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The effects of sudden oak death on foliar moisture content and crown fire potential in tanoak

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The introduction of non-native pathogens can have profound effects on forest ecosystems resulting in loss of species, changes in species composition, and altered fuel structure. The introduction of *Phytophthora ramorum*, the pathogen recognized as causing Sudden Oak Death (SOD), leads to rapid decline and mortality of tanoak (*Lithocarpus densiflorus*) in forests of coastal California, USA. We tracked foliar moisture content (FMC) of uninfected tanoaks, SOD-infected tanoaks, SOD-killed (dead) tanoaks, and surface litter for 12 months. We found that FMC values differed significantly among the three categories of infection. FMC of uninfected tanoaks averaged 82.3% for the year whereas FMC of infected tanoaks had a lower average of 77.8% (ANOVA, $P = 0.04$). Dead trees had a significantly lower FMC, averaging 12.3% (ANOVA, $P < 0.01$) for the year. During fire season (June–September), dead tanoak FMC reached a low of 5.8%, with no significant difference between dead canopy fuels and surface litter (ANOVA, $P = 0.44$). Application of low FMC values to a crown ignition model results in extremely high canopy base height values to escape crown ignition. Remote estimation of dead FMC using 10-h timelag fuel moisture shows a strong correlation between remote automated weather station (RAWS) 10-h timelag fuel moisture data and the FMC of dead leaves ($R^2 = 0.78$, $P < 0.01$). Results from this study will help refine the decision support tools for fire managers in SOD-affected areas as well as conditions in other forests where diseases and insect epidemics have altered forest canopy fuels.

1. Introduction

Plant pathogens and insects are found in all forest ecosystems and are responsible for forest dynamics at both small (gap phase) and large (landscape pattern) scales (Castello et al., 1995). Often, pathogens and insect attacks manifest as recurring disturbances and, as such, are essential to maintaining forest structure (Turner, 1989; Haack and Byler, 1993; Hessburg et al., 2000). These disturbances will often work in concert with secondary disturbances that synergistically influence the larger disturbance regime (White and Pickett, 1985). In many cases diseases will alter surface fuels (Dickman and Cook, 1989; Castello et al., 1995) where the subsequent fire intensity and severity are increased.

Non-native plant pathogen introduction can have an even greater impact on the invaded ecosystems (Coblentz, 1990; Vitousek et al., 1996). Host species typically have limited or no resistance to non-native pathogens resulting in substantial population decline or elimination of a species. The introduction of chestnut blight (*Cryphonectria parasitica*) and white pine blister rust (*Cronartium ribicola*) are two well-known North American examples (Paillet, 2002; Ellison et al., 2005). As with native pathogens and insects, there is potential for secondary disturbances, especially fire. Trees weakened by pathogens may suffer greater mortality during fire than healthy trees (Agee, 1993), and trees killed can elevate fuel loads and exacerbate fire effects (Harrington and Hawksworth, 1990; Hummel and Agee, 2003).

The introduction of the non-native pathogen *Phytophthora ramorum*, recognized as causing Sudden Oak Death (SOD), has caused profound effects at the ecosystem and landscape scales in coastal forests of central and northern California, USA (Rizzo and Garbelotto, 2003; Waring and O'Hara, 2008). Since its discovery in 1995 in the San Francisco Bay area, SOD has quickly spread north and south along the coastal forests and woodlands from Monterey to Humboldt County and isolated areas of southwest Oregon infecting all dominant tree species including coast redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziesii*), coast live oak (*Quercus agrifolia*), Pacific madrone (*Arbutus menziesii*) and tanoak (*Lithocarpus densiflorus* (Hook. & Arn.) Rehd.) (Davidson et al., 2005; Rizzo et al., 2005; Murphy et al., 2008). Among these species, tanoak is most susceptible to SOD, with tree mortality exceeding 95% in some areas and over 3 million trees killed to date (Moritz et al., 2008; USDA Forest Service, 2009a). Since tanoak is common as an

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understory component, a co-dominant, or found in pure stands (Sawyer et al., 1977; Tappeiner et al., 1990), SOD infection has the potential to severely diminish or eliminate this species and change the composition and structure of forests where tanoak is a significant component (Waring and O'Hara, 2008).

In addition to changes in species composition, changes in forest fuel structure are also eminent as tanoaks succumb to SOD. These changes often follow a pattern that can be considered as four distinct phases (Fig. 1): *Phase 1*—individual trees are infected, crowns become yellow with reduced foliar density; *Phase 2*—the tree remains standing dead with leaves attached one or more years (D. Rizzo, unpublished data, 2010). Due to the characteristics of *P. ramorum* infection, the mechanism of leaf abscission is interrupted, resulting in prolonged dead leaf retention. *Phase 3*—leaf fall occurs, adding considerable litter fuel to the forest floor fuelbed, thereby elevating surface fire hazard (crown fire potential is reduced while surface fire hazard increases); *Phase 4*—branches, limbs, and entire stems begin to fail, falling to the forest floor resulting in a substantial increase in surface woody fuel loading. These phases are not necessarily sequential. For example, stem failure can occur at any point in the sequence as a result of secondary organisms such as *Hypoxylon thouarsianum* and/or ambrosia beetles (Swiecki and Bernhardt, 2005). Across this sequence, the incipient Phases 1 and 2 likely represent the most acute crown fire hazard attributable to lower foliar moisture. Crown foliar mass in these phases may remain high enough to sustain crown fire spread (Van Wagner, 1977). Beyond phase 2, surface fire intensity may increase as a result of elevated fuel loading; however, the reduction of crown fuel density makes the probability of crown ignition and/or spread unlikely.

Since crown fuels (foliage and twigs <0.6 mm) become more available for combustion as foliar moisture declines, and managers in the region have reported an increase in crown fire ignition in SOD-affected forests (Lee and Valachovic, 2009), there is an immediate need to quantify the susceptibility of crowns to ignition. Van Wagner (1977) developed the crown fire model used in the majority of fire behavior and spread prediction software (Scott and Reinhardt, 2001; Finney, 2004). The Van Wagner model requires four parameters: (1) fireline intensity (FLI); (2) canopy base height (CBH); (3) crown bulk density (CBD); (4) and foliar moisture content (FMC) (Van Wagner, 1977). Small changes in FLI and CBH have considerable influence on the probability of crown ignition. Applying the range of normal FMC values found in healthy trees (73–150%; Keyes, 2006), to the Van Wagner model, the effect of FMC on crown ignition is minor (Scott and Reinhardt, 2001; Cruz et al., 2006). To date, no work has evaluated the effect of reduced FMC (below 70%) on crown fire ignition, an important oversight if dead foliage remains attached to standing trees for a prolonged period of time, as is the case with SOD-killed tanoak.

Substantial research has been conducted to quantify foliar moisture of conifers (Johnson, 1966; Philpot and Mutch, 1971; Agee et al., 2002; Keyes, 2006), however considerably less is known about the foliar moisture characteristics of broadleaf trees and foliar moisture patterns of evergreen hardwoods is lacking altogether. Limited research has been conducted on the diurnal FMC pattern of whiteleaf manzanita (*Arctostaphylos viscida*) foliage (Philpot, 1965), seasonal trends in sugar maple (*Acer saccharum*) and trembling aspen (*Populus tremuloides*) (Van Wagner, 1967), and understory shrubs (as a group) in Pacific Northwest forests (Agee et al., 2002). For deciduous hardwood trees, Van Wagner (1967) found FMC values that far exceeded co-occurring conifers. For tanoak, limited FMC data were collected following the Biscuit Fire in southwest Oregon during late summer (Raymond and Peterson, 2005). Clearly, current data typifying the FMC of hardwoods is lacking.

Given that SOD-killed tanoaks retain dead foliage for one or more years following death, and tanoak can typically comprise one third or more of the basal area in these coastal forests, we sought to quantify the decline in FMC and evaluate its magnitude on potential crown fire ignition. The objectives of this study were to: (1) quantify the patterns of FMC monthly over a one year period; (2) compare FMC among healthy tanoaks, tanoaks infected with SOD, and dead tanoaks across the same period; (3) compare the FMC of standing dead trees to surface litter moisture and; (4) investigate the potential of using 10-hour timelag fuel moisture data (representing woody fuels 0.63–2.53 cm in diameter) obtained from a remote automated weather station (RAWS) to predict the FMC of dead tanoak leaves. Methodology developed for this study can be applied to other ecosystems where pathogens and insects are reducing FMC and causing prolonged dead leaf retention of trees (i.e. vascular wilts, root diseases, and beetle-killed trees). Data derived from this study would be an important contribution in order to link crown ignition to spread rates via crown fire and/or spotting, a topic not considered in this study due to the complexity of the canopy fuel strata in forests where tanoak is co-dominant or an understory component. Results from this study are also critical for decision support software used to evaluate the likelihood of crown fire ignition by resource managers in tanoak forests.

2. Methods

In March 2008, we began tracking the FMC of uninfected tanoak, live SOD-infected tanoak, and dead tanoak. Individual tanoak trees were selected in an area of known SOD infection on CAL FIRE Eel River Camp and adjacent properties near Redway, CA, USA (40°08′29.12″N, 123°49′29.80″W) where SOD has been known to exist since 2004 (Y. Valachovic, personal communication, 2007). The species composition in the study area consisted of California bay, Douglas-fir, Pacific madrone, and coast redwood (occasionally) with tanoak as a dominant, co-dominant or understory component. Concerned that uninfected tanoaks in the study area could become infected during the course of the study, but not detected until after sampling had finished, a second site was selected as a control, 70 km north of the area of infection at the L.W. Schatz Demonstration Tree Farm (LWSDTF) near Maple Creek, California (40°46′07.04″N, 123°52′12.29″W). The LWSDTF site offered stand and weather conditions similar to the Eel River Camp with a comparable elevation (172 m for Eel River Camp, 245 m for LWSDTF) and distance to the ocean (23 km for Eel River Camp, 27 km for LWSDTF; Fig. 2).

At Eel River Camp a total of 25 trees were selected for monthly sampling: 8 live uninfected tanoaks, 10 live SOD-infected tanoaks, and 7 standing dead tanoaks (SOD killed with leaves on). Given that individual trees could change from uninfected to infected or infected to dead during the course of the study, less importance was given to attaining even sample sizes across infection categories. More importance was given to selecting individual trees based on their similar size and stand characteristics, and their proximity to one another allowing field sampling to occur within the narrow windows used in previous FMC research (Philpot, 1965). At the LWSDTF 12 tanoaks (uninfected) of similar size and canopy position as that of the tanoaks at Eel River Camp were chosen for sampling monthly. Samples from each tree consisted of removing approximately 30 g of >1-year old leaves, <1-year-old leaves, and twigs (0.0–0.6 mm) with a 6 m pole pruner. On each sampled tree, we collected leaves from randomly selected branches, removing foliage without regard to presence of flagging, dead margins, or entirely dead leaves. Additionally, we also collected 15 g of surface leaf litter (at the upper surface of the litter layer) beneath sampled dead tanoaks monthly. We collected surface litter to compare this commonly measured variable in surface fire rate of spread (Rothermel, 1972) to FMC patterns and to provide perspective on the magnitude of moisture dynamics in SOD-infected ecosystems.