Forest Ecology and Management 261 (2011) 1973–1986

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Sudden oak death-caused changes to surface fuel loading and potential fire behavior in Douglas-fir-tanoak forests

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ARTICLE INFO

Article history:
Received 20 December 2010
Received in revised form 17 February 2011
Accepted 21 February 2011
Available online 22 March 2011

Keywords:
Wildland fire
Disease
Fuel models
Fire suppression
Herbicide

ABSTRACT

We compared stand structure and fuel loading in northwestern California forests invaded by *Phytophthora ramorum*, the cause of sudden oak death, to assess whether the continued presence of this pathogen alters surface fuel loading and potential fire behavior in ways that may encumber future firefighting response. To attempt to account for these kinds of changes over a longer term than *P. ramorum* has been present in California, we supplemented sampling of pathogen-killed stands with those killed by herbicides. Although fuel loadings were greater in diseased than in undiseased stands, great variability was observed and the differences did not rise to the level of significance. Fuel loading observed in herbicide-treated stands was significantly greater than that in control stands ($P < 0.001$); total weight of downed woody debris (1-, 10-, 100-, and 1000-h fuel loadings) approximately doubled with the herbicide treatment ($\bar{x} = 106.3$ Mg ha^{-1}) over the control condition ($\bar{x} = 58.1$ Mg ha^{-1}). The increasing trends in herbicided and diseased plots resembled each other, suggesting that fuel loadings in diseased plots will continue to increase relative to the controls over a longer time horizon than observed. Fuel models based on the observed surface fuel accumulations in herbicide-treated and diseased plots predict that for some early-to-mid-phase (2–8 years) herbicide-treated forests, and for late-phase (8 years plus) diseased forests, rates of spread, flame lengths, and fireline intensities could increase significantly over the baseline, challenging effective firefighter response. These results, together with the "background" surface fuels observed in the control stands, highlight the need for fuels treatments and effective disease management strategies in infested stands and as sudden oak death expands throughout a broader region.

1. Introduction

The disease sudden oak death, caused by *Phytophthora ramorum* Werres (de Cock & Man in't Veld) has killed hundreds of thousands of true oak (*Quercus* spp.) and tanoak (*Lithocarpus densiflorus* (Hook. & Arn.) Rehder) trees in coastal California and Oregon since the mid 1990s (Meentemeyer et al., 2008). The pathogen inhabits several forest types in this region, among the most prominent being the widely distributed *Pseudotsuga menziesii* – *L. densiflorus* (Douglas-fir-tanoak) forest common in the northern Coast Ranges and Klamath Mountains in northwestern California (Douglas-fir = *P. menziesii* (Mirbel) Franco var. *menziesii*) (Sawyer et al., 2009; Fig. 1). We believe the potential impact of sudden oak death will be greater in this forest type than in other forest types in this region, because tanoak often shares the dominant canopy position in these Douglas-fir-tanoak stands. Within these forests, the pathogen produces patches of tanoak mortality that vary widely in size and density. Mortality is dependent on weather patterns from year to year, generally increasing within 1–2 years after wet winters and springs (Rizzo et al., 2005). Accumulating tanoak mortality following wet years in 2003, 2005, and 2006, in tandem with some large wildfires, has recently kindled concern that pathogen-caused mortality could provide fuel that might increase fire intensity and alter its effects in this fire-prone region (Kuljian and Varner, 2010; Lee et al., 2010; Metz et al., 2010).

The 2008 Basin Complex of fires and the Chalk Fire in the Big Sur ecoregion of California are examples of the kinds of wildfires that provide impetus for these concerns. Anecdotal evidence suggested

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doi:10.1016/j.foreco.2011.02.024

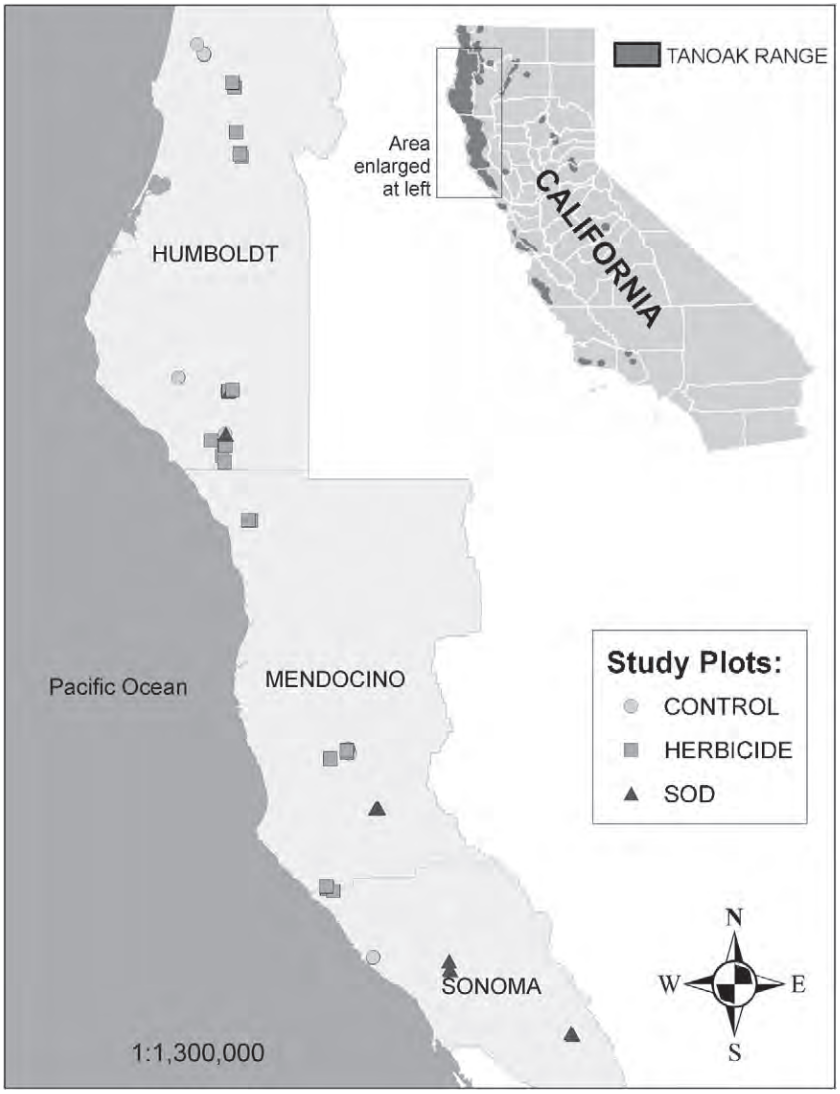

Fig. 1. Map of study and plot locations.

that patchy accumulations of surface fuels resulted from *P. ramorum* mortality in this region and influenced flame lengths, firebrand generation, and spotting distances on some areas of these fires (Lee et al., 2010). The Big Sur plant communities resemble coastal landscapes located farther north, for example in Sonoma County, where accumulating tanoak mortality has sparked community concern and the advent of government-assisted community fuels reduction projects in infested areas (Alexander and Lee, 2010). Of the affected forest types, Douglas-fir-tanoak forests have the greatest potential for individual tree torching and canopy fire spread; they also harbor species with a variety of resistance to fire-caused mortality. Douglas-fir-tanoak forests tend to occur on dry, upper slopes that can result in higher intensity and severity fire than the more fire-resilient grasslands and oak woodlands, and in contrast to the typically lower-slope coast redwood ecosystems that sustain low-severity fire (Finney and Martin, 1993; Lorimer et al., 2009). Although the vegetation of Douglas-fir-tanoak communities has been well-studied (e.g., Thornburgh, 1982; Sawyer et al., 1988; Stuart et al., 1993; Hunter and Barbour, 2001), as have the effects of fires (Wills and Stuart, 1994; Taylor and Skinner, 1998; Hanson and Stuart, 2005; Raymond and Peterson, 2005), the fuels that drive these fires have not received as much attention (but see Maxwell and Ward, 1980). Information about how sudden oak death changes these fuel complexes would enable land managers to make more informed decisions about fire suppression, strategic placement of fuels reduction projects, and attempts to slow pathogen spread, among others.

It is generally recognized that forest disease-related disturbances often link to other kinds of disturbances, such as insect activity, wildfire, and wind damage (Hessburg et al., 1994; Lundquist, 2007; Edmonds et al., 2010). Many studies of pathogen or insect disturbances linked with wildfire emphasize the importance of crown fire because this fire type can quickly produce large and long-lasting ecological impacts on the landscape. However, surface fire behavior is of particular interest to fire managers, because it is during surface fire advance that the opportunity for suppression exists. Crown fires are unambiguous in that little can be done to stop them, but the same is not true for surface fires. Some portions of surface fires can be directly attacked to limit fire impact on the landscape; some can be indirectly attacked with backing fires to eventually limit the size of this impact; and some cause enough torching and spotting that they approach crown fires in their resistance to control (Andrews and Rothermel, 1982; Edmonds et al., 2010; NWCG, 2010). Calibrating the differences between these varying potentials is important in northwestern California, where widely scattered private properties are often embedded in a diverse matrix that varies widely in stand composition and structure. To attempt to approach these questions with reference to sudden oak death, the specific objectives of this project were the following: (1) to quantify the impact of *P. ramorum* infestation on surface fuel loading and potential fire behavior in Douglas-fir-dominated stands with a significant tanoak component and (2) to gain a better understanding of the timelines from tree death to surface fuel recruitment in these stands. Answers to these questions or the methodology used to approach them may be applicable to other, similar ecosystems affected by non-native pathogens.

2. Methods

2.1. Study sites and study region

Our study area encompassed Douglas-fir-tanoak forests across three counties in northwestern California: Sonoma, Mendocino, and Humboldt (Fig. 1). These counties span a 400 km latitudinal range, covering ca. 25,000 km^2, throughout which this forest type is consistent in vegetation, topography, and climatic influence (Stuart and Stephens, 2006). To the north, Del Norte County also contains similar vegetation, but to date no *P. ramorum*. Counties to the east represent a reduced likelihood of natural *P. ramorum* establishment because of a generally warmer and drier climate (Rizzo et al., 2005) and less host vegetation. To extend the geographic range for this study, we selected two areas in Humboldt County within which to locate plots: southern Humboldt County, where the pathogen is established in wildland vegetation, and northernmost Humboldt County, in two areas 17 and 55 km south of Del Norte County (Fig. 1).

P. ramorum has not inhabited California and Oregon forests for long enough to enable direct observation of surface fuel dynamics over long periods of accumulation or over wide geographic areas. As a surrogate for *P. ramorum* infection's long-term (8–12 years) effects on surface fuels, we selected additional forest stands with herbicide-killed trees. Both *P. ramorum*-infested and herbicide-treated stands regenerated after timber harvest activities 40–60 years ago when Douglas-fir stems were removed and subsequent tanoak sprout growth was not controlled. Little planting was likely done in these sites, but even where Douglas-fir seedlings were planted, tanoak often quickly outcompeted and overtopped the planted seedlings (Tappeiner et al., 1992). Tanoak trees in the study sites were killed via 'hack and squirt' injections of either glyphosate or imazapyr (DiTomaso et al., 2004) so that dead trees were killed while standing, as in the situation with *P. ramorum*. It has been observed that the pattern of tanoak mortality across the landscape in many herbicide treatment areas strongly resembles that caused by *P. ramorum*. Planting was done in some, but not all, herbicide-treated sites after treatment.

A clear understanding of historical fire frequency, intensity, and size in the north coast's Douglas-fir-tanoak forests is still developing (Stuart and Stephens, 2006) but is important to understand as a context for alteration in fuel loading caused by *P. ramorum*. Lightning is relatively infrequent in the north coast (Keeley, 1982) but in concert with intentional Native American burning over the past 8000 years, fires frequented this diverse landscape. Tribes burned certain areas, especially grasslands and oak woodlands, frequently. Douglas-fir-tanoak forests probably burned at mixed frequencies and with mixed severity, and they probably experienced more lightning-ignited fires than lower-elevation forests in the region. These frequencies increased somewhat during the settlement period (post-1860s through the first half of the twentieth century), with large fires becoming more common as ranchers and loggers used fire for various intensive resource management purposes (Stuart, 1987). There appears to have been no "typical" fire size or intensity in Douglas-fir-tanoak forests in the pre-settlement period; these parameters depended on proximity to native settlements, elevation, distance from the coast, topographic variables, and a number of other factors. In general, pre-suppression fire intervals probably ranged from 10 to 16 years, and most fires were probably surface fires. Fire exclusion throughout the north coast region since the mid-1940s has meant that while the number of fires has been much lower since that time, fire sizes have dramatically increased. In many Douglas-fir-tanoak forests, fire suppression has encouraged the development of denser midstories and ladder fuels (Stuart and Stephens, 2006).

2.2. Field sampling

Within counties, plot locations were initially stratified by (1) mortality type (*P. ramorum* or herbicide) and (2) length of time since pathogen invasion or herbicide treatment. The length of time was divided into "early phase" (2–5 years), "middle phase" (5–8 years), or "late phase" (8–12 years) (Fig. 2). Not all conditions were represented equally in all counties. For example, Sonoma County contained plots infested with *P. ramorum* for the entire spectrum of time categories; Mendocino and southern Humboldt Counties contained plots infested with *P. ramorum* only for the past 2–5 years; and northern Humboldt County contained no plots infested with *P. ramorum*, since the disease was only discovered in one isolated area in 2010 and is undergoing active management. Untreated, uninfested control plots were visited in each county/county area. Throughout the four county areas, 105 plots were established.

We reduced variability among our study stands by limiting plots to those located on southerly aspects. We defined our study stands by presence of Douglas-fir with tanoak as a dominant or co-dominant overstory tree. Furthermore, we selected plots with 40–60-year-old Douglas-fir where tanoak substantially contributed to the stand basal area, because these are the stand types most often chosen for herbicide treatment. These young, hardwood-dominated stand types increased during the twentieth century in local areas of the north coast because of widespread harvest activity during the 1950s and 1960s that fundamentally replaced conifer stocking with hardwoods (Thornburgh, 1982; Bolsinger, 1988; Waddell and Barrett, 2005; Hicke et al., 2007). We avoided other forest types, such as coast redwood stands, as well as drainages or areas differentiated by microclimate and increased moisture availability.

Additionally, we selected stands that would clearly be assigned to timber-type fuel models rather than to shrub- or grass-type models (Anderson, 1982; Scott and Burgan, 2005) and that did not contain riparian vegetation. We chose stands containing, among other hardwood species, both bay laurel (*Umbellularia californica* (Hook. & Arn.) Nutt.) and tanoak, because these two species are the main transmitting hosts that drive the epidemic in California wildlands (Rizzo et al., 2005); although other species in these forests can be infected, they are not epidemiologically significant. We did not make a threshold level of bay laurel a criterion for stand selection, because even small numbers of bay laurel leaves can produce vast numbers of infective *P. ramorum* sporangia (Davidson et al., 2008). Consequently, the chosen stands contained varying levels of bay laurel stocking.

Plots were located within stands by randomly choosing a coordinate from a UTM grid overlain onto the stand of interest for initial plot establishment and then traveling at least 50 m in cardinal directions from the initial randomly located plot for establishment of subsequent suitable plots. We selected at least 50 m plot separation to maintain independence between *P. ramorum* populations. Within each plot, slope and aspect and the UTM coordinates of plot center were recorded. Then, within a fixed 0.04 ha circular plot, we collected an inventory of trees (>12.7 cm diameter), both dead and living, by species and diameter. Basal sprouts were

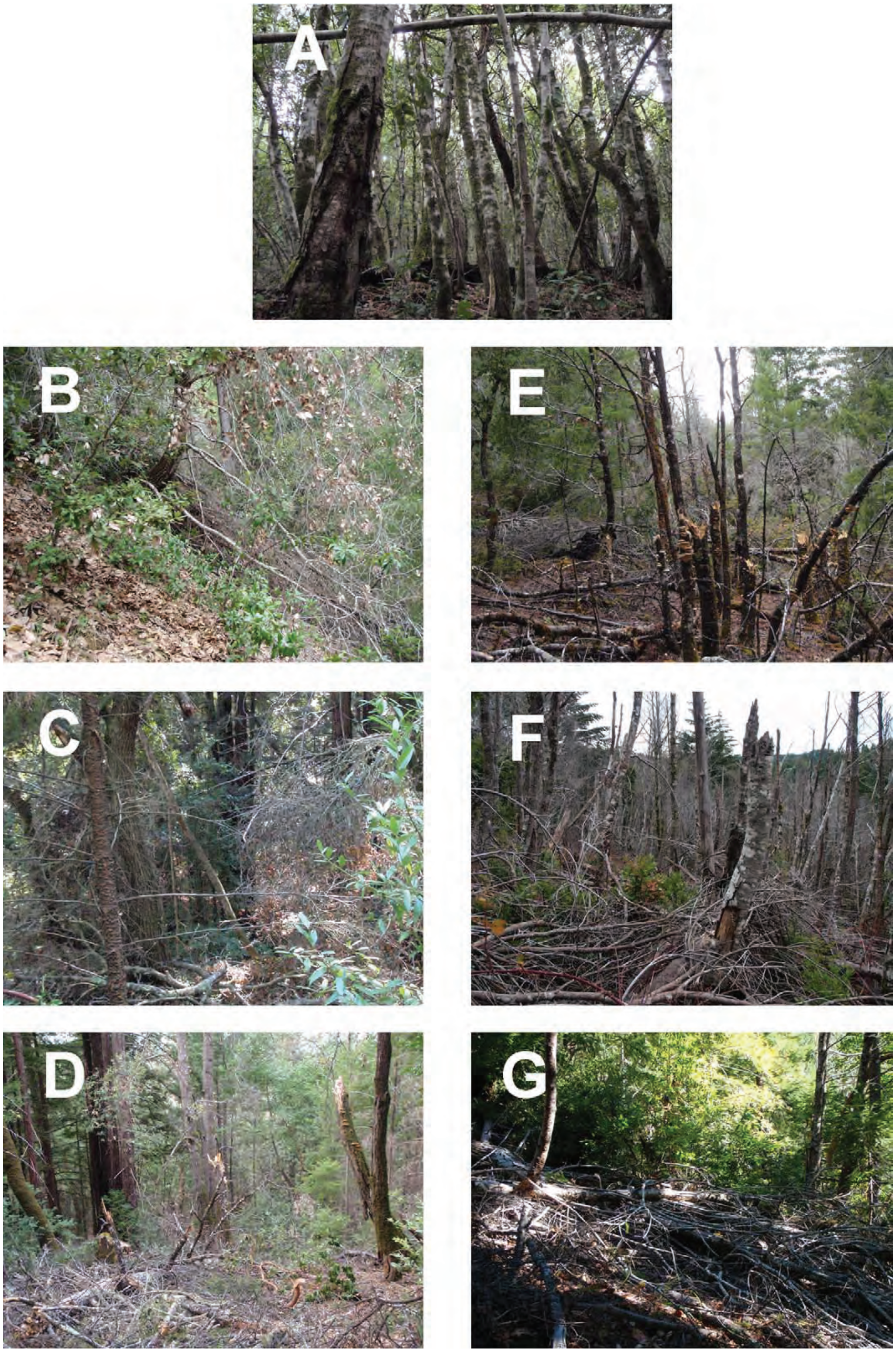

Fig. 2. Photos of diseased or herbicide-treated stands by phase. (A) Control (northern Humboldt County), (B) sudden oak death early-phase (Mendocino County), (C) sudden oak death mid-phase (Sonoma County), (D) sudden oak death late-phase (Sonoma County), (E) herbicide early-phase (Humboldt County), herbicide mid-phase (northern Humboldt County), herbicide late-phase (Mendocino County).

often present at the bases of living trees and dead standing trees; however, since our study concentrated on stand attributes with influence on surface fuels, sprout sizes and numbers were not noted or included in density and basal area calculations. Surface fuels were measured using a modified planar intercept method (Brown, 1974). Within each plot, three 13.72 m transects were established 120° apart starting from a random azimuth (i.e., a Y-shaped arrangement). Along each transect, we tallied numbers of 1-h (diameter < 0.64 cm), 10-h (diameter = 0.65–2.54 cm), 100-h (diameter = 2.55–7.62 cm), and 1000-h (diameter->7.62 cm) woody fuels. 1000-h fuels were assigned to decay classes using the categorization of Maser et al. (1979). We also measured surface litter (Oi horizon) and duff (Oe + Oa, where present) depths at three points along each transect and constructed depth:dry mass relationships for each layer ($R^2 > 0.67$). Fuelbed depth was estimated using a photographic method: two independent observers estimated the depth at a fixed point in a photo taken along each of the four cardinal directions in each plot. The estimated depths at each point were averaged, and the two observers' estimates were averaged. The resulting estimate of fuel bed depth was assigned to one of 6 categories (0–0.15, 0.16–0.30, 0.31–0.61, 0.62–1.22, 1.23–2.44, 2.45+ m).

All plots were further categorized post hoc by whether the majority of fuels were present in the canopy ("aerial") or on the forest floor ("surface") by analyzing the decay stage of the snags recorded on each plot and confirmed by the landscape photos taken from plot center in four cardinal directions.

2.3. Modeling predicted fire behavior

Fuel models were compared using BehavePlus v. 5.0.1 (Andrews et al., 2008) with the standard BasicStart (Surface) worksheet for fuel model response to a head fire for rate of spread and flame length. All simulations were developed using fuel moisture, wind, and topographic conditions common to wildfires in the region. We used a range of 1-h dead fuel moisture values (from 3% to 12%, representative of local field conditions). Woody fuel moistures in the 10- and 100-h categories were held constant at 5% and 6%, respectively. The mid-flame wind speed was held constant at 3 mph and slope was set to 45%. Since live fuels play a minor role in fires in these ecosystems, live fuel moisture was omitted from simulations.

The analysis compared fuel loads as sampled, and built into a custom fuel model, to standard fuel models (Anderson, 1982; Scott and Burgan, 2005). The fuel loads were grouped and evaluated in several different cohorts. Categories of affected fuels (diseased and herbicide-treated) were analyzed across geographic areas by early, middle, and late stages as well as by their distribution (aerial vs. surface) within the plot.

2.4. Fire suppression operations safety analysis

In order to estimate likelihood of successful ground-based suppression of surface fires burning in the stands and under the conditions studied here, we used the predicted rates of spread, flame lengths, and fireline intensities generated in BehavePlus (Andrews et al., 2008). Predicted rate of spread was compared to the standard sustained line production rate for a Type I Handcrew. Success was considered likely if a crew's production could exceed half the predicted rate of spread, representing line construction on both flanks of the fire. In this analysis the assumed line production was forecast as for a Model 8 (Anderson, 1982) understory if fuel loading was <22.8 Mg ha^{-1} (805 m h^{-1} max). Where the fuels exceeded 22.8 Mg ha^{-1}, the maximum line production rate was shifted to a light slash standard (302 m h^{-1} max).

Predicted flame lengths were compared to Hauling Chart standard values for successful suppression action (<1.22 m for handcrews; <2.44 m for engines or bulldozers; NWCG, 2010). Results were characterized in terms of whether a standard crew could directly attack the predicted fire for both diseased and herbicide-treated conditions, by early, middle, and late stages. Results were also characterized by fuel distribution (aerial vs. surface).

2.5. Data analysis

Treatments (disease at three time stages, herbicide treatment at three time stages, control) were compared using one-way analysis of variance (ANOVA; $\alpha = 0.05$), with post hoc Tukey–Kramer HSD tests for pair-wise means separation (Sokal and Rohlf, 1995). Variables included in the comparison encompassed stand information (density, basal area, and species composition of living and dead forest components), fuel loadings by timelag category, and fuel depths. Predicted fire behavior (i.e., flame lengths, rate of spread, and fireline intensity) was placed into categories according to the likelihood of success for standard fire suppression crew types to be able to attack the fire using the specified levels of resources detailed above. For all analyses, tests of normality were investigated using box plots and probability plots and using Levene's test for relative variation (Schultz, 1985; $\alpha = 0.05$) and the Shapiro–Wilk W-test (Zar, 1999; $\alpha = 0.05$). If required, data were transformed using log and square root functions then reanalyzed (Sokal and Rohlf, 1995). Where necessary, data were analyzed using Kruskal–Wallis nonparametric ANOVA with a post hoc Bonferroni multiple comparisons test (Zar, 1999). All statistical analyses were performed using NCSS 2007 (Hintze, 2007).

3. Results

3.1. Control stand comparison across counties

Stand structure within the control plots was similar among counties (Table 1). Density of live trees ranged between 776 and 1290 trees ha^{-1} and basal area between 55.7 and 79.8 m^2 ha^{-1}. Across all counties, tanoak was the principal component of the living forest (>60% of all live trees). Surface fuel loads within the control plots were similar among counties (Table 1). Total weight of surface fuels ranged between 37.9 and 97.7 Mg ha^{-1} and was composed mostly of 1000-h logs (range = 50–90%), which were unequally distributed and a product of past management. Fine fuel loading (the fraction most relevant to surface fire behavior) was distributed among litter (22%), 1- (16%), 10- (30%), and 100-h woody fuels (32%).

3.2. Temporal fuel dynamics following disease and herbicide treatment

In the early stage following *P. ramorum* infection, total live tree density was reduced by half, then continued to decline through the middle and late stages. Although no significant differences in density were detected among the three temporal stages, all were different than the control ($P < 0.001$; Table 2). Initially, dead trees made up only 6% of stand density, but increased to 21% immediately following infection, peaking in the late stage at 28%; no differences were detected among categories, yet all were different than the control ($P < 0.001$). Of the dead trees, tanoak represented 40% initially, increasing to 82% during the early stage of infection ($P = 0.01$). Basal area of dead tanoak trees, just 1.4 m^2 ha^{-1} initially, peaked in the early stage at 10.7 m^2 ha^{-1} then sharply declined during the middle stage (4.28 m^2 ha^{-1}; $P = 0.001$) as snags began to fall to the forest floor. Surprisingly, even as snags were recruited to the surface fuel, we did not detect these changes in total mass of surface fuels across infection phases, ranging between 33.4 and 58.1 Mg ha^{-1} ($P = 0.503$). The only temporal difference among fuel categories was in litter mass, which was at a minimum during the early post-infection stage (3.1 Mg ha^{-1}), increasing with time to a maximum of 4.7 Mg ha^{-1} during the late stage ($P = 0.046$).

In the stands treated with herbicides, stand attributes deviated significantly from control conditions over time (Table 2). Live tree density fell from 1072 trees ha^{-1} in the control to 200 during the early and middle stages, then rebounded to 445 during the late stage ($P < 0.001$; data not shown). The largest pulse of mortality was observed in the stands shortly after treatment, shifting stand composition from 6% to 73% dead ($P < 0.001$). Initially, tanoak accounted for 73% of living trees, but it was significantly reduced

Table 1
Estimates and results of one-way ANOVAs used to investigate site effects on vegetation and fuel properties in control stands. Sample size (n), mean, and standard error of the estimates (SE) are provided. Total live tree estimates include tanoak, conifer, and broadleaf species. Fine woody debris (FWD) includes 1-, 10-, and 100-h particles. Downed woody debris (DWD) includes FWD and 1000-h sound and rotten logs.

	Sonoma		Mendocino		Humboldt		N. Humboldt		P
	n	Mean (SE)	n	Mean (SE)	n	Mean (SE)	n	Mean (SE)	
Tanoak (dead)									
Density (trees ha^{-1})	5	25 (11.1)	5	5 (5.0)	5	94 (48.9)	5	44 (14.3)	0.139
Basal area (m ha^{-1})	5	0.8 (0.4)	5	0.2 (0.2)	5	3.9 (1.6)	5	0.9 (0.3)	0.078
Tanoak (live)									
Density (trees ha^{-1})	5	702 (113.9)	5	603 (58.3)	5	880 (237.7)	5	696 (121.3)	0.322
Basal area (m^2 ha^{-1})	5	38.0 (7.9)	5	33.5 (4.8)	5	48.1 (13.0)	5	45.8 (11.7)	0.710
Conifer (live)									
Density (trees ha^{-1})	5	213 (83.8)	5	129 (46.5)	5	133 (67.0)	5	282 (105.5)	0.485
Basal area (m^2 ha^{-1})	5	18.8 (6.2)	5	8.0 (2.8)	5	15.8 (7.3)	5	31.8 (8.1)	0.107
Total (live)									
Density (trees ha^{-1})	5	954 (61.8)	5	776 (72.6)	5	1290 (204.1)	5	1270 (188.3)	0.066
Basal area (m ha^{-1})	5	60.4 (7.3)	5	55.7 (11.5)	5	78.2 (8.2)	5	79.8 (4.3)	0.127
Fuel weight (Mg ha^{-1})									
Litter	5	3.6 (0.2)	5	2.9 (0.4)	5	3.1 (0.2)	5	4.7 (0.7)	0.071
1-h	5	2.7 (1.1)	5	2.0 (0.4)	5	2.5 (0.4)	5	3.4 (1.3)	0.735
10-h	5	6.1 (1.8)	5	2.5 (0.7)	5	5.4 (0.4)	5	5.8 (1.6)	0.192
100-h	5	3.1 (0.7)	5	4.5 (1.6)	5	7.6 (2.2)	5	5.4 (1.8)	0.308
1000-h sound	5	11.9 (6.7)	5	76.7 (76.0)	5	15.2 (8.1)	5	4.9 (1.8)	0.595
1000-h rotten	5	10.5 (4.5)^{ab}	5	9.2 (6.1)^{ab}	5	3.1 (1.6)^{a}	5	35.2 (15.0)^{b}	**0.046**
Stratum depth									
Duff (cm)	5	2.8 (0.5)^{a}	5	1.5 (0.3)^{a}	5	2.8 (0.5)^{a}	5	5.1 (0.5)^{b}	**0.008**
Litter (cm)	5	3.6 (0.3)	5	3.0 (0.5)	5	3.3 (0.3)	5	5.1 (0.8)	0.065
Fuel bed (m)	5	0.2 (0.1)^{a}	5	0.2 (0.1)^{a}	5	0.5 (0.1)^{b}	5	0.3 (0.l)^{b}	**0.004**

Significant P-values ($\alpha = 0.005$) are in bold type.

by the treatment to only 9% by the late stage ($P < 0.001$). During the late-post-treatment stage, basal area of dead tanoak showed no difference from pre-treatment conditions; dead tanoak basal area peaked in the early and middle stages and differed significantly from the control and late stages ($P < 0.001$). On average during the mid-stage time horizon of 5–8 years post treatment, dead tanoak trees began to fail and fall into the surface fuel complex; however, not all trees had fallen by the late stage (Table 2).

The herbicide treatment increased surface fuels across all categories of time post-treatment. Following the temporal pattern of tree failure, 1-, 10-, and 100-h woody fuels slightly increased during the early stage, then significantly increased during the middle and late stages ($P < 0.001$; Table 2). Total weight of downed woody debris (1-, 10-, 100-, and 1000-h) approximately doubled with the herbicide treatment, ranging from the initial condition of 58.1 Mg ha^{-1} to 106.3 Mg ha^{-1} during the middle stage. Fuelbed depth also appeared to follow the same temporal pattern, which doubled during the early stage and peaked during the middle stage, as the majority of dead trees began to shed limbs ($P < 0.001$). Weight of rotten logs ($P = 0.673$) and depth of duff ($P = 0.499$) did not change over time since treatment; these fuels were artifacts of management (rotten logs) and disturbance history (duff depth) in the study stands. Additionally, no differences were detected in litter weight ($P = 0.222$) or depth ($P = 0.207$) across treatment phases.

Fuel weight differences among treatments were consistent, with middle and late stages of the herbicide treatment usually greater than the control and early stage of *P. ramorum* infection. Overall, the rate of litter and fine fuel accumulation in the herbicide stands was greater than in the diseased stands and initiated more quickly than in diseased stands. Rapid accumulation began in the early stage in the herbicide-treated plots, while fuels in the infected plots slightly decreased between the control and early stage then increased through the middle and late stages (Table 2). However, this rate appeared to attenuate in the herbicide-treated stands between the middle and late stages post-treatment, contrary to the same stages observed in diseased stands, when the rate sharply increased. Similarly, input of 1000-h sound logs in the herbicide stands predominantly occurred during the early and middle stages then tapered off between middle and late stages, in contrast to stands infected with *P. ramorum*, where logs were not recruited to the forest floor until the middle and late stages (Table 2).

Both diseased and herbicide-treated plots had increased fuel loads in "surface" plots relative to "aerial" plots (Table 3). Large, sound logs and 10- and 100-h particles were consistently greater in "surface" plots. Exceptions to this trend were in the smallest fuel categories, litter and 1-h, where the weight differences were insignificant. Composition of the contributing stands support these patterns, as the density ($P < 0.001$) and basal area ($P < 0.001$) of standing dead trees was greater in "aerial" plots than in "surface" plots.

3.3. Fuel model prediction

Modeled fire behavior based on observed surface fuels demonstrated that for control plots or the early stage of diseased plots, the existing activity fuel model SB2 (a moderate activity fuel/low-load blowdown model) tracked the surface rate of spread and flame length simulations well (Figs. 3 and 4). Slash models 12 and 13 overpredicted flame lengths, and slash model 11 and model SB1 (a low load activity fuel model) underpredicted both rate of spread and flame length (Figs. 3 and 4). However, as the surface fuels increased under the conditions observed in the herbicide-treated plots, even in the early stages, fire behavior prediction did not align well with any of the existing fuel models. Model 12 closely estimated flame length, but under-predicted rate of spread (Figs. 3 and 4). Overall, looking at a comparison of phases, two groupings of fire behavior are apparent. Early- and mid-phase post-herbicide treatment and late-phase diseased plots display similar predicted fire behavior. The late-stage herbicide category was similar to control plots and to early- and mid-phase diseased plots for rate of spread and flame length.

Using the aerial and surface categorization of plots, the predicted fire behavior again fell into two groupings: (1) control and aerial diseased plots tracked together, and fuel model SB2 provided a good approximation for modeled fire behavior on these plots; and (2) surface diseased plots, aerial herbicide-treated plots, and sur-

Table 2
Temporal effects of *Phytophthora ramorum* infestation and herbicide treatment on vegetation and fuel properties in northern Coast Range Douglas-fir-tanoak stands. Temporal categories based on years since initial infection (early-phase: 2–5; mid-phase: 5–8; late-phase: 8–12). Sample size (*n*), mean, and standard error of the estimates (SE) are provided. Total live and dead tree estimates include tanoak, conifer, and broadleaf species. Fine woody debris (FWD) includes 1-, 10-, and 100-h particles.

	Infested (sudden oak death) plots									Herbicide-treated plots								
	Control		Early		Mid		Late			Control		Early		Mid		Late		P
	n	Mean (SE)	n	Mean (SE)	n	Mean (SE)	n	Mean (SE)	P	n	Mean (SE)	n	Mean (SE)	n	Mean (SE)	n	Mean (SE)	
Tanoak (live)																		
Density (trees ha^{-1})	20	788 (75.6)^{a}	15	203 (31.4)^{b}	5	89 (60.8)^{b}	5	40 (24.2)^{b}	**<0.001**	20	788 (75.6)^{a}	20	30 (10.9)^{b}	20	53 (12.6)^{b}	20	37 (13.1)^{b}	**<0.001**
Basal area (m^2 ha^{-1})	20	41.3 (4.7)^{a}	15	15.4 (4.5)^{b}	5	7.8 (4.8)^{b}	5	1.1 (0.8)^{b}	**<0.001**	20	41.3 (4.7)^{a}	20	3.5 (1.7)^{b}	20	6.5 (2.5)^{b}	20	3.1 (1.5)^{b}	**<0.001**
Tanoak (dead)																		
Density (trees ha^{-1})	20	42 (14.3)^{a}	15	114 (25.7)^{b}	5	64 (18.5)^{ab}	5	84 (12.6)^{ab}	**0.017**	20	42 (14.3)^{a}	20	515 (60.0)^{b}	20	397 (87.7)^{b}	20	98 (24.0)^{a}	**<0.001**
Basal area (m^2 ha^{-1})	20	1.4 (0.5)^{a}	15	10.7 (3.3)^{b}	5	4.5 (1.7)^{ab}	5	6.5 (2.9)^{ab}	**0.001**	20	1.4 (0.5)^{a}	20	27.5 (3.8)^{b}	20	18.5 (2.5)^{b}	20	5.5 (1.3)^{a}	**<0.001**
Fuel weight (Mg ha^{-1})																		
Litter	20	3.6 (0.2)^{ab}	15	3.1 (0.2)^{a}	5	3.6 (0.4)^{ab}	5	4.7 (0.4)^{b}	**0.046**	20	3.6 (0.2)	20	3.6 (0.4)	20	3.8(0.7)	20	2.9 (0.4)	0.222
1-h	20	2.7 (0.4)	15	2.5 (0.4)	5	1.8 (0.7)	5	2.9(0.7)	0.715	20	2.7 (0.4)^{a}	20	3.1(0.4)^{ab}	20	4.3 (0.4)^{bc}	20	4.7 (0.7)^{c}	**0.018**[*]
10-h	20	4.9 (0.7)	15	4.0 (0.9)	5	4.3(1.6)	5	6.3(1.8)	0.407	20	4.9 (0.7)^{a}	20	5.4 (0.7)^{ab}	20	8.5 (0.9)^{bc}	20	9.9(1.3)^{c}	**0.001**
100-h	20	5.2 (0.9)	15	2.9 (0.9)	5	4.5(1.6)	5	8.1(2.5)	0.065	20	5.2 (0.9)^{a}	20	6.3 (0.9)^{a}	20	11.2 (1.3)^{b}	20	13.0 (2.0)^{b}	**<0.001**
1000-h sound	20	27.1(18.8)	15	15.0(7.8)	5	11.7(8.5)	5	19.3 (4.0)	0.166	20	27.1 (18.8)^{a}	20	61.9 (13.9)^{ab}	20	52.7(17.9)^{b}	20	51.6(16.1)^{b}	**0.013**
1000-h rotten	20	14.6 (4.7)	15	12.3 (4.5)	5	7.4 (2.9)	5	1.6(0.9)	0.336	20	14.6 (4.7)	20	16.1(6.1)	20	25.8(11.7)	20	14.6 (7.4)	0.673
Stratum depth																		
Duff (cm)	20	3.0 (0.3)	15	2.0 (0.5)	5	2.3 (0.3)	5	3.0 (0.8)	0.119	20	3.0 (0.3)	20	2.5(0.3)	20	3.0(0.3)	20	2.8 (0.3)	0.499
Litter (cm)	20	3.8 (0.3)^{ab}	15	3.3 (0.3)^{a}	5	3.8 (0.5)^{ab}	5	4.8 (0.5)^{b}	**0.038**	20	3.8(0.3)	20	3.8(0.5)	20	4.1(0.8)	20	3.0 (0.5)	0.207
Fuel bed (m)	20	0.3 (0.0)^{ab}	15	0.2 (0.1)^{a}	5	0.3 (0.1)^{ab}	5	0.6 (0.2)^{b}	**0.012**	20	0.3 (0.0)^{a}	20	0.6(0.1)^{bc}	20	0.8 (0.1)^{c}	20	0.5(0.1)^{ab}	**<0.001**

Significant *P*-values ($\alpha = 0.05$) are in bold type.

[*] Kruskal-Wallis nonparametric ANOVA used; no significant Bonferroni differences found during multiple comparisons test; different groupings based on standard Dunn's test (Zar, 1999).

Table 3
Differences among treatment groups and fuel distribution categories in northern Coast Range Douglas-fir tanoak stands. Distribution categories correspond to the layer occupied by the majority of fuels (AERIAL: not yet recruited to the forest floor; SURFACE: recruited to the forest floor). Sample size (n), mean, and standard error of the estimates (SE) are provided. Total live and dead tree estimates include tanoak, conifer, and broadleaf species. Fine woody debris (FWD) includes 1-, 10-, and 100-h particles.

	Control		SOD (aerial)		SOD (surface)		Herbicide (aerial)		Herbicide (surface)		*P*
	n	Mean (SE)	*n*	Mean (SE)	*n*	Mean (SE)	*n*	Mean (SE)	*n*	Mean (SE)	
Tanoak (live)											
Density (trees ha^{-1})	20	788 (75.6)^{a}	14	196 (36.3)^{b}	11	85 (29.9)^{bc}	26	34 (8.9)^{c}	34	44 (10.4)^{c}	**<0.001**
Basal area (m^{2} ha^{-1})	20	41.3 (4.7)^{a}	14	15.8 (4.8)^{ab}	11	5.0 (2.2)^{b}	26	3.4 (1.3)^{b}	34	5.1 (1.7)^{b}	**<0.001**
Tanoak (dead)											
Density (trees ha^{-1})	20	42 (14.3)^{a}	14	115 (26.9)^{ac}	11	76 (12.1)^{ac}	26	504 (70.4)^{b}	34	209 (40.5)^{c}	**<0.001**
Basal area (m^{2} ha^{-1})	20	1.4 (0.5)^{a}	14	12.0 (3.4)^{bc}	11	4.2 (1.0)^{ab}	26	25.0 (3.1)^{c}	34	11.2 (2.0)^{b}	**<0.001**
Fuel weight (Mg ha^{-1})											
Litter	20	3.6 (0.2)	14	3.4 (0.2)	11	3.8 (0.2)	26	3.8 (0.4)	34	3.1 (0.4)	0.173
1-h	20	2.7 (0.4)^{a}	14	2.5 (0.4)^{a}	11	2.5 (0.4)^{a}	26	3.8 (0.4)^{ab}	34	4.3 (0.4)^{b}	**0.026****
10-h	20	4.9 (0.7)^{a}	14	4.0 (0.9)^{a}	11	5.2 (1.1)^{ab}	26	6.1 (0.7)^{a}	34	9.4 (0.9)^{b}	**<0.001**
100-h	20	5.2 (0.9)^{a}	14	3.1 (0.9)^{a}	11	5.8 (1.3)^{a}	26	7.2 (1.1)^{a}	34	12.3 (1.3)^{b}	**<0.001**
1000-h sound	20	27.1 (18.8)^{a}	14	15.7 (8.3)^{a}	11	14.6 (4.3)^{ab}	26	22.4 (6.1)^{ab}	34	65.9 (14.8)^{b}	**<0.001**
1000-h rotten	20	14.6 (4.7)	14	11.4 (4.7)	11	6.3 (2.5)	26	24.2 (9.6)	34	15.0 (4.9)	0.887
Stratum depth											
Duff (cm)	20	3.0 (0.3)	14	2.0 (0.3)	11	2.8 (0.5)	26	2.8 (0.3)	34	2.5 (0.3)	0.173
Litter (cm)	20	3.8 (0.3)	14	3.6 (0.3)	11	3.8 (0.3)	26	3.8 (0.5)	34	3.3 (0.5)	0.156
Fuel bed (m)	20	0.3 (0.0)^{a}	14	0.2 (0.1)^{a}	11	0.5 (0.1)^{ab}	26	0.5 (0.1)^{b}	34	0.7 (0.1)^{b}	**<0.001**

Significant P-values ($\alpha = 0.05$) are in bold type.
*Non-significant Kruskal-Wallis ANOVA; different groupings based on Bonferroni multiple comparisons test (Zar, 1999).
** Significant Kruskal-Wallis ANOVA; no significant Bonferroni differences found during multiple comparison test; different groupings based on standard Dunn's test.

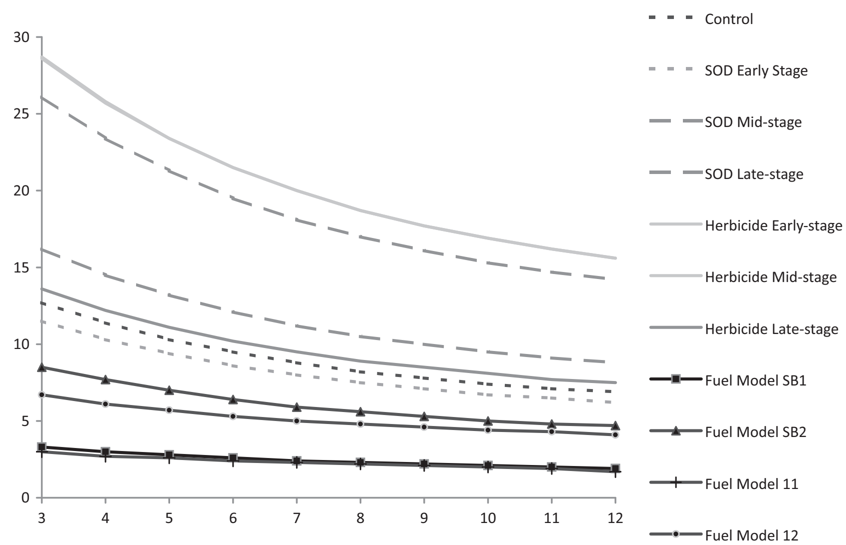

Fig. 3. Comparison of predicted surface rate of spread to existing and custom fuel models by condition/time category.

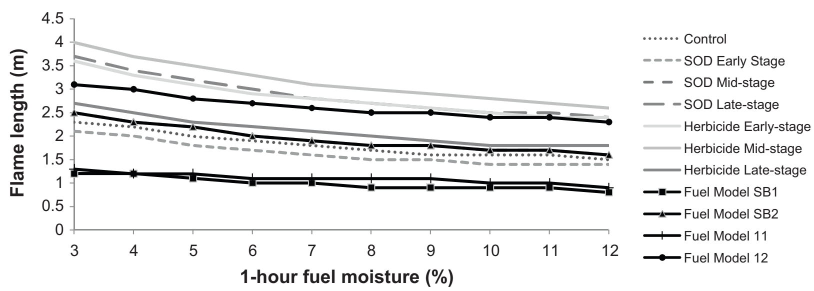

Fig. 4. Comparison of predicted flame length to existing and custom fuel models by condition/time category.

face herbicide-treated plots tracked together and were predicted to produce much higher rates of spread and flame length; however, no standard fuel model fit these conditions (Figs. 5 and 6).

3.4. Fire suppression operations safety analysis

Whereas the comparisons with existing fuel models employed a range of fuel moistures and assumed a constant wind speed, the safety analysis for fire suppression operations investigated a variety of wind speed scenarios using constant fuel moistures. For both rate of spread and flame length analyses, the stands with late-stage disease conditions and the mid- and late-stage herbicide-treated stands exceeded thresholds for direct attack or the production rates for a crew for almost all wind speeds (Table 4). At increasing wind speeds in the control conditions, Type 1 handcrews' capacities (at 6.44–8.05 km h^{-1}) and production rates (at 3.22–8.05 km h^{-1}) were exceeded as well.

The complexity of these results can best be observed in the analysis of aerial vs. surface fuels conditions (Table 5). In this analysis, herbicide-treated stands with the majority of fuels found on the surface of the forest floor were found to exceed Type 1 handcrews' production rates with any wind speed. For both rate of spread and

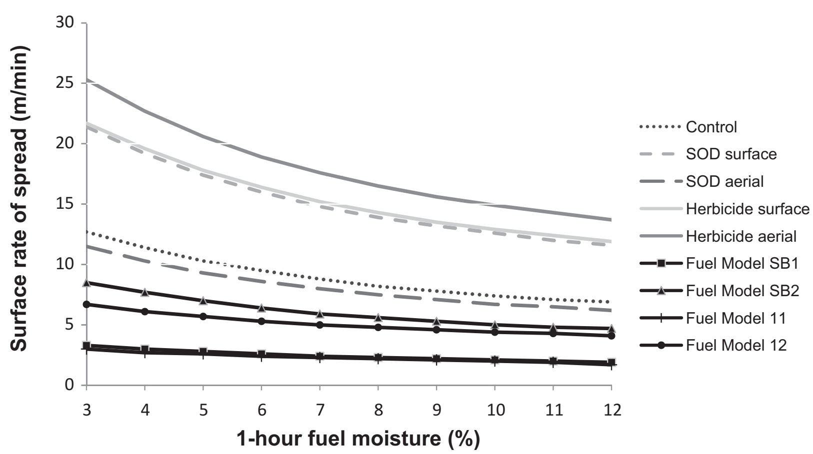

Fig. 5. Comparison of predicted surface rate of spread to existing and custom fuel models by fuels distribution category.

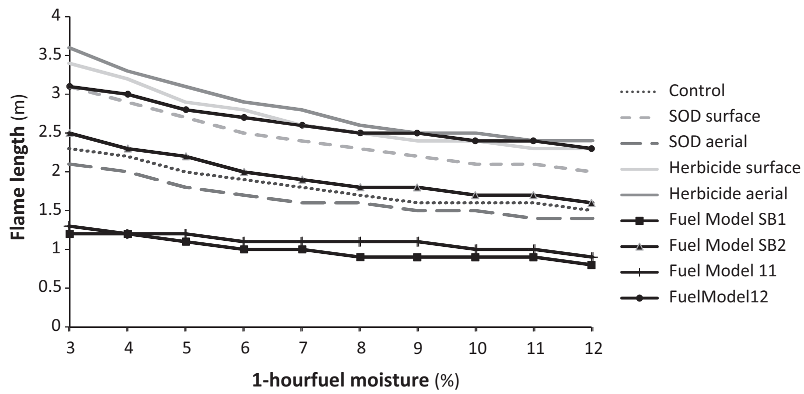

Fig. 6. Comparison of predicted flame length to existing and custom fuel models by fuels distribution category.

flame length analyses, the stands with late-stage disease and the mid- and late-stage post-herbicide treatments exceeded thresholds for direct attack or the production rates for a crew for almost all wind speeds. Increasing wind speeds in the control conditions also exceeded Type 1 handcrews' capacities (at 6.44–8.05 km h^{-1}) and production rates (at 3.22–8.05 km h^{-1}). Under most of the conditions analyzed, predicted flame lengths would warrant suppression activities by engines and/or bulldozers rather than by handcrews.

4. Discussion

4.1. Surface fuel recruitment after pathogen-caused disturbance

The contributions of tree pathogens to fuel complexes have received relatively little study, aside from Dickman and Cook (1989) and Fields (2003), examining the effects of root diseases on fuels; Hoffman et al. (2007), examining the effects of dwarf mistletoes; and the studies reviewed in Parker et al. (2006), which touch on the subject of fuels changes with relation to a diverse group of pathogens, including decays, root diseases, and dwarf mistletoes. More attention has recently been paid to the effects of bark beetle outbreaks on fuel dynamics and potential fire behavior (Simard et al., in press). Like sudden oak death but at a larger scale, these outbreaks have touched off intense community concern across large areas of the western United States and Canada (McFarlane et al., 2006; Flint et al., 2009). In some ways, the cyclical, long-term nature of some of these epidemics resembles that of *P. ramorum*. The most recent reviews and studies disagree on whether bark beetle attacks elevate fine fuels (≤7.62 cm diameter) to a level that exacerbates surface fire behavior (Page and Jenkins, 2007; Jenkins et al., 2008; Klutsch et al., 2009; Simard et al., in press). There is still general disagreement on the relative importance of fuels and weather in

Table 4
Predicted rates of spread and flame lengths by condition/time category under a variety of mid-flame wind speeds. Shown in white: rate of spread OR flame length enabling attack by a Type I handcrew. Shown in gray: rate of spread requiring two Type I handcrews, one to catch each fire flank, OR flame lengths between 1.2 and 2.4 m, enabling attack with fire engines and bulldozers. Shown in black: rate of spread which exceeds the production rate for a Type I handcrew OR flame lengths ≥2.4 m, exceeding crew capability for direct attack.

Treatment Condition	Litter + FWD (Mg/ha)	Fuel Bed Depth (m)	Rate of Spread (m/min)					
			Mid Flame Wind Speed (km/hr)					
			0	1.6	3.2	4.8	6.4	8
SOD_E	12.6	0.2	2.6	3.0	3.9	5.1	6.7	8.6
SOD_M	14.3	0.3	3.6	4.2	5.4	7.2	9.4	12.1
Control	16.4	0.3	2.8	3.3	4.3	5.6	7.4	9.5
Herb_E	18.2	0.6	6.3	7.3	9.5	12.7	16.7	21.5
SOD_L	21.7	0.6	5.8	6.7	8.7	11.6	15.2	19.5
Herb_M	27.8	0.8	6.4	7.4	9.6	12.8	16.8	21.5
Herb_L	30.7	0.5	3.1	3.6	4.7	6.2	8.1	10.3
			Flame Length (m)					
			Mid Flame Wind Speed (km/hr)					
			0	1.6	3.2	4.8	6.4	8
SOD_E	12.6	0.2	1.0	1.0	1.2	1.3	1.5	1.7
SOD_M	14.3	0.3	1.2	1.2	1.4	1.6	1.8	2.0
Control	16.4	0.3	1.1	1.2	1.3	1.5	1.7	1.9
Herb_E	18.2	0.6	1.6	1.8	2.0	2.3	2.6	2.9
SOD_L	21.7	0.6	1.7	1.8	2.1	2.3	2.7	3.0
Herb_M	27.8	0.8	1.9	2.0	2.3	2.6	2.9	3.3
Herb_L	30.7	0.5	1.2	1.3	1.5	1.7	2.0	2.2

Table 5
Predicted rates of spread and flame lengths by fuels distribution category under a variety of mid-flame wind speeds. Shown in white: rate of spread OR flame length enabling attack by a Type I handcrew. Shown in gray: rate of spread requiring two Type I handcrews, one to catch each fire flank, OR flame lengths between 1.2 and 2.4 m, enabling attack with fire engines and bulldozers. Shown in black: rate of spread which exceeds the production rate for a Type I handcrew OR flame lengths ≥2.4 m, exceeding crew capability for direct attack.

Treatment Condition	Litter + FWD (Mg/ha)	Fuel Bed Depth (m)	Rate of Spread (m/min)					
			Mid Flame Wind Speed (km/hr)					
			0	1	2	3	4	5
AERIAL SOD	12.8	0.2	2.6	3.0	3.8	5.1	6.7	8.5
CONTROL	16.4	0.3	2.8	3.3	4.3	5.6	7.4	9.5
SURFACE SOD	17.3	0.5	4.7	5.5	7.1	9.5	12.4	16.0
AERIAL HERB	20.6	0.5	5.6	6.5	8.4	11.2	14.7	18.9
SURFACE HERB	29.4	0.7	4.9	5.7	7.4	9.8	12.8	16.4
			Flame Length (m)					
			Mid Flame Wind Speed (km/hr)					
			0	1	2	3	4	5
AERIAL SOD	12.8	0.2	1.0	1.1	1.2	1.4	1.5	1.7
CONTROL	16.4	0.3	1.1	1.2	1.3	1.5	1.7	1.9
SURFACE SOD	17.3	0.5	1.4	1.5	1.7	2.0	2.2	2.5
AERIAL HERB	20.6	0.5	1.6	1.8	2.0	2.3	2.6	2.9
SURFACE HERB	29.4	0.7	1.6	1.7	1.9	2.2	2.5	2.8

driving surface fire behavior, the transition from surface to crown fire, and the movement of crown fire through the forest canopy. If any area of agreement between these studies exists (and earlier studies involving spruce budworm also bear this out), it is that the effects of the epidemics on fuels play out over long time scales, as killed trees fall, leading to continuous inputs of coarse fuels and decreasing the vegetative sheltering that moderates local winds (Stocks, 1987; Page and Jenkins, 2007; Klutsch et al., 2009; Simard et al., in press). After the period of time when dead needles remain in tree crowns post-bark beetle outbreak, most of these studies point to a general trajectory in affected stands that most likely involves surface fire exclusively for some period of time, followed by a gradual resurgence of torching and crown fire hazard as regeneration provides ladder fuels and canopy bulk density regains its former levels.

Though these bark beetle studies may apply in broad outline to coastal forests with large hardwood components, broadleaf tree crowns have different properties and hardwoods fall and decay at different rates from conifers, so specific timelines are likely to differ. Two recent studies have approached questions specifically related to fuels and *P. ramorum*. Kuljian and Varner (2010) documented critically low foliar moisture content in tanoak leaves remaining on tree crowns after the pathogen kills the tree. This has implications for possible crown fire initiation and spread during the post-mortality marcescent phase when the trees retain dead leaves. Metz et al. (2010) evaluated fire severity in Big Sur forests that were infested by *P. ramorum* for varying lengths of time previous to the Basin Complex fires. Overall, Metz et al. (2010) found that patterns of burn severity did not vary between infested and uninfested areas. Recently infested areas with dead trees exhibited greater overstory burn severity than older infested areas—supporting the suggestion of Kuljian and Varner (2010) concerning exacerbated crown fire behavior in infested stands—whereas older infested areas with more downed woody logs exhibited greater soil burn severity than recently infested areas. Like the bark beetle studies, these point to the importance of considering what stage a given epidemic is in, and the trajectory of epidemic effects over a long time horizon, when seeking to understand the epidemic's effect on fuels dynamics.

Douglas-fir-tanoak forests affected by sudden oak death may differ from conifer-dominated forests affected by bark beetles in the trajectory of ladder fuels development. Tanoak is well-known as a strong early competitor of Douglas-fir on recently cleared sites or in canopy gaps, usually outcompeting the conifers quickly (Tappeiner et al., 1992). Such sites typically require decades for Douglas-fir to overtop the broadleaf trees and regain site dominance (Radosevich et al., 1976; Tappeiner et al., 1992; Harrington and Pabst, 1994), thus the rationale for herbicide use to control competition on sites intensively managed for Douglas-fir production. It is conceivable that in stands containing a heavy broadleaf component, the observed trajectory described above (from early crown fire hazard during leaf retention, to surface fire behavior while dead trees are breaking down and falling, to slowly increasing crown fire hazard while ladder fuels develop and the canopy increases in bulk density) may be accelerated relative to that in the bark beetle-affected stands. These fuel dynamics depend on several factors, including inoculum pressure on the resprouting tanoaks and tanoak seedlings, ages and densities of existing conifers on the site, and the competitive silvics of other onsite broadleaf trees and shrubs. If dominant Douglas-fir trees already exist they will likely capture more resources, controlling understory and ladder fuel development, and the trajectory of ladder fuels development will likely be different—as it also will if dense cohorts of Douglas-fir seedlings exist ready to capture the site. Clearly, more research on post-disease stand (Waring and O'Hara, 2005) and fuel (Kuljian and Varner, 2010) dynamics should be pursued.

Discussions with land managers prior to the onset of this study revealed a widely held belief that hardwood surface fuels in this forest type, especially tanoak fuels, do not constitute a major concern, because it is assumed that these fuels decompose quickly on the forest floor. In these discussions, land managers usually reported that they expected to see many tanoak fuels down on the forest floor quickly and at a very advanced stage of decay within 3–5 years of falling (see, for example, anecdotal evidence in Sonoma

County Permit and Resource Management Department, 2008). Our results do not fully support this view, as trees failed and fell at widely varying intervals across our network of plots, in some places contributing a more continuous supply of surface fuels, including sound large-diameter fuels, than anticipated over at least a span of 5–8 years. Like the recent bark beetle studies, this study demonstrated that the changes in fuels brought about by insect or disease epidemics often manifest themselves over a long time horizon. The coarse woody fuels contributed by falling dead trees in those situations are more decay-resistant and will likely persist longer than tanoak fuels; nevertheless, coarse tanoak fuels do not appear to break down as quickly as conventional wisdom suggests. When considering the effects of *P. ramorum* infection, the magnitude of surface fuel accumulations and changes to potential fire behavior may partly depend on whether the cycle of wet springs supporting major outbreaks and killing large numbers of trees outstrips the cycle of decay.

4.2. Herbicide-treated units as a surrogate for sudden oak death

Growing interest in the potential impacts of sudden oak death has led to standing community concerns and interest in evaluating the potential risk this disease poses for Californians. One challenge to addressing this concern has been the limited number of fires that have burned in diseased areas (i.e., Big Sur in 2008) and limited studies of prescribed fire in diseased stands (K. Julin, Marin County Fire Department, personal communication, May 2006). Furthermore, *P. ramorum*-linked mortality has been temporally and spatially limited in California, although it is expected to increase exponentially in the future (Meentemeyer, 2009).

To explore landscape-level impacts of the disease given these limitations, stands where herbicides were used to reduce tanoak dominance were evaluated for suitability as a surrogate for disease effects. While the effects of these two treatments share much in common (i.e., species-specific mortality of tanoak) they also differ in rate of mortality, assumed rate of decomposition and spatial extent. Furthermore, *P. ramorum*'s wave-like spread in response to annual/multi-annual fluctuations in climate stands in stark contrast to herbicide treatment, which by practice generally involves treatment of all tanoak trees at one time. Herbicide conditions can, however, be thought of as an extreme example of the disease's potential impacts, since in 2010, *P. ramorum* invasion of California forests still rests near the bottom of the growth curve typical of plant disease epidemic dynamics (Meentemeyer et al., 2009). In this study we found that late-stage diseased and mid- and late-stage post-herbicide treatment conditions produced surface fuel loadings above those in the untreated stands used as a control. Herbicide-treated stands, while limited in extent on the landscape, do have the most surface fuels observed relative to the control stands. If we take them as representative of the extreme potential for the disease, this implies that given the right climatic conditions, *P. ramorum* could substantially increase surface fuels and challenge firefighter response in this region.

The implications of this finding range beyond the ecological impacts of wildfire in this region to encompass social, safety, and economic factors. It is apparent not only from this study, but also from recent work (Kuljian and Varner, 2010; Metz et al., 2010), that the influence of *P. ramorum* upon surface and aerial fuel loadings, potential fire behavior, and fire severity depends heavily upon the stage (and perhaps the spatial extent) of disease progression. However, even in areas where the stage is such that potential fire severity is low, the fuels present may cause surface fire behavior that triggers local tactical suppression decisions with repercussions for area landowners and the larger suppression strategy. It is beyond the scope of this paper to speculate about the positive or negative consequences of such choices, but the choice of attack strategy can affect the resources required for suppression, firefighter safety concerns, and the amount of landscape ultimately burned, among other considerations.

While herbicide treatments temporarily elevate surface fuels, these treatments are limited in area on the landscape, are generally associated with other forest management activities, and, provided that roads remain accessible, generally facilitate rapid firefighter response. Furthermore, decomposition will reduce these single-pulse-driven surface fuels over time. This is in contrast to *P. ramorum*, which will continue to contribute fuels over the long term, serving as a chronic wider-scale forest health hazard that will likely predispose these stands to future wildfire or other cascading ecological issues (Rizzo et al., 2005).

4.3. Using fuel models for fire behavior prediction

While no existing fuel model perfectly approximated the conditions observed in this study, the slash models were the closest fit with a wide degree of variability. On the Basin Complex in Big Sur, slash model 11 or 12 was used by fire behavior analysts to approximate surface fuel conditions on the ground (Lee et al., 2010). Our data corroborate the challenges posed by *P. ramorum* for fire behavior modeling used to determine appropriate suppression response, as well as the high degree of variability present in these stands prior to pathogen invasion. The control stands used in this study are approximated by the SB2 timber model, illustrating the fuels that these types of stands already contain (model SB2 includes a moderate level of activity fuels). These stands have received no fuel treatments or timber stand improvement activities since harvest 40–60 years ago. Our results illustrate the need for regional and landscape level fuel treatments in stands similar to the ones we observed, since the control stands already have moderate surface fuel accumulations and developed fuel ladders that may increase the difficulty of future fire suppression. Furthermore, our results suggest that *P. ramorum* will exacerbate these conditions. The need for fuel treatments in *P. ramorum*-affected areas will likely persist for decades in places where broadleaf trees regenerate in canopy gaps (Tappeiner et al., 1992), outcompeting conifers and providing dense ladder fuels.

Although perfect matches with existing fuel models are rarely possible, the categorical variable utilized in this study, which assesses whether the majority of fuels are found on the surface of the forest floor or still within the canopy (i.e., "surface" vs. "aerial" conditions), offers a reasonable technique for assessing hazards, predicting associated fire behavior, and determining appropriate firefighter resource response. One important advantage of this assessment is that it avoids the challenge of knowing the timeline since infection or treatment and the associated rates of mortality and treefall. While some predictable patterns were observed in the timeline associated with this study, there was variability in these rates, and some trees seemed to fall more as a function of wind exposure than time. Few firefighters will know the stand history of an area upon initial response, but a quick visual inspection will enable them to make the "aerial" or "surface" assignment relatively easily. Similar ocular estimation procedures have been used to assess ladder fuels (Menning and Stephens, 2007) and those used in photo series approaches (e.g., Maxwell and Ward, 1980; Fischer, 1981; Scott and Reinhardt, 2005).

4.4. Future research

Future research should address longer time horizons for both herbicide-treated and *P. ramorum*-infested stands and the interactions between elevated surface and aerial fuels as they influence potential fire behavior. For example, previous findings of elevated crown fire ignition hazard (Kuljian and Varner, 2010) in concert with the findings of elevated surface fire hazard here, when paired, may predict fire behavior and effects that deviate substantially from historic fire regimes. Results from Metz et al. (2010) support this speculation; empirical data should be sought to better calibrate these complex interactions. Ongoing modeling efforts that include both acute (marcescent phase) and longer-term (with increased surface woody fuels) time scales hold promise for the study of sudden oak death and other pathosystems. Additionally, similar research in other forest types—such as the dry broadleaf-dominated forest types in the central coast of California where other *P. ramorum*-susceptible trees such as coast live oak (*Q. agrifolia* Nee) and Shreve oak (*Q. parvula* var. *shrevei* (C.H. Muller) Nixon) are common—would yield an even better understanding of the possible changes to fire behavior and difficulties for effective fire suppression that may characterize the broadening range of *P. ramorum* in California in the future.

Acknowledgements

This project was funded by the USDA Forest Service, Pacific Southwest Research Station. In addition, we gratefully acknowledge the following individuals for their assistance: S. Frankel, B. O'Neil, S. Murphy, and H. Kuljian. We thank the numerous private landowners and land managers who provided access to the study plots and logistical assistance, as well as California State Parks and Redwood National and State Parks.

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