Sudden Oak Death and Fire in the California Coast Range

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Introduction

On January 18, 2021 ferocious winds of up to 80 mph whipped through the interior Santa Cruz mountains, reigniting several forest fires from embers that lay smoldering from the devastating and large-scale wildfires of the previous summer and fall. This event was exceptional in at least two ways, and both serve to illustrate the environmental issues discussed in this paper.

First, and most obvious, January is typically the wettest month of the year in Northern California, characterized by heavy precipitation from offshore weather systems. The winds experienced in the Bay Area on Martin Luther King Jr. Day, 2021 were offshore, dry, and more consistent with weather patterns and katabatic winds typically experienced in the late summer/fall, which is generally the height of fire season. While irregularities in seasonal weather patterns have always occurred in California, the frequency of such events has increased as climate change disturbs local climactic balance.

Second is the persistence of embers that continued to smolder in the forest through several months of late fall and winter, and despite a few moderate rain storms. Embers could only survive as such if they were the result of a high intensity fire that burnt through large diameter wood.

Prior to modern regimes of land management of fire suppression policies, fire was used by native peoples to maintain landscapes and species diversity. Low intensity blazes were employed to reduce the build up of excessive biomass, and high intensity canopy fires seem to have been rare. Typically, a fire will only reach high intensity through crown ignition, wherein flames from ground level ignite a fire ladder of some kind, and climb into the canopy of the forest. Once the flames reach canopy level the fire increases in temperature, as entire trees are torched. The oily needles of conifers, typically high above the forest floor and out of reach of low intensity blazes can ignite explosively and in rapid succession. With the entire canopy of trees ablaze, fire can then burn through the large limbs and trunks of mature trees, creating embers of such strength that they will last deep into the winter.

High intensity, crown ignition fires of the sort described above are not theoretical. In fact such fires have essentially been part of seasonal weather in northern California for many of the last 5-10 years. These fires have threatened and in some cases devastated neighborhoods throughout California, and affected the air quality for millions of people. Therefore, the health and condition of California's forests, particularly as it relates to fire behavior, is not an issue that only concerns academics and forestry researchers. Rather, forest health and fire susceptibility have come be be intertwined in very direct ways with issues of urban planning, human health, and public safety. Responding to this threat is a complicated and challenging task. It involves considering many factors, and must involve authorities at several different levels of government and land management. This paper will attempt to isolate a particular factor related to fire behavior— the pathogen responsible for the disease known as sudden oak death, and examine how this particular issue fits into the overall consideration of fire management and public safety in the Santa Cruz Mountains and other parts of the California Coast range.

A. Purpose

Figure 1: Tanoak Mortality in mixed Conifer-Hardwood Forest

This paper began with the following question: do the many thousands of dead standing tanoaks present throughout the forests of the Santa Cruz mountains contribute in a measurable way to the intensity and severity of wildfires in the area? This question came largely from simple observation. Even a casual observer, on a walk through the Douglas-fir/tanoak/redwood forests around Woodside, Los Gatos, Boulder Creek, or Bonny Doon, can't help but notice the presence of brown, dried out *Nolithocarpus densifolia*—dead but still standing. This has been the case for years if not decades at this point, long before the most recent and devastating fires in the area.

The observation that tanoaks are dying en mass, is backed up by years of field work quantifying the exact extent of sudden oak death's impact on *Nolithocarpus.* Even as early as 2002, researchers estimated that oaks and tanoaks were experiencing "mortality rates that are two and four times above historical levels for these two species, respectively" (Swiecki et al., 2002). Some researchers project that within 20 years many forests will experience the "functional extinction of tanoaks" (Varner et al., 2017).

The purpose, therefore, of this paper, is to explore 1) the current state of California's SOD infestation, and 2) if and how SOD impacted Tanoak stands influence wildfire behavior. In the course of exploring this question, the impact of SOD on true oak (*quercus*) populations will also be considered, as well as what measures are being taken by communities to address SOD and reduce the destructive impact of wildfires.

Background and Literature Review

I. History

Figure 2: Typical SOD symptoms on *Quercus agrifolia*

"Sudden oak death" was first detected in Northern California in the mid 1990s, and quickly became a major cause of concern among local ecologists. Otherwise healthy California coast live oak and tanoak trees in Marin county began dying at far above the natural rate, and in clusters. The signs of this previously unknown infection were distinct if you knew what to look for. Streaks of dark, rusty discoloration appeared on the trunk of the infected tree, which would progress into an oozing of black, gummy sap. In some cases, a tree could deteriorate rapidly, going from asymptomatic to dead in less than a year. In other instances, trees would live for several years with visible symptoms, though long term survival of infected trees is extremely rare. Because the disease moved so fast, and was, for a time, unknown to science, it was given the common name of "Sudden Oak Death."

The pathogen was identified as *Phytopthora ramorum* in 2001(Grünwald et al., 2012) and in the years since a picture has emerged regarding its etiology, distribution, effects, and likely future course of its impact on CA forests. In order to understand how *P. r*amorum will likely impact fire regimes and behavior, it will be necessary to examine this pathogen and its patterns of spread.

Phytopthora ramorum is a waterborne slime mold, classified biologically as an oomycete, in the Eukaryote kingdom. It is sometimes improperly referred to as a fungus. *P. ramorum* is closely related to *Phytophthora infestans,* the biological cause of several European potato blights, including the Irish Potato Famine.

The exact geographic and ecological origins of SOD are not entirely clear, though genetic analysis work is advancing rapidly. It has been confirmed that the pathogen originally emerged from the nursery trade, probably from European rhododendrons (Croucher et al., 2013). Phylogenetically, *P. ramorum* is placed in clade 8c of the genus Phytophthora. All species in this clade are "poorly understood and thought to be invasive pathogens that emerged in North America" (Grünwald et al 2019). Research suggests that "all currently known clade 8c taxa are introduced, exotic pathogens originating in Asia, but further work is required to support this hypothesis" (Grünwald et al., 2019). Genetic testing has confirmed the hypothesis that the pathogen has been introduced independently into the forest up to twelve times in California, and at least twice in southern Oregon (Grünwald et al., 2019). More recently *P. ramorum* has emerged in northern Europe where it is causing significant tree dieback on Japanese Larch plantations (Grünwald et al., 2012).

II. Etiology in California Forests

Phytophthora ramorum is known to infect over one hundred species of forest shrubs and trees (Rizzo et al., 2005). In California coast range oak woodland and conifer dominated ecosystems, the pathogen can infect almost every native tree and woody shrub. However most species are asymptomatic hosts that do not suffer significant negative consequences, or spread the pathogen. Some of the common asymptomatic, non-spreading vector species include Pacific madrone (*Arbutus menziesii*), evergreen huckleberry (*Vaccinium ovatum*), buckeye (*Aesculus californica*), bigleaf maple (*Acer macrophyllum*), toyon (*Heteromeles arbutifolia*), manzanita (*Arctostaphylos spp*.), coast redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziesii*), coffeeberry (*Rhamnus californica*), and honeysuckle (*Lonicera hispidula*). Some of these species suffer minor leaf dieback from *P. ramorum,* many have no symptoms at all. More research is needed to be sure that these species are only dead-end vectors to the pathogen, and do not in fact play an as yet unknown role in its transmission and lifecycle.

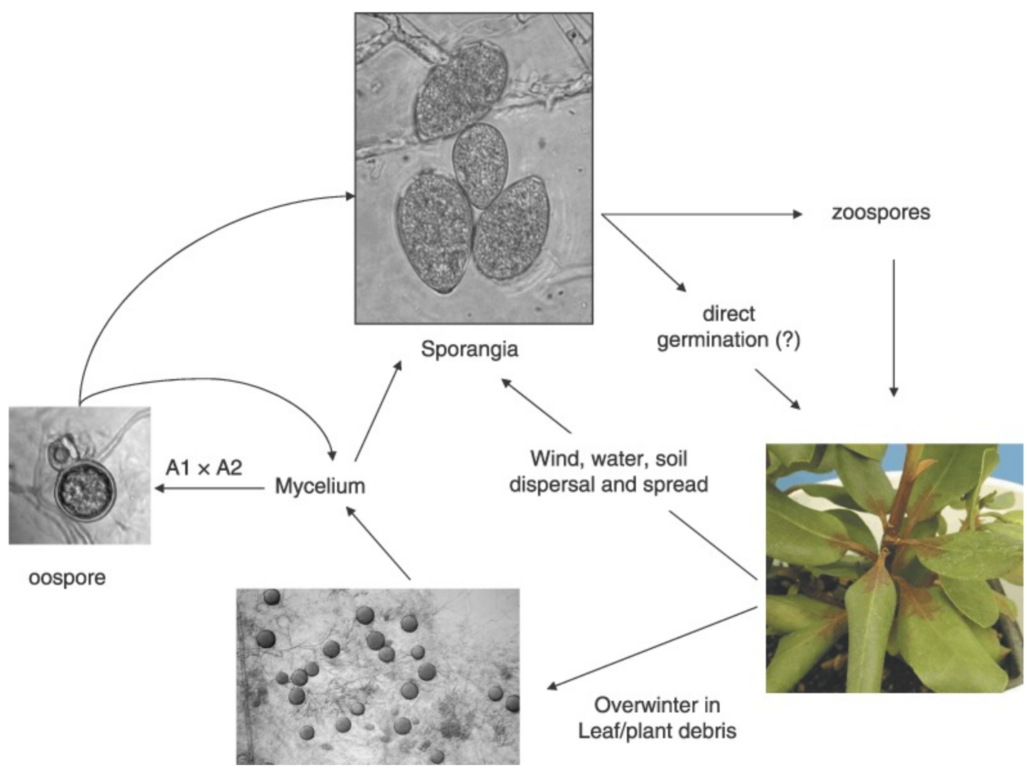


Figure 3: ***P. ramorum*** transmission patterns (Grünwald et al., 2008)

The two key species in SOD transmission, are California bay laurel (*Umbellularia californica*), and tanoak (*Nolithocarpus densifolia)* which, when infected, produce inoculum in their leaves. As illustrated in **figure 3**, *P. ramorum* inoculum can take the form of both resting spores (chlamydospores) and zoospores, which have flagella that enable swimming (Rizzo et al., 2002). The inoculum can then can reach new hosts in multiple ways. The first is via leaf litter from the host tree landing on the forest floor, whereby clamidaspores are taken up into the target tree by mycelium in the soil. The second option is via "slash dispersal" whereby sporangia (zoospores) slough off of leaves during a rain storm, and spread through water droplets to make direct contact with the trunks of susceptible species. (Grünwald et al., 2008). It is believed that splash dispersal, particularly when combined with wind and rain is the primary means through which *P. ramorum* spreads through a landscape. This mechanism has been documented with spread of 40 meters through the air, though it is suspected to have the potential to transmit over greater distances in windy rain storms (Davidson et al, 2003). Almost all sporangia infections from from the leaves of bay and tanoak trees (Garbaletto, 2020).

Trees that experience rapid mortality from SOD in California include tanoak (N*olithocarpus densifolium),* and several true oak (*Quercus)* species, such as coast live oak (*Quercus agrifolia*), and California black oak (*Quercus kelloggii*), and Canyon Live Oak (*Quercus chrysolepis).* It is currently believed that oaks from the white oak group do not get the disease, only red oak and intermediate/golden oak species (Rizzo & Garbaletto, 2003).

There is a significant difference in the number of sporangia needed to infect oaks vs tanoaks. Oaks require "an order of magnitude" (Garbaletto, 2020) more sporangia-to-trunk exposure than tanoaks to reach the threshold for infection.

For the disease to spread to a given stand of *Quercus* trees there are several factors that must be in place. First, the trees must be within a certain radius of infected Bay trees that are sloughing sporangia. The exact range of this radius can vary depending on wind patterns, topography, and other factors, but Garbaletto estimates it to be about 60 feet (Garbaletto, 2020).

Second, the tree must experience consistent precipitation for roughly 6 weeks. This is the duration of exposure to sporangia that is needed for the pathogenic load to reliably breach the threshold for oak trunk infection. *P. ramorum* is a water-based organism. The zoospores are motile and propel themselves through water, so they only spread during precipitation events (Widmer, 2009).

Finally, average temperatures have to be relatively high. It has been observed that sporangia production in *Umbellularia* leaves is lower during early and mid-winter rains vs later season warmer rains (Hüberli et al., 2003). Because of the specific weather conditions necessary for sporangia to infect true oaks, significant *Quercus* infection only occurs every several years when there is abundant spring rainfall. Absent these factors there can still be limited spread, but large-scale infection is unlikely.

Because tanoak has a lower threshold of sporangia exposure needed to infect its trunk than do true oaks, they are experiencing much higher infection and mortality rates. In some of the most heavily infested areas, Tanoak is surviving solely through vegetative reproduction, as SOD does not affect below ground rhizomes. It is projected that a significant portion of surviving tan oak will be re-sprouted stems from existing rhizomes (Varner et al. 2017).

Once infected, the bark lesions of symptomatic *Quercus* trees do not produce any form of inoculum (Davidson et al., 2005). *Quercus* are thus considered to be dead end hosts for the pathogen (Davidson et al, 2005). Compared to the impact on *Nolithocarpus* populations*,* the impact of *P. ramorum* on *Quercus,* is at present, relatively minimal. However, *Quercus* species are typically more highly valued trees than *Nolithocarpus*. True oaks are cherished as ornamentals, produce high quality wood, and are an iconic part of Californian landscapes. As such, much of the public awareness of and concern for the disease relates to the threat posed to *Quercus*, despite being significantly less impacted by the pathogen thus far.

III. Ecological Background— Fire History in California

Forest and land cover in California is a dynamic system, that has changed and continues to change depending on prior forest composition, fire history, and human intervention. The impact that *P. ramorum* has on any given stand of forest depends on these same factors.

Indigenous peoples intentionally lit fires for thousands of years in Californian forests, before this practice was largely halted by the Spanish colonial government, and later the American authorities. Tribal groups had a deep and intimate knowledge of how fire interacted with the landscape. Their use of fire varied depending on a number of factors, such as landscape type, season, and the intended outcome (Erikson & Hankins, 2014). Fires were often lit early in the dry season to ensure that fire later in the year wouldn't burn at such a high intensity that it would have negative effects on acorn producing oaks and other useful plants. The use of fire in oak woodlands seems to have served to increase species diversity, and probably favored trees and plants that provided food, or served another use (Erikson & Hankins, 2014).

As has already been noted, *P. ramorum* transmission is dependent on, and correlated with, the presence of California bay and tanoak trees, which serve as the primary source of disease spreading sporangia. There is evidence that forest and fire management regimes over the last 150 years may have significantly increased the prevalence of both of these species. Two interrelated factors can explain this trend— fire suppression and logging.

Intentional burning was first banned by the Spanish in 1793, as part of a broader regime of suppressing and erasing native culture and land use practices. (Erikson & Hankins, 2014) The practice of suppressing fires causes "critical changes to forest structure, including increases in the density of small, young trees, decreases in tree canopy gaps, and expansions in the perimeter of woodlands (Meentemeyer et al., 2008)." Bay and tanoak trees both have thin bark, and young trees in particular can experience mortality even in low intensity blazes. Fire suppression has also led to an expansion of forests into areas that "may have been different types of vegetation" such as meadow, or chaparral, "only decades ago (Meentemeyer et al., 2008)."

The second main factor is logging, and the forest succession that follows clear cutting. Evidence shows that bay and tanoak can, when aided by fire suppression, outcompete redwoods and Douglas-fir in recolonizing a logged area. The result being that "logging practices have shifted forest composition to tanoak and bay laurel due to loss of coast redwood and Douglas-fir (Barbor et al., 1993)."

Because of these practices California forests have a much higher percentage composition of bays and tanoaks than they did before European land use practices began. Average stem size has decreased, and stems per square meter has increased, across multiple forest types. These changes have left forests with dense stands of bay and tanoak, which makes them far more susceptible to SOD transmission and mortality than they would have been before fire suppression practices, and logging took place.

It is also possible that fire suppression is influencing SOD etiology in a more direct way. One study sought to determine if previous burning of an area would reduce the incidence of SOD infection. One study used GIS data to directly compare areas that had burned recently with maps showing *P. ramorum* infection. The data seem to suggest that "the two layers do not coincide (Moritz & Odion, 2005)." However, the authors of the study acknowledge limitations based on our incomplete knowledge of where the pathogen is hosted asymptomatically, or undetected.

IV. Ecological Impact of *P. ramorum* and Potential Implications for Fire Behavior

There are several first order effects of SOD that are cause for some concern. Tanoaks are one of the main sources of acorns for both indigenous peoples, and a variety of animals. A drastic reduction in the number of tanoaks may have "cascading effects on the food webs of these ecosystems (Grünwald et al., 2019)." Cobb & Rizzo have also demonstrated that changes in forest composition due to SOD have effects on nutrient cycling. These seemingly minor ecological impacts may eventually be revealed to have significant influence on a forest system.

SOD has a different etiology and pattern of spread and impact than previously studied pests, such as bark beetle. While beetle damage typically exhibits more of an "acute pulse disturbance," SOD often results in more "patchy patterns of mortality and fuel accumulation (Kuljian & Varner, 2010)." Therefore, existing fire models used to incorporate the impact of pests may not be adequate in accounting for ways in which SOD will affect fire behavior.

As discussed in the previous section, the exact impact of the pathogen on a forest depends on a number of complex and interrelated factors, including baseline species composition, fire history, intensity of the infestation, and weather pattern history. Spatial patterns also play a role. For example, a stand of tanoaks isolated from infectious trees by a mature conifer forest might never become initially infected, despite having inherent conditions that would make the stand highly susceptible to the pathogen (Metz et al., 2017).

The impact of *P. ramorum* on fire behavior will vary significantly based on the specifics of the infestation, and other underlying ecological conditions. Furthermore, and perhaps most importantly, any quantification of the impact depends upon the time frame used in the analysis.

P. ramorum girdles the cambium on the lower trunk of an infected tree, constricting the flow of water in the xylem (Garbaletto, 2012). As this occurs the canopy of the tree will begin to dry out, while the tree is still standing. However, the leaves do not immediately fall to the ground. *P.*

ramorum infection interrupts the mechanism of leaf abscission, "resulting in prolonged dead leaf retention (Kuljian & Varner, 2010)."

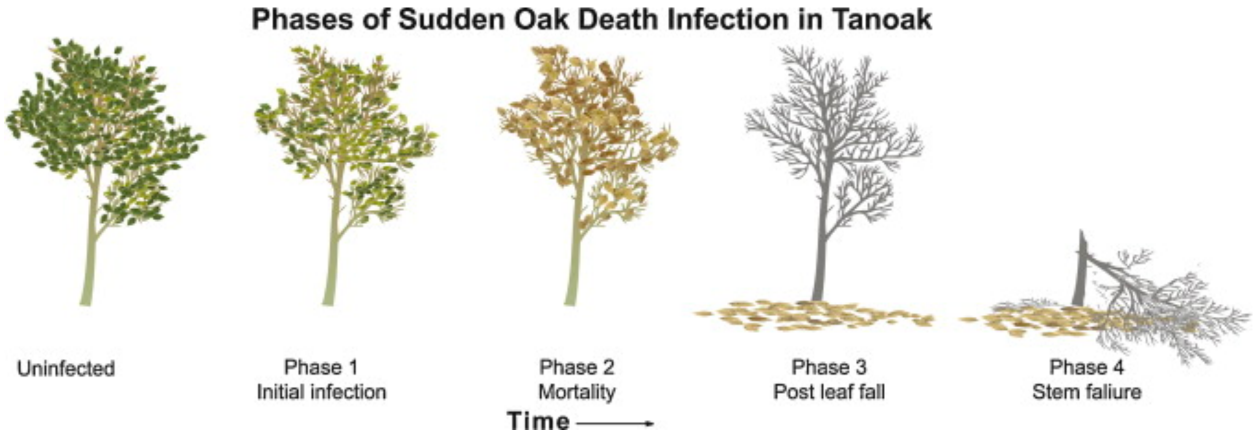


Figure 4: Progression of *P. Ramorum* disease in *Notholithocarpus densiflorus* [Kuljian and Varner, 2010]

Thus, the immediate result of SOD in tanoaks is a sudden proliferation of standing dead tanoaks with dry leaves still attached, as illustrated in phase 1-2. The key metric to consider here is foliar moisture content (FMC). Uninfected tanoaks have an average FMC of 82.3%, while for SOD killed standing trees the average is 12.3%, with some trees measured as low as 5.8%. These trees present an extremely high risk of crown fire ignition in the event of a surface blaze passing below the tree, and crown "foliar mass may remain high enough to sustain crown fire spread (Kuljian & Varner, 2010)." Such conditions also increase the likelihood of crown ignition more during fires of normal intensity.

Tanoak canopy base heights, which is the height of the lowest canopy leaf to the ground, span a wide range, from 0.25m to 9m. Such a range increases the likelihood that a stand of SOD killed tanoaks can act as a fire ladder. Kuljian and Varner conclude that as SOD "changes the fuel dynamics of tanoak forests, an assumption can be made that crown fire ignition and/or individual tree torching will become more probable."

Forrestel et al. (2015) measured fuel loads in infested redwood and Douglas-fir forests with tanoak understory in Pt. Reyes. They found, first, that mortality progressed rapidly where stands were newly infected, increasing from "20% of basal area to upwards of 90% of basal area by the end of the study period." Correlated with tanoak mortality, the study found a concurrent increase in surface fuel loads. They conclude that the "potential for uncharacteristically intense fire behavior may be increasing, at least for some window of time until decomposition catches up with fuel inputs from this disease (Forrestel et al., 2015)."

A crucial consideration in this analysis is that phase 2, when the tree is standing, dead, and retaining dry foliage, lasts for 2 years on average. After phase two, the tree will typically fall to the ground. Having dead trees lying on the ground does increase the surface fuel load, and therefore also increases the burning temperature of the fire, but it does not significantly increase chances of crown ignition.

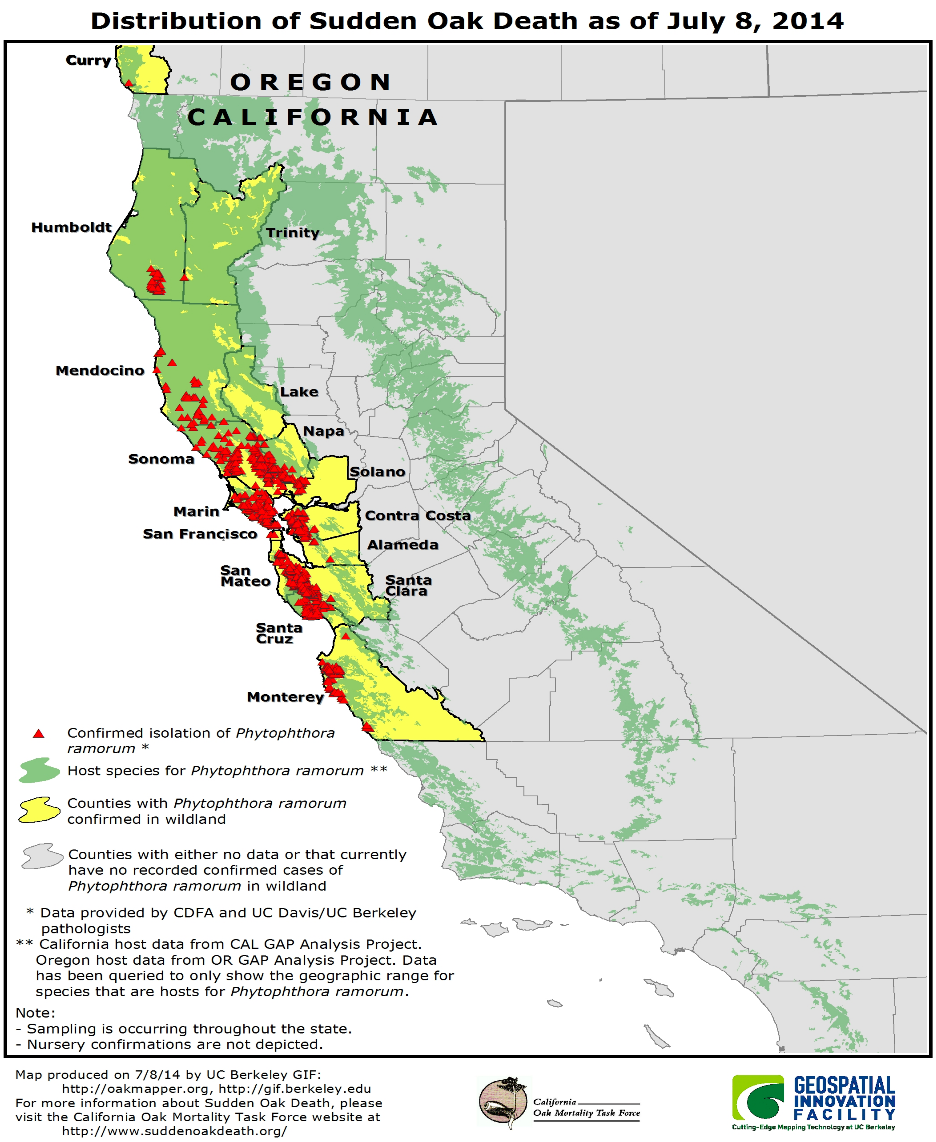


Figure 5: P. *ramorum* infects trees across a wide geographic range in many different types of forest

V. California Forests without Tanoak

It is estimated that, *P. ramorum* will continue to decimate tanoak communities in the coming decades. The mortality rate in infested sites has been observed to be far greater than baseline mortality of 5.5 to 6% per year. The average mortality of infested sites has been found to be "20% to 25% of basal area dead at the landscape scale but with up to 60% to 100% of mature stems at the level of the plot." A model by Cobb et al. (2012) indicates that "the complete loss of tanoaks as a codominant overstory species is likely to occur in large portions of the tanoak's geographic range." Meentemeyer et al. (2011) have also suggested that it is reasonable to expect that tanoak will be extirpated and functionally extinct in large areas of its native range within the next few decades. Therefore, looking beyond the short term implications of standing dead trees, it is worth examining what California forests will look like without tanoak, and how this will impact fire behavior.

How the "functional extinction of tanoak" will affect fire behavior depends heavily on what kind of forests/trees replace the killed tanoak. Varner et al. (2017) compared (uninfected) leaf litter flammability of different species to estimate the effect of tanoak extirpation in California forests on likely fire behavior. They note that "[a]mong native hardwoods in the western US, tanoak litter ranks among the most flammable (Engber & Varner, 2012), and where it is replaced by Douglas-fir, one of the "lease flammable of western USA conifers," surface litter flammability decreases markedly.

In the case of other trees, such as California bay, redwood, and madrone, which are likely to succeed in post-SOD forests, the effect on leaf litter flammability is harder to predict. Tanoak is the most common hardwood understory tree for redwood forests California (Tappeiner et al., 1990). The future leaf litter flammability of redwood forests will depend on what hardwood colonizes these areas, and to what extent.

Some infected true oak forests are also experiencing high rates of mortality. According to Brown et al. (2012), stand reconstruction and modeling suggests that some infected forests in Marin lost 70% percent of their coast live oak basal area between 1994 and 2014. The average rate of coast live oak mortality is estimated to be 0.5%/year. However in infected sites the rate is 5%, a ten-fold increase over the base rate. Brown et al. (2012) suggests that California bay is the most likely tree to colonize areas vacated by coast live oak mortality.

There are many other factors that could potentially play a role in assessing the long-term changes wrought by the functional extinction of tanoak in California's forests. Other pests and diseases may have significant impacts on other native trees. Climate trends may create dry and windy conditions more often, changing the calculus of existing fire behavior models. And invasive species, such as French broom (*Genista monspessulana)*, may accelerate their colonization of oak forests, creating a near permanent fire ladder from chaparral and grassland into madrone and coast live oak canopy.

Discussion

I. Implications for Wildland and Urban Forestry

While *P. ramorum* is a significant phenomenon, it is hard to isolate as a variable in assessing how fire will affect a forest. Therefore, the steps that should be taken at a municipal and land management level to mitigate the threat it poses are neither obvious nor universal.

Much of the activity and community level SOD mitigation work is done to protect prized stands of economically valuable true oak trees. SODmap.com is a website run by UC Berkeley professor Matteo Garbaletto, which consolidates the results of large-scale testing of bay trees, in order to map the exact location of infected/infectious trees. In conjunction with this project, Garbaletto also heads the "Oak Mortality Task Force," which agglomerates practical information about the disease's behavior, best practices, and management tips for protecting trees.

The main recommendation for the protection of individual oak trees is to remove California bay trees that are known to be infected, and possibly all bay trees, with some exceptions such as those on slopes or in riparian zones, within a buffer zone of at least 30 feet. This tactic, which potentially advocates large scale California bay tree removal is predicated on research showing that bay trees currently exist at roughly 3x their natural rate, due to fire suppression policy, as discussed above. Garbaletto notes that even freshly sprouted stems, coming from trees previously reduced to below ground rhizomes, can harbor the disease. Therefore, effective bay tree removal may have to be accompanied by herbicide treatment.

The only other intervention that is really on offer at the moment is phosphonate treatment of select oak trees. This treatment is available as an over the counter "fungicide" under several different trade names, such as Agrifos and Reliant. Despite being marketed as a fungicide, this product does not kill fungal organisms (or SOD for that matter) on contact. Rather, the "phosphonate induces the trees to express their disease resistance genes more readily, essentially triggering a natural immune response in the tree (Garbaletto, 2020)." Garbaletto suggests that this treatment can be effective if properly applied, and administered as a prophylactic. However it is difficult to apply at the scale of forest wide intervention (Garbaletto et al., 2007).

The above recommendations, for how to protect economically valuable *Quercus* specimen from SOD infection can and should be part of the toolkit of any urban forestry program in Californian cities where *P. ramorum* is known to be established. Centuries old *Quercus* trees are often the centerpiece of city parks, squares, and neighborhood forests. Protecting such trees probably merits some extra costs. However, practices for reducing wildfire risk are typically the province of land managers at a larger scale.

Mid-Peninsula Open Space District (Mid-Pen) is an "independent special district" that covers 63,000 acres in northern Santa Clara County and southern San Mateo County. This land includes several different forest types where SOD has had an impact, including tanoak, Douglas-fir/tanoak/redwood forest, and coast live oak dominated woodland. Midpeninsula Open Space is notable for being the first place where canyon live oaks (*Quercus chrysolepis*) were observed experiencing symptoms, and eventually, mortality, from SOD.

Thus far, much of Mid-Pen's response to SOD has been researching how the pathogen is affecting their forest. The district created a 10-year plan in 2005 and allocated more than $500,000 to "pursue SOD research and management responses." The district has also contributed to research efforts at UC Berkeley determine if some tanoak trees are developing/displaying a resistance to SOD.

Mid-Pen has also been running a control trial designed to compare 1) oaks that are sprayed with Agrifos, 2) oaks that have had all bay trees within a 15-foot radius of their drip-line removed, and 3) a control plot of oaks for which no interventions have been made. According to their 10-

year plan update, SOD levels are lower in areas "treated by bay removal," while "there has been no detectable level of difference in the fungicide-treated plots compared to nearby control plots." This result may change with more time, and the report does note that the results coincide with several years of low rainfall.

II. Public Safety and Legal Considerations

The rapid tree mortality caused by sudden oak death will have additional implications for public safety beyond fire risk that must be addressed by local land managers. SOD may factor into considerations of public safety, given that the disease will rapidly weaken the supporting tissue in the trunk of an infected tree. The sudden proliferation of weakened, yet standing, dead or dying trees of should influence the tree risk assessment for any given area.

Tree risk assessment refers simply to the process of assessing risks from the failure of trees. Ellison (2005) emphasizes the precise use of relevant terms. *Risk*, which refers to "the probability of something adverse happening," must be distinguished from *hazard*, "the disposition of a thing, a condition, or a situation to produce injury." In other words, a tree that is nowhere near people or property, even if it is likely to fall down or drop large limbs, is not a hazard tree. A tree is only a hazard if it threatens a target of some kind of value. An assessment of tree risk gets to the core of urban forestry as a discipline, where an understanding of trees and forests as biological and ecological systems is understood and evaluated in the context of people, infrastructure, and property.

Sudden oak death can quickly alter the conditions in a forest, and can present a significant challenge to anyone charged with assessing the risks presented by oak or tanoak trees situated near people, property or infrastructure. Campsites and State Park facilities present a challenging case for such assessments, as illustrated by the case of Zachary Rowe in 2012. Rowe, who was 12 years old at the time, was sleeping in his tent at a county park in San Mateo County, when a 70 ft tall tanoak tree fell, striking his lower body and causing devastating injuries to his right leg and pelvis.

After the incident, Rowe sued the San Mateo County Parks and their contractors, "alleging dangerous condition of public property and negligence." (Rodriguez, 2017) The county of San Mateo had hired Davey Tree in 2007 to inspect the park for hazardous trees. PG&E was also sued as the trees were within striking range of power lines. In 2017 Rowe was awarded a total of $47.5 million in damages.

It is difficult to discern from public records if the tanoak was infected with SOD specifically, though the tree seems to have been in visibly compromised health. One article mentions a declaration by a witness detailing "the negative impacts of construction activity on the tree's health that made the tree more susceptible to fungal disease." (Eslinger, 2018) Ultimately, the tree was standing and in poor health, a condition that could plausibly have been caused by sudden oak death. The public relations manager for Davey Tree released a statement after the settlement, saying "Davey denies any responsibility for the accident, which occurred five years after its visual inspection for 'imminent hazards' in the park." (Eslinger, 2018)

While Davey only paid $6 million of the $47.5 million settlement, the case does appear to set an extremely high bar for tree risk assessment contractors. Rapidly progressing forest diseases such as *P. ramorum* can cause forest conditions relevant to tree risk to change significantly in much less than 5 years. The specifics of this case are relevant, particularly in regards to the aforementioned construction that is alleged to have affected the health of the tree. Nonetheless, the case makes clear that tree risk assessment must take into account, or at least include disclaimers regarding SOD, or even the potential for it to emerge if certain forest conditions are present.

This principle will apply to any portion of the urban-woodland interface, particularly where vulnerable trees are located. While it is never possible to fully predict where and when sudden oak death will kill trees, urban forest professionals should at the very least be on the lookout for signs and symptoms of the disease, and pay attention to the underlying conditions that make rapid spread of the disease more likely, such as proximity to infected bay trees, and late season rains.

Across the state of California efforts are being made to minimize the risk posed by standing dead oak and tanoak trees. Often times the risks posed by crown fire ignition and other aspects of public safety are folded together. In March of 2019 the Governor of California, Gavin Newsom, declared a state of emergency in order to expedite the removal of trees that had been killed by SOD at 35 different sites across the state. In a statement, Cal fire specified that the risk posed by the dead trees included both crown ignition, and blocked evacuation routes and access roads. They acknowledged the impact of SOD directly, saying "[h]igh mortality in oaks and Tan Oaks, and densely stocked redwoods with a heavy brush component impact the main evacuation route for populated areas."

An understanding of forest history and health in California, as has been detailed in this paper, may suggest that in certain forest types some degree of thinning could be beneficial, whether mass tree mortality has occurred yet or not. Logging, fire suppression, and other factors have led to overcrowded forests, often with lopsided species distribution. However, it is not generally feasible to do tree removal at the scale of an entire forest. Therefore, this emergency declaration seems like an especially good use of funds, as it is addressing risks posed by dead trees at specific sites in the urban rural interface, and attempts to do so preemptively.

However, this project, and others like it, have encountered resistance from environmental groups, who criticize Newsom's use of emergency powers as a means of circumventing environmental regulations. The Sierra Club also argued that removing large numbers of trees could lead to mudslides and erosion. Similar pushback has been encountered by PG&E when they attempt to remove trees near power lines in certain areas.

Forestry is not simple, and the "environmental" option is rarely unambiguous. Well-meaning parties can have opposing views on individual issues. However, a blanket opposition to any manner of intervention into forests, especially those at the urban-rural interface, does not seem like a tenable position to hold. This will be increasingly true if wildfires continue to occur on a yearly basis, and the possible influence of forest pathogens on burn fire behavior become more widely acknowledged, along with the effectiveness of strategic forest thinning and tree removal practices.

III. Recommendations

Computer modeling suggests that the spread of sudden oak death will accelerate in the coming years, especially in the forests of Humboldt and northern Mendocino County (Cunniffe et al., 2016). These same models suggest that had prevention efforts and funding been "front-loaded," beginning around 2002, it may have been possible to significantly curtail the spread of *P. ramorum.* However, control efforts started more recently are expected to have "very little effect on the area lost by 2030 (Cunniffe et al., 2016)." The study concludes "that statewide action to eradicate or even slow the spread of *PR* is no longer feasible, even with a substantial budget."

Therefore, management efforts to control the impact of SOD will be best achieved at the scale of local intervention, within feasible geographic parameters. Cuniffe (2016) echoes the findings of the Mid-Peninsula District and many other control trials in suggesting that "the only treatment shown to be effective in reducing pathogen prevalence at the landscape scale is removal of host species." Therefore, for homeowners intent on preserving a stand of prized oak trees, the best strategy will be to remove all California bay trees in a 60ft radius of the trees. This treatment will be most effective if completed preemptively.

Mapping infected/infectious bay and tanoak trees, as done by the Oak Mortality Task Force is theoretically a useful tool in assessing the feasibility of control efforts, or predicting future large-scale mortality events. However, the comprehensiveness of the survey results are constrained by challenges such as trees lying on private land holdings, lack of resources, and the massive scale of the task.

Research regarding the potential for immunity in oaks and tanoaks may prove to be a fruitful area for long term SOD mitigation efforts. Conrad (2019) found that in a plot of coast live oaks artificially infected with the pathogen*, "*27% of CLO expressed resistance to *P. ramorum*, while 61% died (N = 149)." Their study also found that resistant trees tend to "co-occur, and that resistance is a heritable trait." Further research on this topic is needed, particularly genetic analysis.

Any suggestions related to fire mitigation must take into account the totality of the landscape, and not just rates of sudden oak death infection. However, certain risk factors can be discerned from an understanding of SOD etiology. Because the risk of crown fire peaks roughly 2 years after mortality, and infection is highest during years of sustained, late-season rain, it would be worth monitoring oak/tanoak forests in the years following an El Nino event. Such monitoring may help land managers predict and preempt especially dangerous forest conditions.

Public awareness of sudden oak death and fire risk also influence the efficacy of mitigation efforts. Some private landholders are very resistant to any form of tree removal from their land, even for the purpose of clearing high voltage power lines. Efforts to increase public awareness of the risks posed by dead standing trees may increase public acceptance of proactive removal efforts. Overall, recommendations will vary depending on the stakeholder involved. In some cases emergency declarations may continue to be a useful tool, as priorities are considered at the state level.

Conclusion

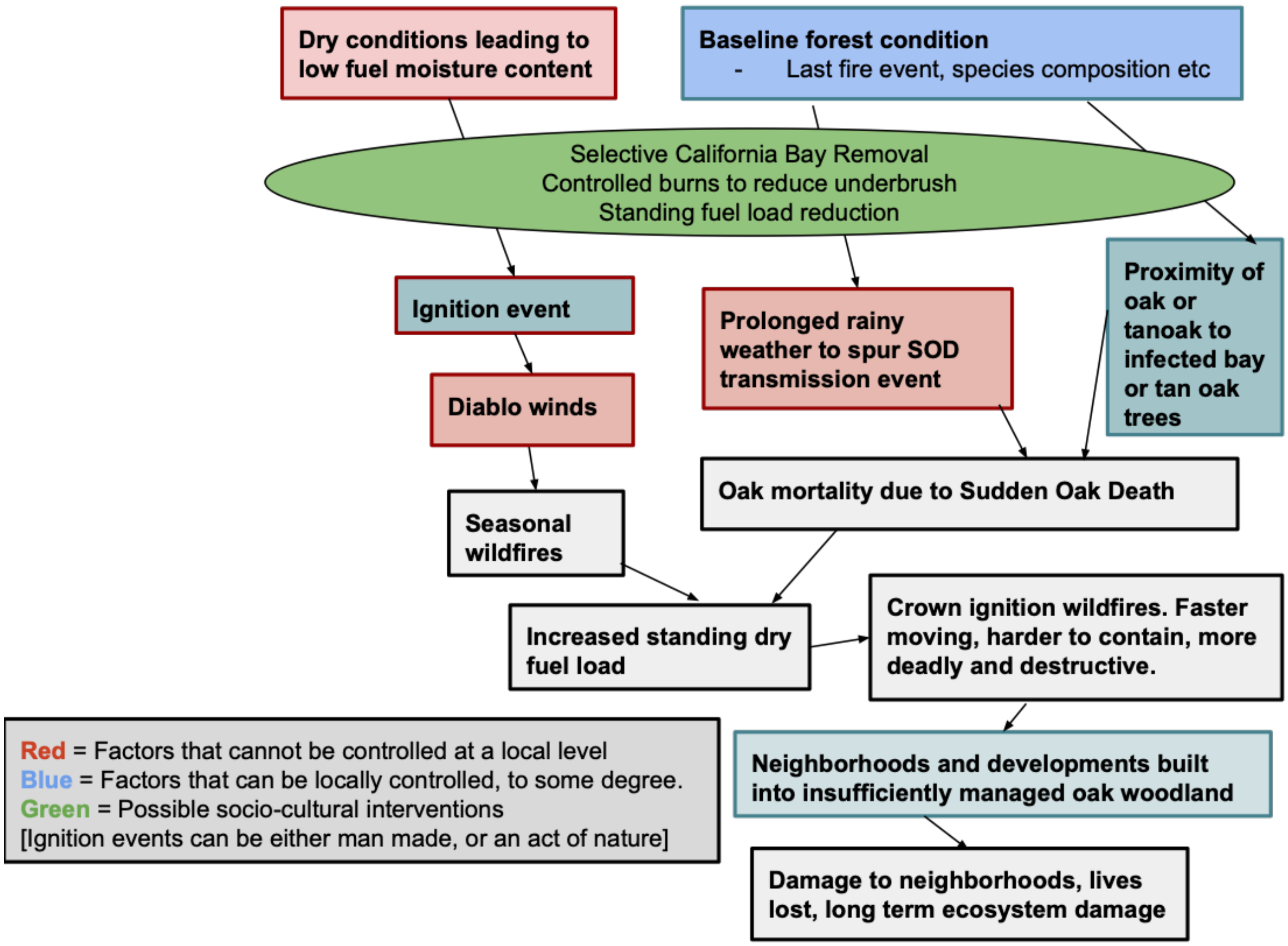
Sudden oak death is and will continue to be a reality for coastal Californian forests in the 2020s, and in the decades to come. While it may have been possible to curtail the spread of *P. ramorum* had large-scale efforts been initiated once the disease was reasonably well understood around 2002, it is no longer possible to do so. Tanoak forests are being affected most rapidly, with some areas experiencing 20% annual mortality, while true oak mortality is projected to accelerate in the coming years. Oaks may experience distinct pulses in mortality following high rainfall years, while tanoaks will probably experience a more even level of yearly infection and mortality due to a lower threshold of sporangia exposure required to infect the tree's trunk.

The period of 1-2 years following oak or tanoak mortality, while the tree is still standing, present the greatest risk of crown ignition for trees in the surrounding forest. Over a longer timeframe, the percentage of oaks and tanoak composition in California's forests is decreasing. The implications that this will have for fire behavior depend on the species/forest types that will follow, as well as continued land management practices, climate patterns, and other forest pathogens.

Land managers have a limited number of options in dealing with SOD. Where scale, resources, and public opinion permit, mass removal of bay trees has been shown to reduce the likelihood of *Quercus* infection and mortality. Using modeling tools based on survey data of bay tree infection, land managers can increase their understanding of the infestation in their area, and make more informed decisions regarding mitigation strategies. Considerations of public safety should also play in to SOD mitigation efforts, and special attention should be given to trees/forests at the urban/woodland interface that may present a hazard to people or property.

Appendix 1: Diagram of System Interactions:

Short Term (1-3 year) effect of SOD on Fire Behavior



Appendix 2: Matrix of Systems Affecting SOD/Fire Interactions

Underlying Condition	Exacerbating Factor	Cascade effect (from previous Resulting Dynamic)	Resulting Dynamic
Oaks/ tanoaks in proximity to affected Bay trees	Sufficient rain during late winter (El Nino?) for transmission event	Spread of pathogen into susceptible oak species	Widespread oak mortality in forest
Dry summer conditions	Low fuel moisture content in in both live and dead fuel	Standing dead oaks and tan oaks in forests	Crown ignition fire
Neighborhoods built into oak woodlands	Haven't allowed controlled low intensity burns for decades	Crown ignition fire moves more quickly and burns hotter than surfiest forest fire	Fast moving fire sweeps into fire. Deadly and destructive effects.
Recognition of SOD altered fire behavior as a threat that can be managed or mitigated at the municipal level	Alteration of UF Master Plans and other documents to include treatment, selective removal, etc	Public support grows when wildfires affect nearby areas	Communities are better prepared to manage and address SOD and the forest dynamics that it creates

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