Restoration Management in Redwood Forests Degraded by Sudden Oak Death[1]

Richard C. Cobb,[2] Peter Hartsough,[3] Kerri Frangioso,[2] Janet Klein,[4] Mike Swezy,[4] Andrea Williams,[4] Carl Sanders,[4] Susan J. Frankel,[5] and David M. Rizzo[2]

Abstract

We describe the foundation, objectives, and initial results from a stand-level experiment focused on restoration of redwood (*Sequoia sempervirens* (D. Don) Endl.) forests impacted by sudden oak death (SOD), caused by *Phytophthora ramorum*. Our study stands were primed for heavy impacts by SOD. Extensive harvesting which ended circa 1910 on Mt Tamalpais (Marin County, California) resulted in high densities of tanoak trees with interspersed residual redwood. The arrival of *P. ramorum* and subsequent emergence of SOD transformed these stands into tanoak shrublands with interspersed redwood trees. Pretreatment understory tanoak densities were extremely high relative to redwood forests of the north coast which have not been invaded by *P. ramorum* but both redwood advanced regeneration and overstory tree densities were low in the same respects. Mastication and hand-crew piling treatments were applied in 2015 on a randomly selected group of plots and each treatment type substantially reduced tanoak densities suggesting redwood establishment may now be possible. Our study is designed to assess tradeoffs of treatment costs with benefits resulting from fuels reduction, redwood regeneration, carbon sequestration, and water provisioning. We cannot yet make strong conclusions about these tradeoffs given the preliminary nature of our datasets. Instead, we describe areas of uncertainty and identify critical questions that must be evaluated to understand the utility and appropriateness of applying these treatments across a broader portion of the redwood forest landscape.

Introduction

Sudden oak death (SOD), caused by *Phytophthora ramorum*, has represented a significant threat to redwood (*Sequoia sempervirens* (D. Don) Endl.) forests since the emergence of the disease circa 1996. Although the causal pathogen, *Phytophthora ramorum*, can infect redwood these infections do not represent a significant threat to the health of individual redwood trees. However, mortality of redwood forest species and the resulting impacts substantial changes at the entire redwood ecosystem level; these impacts include increased ground fuels, dense resprouting of the most susceptible individual redwood trees and reduced ecosystem services provided by these forests (Cobb et al. 2012a, Metz et al. 2013). Tanoak (*Notholithocarpus densiflorus* (Hook. & Arn.) P.S. Manos, C.H. Cannon, & S.H. Oh) is a unique component of redwood ecosystems; it is the dominant nut-producing species in redwood forests and is often the sole ectomycorrhizal species when Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) is not present in the stand. Tanoak is also notable for the potent combination of supporting high pathogen sporulation rates from infected tissue as well as the development of lethal bole infections that kill the above ground biomass. Thus, tanoak can both transmit the pathogen and develops the disease SOD which causes extensive mortality, increases fuel loads, and changes stand-level carbon cycling (Cobb et al. 2012a, 2016). The high densities and basal area of tanoak in many redwood stands means that many redwood forests have been impacted by this disease and many others are threatened in the coming decades (Cobb et al. 2013b, Cunniffe et al. 2016).

---

[1] A version of this paper was presented at the Coast Redwood Science Symposium, September 13-15, 2016, Eureka, California.
[2] Department of Plant Pathology, UC Davis, Davis, CA 95616.
[3] Department of Land Air and Water Resources, UC Davis, Davis, CA 95616.
[4] Marin Municipal Water District, Corte Madera, CA 94925.
[5] USDA Forest Service, Pacific Southwest Research Station, Albany, CA 94710.
Corresponding author: rccobb@ucdavis.edu.

Phytophthora ramorum has invaded throughout the greater San Francisco Bay Area, and damaged the culturally, ecologically, and economically important forests of Mount Tamalpais (Marin County) including many stands managed by the Marin Municipal Water District (MMWD) for water yield and recreation. Sustained inoculum loads have resulted in extensive tanoak mortality. In some stands almost 100 percent of initial overstory tanoak trees have been killed by the disease. Tanoak resprouting has formed undesirable forest structure where occasional redwood overstory trees co-occur with dense, tanoak shrub understories. Some of the most impacted redwood forests in California occur on Mount Tamalpais; these stands have significantly higher understory tanoak densities in comparison to a survey of 500 m^2 plots (172) located in uninvaded redwood forests from Sonoma to Del Norte counties (fig. 1; Cobb et al. 2012b, Metz et al. 2012). Dense understory conditions are significant management concerns from the perspectives of fuel loads, maintenance of biodiversity, aesthetics and provisioning of water resources. These concerns motivated an effort to design and test potential ecosystem restoration techniques for redwood forests impacted by this disease.

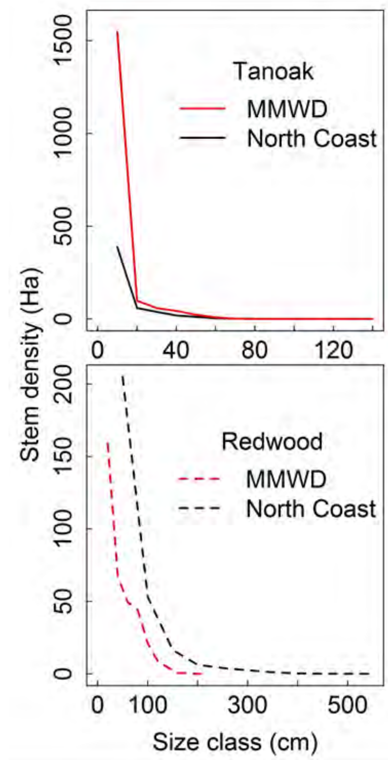

Figure 1. Tanoak (upper panel) and redwood (lower panel) stem densities in pre-treatment restoration experimental study plots (MMWD) compared to a survey of 172 - 500 m^2 long term study plots located in stands uninvaded by *Phytophthora ramorum*.

We instituted a series of replicated management experiments on MMWD lands to identify the most economically and ecologically effective actions to restore overstory trees and key ecological functions of our study area including carbon sequestration and water provisioning. Our goals were to understand if different treatment approaches have comparable benefits in terms of disease suppression and how these effects may augment or offset gains in ecosystem processes. We also aimed to understand what treatments are most effective in increasing the dominance of redwood in a set of stands where historical harvesting resulted in high densities of tanoak relative to redwood other regional forests (fig. 1). SOD kills the above ground portion of tanoak but basal sprouting can be extensive. Our restoration study sites had extremely high densities of small (~1cm diameter at breast height;1.37 m, DBH) tanoak stems with average values greater than 1500 stems ha^{-1} (fig. 1,upper panel). In contrast, North Coast redwood stands had significantly lower mean tanoak densities for the same size classes. Although redwood can dominate the overstory of upland redwood forests of our study area, the relatively low density of redwood in larger diameter classes compared to North Coast stands indicates that redwood has not regained pre-harvest dominance in the study site since extensive harvesting ended circa 1900. SOD could delay natural (e.g., without silvicultural intervention) succession at this and similar study sites if tanoak resprouting also inhibits redwood regeneration in the understory. Lower densities of redwood in small diameter classes at our study site compared to North Coast redwood forests suggests the disease may lock stands into an undesirable condition dominated by small diameter tanoak. This condition is akin to a tanoak shrubland with occasional overstory redwood trees but little or no redwood regeneration (fig. 2). Our study uses a suite of carbon cycling measurements including litterfall, soil C stocks, soil C dynamics (soil respiration, methane, and N_2O flux) to understand the extent of these restoration treatments in reducing greenhouse gas emissions, an important state-level policy goal. Therefore, our study is designed to determine the most cost-effective treatments for a set of management goals broadly applicable across the range of redwood forests at risk from SOD. In addition, the study design, both in terms of treatments and measurements, was constructed to identify potentially conflicting treatment outcomes, such as reduced water provisioning in stands with greater above ground carbon storage.

Experimental Design and Measurements

We established 30, 0.405 ha (1 ac) treatment plots across three MMWD sites and randomly assigned treatments within blocks of five plots. Randomly applied treatments included reference (no treatment), understory mastication (up to ~10 cm DBH), hand crew thinning and piling of residual materials, hand thinning with burning of piles, and mastication with follow-up removal of resprouting tanoak. Mastication was conducted using a combination of an excavator with a masticating head and/or a skid-steer with a forestry attachment (masticator head). Hand crews sought to apply similar levels of forest thinning and we found no significant differences between post-treatment stem densities for piling stem densities were 260 stems ha^{-1} ± 220 (Interquartile range - IQR) vs masticating 425 stems ha^{-1} ± 315 (IQR). The principle difference between treatments is that residual materials were concentrated in piles whereas mastication treatments conducted with heavy machinery were designed and applied with the goal of uniform distribution of residual materials. Treatments were designed and applied to remove all hardwoods while retaining conifer (redwood, Douglas-fir) regeneration. These efforts were generally successful for individual trees greater than ~1m in height.

Figure 2. Tanoak shrubland-like stand conditions with interspersed overstory trees, mostly redwood. These high density tanoak stand conditions are broadly representative of pre-treatment stand structure in upland redwood forests of Mt Tamalpais. Fuels mastication treatments are shown in the foreground.

Each plot was instrumented to measure water outflow by placing two soil moisture sensors at the parent material – mineral soil interface (between 70 and 100 cm) and at 30 cm depth. Soil moisture was measured every half hour and monitored continually with a cellular data uplink. Precipitation gauges were established in the reference treatments in four of five study blocks at the drip line of an individual redwood tree within the respective plot. We installed 15 cm length PVC collars in the shallow mineral soil (to ~12 cm depth) to conduct repeated measurements of greenhouse gas dynamics on a monthly basis. We attached portable air-tight chamber tops to each of these PVC collars for a 15 min period and withdrew soil gas samples drawn every 5 min to calculate rates of efflux. We also placed two plastic bins within each plot to quantify treatment effects on foliar litterfall, an important component of above ground productivity which can change rapidly with changes in growth and year-to-year climate variations (Cobb et al. 2013a). Lastly, we conducted quarterly samplings of shallow mineral soil (~15cm surface soil) to determine treatment effects on fine root dynamics, also an important component of ecosystem productivity sensitive to management and disturbance (Kaye et al. 2005). Roots were gently washed from soil in a low-pressure cold-water stream and sorted into live and dead fine root pools (all species between 2-0.5 mm diameter).

Results and Discussion

Mastication treatments greatly reduced fuel loads, understory density, and prevalence of sporulation-supporting species; these treatments reduced densities from 3475 stems ha^{-1} (± 2045 IQR) to 425 stems ha^{-1}. Hand crew piling was also similarly effective in reducing understory tree density and density of species which transmit *P. ramorum*; piling reduced stem densities from 1675 stems ha^{-1} (± 1260 IQR) to 260 stems ha^{-1}. The large interquartile range values (IQR), a measure of data spread, indicate the pretreatment variation in stem density across sites and also indicate that plots selected (randomly) for hand crew treatments had somewhat lower pre-treatment stem densities. Using a set of models parameterized with data from this experiment, we found that 90 percent of intact tanoak overstory trees are expected to be retained by the treatment, in part because these individual trees will be isolated from inoculum sources. Although SOD has been devastating to overstory tanoak individuals, residual tanoak trees are still present throughout the experimental area albeit at much lower densities compared to pre-treatment levels. A body of previous monitoring and modeling work suggests these individual trees will survive for much longer periods relative to untreated (high tanoak density) areas due to reduced inoculum pressure on residual trees (Cobb et al. 2012b, 2013b, Valachovic et al. 2013b). These disease suppression effects are likely to realize their greatest benefits in treatments that maintain low tanoak densities (such as follow-up sprout removal). This expectation follows from field experiments showing sprout removal provides pathogen suppression but only on the order of 3 to 5 years without maintenance of low-density conditions (Valachovic et al. 2013a).

Each understory removal treatment was effective in reducing tanoak density regardless of the treatment applied (mastication vs. piling, etc). However, the cost efficiency of applying one method over another has not yet been evaluated and is a subject of ongoing analysis. Each treatment type was effective in reducing understory dead fuels apart from unburned piles and also greatly compacted fuel beds (reduced fuel heights). Mastication treatments also tended to increase forest floor depth and mass, an effect of deliberately redistributing understory plant materials. The same effect was found for fine ground fuels, each treatment had the effect of redistributing understory biomass by transforming relatively large fuels (100 hr and above) into woody material that is generally 5 to 15 cm in length and ~2 cm diameter. Hand-crew pile treatments where piles were not burned are the sole exception among these treatments. Unfortunately, rather little is known about masticated fuel beds in terms of their effects on flame lengths and burn time although the depth and density of masticated fuel beds is likely an important driver of these fire behaviors (Kreye et al. 2014). In California, similar mastication treatments have been conducted to reduce shrub (primarily *Arctostaphylos* and *Ceanothus* species) and tanoak (Kane et al. 2009). As noted in these previous field studies and synthesis, masticated fuel beds have unique fuel composition and density for which current fire models do not adequately integrate. Although the reduced particle size and increased surface area of fuel particles in our mastication treatments could increase fuel decomposition rates, this has not been quantified in our treatments and the current state of research on masticated fuel beds does not support much more than speculation about decomposition rates (Kreye et al. 2014).

Initial data indicate these restoration treatments have also impacted the ecosystem processes we aimed to assess. Across treatments, soil moisture rapidly increased to field capacity during the onset of winter rains and all treatments showed outflow to deep soil layers during particularly heavy precipitation events. However, thinning treatments (all types) increase soil moisture of both shallow and deep soil layers, a common pattern of soil water dynamics following management or disturbances which reduce above ground transpiration. Our ongoing work aims to quantify potential differences in outflow and any changes in the proportion of water reaching the soil surface and outflow among treatments. From a longer-term and broader perspective, our study is structured to inform mastication treatment effects on water quality and quantity at the watershed-scale. This information is particularly important for the MMWD, a municipal water district that provides drinking water for approximately 187,000 people. SOD and the management responses to the disease has or will in the near future impact watersheds for thousands of others in coastal California as well as numerous fish-bearing streams in the region. Additional measurements of ecosystem dynamics (litterfall and soil GHG dynamics) were begun in summer 2016 and we have insufficient data to make robust assessments of our study aims. However, we have found a consistent net consumption of methane in our redwood soils in July and August 2016. While the timing of these observations corresponds to low soil moisture levels which generally favor methane diffusion into soils and consumption of this important GHG, methane consumption has not been documented in redwood forests; this argues for continued monitoring to determine the relevance of these observations to greater GHG policy goals.

Long-term efficacy of our treatments in restoring carbon sequestration and sustaining water yield will almost certainly depend on the reestablishment of overstory redwood given that carbon sequestration in this species is unlikely to be impacted when ground fuels can be reduced (Metz et al. 2013). It must be noted, that this reestablishment of redwood is unlikely to occur in stands similar to our study sites whether they have been impacted by disease or not. Harvesting in our study sites ended over a century ago and prior to disease these stands were primarily tanoak overstories with scattered redwood overstory trees and little advanced redwood regeneration. Post disease, the high densities of tanoak understories also lacked advanced redwood regeneration (fig. 2) indicating these conditions are unlikely to change without intervention that increases redwood regeneration. It is well known that removal of tanoak competitors is needed to increase conifer growth and dominance in the overstory (Harrington and Tappeiner 2009) and this same lesson can be applied to SOD-impacted redwood forests. Of course, in order for these treatments to be applied more broadly, cost effectiveness and tradeoffs among the various benefits (fuels, carbon sequestration, etc.) will also likely determine the optimal treatment for a particular landowner and disease condition. Restoring redwood forests impacted by SOD will clearly require a long-term adaptive management commitment.

Acknowledgments

This work is supported by grants from the Marin Municipal Water District, the Pacific Southwest Research Station, and a CalFire Greenhouse Gas Emissions Reduction grant. Previous versions of the manuscript were improved by critical comments from Chris Lee and Don Owen. We also thank Tinman Gist, Future Hunsucker, Nicole Greenfield, Elliot Gunnison, Ashley Hawkins, and Tom Nocera for help in establishing the field plots and Dan Wooden, Darel Patchin, Kevin Cook, Jonathan Fouche, and Lito Brindle for their efforts in applying treatments.

Literature Cited

Cobb, R.C.; Chan, M.N.; Meentemeyer, R.K.; Rizzo, D.M. 2012a. Common factors drive disease and coarse woody debris dynamics in forests impacted by sudden oak death. Ecosystems. 15: 242–255.

Cobb, R.C.; Eviner, V.T.; Rizzo, D.M. 2013a. Mortality and community changes drive sudden oak death impacts on litterfall and soil nitrogen cycling. New Phytologist. 200: 422–431.

Cobb, R.C.; Filipe, J.A.N.; Meentemeyer, R.K.; Gilligan, C.A.; Rizzo, D.M. 2012b. Ecosystem transformation by emerging infectious disease: loss of large tanoak from California forests. Journal of Ecology. 100: 712–722.

Cobb, R.C.; Meentemeyer, R.K.; Rizzo, D.M. 2016. Wildfire and forest disease interaction lead to greater loss of soil nutrients and carbon. Oecologia. 182: 265–276.

Cobb, R.C.; Rizzo, D.M.; Hayden, K.J.; Garbelotto, M.; Filipe, J.A.N.; Gilligan, C.A.; Dillon, W.W.; Meentemeyer, R.K.; Valachovic, Y.S.; Goheen, E.; Swiecki, T.J.; Hansen, E.M.; Frankel, S.J. 2013b. Biodiversity conservation in the face of dramatic forest disease: an integrated conservation strategy for tanoak (*Notholithocarpus densiflorus*) threatened by sudden oak death. Madroño. 60: 151–164.

Cunniffe, N.J.; Cobb, R.C.; Meentemeyer, R.K.; Rizzo, D.M.; Gilligan, C.A. 2016. Modeling when, where, and how to manage a forest epidemic, motivated by sudden oak death in California. Proceedings of the National Academy of Sciences. 113: 5640–5645.

Harrington, T.B.; Tappeiner, J.C. 2009. Long-term effects of tanoak competition on Douglas-fir stand development. Canadian Journal of Forest Research. 39: 765–776.

Kane, J.M.; Varner, J.M.; Knapp, E.E. 2009. Novel fuelbed characteristics associated with mechanical mastication treatments in northern California and south-western Oregon, USA. International Journal of Wildland Fire. 18: 686–697.

Kaye, J.P.; Hart, S.C.; Fulé, P.Z.; Covington, W.W.; Moore, M.M.; Kaye, M.W. 2005. Initial carbon, nitrogen, and phosphorus fluxes following ponderosa pine restoration treatments. Ecological Applications. 15: 1581–1593.

Kreye, J.K.; Brewer, N.W.; Morgan, P.; Varner, J.M.; Smith, A.M.S.; Hoffman, C.M.; Ottmar, R.D. 2014. Fire behavior in masticated fuels: a review. Forest Ecology and Management. 314: 193–207.

Metz, M.R.; Frangioso, K.M.; Wickland, A.C.; Meentemeyer, R.K.; Rizzo, D.M. 2012. An emergent disease causes directional changes in forest species composition in coastal California. Ecosphere 3(10): 86.

Metz, M.R.; Varner, J.M.; Frangioso, K.M.; Meentemeyer, R.K.; Rizzo, D.M. 2013. Unexpected redwood mortality from synergies between wildfire and an emerging infectious disease. Ecology. 94: 2152–2159.

Valachovic, Y.; Cobb, R.; Rizzo, D.; Twieg, B.; Lee, C.; Glebocki, R. 2013a. Is stump sprout treatment necessary to effectively control *Phytophthora ramorum* in California's wildlands? In: Frankel, S.J.; Kliejunas, J.T.; Palmieri, K.M.; Alexander, J.M., tech. coords. Proceedings of the sudden oak death fifth science symposium. Gen. Tech. Rep. PSW-GTR-243. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 114–117.

Valachovic, Y.; Lee, C.; Twieg, B.; Rizzo, D.; Cobb, R.; Glebocki, R. 2013b. Suppression of *Phytophthora ramorum* infestations through silvicultural treatment in California's North Coast. In: Frankel, S.J.; Kliejunas, J.T.; Palmieri, K.M.; Alexander, J.M., tech. coords. Proceedings of the sudden oak death fifth science symposium. Gen. Tech. Rep. PSW-GTR-243. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 108–113.