



# Soil water availability effects on the distribution of 20 tree species in western North America



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## ARTICLE INFO

### Article history:

Received 13 September 2013

Received in revised form 8 November 2013

Accepted 9 November 2013

Available online 3 December 2013

### Keywords:

3-PG model

Species distributions

Available soil water holding capacity

Decision tree model

## ABSTRACT

The distribution of tree species is largely shaped by regional variation in climate and soils. Current models make very simple assumptions about soil water availability with limited inclusion into the predicted distribution of species. Recently, methods have been developed that integrate observations from satellites on maximum leaf area index. These remote sensing estimates, when combined with physiology can provide more detailed maps of available soil water holding capacity (ASWC) and soil fertility. By allowing soil properties as well as climate to vary across western North America, our process-based decision tree models predicted the occurrence of 20 tree species with an average accuracy of 84% ( $\kappa = 0.79$ ), based on their recorded presence and absence on 43,404 field plots. Changes in productivity and distributions were assessed with varying soil water inputs. ASWC was increased and decreased by 50% from the originally mapped values to evaluate the effects on predicted species distributions. Soil water availability helped explain the variation in the distribution of 75% of the tree species. We found that 30% of the species were very to extremely sensitive to changes in ASWC, while 45% were somewhat sensitive. We conclude that knowledge of soil properties generally improves overall accuracy of species distribution models. Our sensitivity analysis identified the most sensitive species to changes in water availability, and indicated where additional information on soil properties would be most critical to verify.

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## 1. Introduction

Most ecologists and botanists recognize that the distribution of tree species within a region is shaped by both climate and soil properties (Syphard and Franklin, 2009). Increased climate change on a global scale is altering the hydrological cycle (IPCC, 2007) and affecting the amount of water available for tree growth. Differences in soil depth and water holding capacities are becoming increasingly important to identify with changes in climatic conditions (Ganey and Vojta, 2011; Peterman et al., 2013).

In the Pacific Northwest, the regional climate has become warmer since 2000 compared to a cooler phase in 1950–1975 (Waring et al., 2011). Such climate alterations are affecting forest ecosystems and their vulnerability to changes in disturbance regimes (Raffa et al., 2008; Westerling et al., 2006). In southwestern parts of the United States, extended periods of drought have been observed, leading to higher rates of tree mortality of pinyon pine–juniper (*Pinus edulis* and *Juniperus* spp.) forests caused by low water content in the soils (Peterman et al., 2013). Ganey and Vojta (2011) reported a die off in mixed-conifer and ponderosa

pine species (*Pinus ponderosa*) in Arizona during a drought event in 1997–2007. They found a high mortality of 85% quaking aspen (*Populus tremuloides*) and 28% white fir (*Abies concolor*) and attributed this to elevated temperatures associated with climate change as well as insect attack. Soil water deficits during the growing season are also prevalent in low elevation areas causing a decline in productivity (Latta et al., 2010). Water stress is known to affect plant growth by inhibiting photosynthesis and transpiration and can lead to mortality under severe conditions (Reichstein et al., 2007). There has been an expressed need to better understand the link between tree responses associated with increased exposure to drought conditions and use this to predict areas where species shifts will occur (Allen et al., 2010). Available soil water content is an essential requirement for successful tree occurrence and productivity, providing a means to quantify tree responses to hydrological changes (Weltzin et al., 2003).

Foresters and ecologists have long recognized species-specific requirements with regard to soils. For example, ponderosa pine, a widely distributed species in the Pacific Northwest, is known to be drought tolerant and can effectively compete in well-drained sandy soils (Tarrant, 1953). Douglas-fir (*Pseudotsuga menziesii*) grows in a wide variety of soils although it prefers sandy loams with good drainage (Farrar, 1995). In contrast, western red cedar

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(*Thuja plicata*) is able to survive anaerobic conditions but has a low tolerance to drought (Harlow and Harrar, 1950). Knowledge about how soil water availability influences tree species establishment and growth plays an important role for forest managers seeking to conserve biodiversity while also increasing forest resources. Soil properties determine the water available to trees and the soil type influences the amount of rainfall that evaporates or infiltrates into the soil and the amount of plant available water released in the rooting zone. A better understanding of the interaction between tree species types and soil moisture can thus improve the ability to maintain healthy, productive forests.

Whilst the importance of soil attributes on tree growth and species distributions is well known, inclusion of this information into predictive models is less common (Syphard and Franklin, 2009) and even rarer in models designed to assess the impact of climate change (Rehfeldt et al., 2009; McKenney et al., 2007). Instead species distribution models often utilize climate data and focus on climatic controls on species occurrence. McKenney et al. (2007) used the climate envelope approach to model the climate niche of 130 tree species in North America. The study did not utilize soil data due to limited maps available on a continental scale. Rehfeldt et al. (2009) modeled the distribution of quaking aspen in western USA using only climate parameters and noted that inclusion of soil factors are also important for accurate model predictions. The challenge to do so is great due to the low spatial resolution of available digitized data sets, however attempts to improve the situation continue through the development of a global digital soil map (Sanchez et al., 2009). In North America, the State Soil Geographic (STATSGO) database is the source that most species distribution modellers utilize (Iverson et al., 2008; Coops and Waring, 2001). Iverson et al. (2008) mapped species habitat in the eastern United States using soil properties derived from STATSGO, indicating that soil parameters influenced tree species distributions. However, they did not provide any further explanation on how soils might assist or constrain species range shifts under climate change. Coops and Waring (2001) also employed STATSGO to derive soil water content in Oregon. They found soil water to have an important impact on forest growth especially during summer drought conditions. All above cited authors agreed that variation in soil parameters influence the predicted distribution and growth of tree species and that coarse-resolution maps of soil properties were insufficient and need to be refined.

Recognizing the need for more accurate spatial information, a new soil map was produced from the relationship between soils, climate and forest productivity (Coops et al., 2012). The spatial variation in available soil water storage capacity (ASWC) and soil fertility (FR) were inferred at 1 km resolution by optimizing the predictive maximum leaf area index ( $LAI_{max}$ ) derived with a process-based growth model with values acquired from satellite measurements.

In this study, we utilize these derived layers of soil properties to model the occurrence of tree species across the Pacific Northwest. We expand the number of native tree species evaluated and extend the area to include most of western North America. We also assess the sensitivity of model predictions to variations in soil water availability by analyzing species predictions when ASWC is increased and decreased by 50%. Finally, we evaluate the implications of recent climatic change on species distributions by comparing shifts in ranges under stable and variable soil water conditions.

## 2. Methods

### 2.1. Study region

The Pacific Northwest Region (PNW) of North America contains a number of diverse ecoregions, with varying climate and

landforms. This diversity in landforms, climate and vegetation gives rise to a wide variety of soil types (Franklin and Dyness, 1973).

Extending from Alaska to Northern California, the Marine West Coast Forest, is the most productive PNW zone with high annual precipitation. These temperate coastal forests contain tree species such as sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), and Douglas-fir, with western red cedar (*T. plicata*), grand fir (*Abies grandis*), Alaska yellow cedar (*Chamaecyparis nootkatensis*) and coast redwood (*Sequoia sempervirens*) abundant in certain areas as well. Soils in this ecoregion can vary from infertile, well-drained shallow soils to nutrient-rich bogs with high organic matter content (Valentine et al., 1978).

In the Interior, the Northwest Forested Mountains has a drier climate and is the second most productive zone. Species such as Douglas-fir, western hemlock, noble fir (*Abies procera*), western larch (*Larix occidentalis*) and pacific silver fir (*Abies amabilis*) are well distributed in this area. The subalpine environment contains species such as lodgepole pine, whitebark pine (*Pinus albicaulis*), mountain hemlock (*Tsuga mertensiana*), subalpine fir (*Abies lasiocarpa*), and Engelmann spruce (*Picea engelmannii*). The soils range from nutrient-poor to moderately rich depending on both parent material and soil formation rates (CEC, 1997).

The North American Deserts found in eastern BC and California has an arid to semi-arid climate caused by the rain shadow of the Sierra Nevada and Cascade Mountains. Species such as ponderosa pine are widely distributed, in addition to pinyon pines and junipers. Only about 2% of the ecoregion is covered by forests (McLaughlin, 1986). The ecological zone contains some very dry soils with low organic matter content associated with sparse vegetation (CEC, 1997).

### 2.2. Climate data

Mean monthly climate data were obtained using ClimateWNA, where long-term measurements of temperature and precipitation are interpolated spatially. PRISM (Parameter-elevation Regressions on Independent Slopes Model) records were downscaled to 1 km through bilinear interpolation and elevation adjustments (Wang et al., 2006; Daly et al., 2002) and elevation data for ClimateWNA were generated by resampling a 90 m Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM). Average monthly atmospheric vapor pressure deficits (VPD) during the daytime were calculated with the assumption that daytime water vapor concentrations are the same as those at mean minimum temperature (Kimball et al., 1997). Maximum VPD was obtained as the difference between the saturated vapor pressure at the mean maximum and minimum temperatures. Average daytime VPD was estimated as two thirds of the maximum, in order to obtain a mean daytime value instead of one derived from the daily extremes (Waring, 2000). The number of days per month with sub-freezing temperatures ( $\leq 2$  °C) was calculated from empirical equations with mean minimum temperature (Coops et al., 1998). Similar to the methodology applied by Schroeder et al. (2009), monthly mean incoming short-wave radiation was estimated by combining the synoptic and zonal variation captured by the North American Regional Reanalysis (NARR) with topographically-driven variation based on Fu and Rich (2002). Spatial biases found through comparison with station networks from the National Solar Radiation Database (NREL) and Environment Canada (ECGC) were then removed.

### 2.3. Tree species plot data

Tree species presence and absence information were acquired from various sources across the PNW. In British Columbia,

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