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Remote measurement of canopy water content in giant sequoias (*Sequoiadendron giganteum*) during drought

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ABSTRACT

California experienced severe drought from 2012 to 2016, and there were visible changes in the forest canopy throughout the State. In 2014, unprecedented foliage dieback was recorded in giant sequoia (*Sequoiadendron giganteum*) trees in Sequoia National Park, in the southern California Sierra Nevada mountains. Although visible changes in sequoia canopies can be recorded, biochemical and physiological responses to drought stress in giant sequoia canopies are not well understood. Ground-based measurements provide insight into the mechanisms of drought responses in trees, but are often limited to few individuals, especially in trees of tall stature such as giant sequoia. Recent studies demonstrate that remotely measured forest canopy water content (CWC) is a general indicator of canopy response to drought, but the underpinning leaf- to canopy-level causes of observed variation in CWC remain poorly understood. We combined field and airborne remote sensing measurements taken in 2015 and 2016 to assess the biophysical responses of giant sequoias to drought. In 49 study trees, CWC was related to leaf water potential, but not to the other foliar traits, suggesting that changes in CWC were made at whole-canopy rather than leaf scales. We found a non-random, spatially varying pattern in mapped CWC, with lower CWC values at lower elevation and along the outer edges of the groves. This pattern was also observed in empirical measurements of foliage dieback from the ground, and in mapped CWC across multiple sequoia groves in this region, supporting the hypothesis that drought stress is expressed in canopy-level changes in giant sequoias. The fact that we can clearly detect a relationship between CWC and foliage dieback, even without taking into account prior variability or new leaf growth, strongly suggests that remotely sensed CWC, and changes in CWC, are a useful measure of water stress in giant sequoia, and valuable for assessing and managing these iconic forests in drought.

1. Introduction

Giant sequoias (*Sequoiadendron giganteum*) are among the most iconic tree species on Earth, yet their existence may be threatened by climate change. As a case-in-point, during 2012–2016, California experienced the most extreme drought ever measured (Diffenbaugh et al., 2015; Swain et al., 2016), and there were visible changes in the forest canopy. In 2014, unprecedented foliage dieback (dead or dying needles visibly present in the canopy) was recorded in giant sequoia (*Sequoiadendron giganteum*) trees in Sequoia and Kings Canyon national parks, in the southern California Sierra Nevada mountains. The foliage dieback was deemed to be drought induced because the patterns of dieback were consistent with a controlled process of drought-driven senescence, and dieback was measurably higher in more stressful environmental conditions: at lower elevations, on steeper slopes and in younger groves of lower density (Stephenson et al., 2017).

Although visible changes in sequoia canopies can be recorded, biochemical and physiological responses to drought stress in giant sequoia canopies are not well understood. In general for tree species, leaf- and canopy-level drought-induced changes are driven by the basic physiological trade-off between minimizing water loss and maximizing carbon gain at the leaf level, leading to a reduction in stomatal conductance, photosynthesis and transpiration rates (Cowan, 1982; Hartmann, 2011). Documented leaf-level responses include changes in

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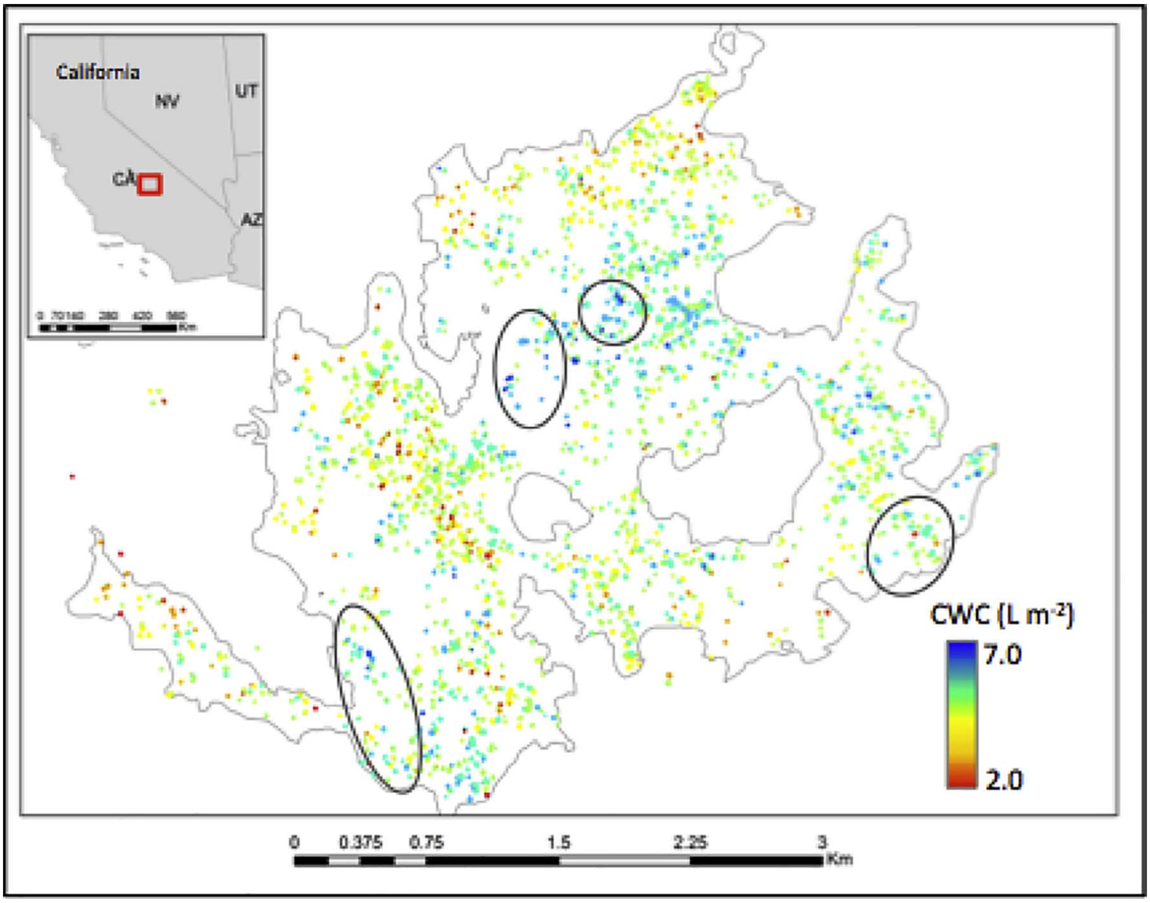

Fig. 1. Map of mean canopy water content (L m^{-2}) in 2015 of giant sequoias in the Giant Forest of Sequoia National Park. Four ellipses indicate the approximate areas where 49 canopies were selected for leaf-level studies.

carbon isotopic signatures due to stomatal closure (Farquhar et al., 1989), which may also lead to a decrease in N uptake (He and Dijkstra, 2014; Niinemets, 2010), decreases in leaf water content or leaf water potential, and changes in non-structural carbohydrate (NSC) stores in the late stages of drought (Adams et al., 2013; Sala et al., 2010). Other canopy-level responses may include phenotypic isohydric behavior, whole- or partial-canopy foliar senescence, also known as foliar dieback, and a loss of canopy leaf area (Ambrose et al., 2016; Jump et al., 2017). Determining which of these drought responses occurs in giant sequoia with ground-based measurements is challenging due to the difficulty in making measurements in trees of such large stature. In addition, current satellites do not provide data with spatial and spectral resolution fine enough to measure biophysical changes in the canopy at the individual scale. Airborne remote sensing offers a means to measure canopy condition of a large number of individual trees, which may provide insight into whether giant sequoias are responding at the leaf or canopy level, or both.

In 2015, airborne high-fidelity imaging spectroscopy (HiFIS) measurements collected over the forests of California revealed that over 800 million trees experienced measurable decreases in canopy water content (CWC) during the 2011–2015 drought period (Asner et al., 2016). HiFIS has proven robust for quantifying the biophysical properties of ecosystems such as those diagnostic of drought stress, including CWC (Ceccato et al., 2001; Gao and Goetz, 1995, 1989; Ustin et al., 2004). CWC is the total amount of liquid water in the canopy foliage expressed in L m^{-2}, and is derived from measurements of the absorption and scattering of light in the regions of the electromagnetic spectrum sensitive to relative amounts of atmospheric water vapor and liquid water of the canopy (Green, 2003). CWC is an integrated measure of both leaf water content and leaf area index (LAI), and thus may be sensitive to leaf and/or canopy level responses to drought stress. CWC is also sensitive to multiple stages of canopy water stress (Asner et al., 2004), making it a useful measurement to link varying levels of observed drought stress to biophysical drought responses in giant sequoia trees. However, the underpinning leaf- to canopy-level causes of observed variation in CWC remain poorly understood.

For giant sequoias, there may be environmentally-mediated conditions under which mapped CWC changes are generated by leaf and/or canopy adjustment to water availability. We used a combination of field and airborne remote sensing measurements taken in 2015 and 2016 to examine biophysical responses of giant sequoias to drought. We focus on tree canopies in the Giant Forest grove of Sequoia and Kings Canyon National Park (Fig. 1). Our goal was to assess variation in leaf and canopy properties present in live foliage as an avenue to understand their relative importance in explaining giant sequoia responses to drought. In addition, we compare leaf and canopy-level measurements from 2015 to those made in 2016 to assess change during drought. Our main question is: Are giant sequoias responding to drought more by varying properties of individual leaves, or by reducing the amount of leaves in their canopies?

2. Methods

2.1. Field data collection

2.1.1. Tree selection

In July 2015, four sites within Giant Forest were selected for an in-depth drought response assessment. The sites were selected using a foliage dieback map (Stephenson et al., 2017) that depicts the percent of drought-induced foliage dieback observed along the Giant.