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# Modeling droughty soils at regional scales in Pacific Northwest Forests, USA

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ABSTRACT

Natural resource managers need better estimates of water storage and supply in forested landscapes. These estimates would aid planning for management activities that maintain and enhance forest health and productivity and help prepare forested landscapes for a changing climate. In particular, low soil moisture in combination with high evaporative demands can induce significant stresses on forests, increasing vulnerability to attacks of insect and disease, as well as increasing wildfire risk. Although high-resolution soils data exist for much of the Pacific Northwest, regional-scale datasets that identify forested areas potentially vulnerable to soil moisture-related drought do not exist. In this study, we used readily available spatial datasets depicting available water supply, soil depth, and evapotranspiration to model the likelihood that soils experience prolonged summer drying. To calibrate the model, we examined soil profile descriptions, lab data, and soil moisture curves for 25 sites throughout the Pacific Northwest and estimated the average annual number of days that soil moisture drops to levels at or below the permanent wilting point, a theoretical lower limit of plant-available water. Using this approach, we found statistically significant relationships between the independent variables and broad classes of soil moisture levels representing the highest and lowest levels of plant-available moisture. We then used these relationships to create a landscape-level droughty soil index for the Pacific Northwest. We expect that this approach can be further developed to include additional soil moisture data outside Washington and Oregon and enhanced with other explanatory variables such as topographic position, elevation, and vegetation type. With the addition of vegetation-related data, in particular, the current modeling approach can aid in identifying vulnerable landscapes in the context of managing for increased forest resiliency in the Pacific Northwest.

## 1. Introduction

Soil moisture modulates the complex dynamics of the climate–-soil–vegetation system and controls temporal and spatial patterns of vegetation (Noy-Meir, 1973). Soil plays a key role in this system by controlling the partitioning of moisture between inputs and outflow including runoff, evapotranspiration, and flow between organisms. Different soil types store and transmit moisture inputs and outputs differently based on their individual properties that govern water holding capacity and climatic influences. The moisture storage function of soils is particularly important in the Pacific Northwest, as over two-thirds of the region's precipitation occurs between October and March, with an average of less than two inches of rainfall occurring in the summer months.

Plants depend on soil water to carry out critical biological functions, as plant physiology is directly linked to water availability. Insufficient water supplies create a water-stressed condition in plants. Plants under stress decrease both their transpiration and photosynthesis in an effort to balance nutrient needs and water loss. The stressed condition leaves them vulnerable to insect attack and, if prolonged, hydraulic failure and death of the plant (Choat et al., 2012).

Loss of soil water by evaporation or transpiration or both is controlled or at a minimum influenced by physico-chemical properties, surface slope and aspect, and biological demand (Hillel, 2003). We generally think of soils as "droughty" when the balance of inputs, losses, and transformations of available soil water is frequently less than the biological demand during the period of interest. Note that this notion of "droughtiness" does not refer to drought conditions per se, i.e. conditions of *uncharacteristically* long or severe moisture deficits. Rather, a droughty soil is one that consistently (chronically) has low seasonal moisture levels, and may therefore be particularly vulnerable when drought does strike. Keeping this distinction in mind, we will use

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the terms "droughty soil" and "drought-vulnerable soil" interchangeably, and refer to such soils as having a high soil moisture drought potential. In the Pacific Northwest, we have a climate marked by dry summers, and so we are interested in summer soil moisture in particular, and its relationship to climate and soil properties.

In practice, the term "droughty soil" is often used imprecisely, referring to a fast-draining or coarse-textured soil, or one that does not receive adequate water recharge relative to vegetation and evapotranspirational demands. The USDA Natural Resources Conservation Service (NRCS) defines soil drought vulnerability in terms of agricultural crops in their metadata for the gridded Soil Survey Geographic Database (gSSURGO; Soil Survey Staff, 2016a): "Drought vulnerable soil landscapes comprise those map units that have available water storage within the root zone for commodity crops that is less than or equal to 6 in. (152 mm)." This definition, however, does not include any consideration of climatic influence. In the metadata's referenced publication (Dobos et al., 2012), it is stated that, "… If the soil receives timely rainfall, AWC (available water-holding capacity) is less important.", explicitly indicating that a full definition of a droughty soil requires the consideration of at least the quantity of precipitation occurring during the growing period. As climatic gradients in the Pacific Northwest can be extremely sharp both seasonally and geographically, we would argue that including climatic considerations in any definition of soil droughtiness is critical. In this work we develop a definition of a droughty soil derived from class breaks in our calibration dataset, and show that this results in a better indication of soil droughtiness than using available soil water storage alone.

The forest management benefits of understanding which landscapes and which soil types have a high soil moisture drought potential are many. Increasing forest growth potential, improving forest resiliency to climate change induced drought and improving prediction of wildfire potential are some key management applications of this work. In addition, knowledge of landscapes with droughty soil helps land managers prioritize limited budget allocations. In this way, managers can ensure that vegetation treatments which reduce forest stand density and decrease fuel loads are targeted to areas where they will be most effective in improving forest health and resilience to climate change.

Chase et al. (2016) found that thinning of dense forest vegetation increased soil moisture during the summer months on their study sites in northern Idaho and northeastern Washington. They found that "thinning high-density stands on low productivity sites will provide the greatest stress relief and benefit to overall forest health because resources are more limited and competition for those resources is high. Alternatively, thinning high productivity, high density stands will maximize the growth response of residual trees". In addition, they found that for the studied forest types, thinning had the greatest relative impact on summer soil moisture, followed by soil N availability, and light interception. Reduced tree water stress by thinning is a viable option for increasing forest resiliency to drought induced by climate change (D'Amato et al., 2013; Elkin et al., 2015; Sohn et al., 2013). Other studies have found that similar soil moisture effects can be realized through prescribed burning (Hatten et al., 2012).

Knowledge of soil moisture conditions can also improve our ability to estimate wildfire danger. Krueger et al. (2015) showed that weather variables alone were insufficient to predict wildfire potential and that fire danger predictions were enhanced when soil moisture data were used. Although the authors recognized that many factors influence fire occurrence and size such as weather, ignition source, fuel characteristics, and suppression efforts, they found that soil moisture information was significantly related to fire size during the growing season. By using a measure of the fraction of available water holding capacity (FAW) of the soil to understand the influence of soil moisture on fire occurrence, they found that all size Class 5 ($>$ 405 ha.) fires occurred at FAW less than 50 percent and that 87% of the largest fires occurred when FAW was less than 20 percent. Inclusion of soil moisture information in wildfire prediction models could improve assessments of wildfire danger, particularly as a possible surrogate for live fuel moisture. Although the current model focusses on whole-column soil moisture, the methodology could be adapted to consider only the top portion of the column, which may be more closely associated with wildfire danger.

The primary objective of this effort was to produce a landscape-level droughty soil index that could help inform forest managers which areas are potentially vulnerable to soil moisture drought. Since we have focused here *exclusively* on modeling summer soil moisture levels, it is important to note that the model does not speak directly to vegetation stress, as plants are generally adapted to their site. Rather, we envision that this index represents one variable among many that can be used in helping managers select areas for treatment that will potentially provide the "best bang for their buck."

## 2. Methods

### *2.1. Study area*

The study covers the forested areas of the USDA Forest Service Pacific Northwest Region, including Washington and Oregon and small areas of National Forest land in northern California (the Siskiyou NF). The Pacific Northwest is a highly diverse landscape both geographically and climatically. The majority of National Forest System (NFS) lands spans seven mountainous Pacific Northwest ecoregions described in Omernik (1987) with minor components of NFS land present in four lowland ecoregions (Fig. 1). Geological diversity is expressed in rocks of different age classes dating from Jurassic to early Pleistocene and from such diverse lithologies as basalt, diorite, andesitic breccia, massive arkosic sandstone, greywacke, quartz-mica schist, peridotite and unconsolidated alluvium. Weathering, tectonic activity, mass wasting, glaciation, fluvial processes and volcanic eruptions have altered exposure of the bedrock throughout most of the study area. Volcanic soils from multiple eruptions and of varying ages and particle sizes blanket the central and eastern Cascades and areas of eastern Oregon and Washington north of Crater Lake. Common soil orders on forest lands include Inceptisols, Andisols and Alfisols. Spodosols have locally developed in coastal areas and on some upper elevation slopes in the Cascades (Heilman et al., 1979). Mollisols can be found in forested areas that were once open savanna.

The study area has a Mediterranean climate with most moisture falling in winter. The majority of the precipitation falls from October to February, and less than 10% occurs during July through September (Western Regional Climate Center, 2017). Two parallel mountain ranges, the Coast Range and the Cascade Range separate the wetter and cooler western half of the study area from the drier and warmer eastern half of the study area. The Pacific Ocean, bordering the western edge of the study area is responsible for moderating the climate from the coast to the Cascade Mountains. Winter storms move from west to east and drop significant rainfall on the windward slopes of the Coast Range and Olympic Mountains, ranging from a mean annual precipitation of 1900–2290 mm (75–90 in.) at the coast up to 5080 mm (200 in.) at the crest. Precipitation on the windward slopes of the Cascades is one half to two thirds of the coastal rainfall. On the eastern, leeward slopes of the Coast Range, Olympic, Cascade, and North Cascade mountains rainfall amounts decline sharply from 5080 mms (200 in.) in the Coast Range to 1020 mm (40 in.) in the Puget Lowlands and Willamette Valleys and from 2030 to 2540 mm (80–100 in.) at the crest of the Cascade Range to a low of 203 mm (8 in.) in the lowlands of the Columbia Plateau and Northern Basin and Range Ecoregions. The Rocky Mountains ecoregion of NE Washington and the Blue Mountains of eastern Oregon experience an increase in precipitation up to 900 mm (35 in.) due to orographic lifting and marine air moving up the Columbia River Basin.

Morning fog can occupy coastal and lowland valleys in the western portion of the study area in late summer and early fall. Because of this, solar flux is not a simple measure of aspect nor is surface soil moisture