seedling establishment is predicted to be difficult for any temperature increase, but not impossible, especially with management. It is possible, however, that pinyon and juniper might establish with ease even if temperatures increase by more than 6°C.

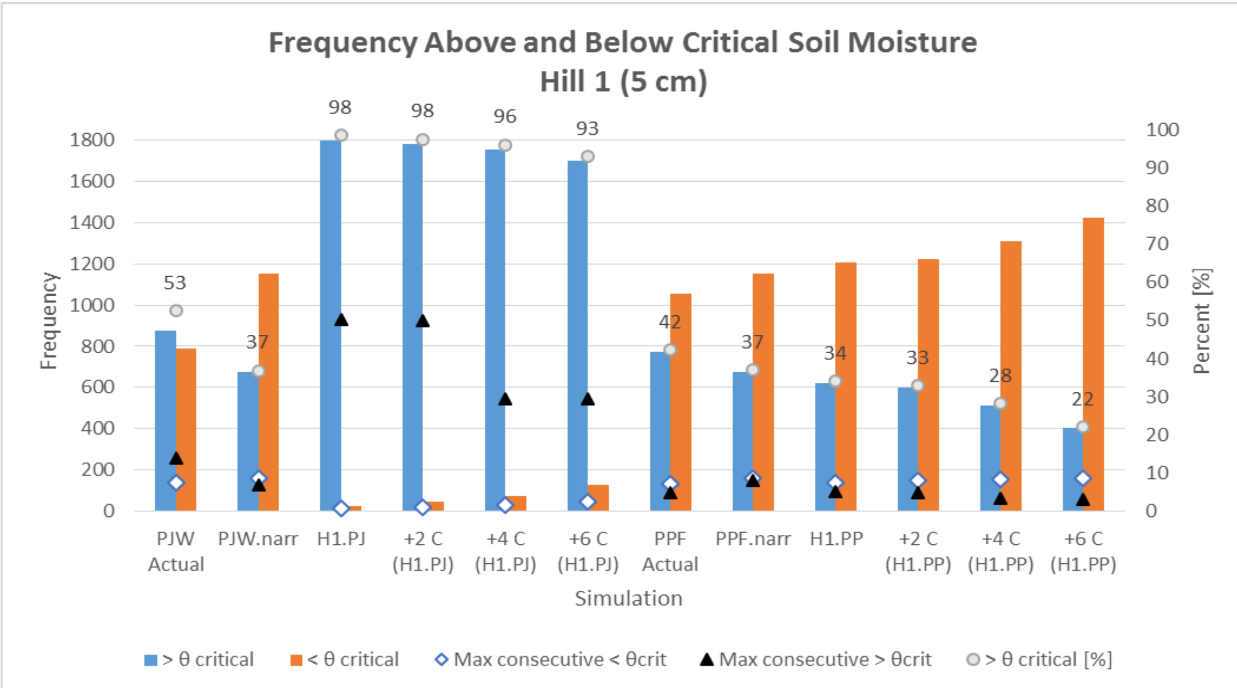


Figure 27: *Hill 1 Soil Moisture at 5cm for Temperature Increases*

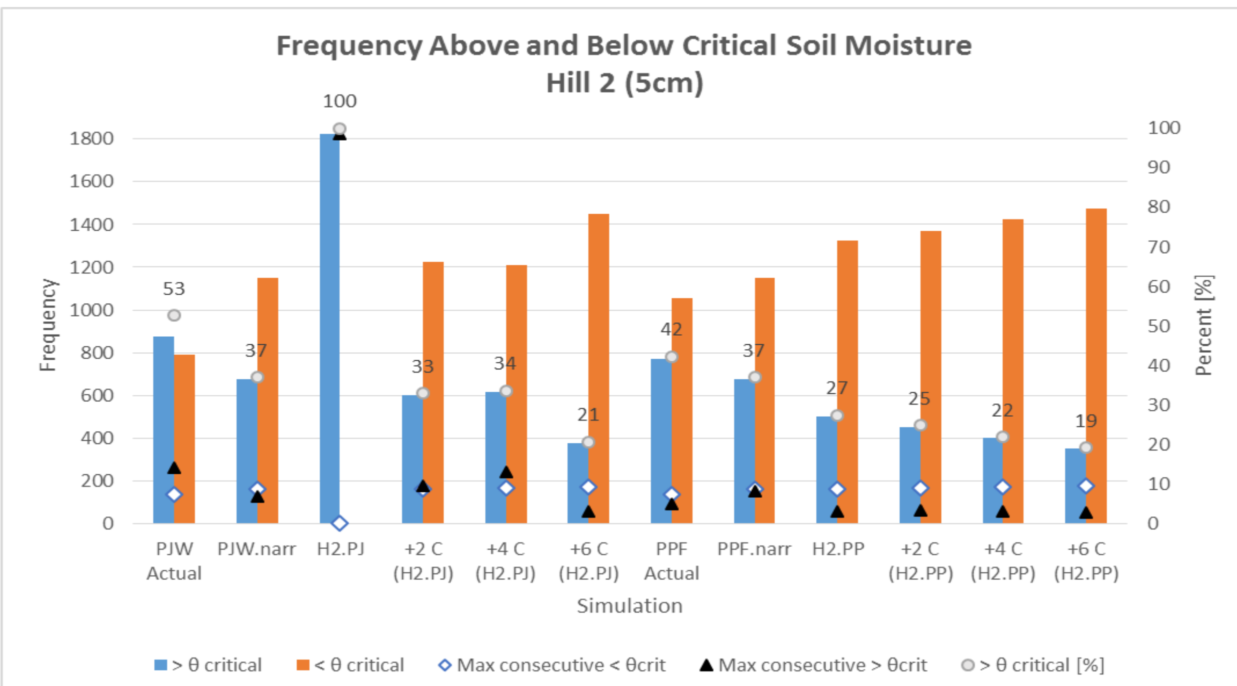


Figure 28: *Hill 2 Soil Moisture at 5cm for Temperature Increases*

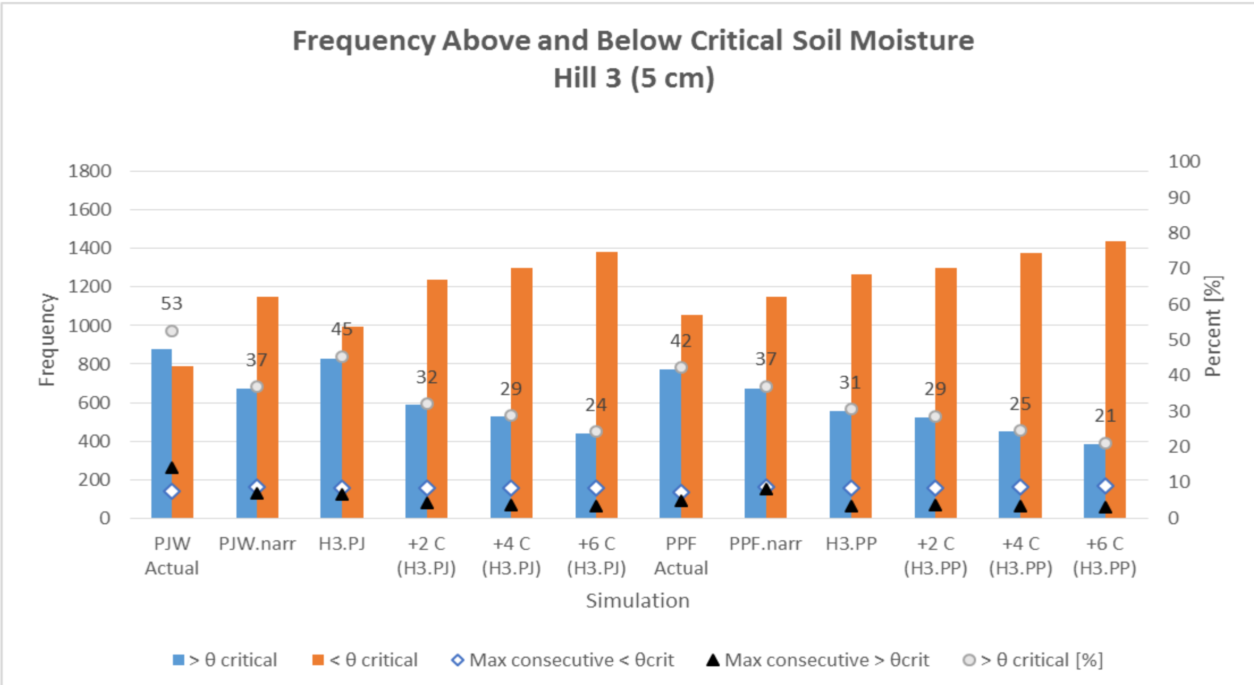


Figure 29: *Hill 3 Soil Moisture at 5cm for Temperature Increases*

Temperature	PJW Model				Ponderosa Model			
	Site	**305 Consecutive Days < θ_{crit}?**	**Max Consecutive Days < θ_{crit}**	**Max Consecutive Days > θ_{crit}**	**Site**	**305 Consecutive Days < θ_{crit}?**	**Max Consecutive Days < θ_{crit}**	**Max Consecutive Days > θ_{crit}**
Current	PJW actual	No	138	260	PPF actual	No	135	90
	PJW.narr	No	161	127	PPF.narr	No	162	152
	H1.PJ	No	14	929	H1.PP	No	140	96
	H2.PJ	No	0	1825	H2.PP	No	162	57
	H3.PJ	No	154	123	H3.PP	No	154	61
+2 °C	H1.PJ	No	21	925	H1.PP	No	152	90
	H2.PJ	No	159	176	H2.PP	No	166	62
	H3.PJ	No	154	77	H3.PP	No	156	68
+4 °C	H1.PJ	No	53	547	H1.PP	No	156	62
	H2.PJ	No	164	239	H2.PP	No	170	54
	H3.PJ	No	156	68	H3.PP	No	163	61
+6 °C	H1.PJ	No	46	553	H1.PP	No	163	59
	H2.PJ	No	171	54	H2.PP	No	178	52
	H3.PJ	No	159	63	H3.PP	No	169	55

Table 8: *Consecutive Days Above and Below θ_{crit} at 5cm for Temperature Increases*

4.5.3 Deep Soil Moisture Regime

The deeper soil moisture regime was differentiated in order to understand long term resilience of mature ponderosa pine. Since ponderosa pine accesses most of its moisture from below 30 cm, adequate moisture in the deeper in the soil profile could indicate resilience to climate change.

Analyzing the deeper soil moisture regime relative to θ_{crit}, as above, reveals that the deeper soil moisture regimes (30 cm for *.PJ simulations and 50 cm for *.PP simulations) are much drier. Almost all of the simulations have at least one instance of 305 consecutive days or more when soil moisture is less than θ_{crit}, including the PJW.narr and PPF.narr simulations (**Figure 30-32** and **Table 9**). In many cases the maximum number of consecutive days less than θ_{crit} is over 900 days and, in some cases, it is as high as 1700 days—a span of over 4 years.

However, in this case, it may be less straightforward to say that 305 days below θ_{crit} is indicative of tree mortality. Both the actual PJW and PPF sites have zero days below θ_{crit}, so if the PJW.narr and PPF.narr simulations are benchmarks that represent typical, healthy ecosystems, then the number of consecutive days below θ_{crit} should be normalized so that PPF.narr and PJW.narr have effectively zero days below θ_{crit}. To do that, the maximum number of consecutive days that soil moisture is less than θ_{crit} for PJW.narr (979) and PPF.narr (624) were subtracted from the same number for each of the *.PJ and *.PP simulations. After normalizing the simulations, there is no instance of 305 consecutive days or more when soil moisture is less than θ_{crit} for the *.PJ simulations, but for the *.PP simulations each still has 900 days or more when soil moisture is less than θ_{crit}.

The frequency of days that *.PP simulations are greater than θ_{crit} decreases in every simulation as temperatures increase, though not by much. The reason could be because the hillslopes were dry to start (i.e. current conditions) and they are nearing a physical limit—the soil water retention. The frequency of days that *.PJ simulations are greater than θ_{crit} also decrease as temperatures increase, but the frequency is greater than or equal to the benchmark for temperature increases except for H2.PJ +6C which is below θ_{crit} 2% more often than the benchmark. Simulation H1.PJ is above the benchmark for all simulations. These results show that a PJW would likely survive as temperatures increase.

The results show that, the deeper soil moisture currently and for temperature increases of up to 6°C is exceptionally dry, having over 900 consecutive days below θ_{crit}. The number of days spent below θ_{crit} combined with the observation that a typical ponderosa pine forest does not have any days below θ_{crit} indicates that the deep soil moisture regime may not be adequate to support ponderosa pine as the climate changes. Even current soil moisture conditions could be too dry to support ponderosa pine.

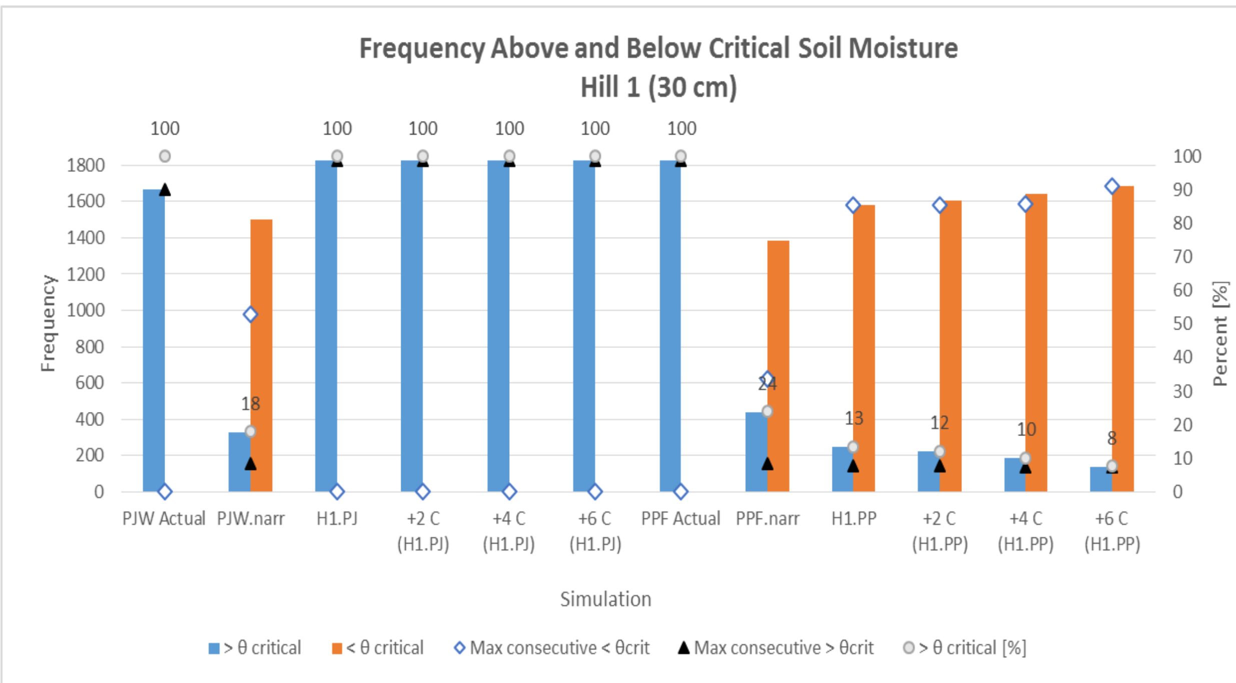


Figure 30*: Hill 1 Soil Moisture at 30 cm (PJW) and 50 cm (PPF) for Temperature Increases*

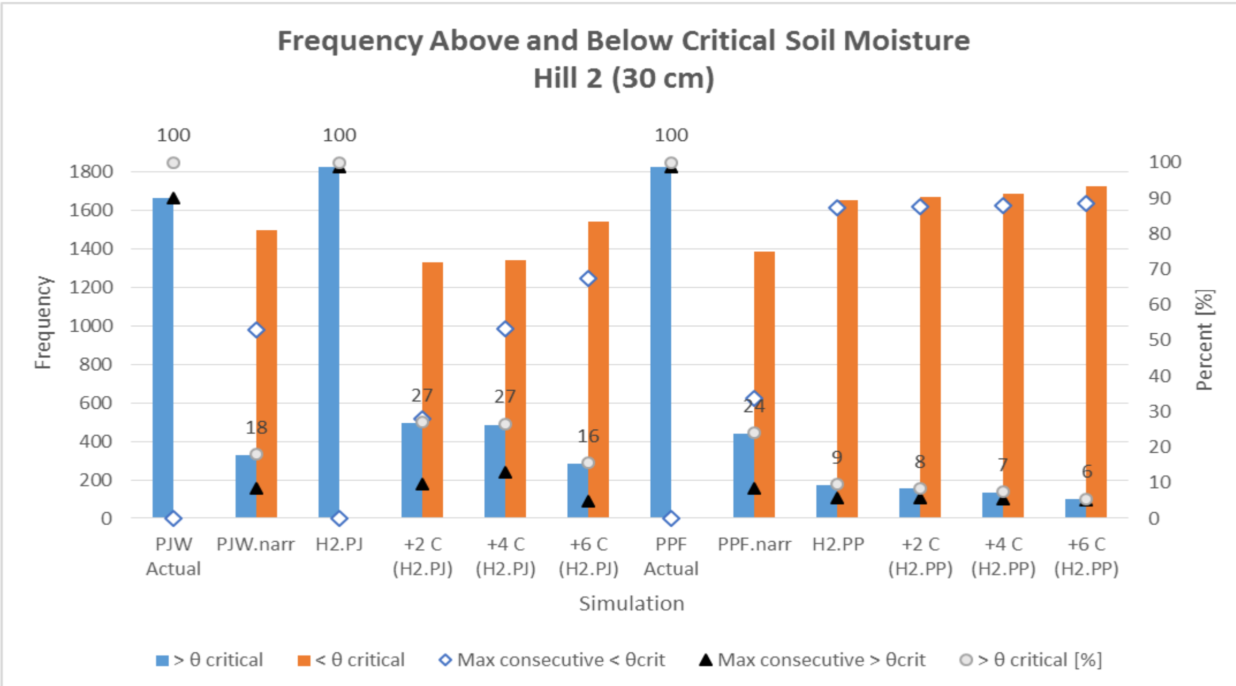


Figure 31: *Hill 2 Soil Moisture at 30 cm (PJW) and 50 cm (PPF) cm for Temperature Increases*

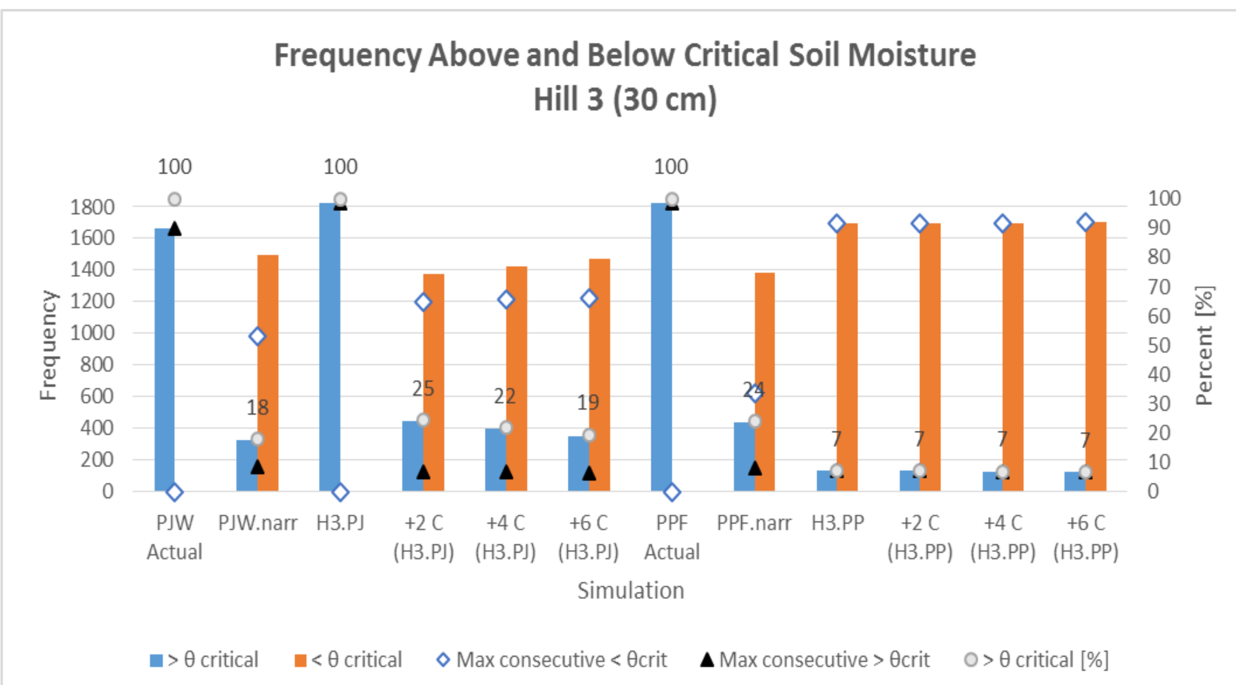


Figure 32: *Hill 3 Soil Moisture at 30 cm (PJW) and 50 cm (PPF) for Temperature Increases*

Temperature	PJW Model				Ponderosa Model			
	Site	**305 Consecutive Days < θ_{crit}?**	**Max Consecutive Days < θ_{crit}**	**Max Consecutive Days > θ_{crit}**	**Site**	**305 Consecutive Days < θ_{crit}?**	**Max Consecutive Days < θ_{crit}**	**Max Consecutive Days > θ_{crit}**
Current	PJW actual	No	0	1666	PPF actual	No	0	1825
	PJW.narr	Yes	979	155	PPF.narr	Yes	624	153
	H1.PJ	No	0	1825	H1.PP	Yes	1579	145
	H2.PJ	No	0	1825	H2.PP	Yes	1617	107
	H3.PJ	No	0	1825	H3.PP	Yes	1693	132
+2 °C	H1.PJ	No	0	1825	H1.PP	Yes	1583	142
	H2.PJ	Yes	515	176	H2.PP	Yes	1621	104
	H3.PJ	Yes	1202	127	H3.PP	Yes	1695	130
+4 °C	H1.PJ	No	0	1825	H1.PP	Yes	1588	140
	H2.PJ	Yes	983	239	H2.PP	Yes	1627	100
	H3.PJ	Yes	1213	123	H3.PP	Yes	1699	126
+6 °C	H1.PJ	No	0	1825	H1.PP	Yes	1686	139
	H2.PJ	Yes	1245	88	H2.PP	Yes	1636	80
	H3.PJ	Yes	1224	118	H3.PP	Yes	1703	122

Table 9*: Consecutive Days Above and Below θ_{crit} at 30cm for Temperature Increases*

The standard used was, if the soil moisture is below θ_{crit} for 305 consecutive days, then the tree will die from cavitation. **Table 10** shows which sites are likely to support ponderosa pine based on that standard. For comparison, **Table 11** shows the ratio of the maximum consecutive dry days to the maximum consecutive wet days. The dark shaded simulations are those for which the dry days exceed the wet days by more than the benchmark value; the higher the number, the drier the soil moisture regime. When comparing the ratio of dry days to wet days there are more simulations that the soil moisture is potentially too dry to support the simulated vegetation. The differences between these two tables highlight the difficulty in determining which hillslopes will be too dry to support a certain ecosystem and at what temperature the hillslopes might become too dry. More work needs to be done to have a reliable measure of when a system is too dry and when it is likely to recover. There is also debate in the literature on plant physiological mechanisms that lead to mortality (Mcdowell et al., 2008; Sala et al., 2010; Sevanto et al., 2014).

	PJW Average	PJW 5 cm	PJW 30 cm		PPF Average	PPF 5 cm	PPF 50 cm
Hill 1							
Current	YES	YES	YES		YES	YES	NO
+2°C	YES	YES	YES		YES	YES	NO
+4°C	YES	YES	YES		YES	YES	NO
+6°C	YES	YES	YES		YES	YES	NO
Hill 2							
Current	YES	YES	YES		YES	YES	NO
+2°C	YES	YES	YES		YES	YES	NO
+4°C	YES	YES	YES		YES	YES	NO
+6°C	YES	YES	YES		YES	YES	NO
Hill 3							
Current	YES	YES	YES		YES	YES	NO
+2°C	YES	YES	YES		YES	YES	NO
+4°C	YES	YES	YES		YES	YES	NO
+6°C	YES	YES	YES		YES	YES	NO

Table 10 *Predictions of whether or not a site can support the simulated vegetation*

The table shows which sites are predicted to support the simulated vegetation based on whether or not there are more than 305 consecutive days below θ_{crit}

	PJW Average	PJW 5 cm	PJW 30 cm		PPF Average	PPF 5 cm	PPF 50 cm
PJW Actual	0.24	0.53	0	**PPF Actual**	0.33	1.5	0
PJW.narr	**1.18**	**1.27**	**6.32**	**PPF.narr**	**0.95**	**1.07**	**4.08**
Hill 1							
Current	0	0.02	0		1.45	1.46	10.89
+2°C	0	0.02	0		1.52	1.69	11.15
+4°C	0	0.06	0		1.63	2.52	11.34
+6°C	0	0.08	0		1.84	2.76	12.13
Hill 2							
Current	0	0	0		2.00	2.84	15.11
+2°C	0.91	0.90	2.93		2.10	2.68	15.59
+4°C	0.71	0.69	4.11		2.24	3.15	16.27
+6°C	2.27	3.17	14.15		2.32	3.42	17.04
Hill 3							
Current	1.25	1.25	0		1.52	2.52	12.83
+2°C	1.35	2.00	9.46		1.62	2.29	13.04
+4°C	1.40	2.29	9.86		1.74	2.67	13.48
+6°C	**1.47**	**2.52**	**10.37**		**1.90**	**3.07**	**13.96**

Table 11 *Ratio of max length dry period to max length wet period*

Shaded cells represent the simulations that might be too dry to support the simulated ecosystem. Cells are shaded if the ratio is higher than the benchmark value

4.6 Sensitivity to θ_{crit}

Small changes in θ_{crit} have a large impact on the interpretation of the soil moisture regimes in Cebolla. To test the sensitivity, to θ_{crit} was increased from 0.056 to 0.066 for the *.PJ simulations and from 0.065 to 0.075 for the *.PP simulations, and then it was decreased from 0.056 to 0.046 for the *.PJ simulations and from 0.065 to 0.055 for the *.PP simulations. For simplicity, only Hill 1 is shown which was the wettest of the three hillslopes for the increased temperature scenarios. With ±1% change in θ_{crit} the results are significantly different, as seen in **Figures 33-38**.

When θ_{crit} is decreased 1%, the deep soil moisture regime in the *.PP simulations is greater than θ_{crit} 100% of the time both currently and for temperature increases up to + 6°C indicating that the site may be suitable to support ponderosa pine now and if temperatures increase. Additionally, all simulations are above θ_{crit} 100% of the time for all depths and for both *.PJ and *.PP simulations.

When θ_{crit} was increased 1%, the soil moisture in every simulation and at every depth was lower than the benchmark and lower than the results described previously. For the *.PP simulations, the average soil moisture and the soil moisture at 5 cm was below θ_{crit} more frequently compared to the original θ_{crit} values. The deeper soil moisture regime was also lower than θ_{crit} more frequently in all simulations, and the maximum consecutive days less than θ_{crit} increased to over 1000 for the *.PP simulations. For the *.PJ simulations the soil moisture regime at all depths is below the benchmark currently and when the temperature is increased. Previous results indicated that a PJW could persist even at +6°C, but a slightly higher θ_{crit} scenario indicates that a PJW might not persist even on Hill 1, the wettest hill studied in Cebolla.

The analysis shows that the interpretation of the soil moisture regimes and their potential capacity for supporting ponderosa pine is very sensitive to θ_{crit}. One θ_{crit} value leads to the interpretation that the soil moisture regimes are suitable to support a PPF both currently and as temperatures increase, while a θ_{crit} that is 1% different can lead to the interpretation that not even a PJW might survive in a +6°C future. Therefore, it is essential to have a precise value of θ_{crit} when using this method to analyze the soil moisture regime.

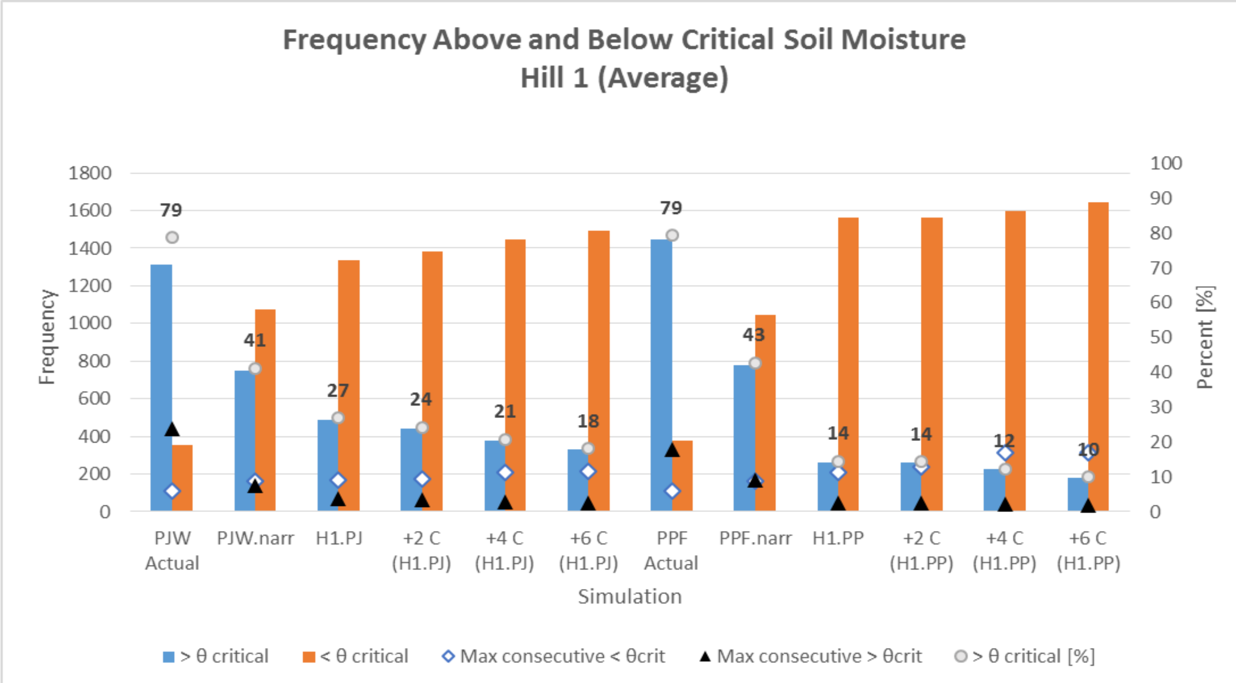


Figure 33: *Higher θ_{crit}: Hill 1 average soil moisture over all depths for temperature changes*

For the *.PJ simulations θ_{crit} was changed from 0.056 to 0.066 and the *.PP simulations were changed from θ_{crit} 0.065 to 0.076

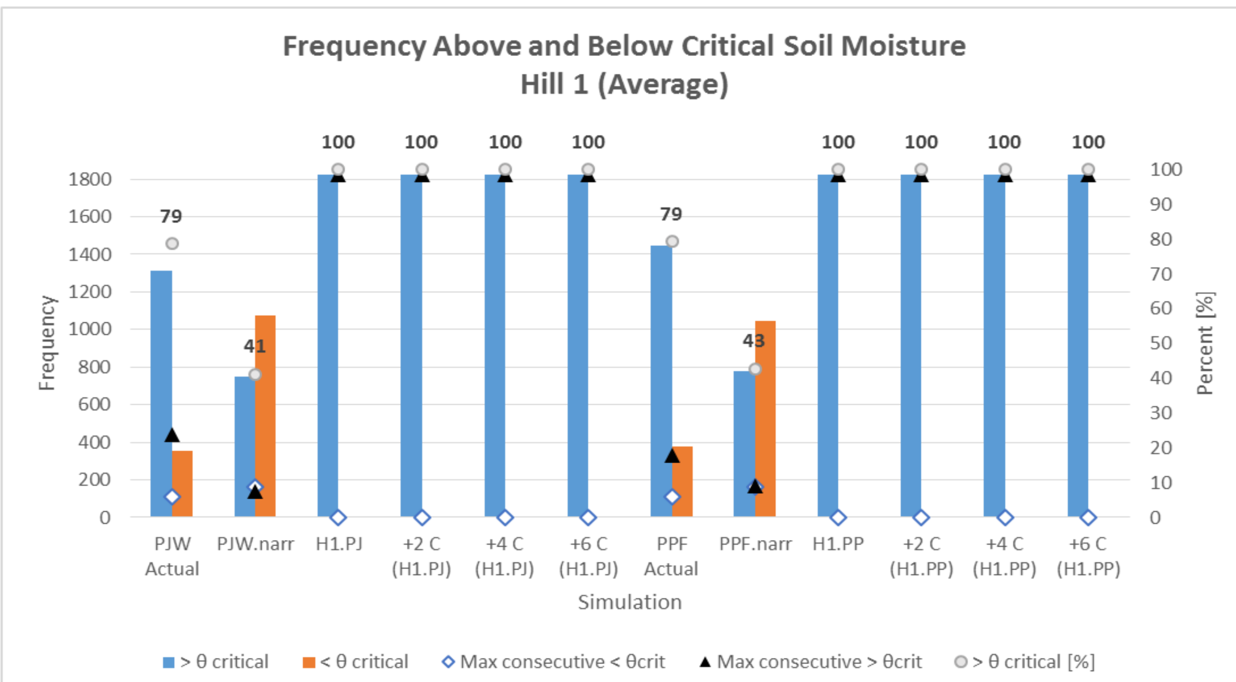


Figure 34: *Lower θ_{crit}: Hill 1 average soil moisture over all depths for temperature changes.*

For the *.PJ simulations θ_{crit} was decreased from 0.056 to 0.046 and the *.PP simulations were changed from θ_{crit} 0.065 to 0.055. The difference between Figure 33 and Figure 34 in the frequency of days greater than θ_{crit} is striking considering only a 2% difference in θ_{crit}

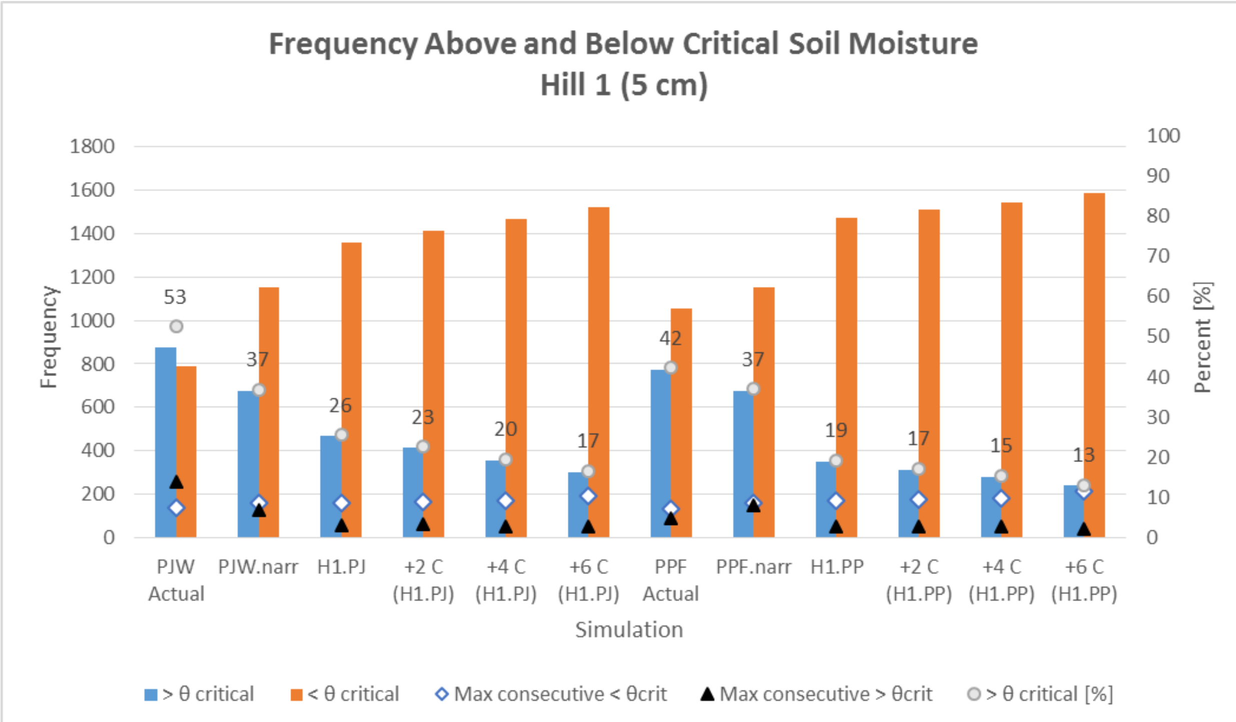


Figure 35: *Higher θ_{crit}: Hill 1 soil moisture at 5cm for temperature changes*

For the *.PJ simulations θ_{crit} was changed from 0.056 to 0.066 and the *.PP simulations were changed from θ_{crit} 0.065 to 0.076

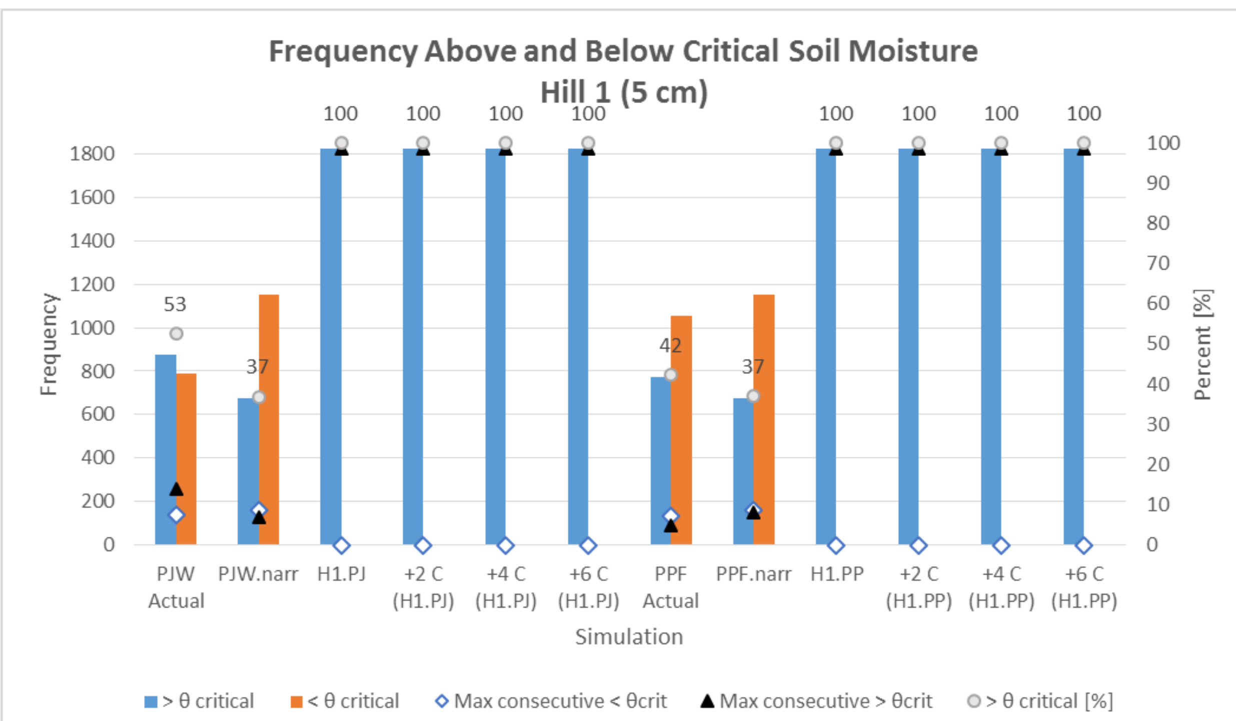


Figure 36: *Lower θ_{crit}: Hill 1 soil moisture at 5cm for temperature changes*

For the *.PJ simulations θ_{crit} was decreased from 0.056 to 0.046 and the *.PP simulations were changed from θ_{crit} 0.065 to 0.055.

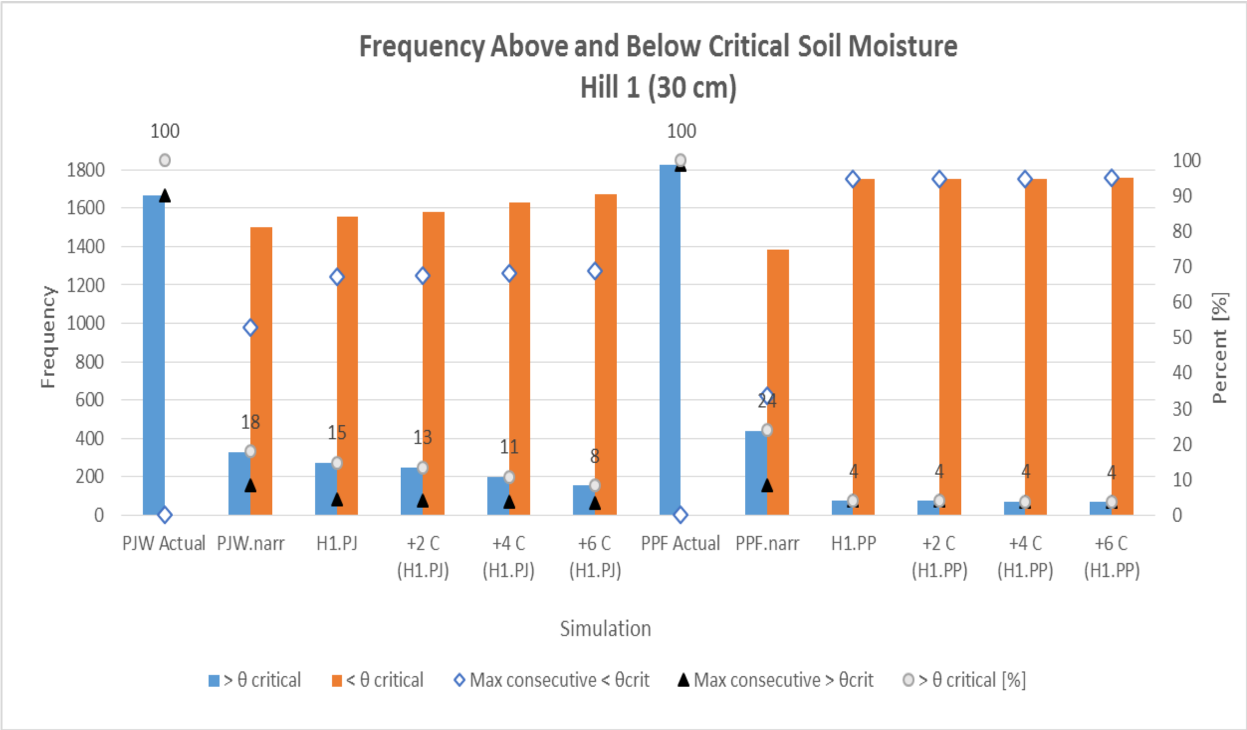


Figure 37: *Higher θ_{crit}: Hill 1 deep soil moisture for temperature changes*

For the *.PJ simulations θ_{crit} was changed from 0.056 to 0.066 and the *.PP simulations were changed from θ_{crit} 0.065 to 0.076

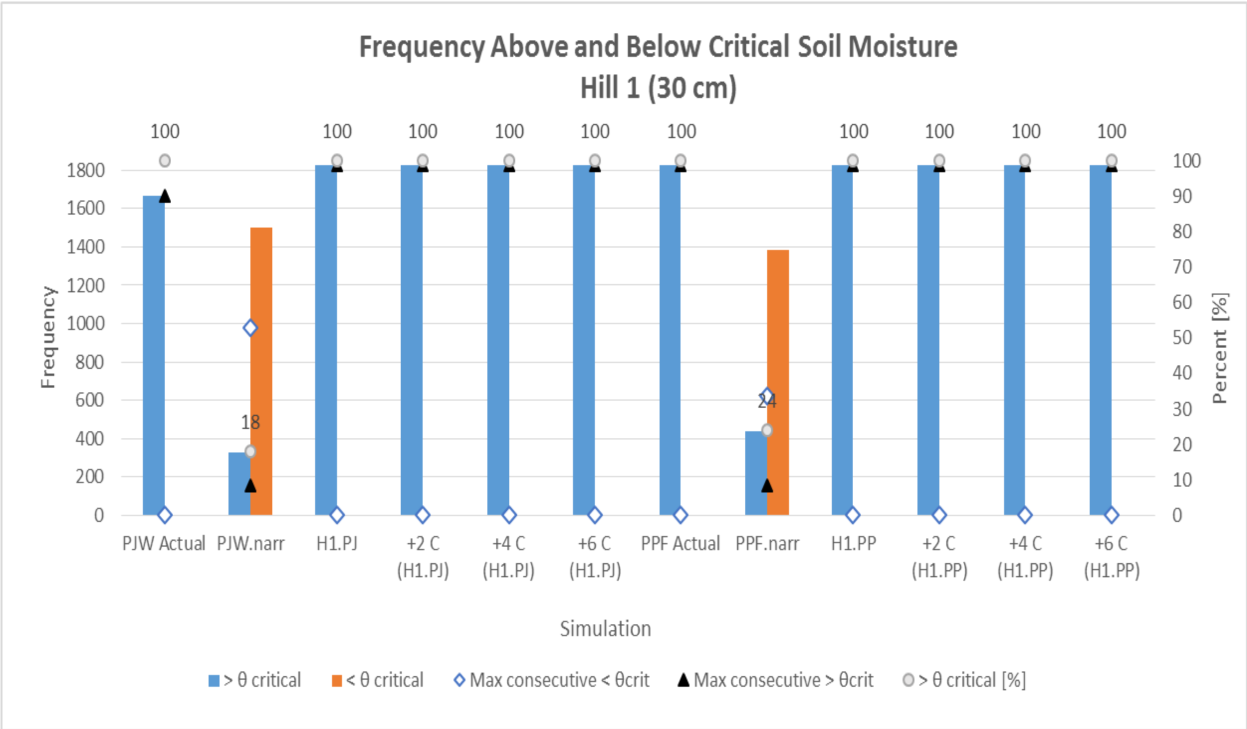


Figure 38: *Lower θ_{crit}: Hill 1 deep soil moisture for temperature changes*

For the *.PJ simulations θ_{crit} was decreased from 0.056 to 0.046 and the *.PP simulations were changed from θ_{crit} 0.065 to 0.055.

5 DISCUSSION

The current soil moisture regimes are drier (below θ_{crit} more often) than a typical PPF (the benchmark, PPF.narr) and wetter (above θ_{crit} more often) than a typical PJW (the benchmark, PJW.narr). Since the hillslopes on Cebolla have a mixture of the two types of vegetation (although more ponderosa pine because the hillslopes have been thinned), the actual soil moisture of Cebolla lies somewhere between these two end-member simulations, as expected. It is difficult to determine how close the soil moisture of each hill is to one ecosystem or the other without site specific information about changes in tree physiology (or indicators of how stressed the trees are) and its relationship to the length and intensity of wet and dry periods.

The simulated current, shallow soil moisture regimes are drier than a typical ponderosa pine ecosystem, but because the maximum number of consecutive days below θ_{crit} is close to that of a typical PPF that does not necessarily indicate that the soils are too dry to support ponderosa pine, which is important for the possibility of seedling establishment. As the temperatures increase, the maximum number of consecutive days below θ_{crit} remains not too far below that of a typical PPF, but the maximum number of consecutive days above θ_{crit} decreases. The length of recovery time that the shallow soil moisture regime has between dry periods is predicted to become shorter as the temperatures increase which could make seedling establishment increasingly difficult as there will be fewer days of adequate moisture. The simulations for PJW indicate that pinyon and juniper could establish relatively easier even if temperatures increase by more than 6°C.

Besides adequate soil moisture, the soil and air temperatures are also critical to seedling survivability. Summer air temperatures from 15-23 °C (59-73 °F) and a soil temperature of 23 °C (73 °F) lead to the most productive seedlings (Oliver and Ryker, 1990). Winter temperatures need to be above -5 °C (23 °F) (Oliver and Ryker, 1990). If the temperatures increase, soil and air temperatures could become too hot in the summer. Currently maximum summer soil temperatures reach 26°C (78.8°F) and air temperatures are 33°C (91.4°F), based on the HYDRUS simulations for soil temperature and NARR data for air temperature, further temperature increases would be potentially very stressful on seedlings, especially in combination with drier than ideal soil moisture.

In addition, ponderosa pine seedlings will compete with pinyon and juniper seedlings. It has been observed that pinyon and juniper seedlings have the greatest survival rates under canopies (Padien *et al.*, 1992). Since ponderosa pine seedlings require ample sunlight to grow, pinyon-juniper seedlings have the competitive edge in dense forests and woodlands. At higher elevations, ecotones between a PPF and a PJW, such as Cebolla, pinyon outcompetes juniper to become the more dominant species (Padien *et al.*, 1992), thus, pinyon will likely be the main competitor for ponderosa pine in stands where conditions are sufficient for both species.

Given the current and predicted soil moisture and soil and air temperatures in Cebolla, it cannot be decisively ruled out that ponderosa pine seedlings will not establish and survive. Given the higher than ideal temperatures, lower soil moisture, and competitive edge that pinyon and juniper have both in ease of establishment and in more ideal temperatures and soil moisture, it will be very difficult for ponderosa pine seedlings to establish on their own, especially in mature ponderosa pine stands. A likely future scenario is that pinyon and juniper seedlings grow to maturity, requiring continuous thinning if ponderosa pine is favored instead. While it might not be impossible for ponderosa pine seedlings to establish, they will likely need dedicated nurturing and possibly some thinning of ponderosa pine to give them ample sunlight. Even then it is not certain that deeper soil moisture conditions will be adequate for them to survive as mature ponderosa pine.

Deep soil moisture is used to determine the potential resilience to climate change because mature ponderosa pine access moisture primarily from below 30 cm. The current deep soil moisture regime for a PPF in Cebolla is exceedingly dry compared to a typical PPF. The simulations show that the soil moisture is below θ_{crit} for over two consecutive years. As temperatures increase, that number is closer to 1000 consecutive days below θ_{crit}. Considering that a typical PPF has no days below θ_{crit}, 1000 consecutive days is exceedingly dry and much more than the 305 consecutive days that indicates cavitation and subsequent mortality.

Given the assumptions that ponderosa pine accesses most of its moisture below 30 cm in the soil profile, that 100% cavitation leading to mortality occurs when the soil moisture has remained below θ_{crit} for more than 305 consecutive days, and that the θ_{crit} values used are correct, the simulations suggest that ponderosa pine should not currently be surviving in Cebolla. Yet there is no evidence that the ponderosa pine that are currently there are unhealthy.

There are several reasons that the ponderosa pine in Cebolla currently appear healthy despite what the simulations suggest. First, the simulations under-predict the soil moisture when using NARR data and it is unknown how much higher the soil moisture would be if meteorological data were measured on site and used instead of NARR data. Second, the HYDRUS model does not have the ability to simulate the increase in soil moisture do to slash or litter without alterations to the HYDRUS code. So it is possible that thinning has significantly helped raise soil moisture in the deeper profile. Third, some studies suggest that short duration drought can lead to adaptations in a species' ability to resist more intense or longer term drought (studies discussed in McDowell *et al.*, 2008). More work needs to be done to define what a short term versus a long term drought is and how to measure the adaptations that might increase a species drought resistance. Fourth, it is possible that ponderosa pine have adapted to take moisture primarily from the shallow regime either out of necessity or because the soil is shallow, or both. Fifth, there may be a significant groundwater flux or base flow along the bedrock that increases moisture in the deeper soil, but more work needs to be done to understand if there is a significant groundwater flux, what the flux is, and how regular it is.

Sixth, the differences in aspect are projected to have an important role in determining soil moisture regimes. The simulations here use NARR data which is on a 35 km x 35 km grid, too large to differentiate climate data between sites, let alone the microclimates within each site. Thus soil moisture on each hillslope is averaged. Yet observations and the impact of increased solar radiation on southern aspects indicate that they will have less soil moisture and northern aspects will have more. This is supported by observations in Cebolla that show few ponderosa pine on southern slopes. By differentiating the soil moisture on the north and south aspects, it is possible that simulations will reveal north facing slopes more closely resemble a typical PPF soil moisture regime.

And seventh, the assumption that 305 consecutive days below θ_{crit} will lead to mortality might be incorrect. The number was observed in a pinyon-juniper stand and might be different for ponderosa pine. The number might also be site specific or conditionally specific. There is currently debate about the plant physiological mechanisms that may lead to drought-caused mortality and their relationship to water availability including wet and dry periods.

Aspect related differences, having an accurate θ_{crit}, and having accurate precipitation data are expected to make the largest differences in the results shown here. Current management (thinning) might also play an important role in increasing the deeper soil moisture to help ponderosa pine since they currently appear healthy despite the prognosis of the HYDRUS simulations. Therefore, it is possible that the thinning on each site has increased soil moisture enough so that 100% cavitation does not occur or by increasing soil moisture enough for ponderosa to increase its resistance to drought, either by adapting to access shallow soil moisture in higher quantities or by lowering its θ_{crit}.

If current management has helped to increase the resilience of ponderosa pine so far, the question remains how helpful it will be as the climate warms. If the soils become as dry as predicted, the existing ponderosa pine will need all the available moisture in the soil which could mean eliminating all of the competition, including shrubs and grasses, and even that might not be enough. It is unreasonable to eliminate all of the competition because without grasses and shrubs erosion rates would increase and that would conflict with BLM management goals to prevent erosion. The slash left from thinning could provide some resistance to erosion, but it is unclear to what extent and if that would meet BLM management goals. Even then, since the PJW simulations were wetter than a typical PJW for current simulations and for scenarios up to +4°C, it is likely they will continue to establish which would require more thinning. Eventually, the existing ponderosa pine will reach the end of their life cycle, if they do not die prematurely from drought, and the clearings would create better conditions to establish ponderosa pine seedlings, but by that time the soil moisture and the soil and air temperatures might be too dry and hot for the seedlings.

The results discussed so far have been for the original θ_{crit} values. As shown, however, small changes to θ_{crit} effect the interpretation of whether or not the soil is wet, dry, or too dry. An accurate θ_{crit} is extremely important. And an important part of determining an accurate θ_{crit} is to determine accurate soil texture and soil hydraulic properties. Looking at table 5 the differences in θ_{crit} only range 1% and reflect the subtle differences in soil texture between hills 1-3. The differences in soil texture between hills 1-3 range 5% for sand and clay, yet the differences in soil texture correspond to differences in θ_{crit} that significantly influence the interpretation of whether the soil is wet or dry. For instance, if the soil texture from Hill 1 was used for all three hills, θ_{crit} would be 1% higher for hills 2 and 3 which would result in slightly drier soil moisture than what was predicted. If the soil texture from hill 3 was used for all three hills, θ_{crit} would be 1% lower which would result in much wetter soil moisture conditions, as shown in section 4.6 when θ_{crit} was increased and decreased. Thus, the more accurate the soil texture and hydraulic properties are, the more accurate the θ_{crit} will be and the more accurate the interpretation of the soil moisture. Currently, the available soil properties from the soil survey do not match those that were measured at Cebolla. Caution should be taken when using data from the soil survey to predict future soil moisture. When possible, samples from the area of interest should be analyzed instead.

5.2 Limitations

- NARR precipitation did not accurately reproduce local conditions; a weather station may be necessary to achieve more accurate simulations
- The spatial scale of NARR data was too large to differentiate aspect related differences in soil moisture regime, even though observation suggests there is a major difference
- Without alteration to the code, HYDRUS cannot account for the effects of slash or litter
- HYDRUS-1D cannot simulate runoff from upslope
- HYDRUS-1D cannot simulate whole stand dynamics only individual locations
- HYDRUS predictions of soil hydraulic properties are estimates only
- θ_{crit} varies with depth and might not be the same as when averaged over depths
- The Hydraulic Failure and Carbon Starvation Hypotheses (McDowell et al., 2008) are based on a limited number of observations
- Limited information on root distribution

5.3 Future Work

- *Long term monitoring* including weather stations in at least two locations, *in situ* soil moisture probes, leaf water potential, site indexing, soil analysis for texture and hydraulic properties, erosion monitoring, soil depth monitoring
- *Capture aspect and hillslope topographic parameters (elevation, slope, aspect, concavity) related differences in soil moisture dynamics*
- *Determine if there is a groundwater influx* in the Cebolla uplands and how the flux varies annually or seasonally
- *Understand how and under what conditions ponderosa pine adapts to drought* and what conditions are detrimental to drought resistance (such as a short period of wetter conditions followed by drier than normal conditions)
- *Understand ponderosa pine root distribution* and under what conditions it might change
- It could be interesting to *investigate the relationship between the ratio of dry days to wet days and tree health* to find out if the length of time between drought periods effects the tree's resistance to drought.

6 CONCLUSIONS

1. The soil texture determined on hills 1-3 is courser (sandier) than the soil survey predicts.
2. NARR data accurately predicts temperature, relative humidity, and net solar radiation parameters, but under-predicts precipitation.
3. HYDRUS is a good predictor of soil moisture, if given accurate parameters. It reproduced the soil moisture at the PJW site using measured data. The PPF site probably has a groundwater flux which made it difficult for HYDRUS to reproduce the soil moisture because groundwater information at the site is unknown. Predictions made when using NARR data are lower than actual soil moisture because NARR data under-predicts precipitation.
4. Current, average soil moisture on the simulated sites is drier than a reference PPF and wetter than the reference PJW.
5. Current, shallow soil moisture on the simulated sites is drier than the reference PPF, but there were no instances of more than 305 consecutive days when soil moisture was below θ_{crit} on the simulated sites. Seedling establishment may be possible, but difficult.
6. Current, deep soil moisture is exceedingly dry on the simualted sites compared to the reference PPF. There are over 900 consecutive days when the soil moisture is below θ_{crit} for the simulated hillslopes and zero days below θ_{crit} in a typical PPF. The deep soil moisture, where ponderosa pine accesses most of its moisture, appears unsustainable for ponderosa pine survival.
7. For temperature increases of +2, 4, and 6°C, the shallow soil moisture regimes became progressively drier on the simulated sites compared the reference PPF. The number of consecutive days when soil moisture is above θ_{crit} on the simulated sites became increasingly fewer as the temperatures increase. Ponderosa pine seedling establishment is projected to become progressively more difficult as soil moisture decreases, air and soil temperatures increase and conditions favor establishment of pinyon and juniper seedlings.
8. As temperatures increased, the deep soil moisture regimes became progressively drier relative to a reference PPF. The soil moisture at each simulated site was very near the soil water retention limit. Thus, the soils do not appear to have enough moisture for long term ponderosa pine resilience.

9. θ_{crit} is extremely sensitive to soil texture and hydraulic properties; 1% changes in θ_{crit} have a significant impact on interpreting whether soils are wet, dry, or too dry. It is extremely important to obtain an accurate measure of θ_{crit} via site specific water retention curves.
10. Since small changes in θ_{crit} have a large impact on whether the soil is wetter or drier than a typical PPF, and ponderosa pine are currently healthy despite the exceedingly dry, current, deep soil moisture predictions, it appears possible that current thinning treatments have helped increase the deeper soil moisture and subsequently prolonged the survival of ponderosa pine in Cebolla. It seems that small increases in the soil moisture might have a large impact as long as those increases reach the deeper soil. Pending a better understanding of drought related mortality mechanisms and adaptations of mature ponderosa pine to drought, however, it appears labor intensive and potentially detrimental to the health of the ecosystem to continue thinning in favor of ponderosa pine. Continued thinning may be advantageous to ponderosa pine survivability, but continued accumulated slash could become a fire hazard. More thinning than has already occurred could exacerbate erosion and decrease the health of the ecosystem. In addition to an accurate θ_{crit}, measured precipitation and differentiating between north and south aspect would alleviate much of the uncertainty discovered here and improve the BLM's understanding of soil moisture and projections for ponderosa pine resiliency as the climate changes.

7 RECOMMENDATIONS

Based on the HYDRUS modelling, it appears that the deep soil moisture regime in Cebolla is currently too low to support mature ponderosa pine as the climate changes. It also appears that management has helped sustain ponderosa pine in Cebolla. Regarding the future of ponderosa pine in Cebolla, there are other factors to consider including the establishment of ponderosa, pinyon and juniper seedlings. It is likely that ponderosa pine seedlings will have difficulty growing unassisted, while pinyon and juniper seedlings are expected to establish much easier and more frequently. It might be important to consider how often stands will need to be thinned in order to reduce competition for ponderosa pine and increase soil moisture. Other considerations include, physiological mechanisms or adaptations that could exacerbate or improve drought tolerance in local ponderosa pines. Actual meteorological conditions, soil hydraulic properties, and θ_{crit} at various depths also need to be accurate.

Since there is uncertainty in the results regarding an accurate θ_{crit} value at depth and precipitation data, the best recommendation is to start a long term monitoring plan and then to use that data to model future scenarios. The plan should include:

- At least two locations in Cebolla for continuous collection of precipitation, temperature, relative humidity, wind speed, and incoming solar radiation. Soil moisture should also be monitored at 2-3 depths in at least three locations near each station
- Soil cores should be collected and analyzed for texture and hydraulic properties
- Development of soil water retention curves
- Periodic soil depth and erosion monitoring
- Ideally, physiological parameters of the tress would be monitored as well to help understand the changes during wet periods and during drought

APPENDIX A

R Code for Processing NARR data:

There were 180-240 files of data for each parameter (precipitation, temperature, relative humidity, wind speed, and net solar radiation) and each file contained 60-90 observations of the chosen climate parameter (about three months of data). For each file, code was written in R to extract the parameter for each time interval at only the coordinates for each site (PPF, PJW, and Cebolla). Then all of the 3-hourly data were averaged to a daily time step and coerced into one vector for each parameter (1826 days). Tables were created with all the climate parameters for each site.

```
# This code will read, open and extract information from netCDF files for climate
# data from Jan 1, 2009- Dec 31, 2013
#accessed from the National Centers for Environmental Prediction (NCEP)
#North American Regional Reanalysis (NARR) dataset
# It also reorganizes the data into a single table that can be exported to excel (.csv)
# and used in HYDRUS
# It takes about 30 mins to run
# set the working directory, where all the files are stored
setwd("D:/NARR data/Temperature/NARR_Temperatures_09_13/NARR_Temperatures")
# Open/install the necessary R packages
library(RNetCDF)
#install.packages("R.utils")
library(R.utils)
# Make a vector of the file names so each file can be read into a command and opened
files.temps = list.files("D:/NARR data/Temperature/NARR_Temperatures_09_13/NARR_Temperatures",
                    pattern = ".nc", full.names = TRUE)
# Create empty lists in which to store information from each file as it is processed
cebolla.center.list <- list()
ponderosa.center.list <- list()
pJs.center.list <- list()
Days_hrs_list <- list()
# Use a loop to perform the desired operations on each file
for(i in 1:180){
  # open the files
  a <- open.nc(files.temps[i])
  # Extract the Temperature variable
  temps <- var.get.nc(a, "TMP_221_SFC")
  # Since each Temperature variable from each file contains 72-96 time steps
  # create another loop to create seperate lists of temperature for each time step
  Temperatures_list <- list()
  x=dim(temps) # this allows the loop to vary over the exact no. of time steps
  for (j in 1:(x[3])){
```

```
  Temperatures_list[[paste("Temperatures", j)]] <-
    append(Temperatures_list[[paste("Temperatures", j)]],
        temps[,,j])
 }
 # Turn list of temps into a data frame and convert temps from Kelvin to Celsius
 Temperatures <- as.data.frame(Temperatures_list)
 Temperatures <- Temperatures-273.15
 # Extract coordinates and convert from matrix to vector format
 lats <- as.vector(var.get.nc(a, "gridlat_221"))
 longs <- as.vector(var.get.nc(a, "gridlon_221"))
 # Create a table of coordinates
 # with their corresponding temperature for each time step
 table <- cbind(lats,longs, Temperatures)
 table <- as.data.frame(table)
 # Extract the grid coordinates closest to the actual coordinates of each site
 # and the 8 surrounding coordinates
 # Coordinates of interest  for Cebolla (34.67133, -107.8617)
 # Coordinates for Ponderosa Pine site in the Caldera (35.86236, -106.5974)
 # Coordinates of Pinyon-Juniper woodland site in Sevillta (34.43845, -106.2377)
 AoI.cebolla <- table[which(table$lats > 34.38518 & table$lats < 34.95656), ]
 AoI.cebolla <- AoI.cebolla[which(AoI.cebolla$longs > -108.2108 &
                AoI.cebolla$longs < -107.5158), ]
 AoI.Ponderosa <- table[which(table$lats > 35.52016 & table$lats < 36.09162), ]
 AoI.Ponderosa <- AoI.Ponderosa[which(AoI.Ponderosa$longs > -106.8291 &
                AoI.Ponderosa$longs < -106.1243), ]
 AoI.PJs <- table[which(table$lats > 34.10335 & table$lats < 34.67398), ]
 AoI.PJs <- AoI.PJs[which(AoI.PJs$longs > -106.4927 &
            AoI.PJs$longs < -105.8010), ]
 # Extract the center points which are closest to the coordinates of each site
 cebolla.center <- AoI.cebolla[5,]
 ponderosa.center <- AoI.Ponderosa[5,]
 pJs.center <- AoI.PJs[5,]
 # Store temperature data for the each set of coordinates in a list
 # Each item in the list will be information from a different data file
 # Eliminate the columns that show coordinates, they aren't needed
 cebolla.center.list[[paste("T", i)]] <-
  append(cebolla.center[[paste("T", i)]], cebolla.center[,3:(x[3]+2)])
 ponderosa.center.list[[paste("T", i)]] <-
  append(ponderosa.center[[paste("T", i)]], ponderosa.center[,3:(x[3]+2)])
 pJs.center.list[[paste("T", i)]] <-
  append(pJs.center[[paste("T", i)]], pJs.center[,3:(x[3]+2)])
 close.nc(a)
}
# convert list of temperatures to data frame
# and transpose temperature data to columns
Cebolla.center.T <- t(as.data.frame(cebolla.center.list))
Ponderosa.center.T <- t(as.data.frame(ponderosa.center.list))
```

```
PJs.center.T <- t(as.data.frame(pJs.center.list))
# Remove all unnecessary files
rm(AoI.cebolla,AoI.PJs, AoI.Ponderosa,cebolla.center,pJs.center,ponderosa.center,
   table,Temperatures,a,cebolla.center.list,files.temps,i,j,lats,longs,pJs.center.list,
   ponderosa.center.list, Temperatures_list,temps,x)
write.csv(Cebolla.center.T, "Cebolla_Temperature.csv")
write.csv(Ponderosa.center.T, "Ponderosa_Temperature.csv")
write.csv(PJs.center.T, "PJ_Temperature.csv")

# set the working directory, where all the files are stored
setwd("D:/NARR data/Precipitation/Precip_unzipped_09_13")
# Make a vector of the file names so they can be read into a command and opened
files.precip = list.files("D:/NARR data/Precipitation/Precip_unzipped_09_13",
                    pattern = ".nc", full.names = TRUE)
# Create empty lists in which to store information from each file as it is processed
cebolla.center.list <- list()
ponderosa.center.list <- list()
pJs.center.list <- list()
# Use a loop to perform the desired operations on each file
for(i in 2:180){
  # open the files
  a <- open.nc(files.precip[i])
  precip <- var.get.nc(a, "A_PCP_221_SFC_acc3h")
  Precip_list <- list()
  x=dim(precip)
  for (j in 1:(x[3])){
    Precip_list[[paste("Precip", j)]] <-
      append(Precip_list[[paste("Precip", j)]],
           precip[,,j])
  }
  Precip <- as.data.frame(Precip_list)
  Precip <- Precip/10 # to convert from kg/m2 to m and from m to cm
  lats <- as.vector(var.get.nc(a, "gridlat_221"))
  longs <- as.vector(var.get.nc(a, "gridlon_221"))
  table <- cbind(lats,longs, Precip)
  table <- as.data.frame(table)
  AoI.cebolla <- table[which(table$lats > 34.38518 & table$lats < 34.95656), ]
  AoI.cebolla <- AoI.cebolla[which(AoI.cebolla$longs > -108.2108 &
                           AoI.cebolla$longs < -107.5158), ]
  AoI.Ponderosa <- table[which(table$lats > 35.52016 & table$lats < 36.09162), ]
  AoI.Ponderosa <- AoI.Ponderosa[which(AoI.Ponderosa$longs > -106.8291 &
                             AoI.Ponderosa$longs < -106.1243), ]
  AoI.PJs <- table[which(table$lats > 34.10335 & table$lats < 34.67398), ]
  AoI.PJs <- AoI.PJs[which(AoI.PJs$longs > -106.4927 &
                       AoI.PJs$longs < -105.8010), ]
  cebolla.center <- AoI.cebolla[5,]
  ponderosa.center <- AoI.Ponderosa[5,]
```

```
  pJs.center <- AoI.PJs[5,]
  cebolla.center.list[[paste("P", i)]] <-
    append(cebolla.center[[paste("P", i)]], cebolla.center[,3:(x[3]+2)])
  ponderosa.center.list[[paste("P", i)]] <-
    append(ponderosa.center[[paste("P", i)]], ponderosa.center[,3:(x[3]+2)])
  pJs.center.list[[paste("P", i)]] <-
    append(pJs.center[[paste("P", i)]], pJs.center[,3:(x[3]+2)])
  close.nc(a)
}
Cebolla.center.P <- t(as.data.frame(cebolla.center.list))
Ponderosa.center.P <- t(as.data.frame(ponderosa.center.list))
PJs.center.P <- t(as.data.frame(pJs.center.list))
# Remove all unnecessary files
rm(AoI.cebolla,AoI.PJs, AoI.Ponderosa,cebolla.center,pJs.center,ponderosa.center,
   table,precip,Precip,a,cebolla.center.list,files.precip,i,j,lats,longs,pJs.center.list,
   ponderosa.center.list, Precip_list, x)
write.csv(Cebolla.center.P, "Cebolla_Precip.csv")
write.csv(Ponderosa.center.P, "Ponderosa_Precip.csv")
write.csv(PJs.center.P, "PJ_Precip.csv")

setwd("D:/NARR data/Relative_Humidity/RH_unzipped_09_13")
# Make a vector of the file names so they can be read into a command and opened
files.RH = list.files("D:/NARR data/Relative_Humidity/RH_unzipped_09_13",
                  pattern = ".nc", full.names = TRUE)
cebolla.center.list <- list()
ponderosa.center.list <- list()
pJs.center.list <- list()
for(i in 2:180){
  a <- open.nc(files.RH[i])
  RH <- var.get.nc(a, "R_H_221_HTGL")
  RH_list <- list()
  x=dim(RH)
  for (j in 1:(x[3])){
    RH_list[[paste("RH", j)]] <-
      append(RH_list[[paste("RH", j)]],
          RH[,,j])
  }
  Rel_Humidity <- as.data.frame(RH_list)
  Rel_Humidity <- Rel_Humidity
  lats <- as.vector(var.get.nc(a, "gridlat_221"))
  longs <- as.vector(var.get.nc(a, "gridlon_221"))
  table <- cbind(lats,longs, Rel_Humidity)
  table <- as.data.frame(table)
  AoI.cebolla <- table[which(table$lats > 34.38518 & table$lats < 34.95656), ]
  AoI.cebolla <- AoI.cebolla[which(AoI.cebolla$longs > -108.2108 &
                              AoI.cebolla$longs < -107.5158), ]
  AoI.Ponderosa <- table[which(table$lats > 35.52016 & table$lats < 36.09162), ]
```

```
  AoI.Ponderosa <- AoI.Ponderosa[which(AoI.Ponderosa$longs > -106.8291 &
                                       AoI.Ponderosa$longs < -106.1243), ]
  AoI.PJs <- table[which(table$lats > 34.10335 & table$lats < 34.67398), ]
  AoI.PJs <- AoI.PJs[which(AoI.PJs$longs > -106.4927 &
                           AoI.PJs$longs < -105.8010), ]
  cebolla.center <- AoI.cebolla[5,]
  ponderosa.center <- AoI.Ponderosa[5,]
  pJs.center <- AoI.PJs[5,]
  cebolla.center.list[[paste("RH", i)]] <-
    append(cebolla.center[[paste("RH", i)]], cebolla.center[,3:(x[3]+2)])
  ponderosa.center.list[[paste("RH", i)]] <-
    append(ponderosa.center[[paste("RH", i)]], ponderosa.center[,3:(x[3]+2)])
  pJs.center.list[[paste("RH", i)]] <-
    append(pJs.center[[paste("RH", i)]], pJs.center[,3:(x[3]+2)])
  close.nc(a)
}
Cebolla.center.RH <- t(as.data.frame(cebolla.center.list))
Ponderosa.center.RH <- t(as.data.frame(ponderosa.center.list))
PJs.center.RH <- t(as.data.frame(pJs.center.list))
# Remove all unnecessary files
rm(AoI.cebolla,AoI.PJs, AoI.Ponderosa,cebolla.center,pJs.center,ponderosa.center,
   table,Rel_Humidity, a,cebolla.center.list,files.RH,i,j,lats,longs,pJs.center.list,
   ponderosa.center.list, RH, RH_list,x)
write.csv(Cebolla.center.RH, "Cebolla_RH.csv")
write.csv(Ponderosa.center.RH, "Ponderosa_RH.csv")
write.csv(PJs.center.RH, "PJ_RH.csv")

setwd("D:/NARR data/Wind/Wind_unzipped_09_13")
# Make a vector of the file names so they can be read into a command and opened
files.wind = list.files("D:/NARR data/Wind/Wind_unzipped_09_13",
                        pattern = ".nc", full.names = TRUE)
cebolla.center.list <- list()
ponderosa.center.list <- list()
pJs.center.list <- list()
# Use a loop to perform the desired operations on each file
for(i in 2:180){
  a <- open.nc(files.wind[i])
  u_wind <- var.get.nc(a, "U_GRD_221_HTGL")
  v_wind <- var.get.nc(a, "V_GRD_221_HTGL")
  wind_u_v <- sqrt(u_wind^2 + v_wind^2)
  wind_list <- list()
  x=dim(u_wind)
  for (j in 1:(x[3])){
    wind_list[[paste("Wind", j)]] <-
      append(wind_list[[paste("Wind", j)]],
             wind_u_v[,,j])
  }
```

```
  Wind <- as.data.frame(wind_list)
  Wind <- Wind*86.4 # to convert from m/s to km/d
  lats <- as.vector(var.get.nc(a, "gridlat_221"))
  longs <- as.vector(var.get.nc(a, "gridlon_221"))
  table <- cbind(lats,longs, Wind)
  table <- as.data.frame(table)
  AoI.cebolla <- table[which(table$lats > 34.38518 & table$lats < 34.95656), ]
  AoI.cebolla <- AoI.cebolla[which(AoI.cebolla$longs > -108.2108 &
                                   AoI.cebolla$longs < -107.5158), ]
  AoI.Ponderosa <- table[which(table$lats > 35.52016 & table$lats < 36.09162), ]
  AoI.Ponderosa <- AoI.Ponderosa[which(AoI.Ponderosa$longs > -106.8291 &
                                       AoI.Ponderosa$longs < -106.1243), ]
  AoI.PJs <- table[which(table$lats > 34.10335 & table$lats < 34.67398), ]
  AoI.PJs <- AoI.PJs[which(AoI.PJs$longs > -106.4927 &
                           AoI.PJs$longs < -105.8010), ]
  cebolla.center <- AoI.cebolla[5,]
  ponderosa.center <- AoI.Ponderosa[5,]
  pJs.center <- AoI.PJs[5,]
  cebolla.center.list[[paste("W", i)]] <-
    append(cebolla.center[[paste("W", i)]], cebolla.center[,3:(x[3]+2)])
  ponderosa.center.list[[paste("W", i)]] <-
    append(ponderosa.center[[paste("W", i)]], ponderosa.center[,3:(x[3]+2)])
  pJs.center.list[[paste("W", i)]] <-
    append(pJs.center[[paste("W", i)]], pJs.center[,3:(x[3]+1)])
  close.nc(a)
}
Cebolla.center.W <- t(as.data.frame(cebolla.center.list))
Ponderosa.center.W <- t(as.data.frame(ponderosa.center.list))
PJs.center.W <- t(as.data.frame(pJs.center.list))
# Remove all unnecessary files
rm(AoI.cebolla,AoI.PJs, AoI.Ponderosa,cebolla.center,pJs.center,ponderosa.center,
   table,u_wind, v_wind, wind_u_v, wind_list, Wind, a,cebolla.center.list,
   files.wind,i,j,lats,longs,pJs.center.list,
   ponderosa.center.list,x)
write.csv(Cebolla.center.W, "Cebolla_Wind.csv")
write.csv(Ponderosa.center.W, "Ponderosa_Wind.csv")
write.csv(PJs.center.W, "PJ_Wind.csv")

setwd("D:/NARR data/Solar_Radiation/Solar_Radiation_unzipped")
# Make a vector of the file names so they can be read into a command and opened
files.solar = list.files("D:/NARR data/Solar_Radiation/Solar_Radiation_unzipped",
                         pattern = ".nc", full.names = TRUE)
# Create empty lists in which to store information from each file as it is processed
cebolla.center.list <- list()
ponderosa.center.list <- list()
pJs.center.list <- list()
# Use a loop to perform the desired operations on each file
```

```r
for(i in 2:180){
  a <- open.nc(files.solar[i])
  dsw <- var.get.nc(a, "DSWRF_221_SFC_ave3h")
  dlw <- var.get.nc(a, "DLWRF_221_SFC_ave3h")
  usw <- var.get.nc(a, "USWRF_221_SFC_ave3h")
  ulw <- var.get.nc(a, "ULWRF_221_SFC_ave3h")
  net_rad <- ((dsw-usw) + (dlw-ulw))
  net_rad_list <- list()
  x=dim(net_rad)
  for (j in 1:(x[3])){
    net_rad_list[[paste("Net_Radiation", j)]] <-
      append(net_rad_list[[paste("Net_Radiation", j)]],
           net_rad[,,j])
  }
  Net.Rad <- as.data.frame(net_rad_list)
  Net.Rad <- Net.Rad*0.0864 # W/m^2 to MJ/m2/d
  lats <- as.vector(var.get.nc(a, "gridlat_221"))
  longs <- as.vector(var.get.nc(a, "gridlon_221"))
  table <- cbind(lats,longs, Net.Rad)
  table <- as.data.frame(table)
  AoI.cebolla <- table[which(table$lats > 34.38518 & table$lats < 34.95656), ]
  AoI.cebolla <- AoI.cebolla[which(AoI.cebolla$longs > -108.2108 &
                              AoI.cebolla$longs < -107.5158), ]
  AoI.Ponderosa <- table[which(table$lats > 35.52016 & table$lats < 36.09162), ]
  AoI.Ponderosa <- AoI.Ponderosa[which(AoI.Ponderosa$longs > -106.8291 &
                                AoI.Ponderosa$longs < -106.1243), ]
  AoI.PJs <- table[which(table$lats > 34.10335 & table$lats < 34.67398), ]
  AoI.PJs <- AoI.PJs[which(AoI.PJs$longs > -106.4927 &
                        AoI.PJs$longs < -105.8010), ]
  cebolla.center <- AoI.cebolla[5,]
  ponderosa.center <- AoI.Ponderosa[5,]
  pJs.center <- AoI.PJs[5,]
  cebolla.center.list[[paste("NR", i)]] <-
    append(cebolla.center[[paste("NR", i)]], cebolla.center[,3:(x[3]+2)])
  ponderosa.center.list[[paste("NR", i)]] <-
    append(ponderosa.center[[paste("NR", i)]], ponderosa.center[,3:(x[3]+2)])
  pJs.center.list[[paste("NR", i)]] <-
    append(pJs.center[[paste("NR", i)]], pJs.center[,3:(x[3]+1)])
  close.nc(a)
}
Cebolla.center.SR <- t(as.data.frame(cebolla.center.list))
Ponderosa.center.SR <- t(as.data.frame(ponderosa.center.list))
PJs.center.SR <- t(as.data.frame(pJs.center.list))
# Remove all unnecessary files
rm(AoI.cebolla,AoI.PJs, AoI.Ponderosa,cebolla.center,pJs.center,ponderosa.center,
   table,Net.Rad,a,cebolla.center.list,files.solar,i,j,lats,longs,pJs.center.list,
   ponderosa.center.list, net_rad_list,net_rad,dsw,dlw,usw,ulw,x)
```

```
write.csv(Cebolla.center.SR, "Cebolla_Net_Radiation.csv")
write.csv(Ponderosa.center.SR, "Ponderosa_Net_Radiation.csv")
write.csv(PJs.center.SR, "PJ_Net_Radiation.csv")
#Put all data into one table
Cebolla_NARR <- table(Cebolla.center.SR, Cebolla.center.T,
            Cebolla.center.RH, Cebolla.center.W)
Ponderosa_NARR <- table(Ponderosa.center.SR, Ponderosa.center.T,
             Ponderosa.center.RH, Ponderosa.center.W)
PJ_NARR <- table(PJs.center.SR, PJs.center.T, PJs.center.RH, PJs.center.W)
write.csv(Cebolla_NARR, "Cebolla_Meteorological_Conditions")
write.csv(Ponderosa_NARR, "Ponderosa_Meteorological_Conditions")
write.csv(PJ_NARR, "PJ_Meteorological_Conditions")
```

REFERENCES

Barth, R. C. (1980). Influence of pinyon pine trees on soil chemical and physical properties. *Soil Science Society of America Journal*, *44*(1), 112-114.

Dee, Dick; Fasullo, John; Shea, Dennis; Walsh, John. National Center for Atmospheric Research Staff (Eds). Last modified 23 Jul 2015. *The Climate Data Guide: Atmospheric Reanalysis: Overview & Comparison Tables*. Retrieved from https://climatedataguide.ucar.edu/climate-data/atmospheric-reanalysis-overview-comparison-tables

Domec, J. C., Warren, J. M., Meinzer, F. C., Brooks, J. R., & Coulombe, R. (2004). Native root xylem embolism and stomatal closure in stands of Douglas-fir and ponderosa pine: mitigation by hydraulic redistribution. *Oecologia*, *141*(1), 7-16.

Grier, C. C., Elliott, K. J., & McCullough, D. G. (1992). Biomass distribution and productivity of Pinus edulis—Juniperus monosperma woodlands of north-central Arizona. *Forest Ecology and Management*, *50*(3), 331-350.

Guan, H., Simunek, J., Newman, B. D., & Wilson, J. L. (2010). Modelling investigation of water partitioning at a semiarid ponderosa pine hillslope. *Hydrological Processes*, *24*(9), 1095-1105. doi:10.1002/hyp.7571

Kricher, J. C. (1998). A field guide to Rocky Mountain and southwest forests. Boston: Houghton Mifflin.

Lajtha, K., & Barnes, F. J. (1991). Carbon gain and water use in pinyon pine-juniper woodlands of northern New Mexico: field versus phytotron chamber measurements. *Tree Physiology*, *9*(1-2), 59-67.

Maherali, H., Pockman, W. T., & Jackson, R. B. (2004). Adaptive variation in the vulnerability of woody plants to xylem cavitation. *Ecology*, *85*(8), 2184-2199.

McDowell, N., Pockman, W. T., Allen, C. D., Breshears, D. D., Cobb, N., Kolb, T., Plaut, J., Sperry, J., West, A., Williams, D. G. and Yepez, E. A. (2008). Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought?. New Phytologist, 178: 719–739. doi:10.1111/j.1469-8137.2008.02436.x

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Vieth, T.L. (2007). Model Evaluation Guidelines for systematic Quantification of Accuracy in Watershed Simulations. Transactions of the ASABE, 50(3), 885-900.

National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce (2005): NCEP North American Regional Reanalysis (NARR). Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. http://rda.ucar.edu/datasets/ds608.0/. Accessed: 27 Aug 2015.

Nielsen, Jamie (2009). Series: Pinyon-Juniper Woodlands. National Parks Service United States. National Park Service https://www.nps.gov/articles/series.htm?id=0216D798-933C-2108-EB4384D97499E89A

Newman, B. D., Wilcox, B. P., & Graham, R. C. (2004). Snowmelt-driven macropore flow and soil saturation in a semiarid forest. *Hydrological Processes*, *18*(5), 1035-1042.

Padien, D. J., & Lajtha, K. (1992). Plant spatial pattern and nutrient distribution in pinyon-juniper woodlands along an elevational gradient in northern New Mexico. *International Journal of Plant Sciences*, 425-433.

Pavel Michna and with contributions from Milton Woods (2015). *RNetCDF: Interface to NetCDF Datasets*. R package version 1.7-3. http://CRAN.R-project.org/package=RNetCDF

Pieper, R. D. (2008). Ecology of piñon-juniper vegetation in the Southwest and Great Basin.

Pockman, W. T., & Sperry, J. S. (2000). Vulnerability to xylem cavitation and the distribution of Sonoran desert vegetation. *American journal of botany*,*87*(9), 1287-1299.

R Core Team (2015). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rew, Russ. "NetCDF FAQ." *NetCDF FAQ*. N.p., n.d. Web. 21 Oct. 2015. http://www.unidata.ucar.edu/software/netcdf/docs/faq.html

Ronco, F. P. Jr. 1990. *Pinus edulis*. Silvics of North America, Vol. 1: Conifers. USDA Forest

Service Agricultural Handbook 654:327-337.

Sala, A., Piper, F. and Hoch, G. (2010). Physiological mechanisms of drought-induced tree mortality are far from being resolved. New Phytologist, 186: 274–281. doi:10.1111/j.1469-8137.2009.03167.x

Sevanto, S., McDowell, N. G., Dickman, L. T., Pangle, R., & Pockman, W. T. (2014). How do trees die? A test of the hydraulic failure and carbon starvation hypotheses. *Plant, Cell & Environment*, *37*(1), 153-161.

Simunek, J., Sejna, M., Saito, H., Sakai, M., van Genuchten, M. Th. (2013). The Hydrus-1D Software Package for Simulating the Movement of Water, Heat, and Multiple Solutes in Variably Saturated Media, Version 4.17, HYDRUS Software Series 3, Department of Environmental Sciences, University of California Riverside, Riverside, California, USA, pp. 342.

Tuller, M., & Or, D. (2004). Retention of water in soil and the soil water characteristic curve. *Encyclopedia of Soils in the Environment*, *4*, 278-289.