Management Strategies and Ethical Considerations for Controlling *Phytophthora ramorum* (sudden oak death): Application to Southern Humboldt County

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ABSTRACT

Humboldt Redwoods State Park in southern Humboldt County, California is a coastal redwood forest, a highly unique and valued ecosystem. It has many social, cultural, ecological, and economic values, including recreational benefits, heritage and aesthetic values, high biodiversity, nutrient cycling, and climate regulation. However, Humboldt County is at risk of infection by the plant pathogen *Phytophthora ramorum*, an oomycete which causes sudden oak death. *Phytophthora ramorum* has had devastating impacts on tree populations in central California and threatens forest ecosystems in the state's northern counties. It has been reported in Humboldt County, and if the pathogen continues to spread, thereby causing mortality in oaks (*Quercus* spp.) and tanoaks (*Lithocarpus densiflorus*), ecosystem stability will be threatened. Due to the many ecosystem services the coastal redwoods provide, it is imperative to mitigate the spread of *P. ramorum* in this area. This case study reviews the status of *P. ramorum* in southern Humboldt County and pathogen management strategies, including quarantine, chemical treatment, and stand thinning. By reviewing the literature on how effective various strategies have been at controlling *P. ramorum* spread, the best management strategies to implement at the study site can be identified. Furthermore, this paper will review ethical considerations of management with the goal of providing managers and policy makers a framework for disease management that considers different landownerships, land-uses, and values. Preventing the spread of *P. ramorum* in southern Humboldt County is essential to preserving coastal redwood forests and their ecosystem services, as well as mitigating the spread of the pathogen into other counties and states.

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Introduction

The plant pathogen, *Phytophthora ramorum*, is an oomycete that causes sudden oak death (SOD). It is known to infect over one hundred plant species, most of which form non-lethal foliar infections (USDA APHIS 2012). On hosts that do suffer mortality (such as tanoaks and oaks) bleeding cankers form that reduce sap flow and hydraulic conductivity, leading to quick tree death (Grünwald et al. 2012). As of the mid 2010's, *P. ramorum* is estimated to have killed about five million trees along the Pacific Coast (Frankel and Palmieri 2014). According to Cobb et al. (2020), about 38.9 million tanoak (*Notholithocarpus densiflorus*) stems have suffered pathogen mortality since the beginning of the outbreak, with a total of 71 million stem infections. They also report that about 95.2 million infections have occurred on California bay laurel (*Umbellularia californica*), a species that contributes greatly to pathogen spread and does not experience mortality (Cobb et al. 2020). Furthermore, it is estimated that nearly 166.2 million total stems have been infected as of 2012, with 42.8 million stems from studied host species (tanoak, coast live oak, and black oak) dying from pathogen impacts by 2019. This has had significant effects on ecosystem services of the coastal redwoods and increased fuel loads (Cobb et al. 2020).

In 2002, *P. ramorum* was reported in southern Humboldt County, near the city of Redway (Filipe et al. 2009; Valachovic et al. 2005). Also, in 2002, *P. ramorum* infection was reported on coastal redwoods (*Sequoia sempervirens*) (Maloney et al. 2002). While *P. ramorum* does not cause lethal infections on redwoods, synergistic effects of mixed disturbances and foliar damage may increase redwood mortality, further reducing ecosystem services. To mitigate infections in Humboldt Redwoods State Park (HRSP) and other nearby natural areas (such as the King Range National Conservation area to the west), coordinated management efforts between many stakeholders should be undertaken to control *P. ramorum* spread.

The aim of this paper is to assess what management strategies can be used to prevent the plant pathogen, *Phytophthora ramorum*, from spreading in southern Humboldt County (Figure 1). Since *P. ramorum* is already present in the area, and Humboldt County is predicted to be at high risk of increased infections, evaluating management strategies to implement is imperative to maintaining ecosystem services and reducing the severity of negative pathogen impacts (Figures 2, 3, 4 and Table 1). By identifying the most effective management and removal strategies for *P. ramorum*, the northward spread of it can be slowed, thereby saving forests from tree dieback, preserving local ecosystems, and maintaining their services. This paper also assesses the ethics of mandatory pathogen management across landownerships, and proposes core messages that can be used to complement the goals, values, and normative frameworks of different stakeholders, so that the purpose and benefits of pathogen management are understood.

Background Site Information

Past and Present Land Use

The Lolangkok Sinkyone lived in what is now known as Humboldt County for thousands of years. They primarily resided along the coast, although their range extended to Eel River, which runs through southern Humboldt County and borders Humboldt Redwoods State Park (California State Parks n.d.). It is estimated that there were 15 politically independent Sinkyone villages that were linked through dialects located along the South Fork Eel River, which was home to about 2,000 Sinkyone individuals. While primarily dependent on the tanoak acorn, the tribe along Bull Creek moved seasonally, hunting small game in the mountainsides, and gathering plants in the summer, then moving down the mountain to fish during the rainy season (California Department of Parks and Recreation 2002). Having lived in this area for so long, there is much traditional knowledge, attachment, and appreciation of the land, providing a strong heritage value to this site (Baker 2004).

Unfortunately, little is known about the Lolangkok Sinkyone, for when settlers arrived members of the tribe were displaced and sometimes killed (The Lolangkok Sinkyone n.d.; Bowcutt 2015). However, it is known that redwood was often used to craft canoes, shelters, baskets, and clothing. Bay laurel leaves and the inner bark of tanoak were used for pain relievers, and numerous berries were used as a food source (The Lolangkok Sinkyone n.d.). As described wonderfully in Frederica Bowcutt's (2015) book *The Tanoak Tree: An Environmental History of a Pacific Coast Hardwood*, tanoak, the host species that suffers the greatest mortality rates from *Phytophthora ramorum*, was extensively used by Native American tribes in Humboldt. Tanoak produces nutritious acorns that were a major food source, not just for tribal members but for animals as well. Many tribes had annual ceremonies to celebrate the first acorns, with the Sinkyone's celebration lasting five nights, and entailed dancing and singing around a fire to increase acorn production next year (Nomland 1935). There were many methods of acorn preparation, ranging from pulverizing and leaching, to roasting, pounding into soups, cereals, and patties. Tanoaks are host to many fungi that can be used as a food source and provide ecosystem services such as water filtration. The bark can be used for tanning, and the wood was often used for tool handles, cabinets, and baskets. The tanoak acorns can also be used as a medicine, such as for soothing coughs and treating facial sores (Bowcutt 2015).

Native American tribes in the area, including the Sinkyone, Kurok, Tolowa, and Yurok, frequently used low intensity burns to favor tanoak acorn production. These fires reduced pests and pathogens, the risk of wildfires by reducing fuel loads, and cleared the understory and forest floor. Since tanoak resprouts more rapidly than Douglas-fir and redwood after fire, these fires greatly favored tanoak production over the production of other tree species. The Sinkyone also considered it a sign of good luck to dream of tanoak, white oak, and black oak (Nomland 1935). Thus, there is a clear, strong connection between tanoak and Native American tribes in Humboldt, a relationship that is threatened by the deadly sudden oak death pathogen.

In the 1850's, European settlers arrived. This migration seems to have been initially driven by the gold rush in 1848, but the value of redwoods and Douglas-fir as timber products were quickly realized, leading to extensive logging (Humboldt County Historical Society n.d.). Settlers also cleared the land for agricultural purposes, for sheep and cattle grazing. Pigs were extensively farmed, with a huge pork industry supported by the tanoak acorns which made the pigs plump and fat (Bowcutt 2015). Tanoak bark was discovered as a useful tanning resource due to the high amount of tannins, so tanoak became viewed as fodder for pigs and for tanning leather, not for other subsistence or production purposes. Redwood and Douglas-fir were viewed by loggers as having more value, due to their harder wood and pleasing appearance. Since tanoak was such a vigorous competitor due to rapid resprouting, it quickly became viewed as a weed to loggers (Bowcutt 2015). Within a few decades, as logging and agricultural opportunities increased, more individuals moved to Humboldt, leading to more railways, roads, and cities being built. (California Department of Parks and Recreation 2002; Humboldt Redwoods Interpretive Association n.d.).

As previously mentioned, when settlers arrived, the relationships they had with Native American tribes were strained. The altered landscapes due to logging and agriculture displaced Native Americans, threatening their survival. As described in Bowcutt (2015), there are reports of indigenous members killing settler's livestock to eat, with settler's violently retaliating. This led to reservations being created in the 1850's, but they did not improve the survival of displaced tribal members, often failing to properly feed or cloth them, nor did it ease tensions. In both Humboldt and Mendocino counties, violence against Native Americans from settlers escalated, with over 500 indigenous people estimated to have been killed in the Mendocino Wars (California Senate 1860; Bigelow 1952). However, the exact number of deaths is unknown. It is also unknown how many died from smaller skirmishes and diseases. Then, with the Homestead Act of 1862, Native Americans were further displaced, since many could not make what the United States considered legitimate claims to land ownership (Bowcutt 2015).

Concerned about the rapid destruction of the redwoods for logging and agriculture, in 1907 Albert Etter inspired the Secretary of the Chamber of Commerce to set some land aside to preserve the trees near the town of Eureka, and a park committee was formed. This aim to protect the redwoods from continued anthropogenic damage was reinforced by John C. Merriam, Madison Grant, and Henry Fairfield Osborn when they toured Humboldt County in 1917. Being conservationists, they were appalled by how much of the forest was converted to wastelands and industrial zones (Save the Redwoods League n.d.). These three founded the Save the Redwoods League (S.R.L) in 1918 to protect coastal redwoods and giant sequoia forests, and established Humboldt Redwoods State Park in 1921. In 1919, the Humboldt County Women's Save the Redwoods League was formed and worked with the S.R.L. to pass the Redwood Preservation Bill in 1921. While this bill added more land to Humboldt Redwoods State Park, a major acquisition was made in 1931, when funding was received from the state of California and the Rockefeller family to purchase land from the Pacific Lumber Company (which is now Humboldt Redwood Company), thus expanding the forest by nearly 10,000 acres (Humboldt Redwoods Interpretive Association n.d.).

Currently, there is a mix of public and private land between Redway, Phillipsville, Redcrest, and Honeydew, the cities that surround Humboldt Redwoods State Park (Figure 1) (National Park

Service 2016). Public lands include parks and recreational areas. The Humboldt Redwoods State Park is co-managed by the California National Park Service and California Department of Parks and Recreation. The surrounding cities have private residences, businesses, and public areas. There are a few privately held lands around the park, although most of it is owned by logging companies, primarily Humboldt Redwood Company (California Department of Parks and Recreation 2002). Other land uses include agriculture and cattle grazing, whose interests are represented by the Humboldt County Farm Bureau.

Climate and Climate Change

Southern Humboldt County is in a temperate coastal climate, receiving 65 – 80" of rain per year (Humboldt Redwoods Interpretive Association n.d.). It has average summer temperature highs of approximately 27°C and lows of about 10°C. The winter highs are about 10°C with lows of -1°C (Humboldt Redwoods Interpretive Association n.d.). On a long-time scale, climate is affected by the Pacific Decadal Oscillation. On a short-time scale, it is affected by the El-Niño Southern Oscillation (ENSO). Since increases in *Phytophthora ramorum* infections have been correlated to years with higher rates of precipitation, awareness of cyclic climate changes, particularly from ENSO's warm extended rains, will influence management decisions over time (Davidson et al. 2005; Rizzo et al. 2005, Swiecki and Bernhardt 2014).

According to Moritz et al. (2012), Humboldt County will experience a slight increase in fire activity by 2039 and it is likely to have increased fire activity by 2100. Other studies estimate a 1.8°C – 3.6°C temperature increase by the end of the century as compared to preindustrial temperatures (Table 2) (Burke et al. 2018). This may increase the incidence of large wildfires by 100 – 300% by the end of the century (Westerling et al. 2011). Increased winter rainfall may lead to a higher baseline of flammable fuels in the fire season. Wildfires may also increase the frequency of wildfires by resetting successional stages, causing the land to have more grass and shrub cover (Torn et al. 1998). With urban sprawl creating more urban/wildland interfaces, economic costs of climate change induced wildfires may increase. This anthropogenic development may also further stress coastal redwood ecosystems, reducing resilience to both climate change and sudden oak death (SOD). Shifts in disturbances events, species composition, and species range may influence *P. ramorum* dispersal, survivability, and management practices. Alterations to disturbance regimes may decrease primary productivity, thus reducing many ecosystem services.

How climate change will impact coastal redwood forests and *P. ramorum* is less clear. Since old growth redwood, which is more resilient to stress than younger redwood, is now estimated to be only 4% of its historical range, management to preserve and enhance old growth redwoods may be imperative to preserving ecosystem health, as well increasing resistances to invasive pathogens (Noss 2000). It is estimated that fog has decreased by 30% in the area over the last century, and it is likely to decline further. This will increase drought stress, especially as temperatures rise (Johnstone and Dawson 2010). Although mature redwoods have a long lifespan and may persist even after their climate envelope has changed, it is estimated that their suitable range may contract significantly, leaving only two refuges in 2080. There will be one refuge in northern California and one in southern California, as the range slightly expands southward (Strittholt et al. 2010).

However, redwoods have 66 chromosomes, and can have 1 – 3 alleles coding for particular enzymes, so there is potential that redwood from any location could adapt to new climates (Rogers 1994). Dagley et al. (2017) found that depending on a redwood seedling's forest of origin, its region of origin, and family, its adaptability to different climates varies. This study found that individuals from Humboldt planted in sites that had some summer fog and were at a lower elevation performed well in height, but not as well in caliper and basal increment compared to central California redwoods. In more extreme sites, which had no fog and was at a higher elevation that received snow, the opposite trend occurred. However, different clones performed well at each site, and high variability in growth suggests that microsite and competition could be more influential on redwood growth than climatic factors (Dagley et al. 2017).

How other species in coastal redwoods will adapt to climate change is uncertain, with one study showing that not all trees are following the projected trend of moving northward or upward in elevation (Serra-Diaz et al. 2016). This study found that climate and range are not necessarily coupled for many species, and variation in local regeneration, expansion, and range constriction varied with disturbances (both natural and anthropogenic), land-use history, succession trajectory changes, and biotic interactions. However, the researchers did project that tanoak would expand in climate space faster than its geographic range shrunk. Interestingly, coast live oak and tanoak had distribution shifts in opposite directions. Thus, management of *P. ramorum* with climate change may expand to new areas as coast live oak and tanoak move into new, and opposite ranges, and create novel ecosystems (Serra-Diaz et al. 2016).

Not only are range shifts of susceptible host species a concern when considering SOD management in coastal redwoods, but climate change may also cause range expansion for *P. ramorum* itself. As will be discussed in the following sections, *Phytophthora ramorum* prefers wet and cool conditions, thus if precipitation increases conditions might become more favorable. As winters become milder and night temperatures increase, *P. ramorum* might have increased persistence and an accelerated life cycle, thereby increasing its population density faster (Harvell et al. 2002). Kliejunas (2011) anticipate that if spring rainfall increases, *P. ramorum* abundance will increase in its current range as well as experience range expansion. Depending on how precipitation varies with climate changes, the likelihood and severity of increased damage anticipated from *P. ramorum* varies. In warm, wet conditions, Kliejunas (2011) anticipates the likelihood of increased damage to be very high, whereas in warm, dry conditions the risk potential is moderate. Since chlamydospores (resting spores) may survive more than a month in moist conditions, wet conditions strongly favor *P. ramorum* (Davidson et al. 2002). Kliejunas (2011) estimates that the consequences of increased disease damage are high, but difficult to estimate due to the costs of management, effects on other species, and ecosystem functions.

Extreme weather events may also increase precipitation rates, increasing favorable conditions for *P. ramorum* sporulation (Anderson et al. 2004). Venette (2009) estimated that by 2050, the favorable habitat for *P. ramorum* will increase, reaching all the way to southern California. As summers get hotter and drier, *P. ramorum* summer survival may decrease. If soils become very dry during these summers, *P. ramorum* growth and survival may be strongly limited (Venette and Cohen 2006). Venette (2009) also found that exacerbated drought will not have significant effects on SOD range, since drought will mostly increase in areas where drought is already occurring, and *P. ramorum* is not currently present. Heat stress may negatively impact *P. ramorum* range, but if hosts are also suffering from heat stress, this may make them more susceptible to infection (Venette 2009). SOD could spread more quickly in climate stressed trees. Climate change is also anticipated to increase the severity of storms. This will increase runoff, erosion, and the likelihood of wind driven rain splash, which may increase *P. ramorum* spread (Blom and Teraoka 2014).

Phytophthora ramorum History and Pathology

History and Distribution

Symptoms of *Phytophthora ramorum* infection were first reported in Germany and California in the 1990's. However, it was not identified until the early 2000's (Grünwald et al. 2012; Garbelotto and Davidson 2003). Since then, it has been reported in the Netherlands, the UK, Spain, Poland, France, Sweden, Belgium, Oregon, and Washington state (Rizzo and Garbelotto 2003). It is a major cause of non-anthropogenic tree mortality along the California coast, being epidemic along nearly 300 kilometers of forest. It has killed at least five million trees as of 2014, infected millions of non-oak hosts, caused stem dieback on at least 45.2 million host species stems, and has a high probability of continued spread (Garbelotto and Davidson 2003; Frankel and Palmieri 2014; Rizzo and Garbelotto 2003; Cobb et al. 2020). While genetic analysis suggests an unknown source of origin, it was likely introduced to the United States through infected imported plants, where it escaped nurseries and created wild populations (Mascheretti et al. 2008).

Four clonal lineages have been identified for *P. ramorum*, three of which have been reported in the US. The most common clone in the United States is the NA1, although the NA2 and EU1 clones have also been reported. NA1 likely jumped from infected nursery plants from an unknown source location, and then spread through the help of humans. It is hypothesized that from foliar infection of bay laurel, it moved to oaks and tanoaks, creating the epidemics seen in California (Grünwald et al. 2012). While epidemic in natural environments, it can be found in urban nurseries and gardens (Grünwald et al. 2012). It infects over 100 species across 40 different genera (USDA APHIS 2012). In coastal redwood forests, nearly all woody plants are known to be suitable hosts for *P. ramorum* infection (Garbelotto et al. 2003). However, a few subgenera of oaks, *Lobatae* (red oaks) and *Protobalanus* (intermediate oaks), are unaffected (Rizzo and Garbelotto 2003).

Life Cycle

Phytophthora ramorum is a small fungal-like diploid oomycete, often referred to as a "water mold." It belongs to the Stramenopile group, which is one of eight eukaryotic phylogenies, including brown algae, diatoms, parasitic flagellates, and more (Werres et al. 2001; Baldauf 2003; Massana et al. 2004; Derelle et al. 2016). *Phytophthora ramorum* has both sexual and asexual phases, although sexual structures (oospores) have not been found. It is heterothallic, so oospores only form when the opposite mating types meet. Thus, only asexual reproduction in *P. ramorum* has been observed, which involves sporangia and chlamydospores (Grünwald et al. 2012). Sporangia form on foliage, which release motile zoospores with flagella. When these zoospores contact susceptible host tissue they encyst, germinate, and penetrate the host. More sporangia are produced with motile zoospores, which again move and re-infect host tissue. Asexual reproduction continues like this, proliferating the pathogen when in environmentally favorable conditions, leading to epidemics. Chlamydospores are a "resting" spore that acts as a spore reservoir, and keeps the pathogen protected from unfavorable environmental conditions (Grünwald et al. 2008; 2012; Davidson et al. 2005). Neither sporangia or chlamydospores are produced within infected bark and are only produced on foliage (Davidson et al. 2002). However, both sporangia and chlamydospores accumulate in water and soil, which can infect plants if it encounters suitable material (Davidson and Rizzo 2002; Garbelotto et al. 2003).

The pathogen can be spread through many mechanisms. It is dispersed through water (rain-splash, streams, irrigation), in wind-rain splashes, soil, humans (on hiking books and transported ornamentals), carried on wildlife, and on plant foliage. It has been found that rainwater can carry spores 5 – 10 meters (m) from the source, high winds may splash it 15 m, and it can travel up to 1 kilometer (km) in streams (Davidson et al. 2005). This same study found that 1/3 – 1/2 of hikers tested had infected soil on their hiking boots during the rainy season, potentially providing very long-distance transport. Furthermore, dropping of infected material, whether from dying tanoak and oaks or other plant materials to the forest floor may serve as inoculum reservoirs (Fichtner et al. 2007). SOD may be able to move from infested soil to bay laurel leaf litter, to aerial bay leaf leaves, and from there infect seedlings (Davidson et al. 2005).

Although it is asexual, *P. ramorum* likely descended from a sexual lineage. The levels of recombination and heterozygosity indicate that its ancestors are sexual, and that lineages mutated and evolved separately through asexual reproduction for at least 100,000 years (Ivors 2006). While some species of *Phytophthora* can hybridize, this has yet to be seen in *P. ramorum* (Grünwald et al. 2012). Despite genetic variation being found within and among populations of *P. ramorum* in California, Mascheretti et al. (2008) found that only three genotypes are the founders of the California epidemic, indicating that long-distance dispersal via human transport has played the most significant role in its spread. They propose that new populations are likely created by this medium or long-range dispersal, where individual genotypes develop locally through somatic and accumulated mutations. When environmental conditions are unfavorable, populations decline, and this may be followed by other genotypes recolonizing sites, leading to the extinction of rare genotypes. This decline and recolonization can also lead to the emergence of more fit genotypes, as evidenced by the one population which has survived in the Big Sur Region of California since the mid 2000's (Mascheretti et al. 2008).

Tolerable Environmental Conditions

Phytophthora ramorum can tolerate a wide range of environmental conditions. While it usually is not found more than 30 km inland, it can tolerate soil pH ranges of 5 – 11 (Kong et al. 2012). It can tolerate temperatures from 2.2°C – 30°C, although the optimum temperature range is 18°C – 22°C (Rizzo et al. 2005; DEFRA 2008; Werres et al. 2001). One study found that at 15°C, up to 2,460 spores were produced per leaf disk on bay laurel, but no spores were produced at 30°C (Davidson et al. 2005). Another study found that at 18°C the bay laurel infection rate was 92%, but only 50% at 12°C and 37% at 30°C (Garbelotto et al. 2003).

Zoospores need water to swim, and it takes about 6 – 12 hours of standing water on the leaf to infect bay laurel leaves. The fog, dew, mist, and rain that are common in coastal redwood forests provide a persistent film of water on plant tissue that favors *P. ramorum* growth (Garbelotto et al. 2003). As conditions become drier and warmer, sporulation rates will change. One study did not find *P. ramorum* spores in the soil or litter during the dry summer months (Davidson et al. 2005). However, even in poor rainfall years, 41% of tanoak became infected in a later study (Davidson et al. 2008). It has been found that elevated rainfall increases the rates of infection (Davidson et al. 2005; Rizzo et al. 2005; Swiecki and Bernhardt 2004). Thus, ENSO climate fluctuations will also impact infection rates on a short time scale.

Furthermore, land-use, forest composition, and environmental changes could change the aggressiveness or success of *P. ramorum*, perhaps promoting the fitness of a single genotype (Rizzo and Garbelotto et al. 2003). These impacts may also affect dormancy, as it is currently unknown just how long *P. ramorum* chlamydospores can be dormant in natural conditions. This means that it may have been in California for many years before it was noticed. Higher diversity forests may be more susceptible to *P. ramorum* invasion and disease, perhaps due to having more potential host species to infect (Garbelotto et al. 2003). There are over 1,000 plant species listed in the CalFlora database for coastal redwood forests, with most woody plants suitable host species for this pathogen (National Park Service 2019). This, combined with climate changes, may make the suitability of environmental conditions for *P ramorum* more favorable in the next several decades.

Infection and Symptoms

Phytophthora ramorum is a generalist pathogen, so has no host specificity (Garbelotto et al. 2002). There are two types of infections: branch and stem infections which are lethal, and non-lethal foliar and twig infections (Rizzo and Garbelotto et al. 2003). The non-lethal foliar infections, also referred to as "ramorum blight," is characterized by leaf discoloration, wilting, shoot tip dieback, and spotting. On the California bay laurel, lesions can be identified on the downward point of leaf tips. Bay laurel also often has infections on leaf margins and petioles. These infections spread until they cover the entire leaf or shoot, making bay laurel a good indicator of when *P. ramorum* has infected a stand (Grünwald et al. 2008). *P. ramorum* often forms on the underside of bay laurel leaves, although the reason for this is unclear. It is hypothesized that protection from UV radiation or stomate position may be the explanation (Davidson et al. 2005). While ramorum blight does not cause mortality, branch dieback on non-oak hosts may reduce photosynthesis by reducing photosynthetic area, thereby decreasing growth, regeneration, and making plants more susceptible to infection by other pests/pathogens (Garbelotto et al. 2003). Coastal redwoods also experience ramorum blight, symptoms of which are needle lesions, cankers on small branches, and dieback of epicormic stems (Davidson et al. 2003).

Lethal infections typically cause bleeding cankers and occur in oak and tanoak. In oak, infections only occur on the main stem. However, tanoak can have both lethal bleeding cankers on the main trunk and ramorum blight on foliage, stems, and branches (Rizzo and Garbelotto 2003;

Grünwald et al. 2012). When *P. ramorum* colonizes plant tissue, it kills the phloem, spreads to the cambium and xylem, which expands and causes cankers that girdle trees, effectively reducing sap flow and hydraulic conductivity (Garbelotto et al. 2001; Grünwald et al. 2012). Bleeding cankers darken the outer bark, release red sap, and can be over 2m long within the inner bark (Rizzo et al. 2002). Cankers do not form below the soil line but can form anywhere from the root crown to 20m up on the tree (Rizzo et al. 2002). Species that suffer non-lethal foliar infections are often good sporulators, providing a place for SOD to continue reproducing, whereas oak, which only suffers bleeding cankers and does not support sporulation, is considered a “dead-end” host (Grünwald et al. 2012).

The time from initial infection to death can range from months to years. Mortality rates are greatly increased in infected hosts, especially when cankers are infected by secondary organisms (Rizzo and Garbelotto 2003; McPherson et al 2005; 2010). Secondary organisms that invade cankers include sapwood decaying fungi, ambrosia beetles, and oak bark beetles (Garbelotto et al. 2001). Mortality rates also increase with the size of the tree (Frankel and Palmieri 2014). Trees that are dominant and fast-growing may have a higher risk of being infected, due to more surface area available for spores to land (Swiecki and Bernhardt 2004). Due to their small size, seedlings and saplings of oaks are not as susceptible to infection as large oaks (Frankel and Palmieri 2014).

Extensive cankers that lead to severe trunk girdling can also lead to rapid tree decline. Swiecki and Bernhardt (2004) found that 1/3 of studied trees declined rapidly, dying within two years. However, more than half that were initially infected were asymptomatic by the end of the study period. Small cankers had stopped bleeding, and large ones formed calluses over the canker. Many of these trees were later re-infected, with new cankers forming. While many trees died, and many became re-infected, the ability to become asymptomatic after infection indicates that some trees have natural resistances to infection (Swiecki and Bernhardt 2004).

Primary Inoculum in Coastal Redwood Forests

Davidson et al. (2008) studied inoculum production on bay laurel, tanoak, and redwood, and found that bay laurel leaves (80%) and tanoak twigs (65%) had the highest percent of sporangia and chlamydospores. Redwood twigs and tanoak leaves had very low levels of SOD (only a quarter of tested materials). In a previous study, they found that bay laurel leaves could produce as many as 5,200 spores/leaf (Davidson et al. 2005). Bay laurel also had the highest amount of inoculum found in crown-throughfall rainwater (9 – 20 times the amount of other species), and inoculum production was highest during extended rainy seasons. They found that the number of zoospores bay laurel produced was significantly higher than zoospores produced on tanoak twigs, with a nearly fourfold increase in zoospore production in each infection site. Bay laurel leaves may have more infection sites and tend to be infected earlier than tanoak, leading to a longer sporulation period and an earlier onset of infections. The authors hypothesize that increased sporulation in bay laurel could be due to more propagules, more *P. ramorum* hyphae being able to grow within the leaf, and/or more sporangia production in long, frequent, rainy, and warm months (Davidson et al. 2005). Thus, in redwood forests, bay laurel seems to be the main transmitter of *P. ramorum*.

Impacts on Primary Hosts

Maloney et al. (2005) found that bay laurel leaves and tanoak have the highest levels of infection, although bay laurel does not suffer lethal infections and tanoak does. Tanoak suffers from both foliar infection and bleeding cankers, often leading to quick mortality when infected. High incidence of disease is associated either with bay laurel importance value, bay laurel stand density, and the presence of small tanoaks. There were more bleeding cankers on small tanoak trees than large ones, and small bay laurel leaves had more leaf lesions than larger ones. Bay laurel also had a higher percent of infected leaf and stem tissue than tanoak (Maloney et al. 2005).

Densities of bay laurel stump sprouts, saplings, and trees around stump clumps is significantly correlated to infection rates in treated stands (Valachovic et al. 2017). Swiecki and Bernhardt (2002) suggest that *P. ramorum* only needs bay laurel to establish in a forest, since from there it transmits from the canopy level to the remaining stand. Furthermore, non-lethal infections on non-oak hosts (such as the California bay laurel) may allow *P. ramorum* to persist indefinitely. With high rates of non-lethal infections of *P. ramorum* on bay laurel, it is a remarkably effective host for disease transmission. In a later study, Swiecki and Bernhardt (2004) found that proximity to and density of bay laurel were strong predictors of *P. ramorum* infection. They hypothesize that more bay laurel leads to more inoculum, and that a higher density of bay laurel increases the likelihood that *P. ramorum* will splash onto an oak host. While 1/3 of the plants studied died, more than half become asymptomatic. They also found that trees with "unweathered bark fissures," had higher stem diameters, were dominant in the canopy, and were at greater risk of infection. They hypothesize that fast growing species have expanding bark fissures where infections can easily occur (Swiecki and Bernhardt 2004).

These results are supported by Cobb et al. (2012), who used an epidemiological model to suggest how tanoak mortality influences forest structure. They found that the prevalence of bay laurel was positively correlated with tanoak infections, mortality, and reduced biomass. They found that mortality increased with tree size, and that the understory tanoak are more susceptible to infection than overstory tanoak. This may be due to vigorous tanoak re-sprouting, serving as inoculum reservoirs in the understory. Importantly, this study estimated that when tanoak is the only sporulating species, tanoak survival is greatly increased. When both bay laurel and tanoak are present, tanoak populations are predicted to decline towards extinction. When tanoak are present in low densities and there are no neighboring host species, tanoak is likely to persist. However, the overstory will be greatly diminished or gone within a few decades, having significant ramifications on forest structure by creating canopy gaps (Cobb et al. 2012).

McPherson et al. (2005) found that in coast live oak over a three-year period mortality increased from 5.8 – 17.4%. Tanoak mortality increased from 8.3% – 22.2% and had the greatest increases in infection rates across asymptomatic stands. Bleeding cankers greatly increased the frequency of beetle colonization, and it is suggested that that ethanol emitted from the infected cankers may be attracting them (Kelsey et al. 2013). It is also proposed that larger tree diameters increase the probability of infection due to complex bark structure and more surface area. These results are corroborated by another study by McPherson et al. (2010) where mortality rates increased, and survival times decreased significantly over the study period. Ambrosia beetles attacked most of the coast live oak that died. Again, larger stem diameter was correlated to higher infection rates and bay laurel basal area. However, over time, the plots with little or no bay laurel had infection rates similar to those of high-density plots, indicating that the long-term impacts of bay laurel on sporulation may not be as important as at the beginning of stand infection (McPherson et al. 2010).

McPherson et al. (2010) also found that the average survival time of asymptomatic (not bleeding) coast live oaks was 13.7 years and 8.8 years for tanoaks. However, once showing symptoms of *P. ramorum* (bleeding), their lifespans decreased to 9.7 and 5.8 years, respectively. Secondary infections on bleeding cankers from ambrosia beetles caused mortality to increase more, to lifespans of about 3 and 1.7 years. McPherson et al. (2010) modeled expected survival rates of trees, and found that in initially asymptomatic stands, it takes about 36.5 years for 90% of coast live oak to form infections, and about 15.4 years on average for 90% of tanoak in initially asymptomatic stands to become infected. Since it may take a decade or more for trees to become infected, and mortality rates drastically increase once they do, the need for ongoing monitoring and management is essential to preserving these ecosystems.

Swiecki and Bernhardt (2002) found a mortality rate of 22% for tanoak and 15% for coast live oak. This is double the historic mortality rate of coast live oak and four times the background tanoak mortality rate. While less than 10% of the total tanoak range was estimated to be infected in 2012, a recent study suggests that of 2019 about 38.9 million infected tanoak stems suffered mortality since the outbreak began, which is about 2.2% of the entire tanoak population (Meentemeyer et al. 2012; Cobb et al. 2020). Infections are expected to continue rising, and the high rates of mortality indicate millions more tanoak may die (Meentemeyer et al. 2012).

Brown and Allen-Diaz (2009) found that due to *P. ramorum* infection, coast live oaks had a tenfold increase in mortality rates between 1994 – 2004. This study predicted that by 2014, coast live oak basal area would decrease 59 – 70% in the most infected sites and total stand basal area of coast live oak would decrease from 60 to 40%. Bay laurel would move into this space, with bay laurel basal area increasing from 22% to 37%, causing significant changes to forest composition, structure, and enabling more SOD sporulation. At the end of their study period, about 50% of coast live oak basal area was lost in infected sites, indicating that these changes are already occurring, and quickly (Brown and Allen-Diaz 2009).

While there is not yet evidence that *P. ramorum* causes mortality in redwoods, they are symptomatic when infected. Symptoms are typically on saplings, which exhibit needle discoloration and cankers on small branches, and on basal sprouts, which develop purple lesions.

While extensive discoloration of the xylem in tree stumps have been observed, and shoot death noted on sprouts, mortality may be from other diseases or stresses (Garbelotto et al. 2003). Even if redwood does not experience mortality, it may experience reduced vigor due to the loss of photosynthetic tissue and leaf abscission (Rizzo and Garbelotto 2003). Waring and Hara (2008) found that in response to tanoak mortality, redwoods had expanded crowns, higher basal sprouting, and higher basal growth area. Tanoak mortality induced by *P. ramorum* greatly exceeded background mortality levels, with tanoak basal area and the number of trees per hectare decreasing by 40 – 50%. They found that tanoak of all ages and size classes were affected. Redwood stands may be less impacted than Douglas-fir stands, with one study showing tanoak and oak mortality were lower in redwood forests (3.2 – 8.2%) than Douglas-fir stands (10.1 – 26.2%) (Ramage et al. 2012).

However, even in hosts that do not suffer mortality, negative physiological impacts may occur. Davidson et al. (2011) found that *P. ramorum* infection can accelerate leaf senescence by three to four years, which may have negative impacts on photosynthesis and growth rates. However, reduced photosynthesis does not seem to occur in bay laurel, despite decreased photosynthetic area (DiLeo et al. 2009).

While less studied, *P. ramorum* may be able to kill mature madrone, and mortality rates from madrone may be underestimated (Rizzo and Garbelotto 2003; Maloney et al. 2005). Brown and Allen-Diaz (2009) found that the mortality of pacific madrone was significant from 1994 – 2004 but was not expected to be significant from 2004 – 2014. This could be due to a reduction in pacific madrone populations, meaning that these hosts have already decreased enough that further infections would not be significant.

Status in Southern Humboldt County

The first reports of *Phytophthora ramorum* infection in Humboldt County and in coastal redwoods were in 2002 (Filipe et al. 2009; Maloney et al. 2002). Since it was first found in Redway, California, it has dispersed to other areas in Humboldt County. Confirmed reports of *P. ramorum* infection in California (as of 2006) can be seen in Figure 2 (obtained from Frankel 2008). In 2010, a new infestation was found in northern Humboldt in Redwood Valley, nearly 80 km north of previously known infections, becoming the northernmost known infection in Humboldt (Valachovic et al. 2012). It is expected that *P. ramorum* will move northward due to prevailing winds, and without landscape interventions the spread will be rapid in the medium and long-term, moving at a rate of 7 – 8 km/year, and increased by ENSO (Filipe et al. 2009; Filipe et al. 2012). Meentemeyer et al. (2004) modeled the potential establishment and risk of spread of *P. ramorum* in California, and found that Humboldt County has the most area in the state that is at very high risk, high risk, and moderate risk of infections, due to having a high amount of suitable hosts in a very favorable climate.

Social, Cultural, Economic, and Ecological Aspects of Study Site and the Impacts of *Phytophthora ramorum* Infection

Social and Cultural Aspects of Site and SOD Infection Impacts

Southern Humboldt County has many important social and cultural values. Humboldt Redwoods State Park is used for recreational purposes such as hiking, fishing, bicycling, boating, and camping. Ecotourism is important for both social and economic aspects of this site. Furthermore, many researchers study coastal redwood ecosystems, populations, and species. Local schools may take field trips for both informational and recreational purposes, thus these forests have important educational value.

In the late 1800’s and early 1900’s, as urban areas developed, migration to Humboldt County increased. More cities and communities were based around the services of this land. While much of it was used for timber and agriculture, the formation of Humboldt Redwoods State Park indicates that the site also had strong recreational and aesthetic value. The population continued to increase, increasing the number of people who valued the land for various purposes, supporting the creation of other landmarks, historical sites, and nature reserves (Humboldt Redwoods Interpretive Association n.d.). The rise of environmentalism in the 1960’s and 1970’s heightened the cultural value of preserving coastal redwood forests (Baker 2004). As discussed previously, Sinkyone knowledge, traditions, and long-term presence on this land provides strong cultural and heritage value.

Currently, the park is working on improving its relationship with locals and nearby communities. They created avenues for visitor surveys and opened the management plan up for public comment in 2002. Comments from the public included appreciating aesthetic value, wanting more informational signs, and wanting to have clearly defined park boundaries. Many of the public comments on the plan regarded concerns about preserving wildlife. Primary issues were determined to be improvements to the trail system, management of agricultural lands that were being purchased by the park, and the future of two groves, the Whittemore and Holbrook groves (California Department of Parks and Recreation 2002). Humboldt Redwoods State Park is improving its social capital by having methods for visitors and locals to share their needs and should keep avenues of communication open.

However, increased tanoak and oak mortality due to *P. ramorum* infection, as well as increased foliar infections on other hosts, will reduce recreational and aesthetic opportunities. While research and educational opportunities on coastal redwood forests in their current state may be reduced, as well as the opportunities to study oak and tanoak, other research opportunities may arise. For example, there may be opportunities for researchers to study how these ecosystems and species therein respond to population changes, disturbance regimes, and different environmental conditions. Since nonlethal foliar infections cause leaf abscission and discoloring, the aesthetic value of these forests may be especially impacted. If management actions are not taken and *P. ramorum* spreads, historic sites and other nature reserves may be threatened.

Economic Aspects of Site and SOD Infection Impacts

Ecotourism, camping fees, marijuana farming, park employment, logging, sawmills, and cattle ranching are the major supporters of Humboldt County's economy. Interest in living in this region has been increasing, thus there has been an increase in rural residential land purchases (Stewart 2007). According the Humboldt Redwoods State Park General Plan (2002), locals were concerned that park growth would negatively impact communities due to a reduced tax base, loss of economic opportunities for expanding towns due to park expansion, and the loss of agricultural land. Local merchants requested that there be more communication between the park and businesses so that local economies are not negatively affected by park changes.

Decreased social/cultural values, such as poorer aesthetics, reduced recreational opportunities, and a loss of ecosystem services, will reduce tourism to the park, negatively impacting the local economy. If timber companies decline due to *P. ramorum* infections, the local economy may suffer, since recreation and tourism are unlikely to fully support local economics. The combination of reduced tourism and logging may severely impact the income of individuals and local economic stability. In addition, funding will be needed to manage a *Phytophthora ramorum* outbreak, which may be more costly than preventing it. Kovacs et al. (2010) estimate that the discounted cost of oak treatment, removal, and replacement in northwest California could cost $7.5 million U.S. dollars, and the discounted property loses could total $135 million. In Humboldt alone, Kovacs et al. (2011) estimated that the county may need to spend between $143,900 – $626,000 to treat and remove between 878 – 2,018 infected oaks, with property losses totaling between $265,000 – $5,509,000. The costs of decreased ecosystem services and loss of tourism is unknown but may be substantial. This study only included the costs of oak management, so the costs of managing tanoak, bay laurel, and other susceptible or priority species increases this funding demand even further.

The damages thus far for the United States are estimated to be tens of millions of dollars. This is due to the mortality and destruction of ornamental and nursery plants, the loss of property values due to tree mortality, the costs of management, eradication, and monitoring, reductions in cultural values, loss of food for local fauna, and research investments (Cave et al. 2005; Dart and Chastagner 2007; Frankel 2008; Kovacs et al. 2011). These costs are likely to accrue if *P. ramorum* proliferates in the region. As species composition and climate changes, disturbance regimes (especially wildfires and landslides) may become more frequent and severe. Additional funding to manage, mitigate, and repair damages from these disturbances may also be necessary.

Ecosystem Services of Site

Coastal redwood forests have a limited range, residing on a narrow band of land that stretches from Southwest Oregon to Monterey County, California (Noss 1999). Despite the narrow range, they provide many regulating, supporting, provisioning, and cultural ecosystem services to dozens of counties. Some of the regulating services include enhancing water quality and quantity, improving air quality, regulating local climate, controlling soil erosion, mitigating extreme events and disturbances, and sequestering carbon in soils and biomass (Perry et al. 2008; Hassen et al. 2005). Supporting ecosystem services include soil formation, soil stabilization, nutrient and biogeochemical cycling, habitat provisioning, and biomass production. However, it has been noted that soil compaction has been increasing in the Humboldt Redwoods State Park due to high visitation, which may have negative impacts on plant roots, water holding capacity, soil erosion, and runoff (California Department of Parks and Recreation 2002).

Provisioning ecosystem services include the production of water, food, and timber. Eel River runs through five counties and is also used as a water source for counties it does not run through (mainly Sonoma County) (Wild and Scenic River Systems n.d.). While hunting is not allowed, fishing is. Many berries, nuts, and fungi are produced. Tanoak, the species that experiences the most mortality from SOD, is a major source of nuts for many animals. As described previously, there are many social and cultural ecosystem services including historic and aesthetic values, as well as recreational activities including camping, hiking, and fishing.

Ecological Impacts of SOD Infection

According to Noss (1999), the loss of tanoak in coastal forests threatens the habitat of 200 vertebrate species, 350 vascular plants, 300 macrofungi, and 90 lichen species. Thus, *Phytophthora ramorum* may have severe short- and long-term changes for species composition and ecosystem health (Grünwald et al. 2012). Increased tanoak mortality due to pathogen infection may decrease habitat available to other flora and fauna, depending on how trees regenerate. Less tanoak will reduce the number of nuts available that many species depend on for sustenance. Important species to ecosystem stability, particularly ground squirrels, black tailed deer, black bears, and various bird species may lose an important food source, potentially creating negative trophic cascades.

If tanoak can regrow, ecological impacts may be minimal. However, redwood and other species may replace them (Ramage et al. 2011; Brown and Allen-Diaz 2008). Ramage et al. (2010) found that in diseased stands redwood and neighbors to dead tanoak may have increased average diameter, height, and crown length. Infected stands had less stems and total basal area, having a thinning effect that may cause long lasting forest structure and composition changes. A homogenizing landscape and the loss of a major food source (nuts from tanoak) may shift species composition. Altered species composition from *P. ramorum* infections may change litter chemistry and mass, and increase soil NO_3 – N availability, further altering ecosystem function, biodiversity, and ecosystem services (Cobb et al. 2013). Furthermore, coarse woody debris (CWD) is often higher in stands infected with *P. ramorum* than in uninfected ones, which also impacts carbon and nutrient cycling, and fuel accumulation (Cobb et al. 2012).

Tanoak mortality due to *P. ramorum* infection will cause gaps in forests, but how the gaps will be filled are unknown. Areas of infection tend to be patchy, with plots with a high incidence of disease close to those with little or no disease (Maloney et al. 2005). How, or what, species will fill in those gaps is not entirely clear. Tanoak may regenerate, but susceptibility to *P. ramorum* may prevent it from filling in those gaps. Non-oak hosts might fill in those gaps, with potentially negative consequences. For example, if tanoak is replaced by species that serve as inoculum without suffering mortality, such as the California bay laurel, *P. ramorum* could proliferate. Epidemics are likely driven by the presence of non-oak hosts, since sporangia are produced on foliage and the host does not die. *P. ramorum* may need these foliar sites to produce inoculum and then jump to oak species. Since so many plants are suitable hosts for *P. ramorum*, no matter what plants fill the gaps, disease incidence is likely going to continue to increase, increasing the rate at which communities change (Maloney et al. 2005).

In the study by Waring and Hara (2008), where tanoak mortality increased redwood growth, gaps and spatial patterns changed in different directions. Redwood had increased basal sprouting, creating a young cohort, but their growth was limited by proximity to other redwood clumps and competing neighbors. The authors state that the middle stratum and understory benefits from tanoak mortality depend on spatial positioning in the stand and the ability to obtain resources, whereas upper stratum redwood trees had expanded crowns, and either higher or sustained diameter growth. Redwood may have been farther away from dead tanoak than surviving tanoak, which may have been in competition, with dead tanoak releasing nutrients for surviving tanoak to utilize. However, the close proximity of tanoaks may lead to few survivors in the case of an epidemic. The authors suggest that redwood dominance is likely in the case of tanoak dieback, with three layers of redwood cohorts (upper, middle, and sprouts) and some remnant tanoak in the understory. They posit that if redwoods do not fill the gap, thereby leaving space for other species to colonize, the impacts will be positive or negative, depending on what species utilizes the establishment opportunity. Dominance of redwood may be desirable for those who log it, but dominance of redwoods and reduced tanoak will have severe ecological impacts in wild settings due to the loss of food for many animals (Waring and Hara 2008).

Phytophthora ramorum can also infect rhododendron roots, where it then colonizes the vascular tissue and spreads to the stem (Parke and Lewis 2007). While root infection has not been reported in other species, this indicates potential disruption to the belowground community. Furthermore, tanoaks are one of the few tree species in redwood forests that have ectomycorrhizal associations. While it is unclear exactly how the reduction of these ectomycorrhizal relationships will impact entire coastal redwood ecosystems, it may cause significant impacts, especially on microbial and soil communities (Rizzo and Garbelotto 2003).

Tanoak mortality may also shift fire regimes of coastal redwood forests. Dead biomass and increased litter fall may increase the amount of flammable fuels, increasing the likelihood of fire ignition. According to Forrestel et al. (2015) increased fuel loads, especially of fine litter, may lead to longer flame lengths, higher rates of spread, and more intense surface fires in diseased stands. These aspects may also increase due to increased fuel loading and decreased foliar moisture content in infected *P. ramorum* stands (Valachovic et al. 2011; Kulijan and Varner 2010). Kulijan and Varner (2010) found that these conditions increase the likelihood of a fire transitioning from the surface to crowns. Fires may become much harder to suppress in these conditions, as well as negatively affect seedling recruitment, regenerating species, canopy mortality, erosion, and soil biological, chemical, and physical properties (Forrestel et al. 2015).

While fires might be able to control SOD by eliminating contaminated materials on the forest floor, creating drier and warmer conditions, and reducing stand density, the impacts of wildfires on *P. ramorum* are not entirely known. However, there are studies that show that fires combined with other disturbances can increase host species mortality. One study found that the presence of SOD and fire may increase tanoak mortality by increasing secondary infection rates from ambrosia beetles (Beh et al. 2014). Metz et al. (2013) found that redwood mortality increased fourfold when both disturbances occurred. Crown scorch was the primary factor in elevated redwood mortality and is also challenging to control. While redwood is normally fire resistant due to its thick bark, and does not suffer mortality from *P. ramorum* infection, the combination of both disturbances may overwhelm its resistance to stresses. Thus, while *P. ramorum* appears not to kill redwoods, the combination of indirect effects is a great threat to this species. Coastal redwood ecosystems have evolved with low to moderate fires, so increased fires could significantly affect species composition, soil communities, soil structure, and wildlife. If other trees do not replace tanoak when they die, and gaps are created, another consequence could be reduced soil stabilization, which may increase the frequency of landslides. Increased soil erosion and increased runoff may not only destabilize forest systems, it may make transport for the pathogen easier as it spreads through water movement downslope.

There is some uncertainty in how fires will change, since it does depend on which species replaces dead tanoak. One study found that in ecosystems where redwood replaces tanoak, changes to fire regimes may be insignificant, but if Douglas-fir replaces tanoak, fires in the short and mid-term may be exacerbated, and reduced in the long-term (Varner et al. 2017). Temporal patchiness due to differences in disease stages may increase mortality due to more aerial and surface fuels. In intermediate and late stages, the fire line will intensify, but in late stages crown scorch and fire severity will be reduced due to reduced wood quality (Metz et al. 2013).

As mentioned previously, Native American tribes in Humboldt County often used frequent, low-intensity fires to favor tanoak production (Bowcutt 2015). However, this has other positive effects on ecosystems including provisions for animals (such as grasses for deer), controlling other pests and pathogen, and reducing fuel loads, thus reducing the risk of severe wildfires (Stewart 2002). Traditional ecological knowledge (TEK) in the form of indigenous fire stewardship (IFS), may be useful to implement for managing potential changes in fire and pest/pathogen behavior as disturbance regimes shift in response to climate change. The uses and strategies of IFS are diverse, but involve knowledge of vegetation, phenology, seasonality, long-term climate cycles, ignition sources, and fire behavior (Lake 2019; Huffman 2013). A thorough understanding of historical and present disturbance regimes and vegetation is critical to managing disturbances, thus incorporating IFS into management plans of these forests may be an important way to manage disturbances, promote certain habitats and species, as well as integrate culturally significant traditions and knowledge (Lake 2019).

Current Monitoring and Management Strategies

Detection Methods

Several methods of detecting *Phytophthora ramorum* in the field exist, ranging from targeted ground surveys, aerial surveys, stream baiting, filtration, and lateral flow devices (LFDs). There is an ELISA test that can be used to confirm that the genus *Phytophthora* is present on plant tissue, but it cannot confirm if it is *P. ramorum*. Thus, once a suspected infection is found, a sample of infected tissue is retrieved and taken to a lab to confirm identification of *P. ramorum* using real-time PCR (polymerase chain reaction). Targeted ground surveys involve a crew of individuals going to a section of forest and assessing plants for symptoms of SOD. While this can identify sources of inoculum, due to cryptic infections sometimes disease will be missed (Sutton et al. 2009). Stream baiting can help identify locations to conduct ground surveys by placing leaf material, usually damaged, into mesh bags and floating them in water downstream from known infection sites. When leaves are infected, crews can search nearby areas for possible infections. Stream baiting is a useful technique, being able to find the pathogen 25 km downstream from known infections (Murphy et al. 2007). It is an especially important tool, because when water levels are high, the pathogen may be able to move back onto land (Murphy et al. 2007). However, it may be difficult to identify the source of inoculum.

Aerial surveys using GIS, LIDAR, and other methods of aerial photography are useful for identifying patches of infection by locating dead trees but have the drawback of not being able to detect infections early. It usually takes several years for a tree to die from SOD, so once detected aerially *P. ramorum* is likely already well-established in a stand. Thus, using a combination of fast, on-site detection methods, primarily stream baiting, is key to finding, locating, and controlling *P. ramorum* (Valachovic et al. 2008).

Oregon has used stream baiting extensively as part of its *P. ramorum* control plan. One study found high seasonal variation, with larger amounts of inoculum recovered in summer, especially in streams with low inoculum densities (Sutton et al. 2009). This same study located *P. ramorum* 1 km downstream from known infection sources, found that it persisted in soil, and that it was in draining sites where eradication treatments had been done previously. This study determined that stream baiting was useful for expanding quarantine areas when targeted ground surveys could not identify the infection source. PCR was used to assess results and it was found that PCR reliably detected *P. ramorum* from stream baits (Sutton et al. 2009). Thus, stream baiting is a good initial method for monitoring both potentially new infection sites as well as previous ones. While filtration has been shown to be more effective than baiting, and provides quantitative data, when the question is if the pathogen is present or not, simply baiting may be a reasonable option (Hwang et al. 2008). If one wants to know how abundant the *P. ramorum* population may be, then filtration is an appropriate method to pair with baiting.

After a potential infection site is found, verification of the presence/absence of the pathogen is needed. Due to the potential for cryptic infections, ground surveys alone are not an effective method. There have been a few PCR methods developed for the field, but these are often costly, time-consuming, and are susceptible to contamination. In the laboratory, traditional PCR can take 6 – 9 days to get a result, due to the time it takes to isolate and culture (Hughes et al. 2006). Several studies have shown the higher efficiency in time, money, and results, of using lateral flow devices (LFDs) (Lane et al. 2007; Tomlinson et al. 2010). LFDs are fast and easy to use, the most common type being the at-home pregnancy test. It requires pipetting of a sample onto the device, which has a control line and a test line that reveals if the test is positive or negative. LFDs can be taken into the field and provide results in 3 – 5 minutes (Lane et al. 2007). These studies have found specificity and sensitivity to be above 90%, with increased wounding of plants and tests being conducted by experienced individuals improving accuracy (Tomlinson et al. 2010; Lane et al. 2007). Although there were a few false positives and false negatives, lab testing can be used for validation. Not only are LFDs quick, cheap, and reliable, they can be a useful tool for helping individuals learn how to identify trees infected with *P. ramorum*. Another benefit is that membranes of LFDs can be directly added to a TaqMan real-time PCR in the field, reducing the potential for cross contamination. This also reduces the time it takes to prepare more samples, thus decreasing falsities and increasing efficiency in time, money, and accuracy (Tomlinson et al. 2010).

Primary Management Strategies

Current *Phytophthora ramorum* management focuses on three strategies: physical removal of hosts, chemical treatments, and quarantine. Host removal strategies include clearcutting, thinning, and sometimes burning. If the infection is caught quickly in tanoak, then the infected individuals can be cut, removed, and replaced with non-host species (Valachovic et al. 2006). If clear-cutting tanoak or oak is not an option, then removing nearby inoculum such as the California bay laurel is a good secondary choice (Valachovic et al. 2008). One can selectively thin an area, which increases the distance between suitable host species and reduces infection spread rate. In areas where removal of oak and tanoak cannot occur, thinning of only bay laurel branches may be a reasonable alternative (Rizzo et al. 2005).

Quarantine is a management strategy with mixed results, depending on the severity and extent of infection, and the resources available to maintain a quarantine. Some have proposed that creating a natural barrier through planting non-susceptible hosts may control *P. ramorum* spread. However, this method has only been shown to slow the spread, not completely prevent it (Filipe et al. 2012). Quarantines are also imposed through restricting the transport and trade of infected ornamental plants, many of which serve as inoculum for *P. ramorum* (Rizzo et al. 2005). However, Humboldt is already in a quarantine zone, which extends from Humboldt to Monterey county. This allows infected materials to move between counties because it is still within the quarantine zone. Thus, quarantine may help prevent materials from moving out of the quarantine zone, but it does not prevent infected materials from moving in.

Chemical treatments in the form of herbicides and fungicides are the cheapest products to buy for managing *P. ramorum*, and are the easiest strategies to implement, compared to hiring crews to cut and replace trees. However, chemical treatments are the most controversial management strategy. There is variation in opinion and legality regarding chemical applications (with herbicide applications being illegal in California state parks) and may also complicate determining infection extent. There are two methods of chemical treatments, which are direct injection of AGRI-FOS (a phosphonate) into the tree and spraying it onto the surface (Kanaskie et al. 2005; 2011). Both methods have been found to temporarily increase the resistance to infections and reduce lesion severity once the tree is infected (Garbelotto et al. 2009).

Garbelotto et al. (2009) found that phosphonates, which are considered environmentally friendly fungicides, and are legal in California, both slow the spread of infection and infection growth rates for at least 18 months. The phosphonate works by upregulating the production of secondary metabolites in the tree that help it fight infections, and it also thickens the protective cell layer (Garbelotto et al. 2009; Lee et al. 2010). Topical treatments require mixing with bark surfactants to increase the adhesion of the fungicide to the tree and increase absorption through the bark, a strategy that is faster and cheaper but less effective than injections. It has been found that the efficiency of absorption can be increased by applying it on warm and sunny days (Garbelotto et al. 2009). In contrast, injections are typically more effective but require drilling holes into the tree bark and may fail. Garbelotto et al. (2009) recommend treating trees twice in the first year, six months apart, then once in the year every fall. Phosphonates are most effective before a tree is infected, so chemical treatments are a good tool for protecting susceptible or high value trees, but not for treating invaded stands. Garbelotto et al. (2009) recommend that when an infection is found, tanoaks 100 – 200m away from the invaded stand be treated.

While a potentially useful pre-infection management tool, fungicides can mask the symptoms of *P. ramorum*, leading to cryptic infections that lead to higher rates of disease than estimated (Grünwald et al. 2012). Herbicides and girdling may be good treatments in areas where rapid treatment is not necessary and where the pathogen is not present. As mentioned previously, chemical treatments are better protections than cures, so in small areas where the expectation for control is high, entire removal of hosts might be the best strategy (Valachovic et al. 2008).

Most treatments (particularly thinning) seem to have short-term effects, with many re-sprouting individuals becoming re-infected (Valachovic et al. 2017). Using herbicides on cut live trees may reduce resprouting, as will killing the tree with herbicides before cutting and burning it.

Broadcast burning may be good for removing small diameter trees, eliminating litter, and reducing the risk of surface fires (Valachovic et al. 2008). But this strategy, as with all physical and chemical treatments, will need to be done continuously, or in conjunction with other techniques due to the rapid regeneration of tanoak, bay laurel, and *P. ramorum*. One study found that while thinned areas had lower infection rates, bay laurel and tanoak stump sprouts that regenerated had high rates of *P. ramorum* re-infection (Valachovic et al. 2017). This same study found that in unburned but thinned areas, gaps were filled by resprouting tanoak and/or bay laurel, meaning that *P. ramorum* regeneration in treated forests is likely. In sites that were both burned and thinned, Douglas-fir mortality increased, meaning that synergistic effects of treatments could have ecological costs better to avoid (Valachovic et al. 2017). It is possible that unknown, synergistic effects of treatments could occur in redwood trees, and this should be studied to prevent negative impacts of management.

In another study, Valachovic et al. (2012) found that three years after cutting hosts in infected stands, there were few signs of re-infection. Young sprouts were less likely to be infected than old ones and cut bay laurel were less likely to be infected than untreated, older sprouts. Infections on cut and uncut tanoak across sites were variable, with both cut and uncut infection rates low at one site but high at another. The authors hypothesize that young stumps may be more resistant, or climatic factors did not favor sporulation during the study (Valachovic et al. 2012). Bay laurel sprouts may need regular herbicide applications, but perhaps not immediately. Thus, re-application of treatments may need to be conducted every two to three years.

Other complications with treatments are described by Valachovic et al. (2012). If bay laurel is scattered in a stand, they may be missed, and become infected. Pathogen reestablishment can occur due to incomplete treatments and the presence of nearby untreated stands. Herbicides may be too expensive for small and medium individual properties, whereas other treatments may not fit the management goal of the landowner. Bay laurel that was not cut within 50m of an individual increased the likelihood of it being infected by 20%. In untreated plots, tanoak mortality was 20 – 24%. While treatments did not fully control the pathogen, with the pathogen establishing in areas thought to be uninfected, the likelihood of infection decreased by about 55%. Bay laurel is the most important host for *P. ramorum* spread and establishment, but tanoak also needs to be removed to reduce mortality and spread in the understory. While the authors recommend treatments extend more than 100m from the nearest infected tree, the effective buffer size is still unknown (Valachovic et al. 2012).

As noted previously, besides the potential ecological consequences of hasty management (and/or a lack of monitoring), deciding what management decisions to make has economic considerations. Kovacs et al. (2011) found that in urban areas it is usually cheapest (besides doing nothing) to remove small oaks and replace them with non-susceptible tree species. If oaks are large, it is cheapest to treat them with fungicides and trim nearby bay laurel. However, homeowners often must pay more for treatment or removal/replacement compared to other landowners, which disincentivizes civilian action. Most of the forested land in California where susceptible host species predominate occurs on private land, making economic incentives for private landowners a significant consideration for effectively combating *P. ramorum* (Barrett et al. 2006). It is critical to work with landowners and managers individually and give various options for management since people have different opinions regarding herbicides and other treatment methods. Furthermore, high human activity increases *P. ramorum* spread, so crews will need to consider sanitation measures when removing trees to ensure that they do not transport *P. ramorum* (Valachovic et al. 2008). This is an important consideration on both private and public lands where management is being conducted. Currently, Humboldt Redwoods State Park has no written section on SOD management within the park, although the plan has opportunities to incorporate SOD management with other park goals, as will be discussed in a later section.

Another potentially useful tool for management is OakMapper, an online tool developed by the California Oak Mortality Task Force (COMTF) (Kelly and Tuxon 2003). Since this tool involves the community, it increases public awareness of the pathogen, the local environment, and environmental management, all while complementing research. The authors suggest it may also encourage the public to participate in decision making. Once a report is submitted, the tree is tested for confirmation. The webGIS platform presents the information, analyzes it, and can display the information on local and regional scales. This helps individuals visualize locations of infection and spread and may help researchers develop hypotheses. Oakmapper has an online form people use to submit reports and symptoms but can also be done by phone or fax. At the time the paper was written, the public usually reported the correct tree but not the correct symptoms, indicating more education is needed on symptoms of SOD infection. Also, there were concerns about internet access creating privacy issues and excluding some groups, but these concerns may be lessened seventeen years later, since internet access is now widespread (Kelly and Tuxon 2003). There is also a phone app, called SODMAP mobile, that users can download on their mobile phones to visualize SOD infections.

Effective *P. ramorum* management may need to incorporate a mix of thinning, prescribed burns, AGRI-FOS treatments, replacement with non-host species, and quarantining infected areas. However, the best management will involve intensive monitoring and early detection, for once the pathogen is widespread, total eradication is unlikely. Filipe et al. (2012) estimate that full containment is improbable in Humboldt County, but that it can be locally reduced and controlled.

A host free barrier is not strong enough to prevent movement due to long distance dispersal, but a 10km wide host free zone does delay progression. Sustained removal on a scale larger than the infected area, increasing the control area, monitoring, and treatment can delay movement. Protecting trees through chemical treatments or preemptive culling, spraying ahead of the origin, and removing infected tissues at the origin, slows the speed and invasion rate of SOD. Early treatments when the infected area small is the most cost-effective strategy, since large areas can reduce and contain the pathogen but not eradicate it. While removal of inoculum on a large scale is unlikely to completely prevent the pathogen from spreading, it could significantly delay it (Filipe et al. 2012).

A Case Study: Redwood Valley

With the various strategies required for effective *Phytophthora ramorum* management, it is evident that education, collaboration, and adequate funding are critical aspects for management success. A case study that shows the potential power of expanded efforts in combating SOD infections is that of Redwood Valley in Humboldt County. The infection in Redwood Valley was found though stream baiting, sampling, and cooperation of landowners, thereby forming an "aggressive early detection strategy" (Valachovic et al 2012; 2008). A plethora of agencies became involved in management, including the United States Forest Service (USFS), National Resource Conservation Service (NRCS), CAL-FIRE, private landowners, Redwood State Park, the Bureau of Land Management (BLM), UC Davis, and the University of California Cooperative Extension (UCCE) (Valachovic et al. 2012).

This effort included expanded stream monitoring, and more aerial and ground surveys. All tanoak and bay laurel were removed within 100m of the infection, then were either lopped and scattered on site, piled and burned, or donated to a local power company. A private timber company used herbicides on their bay laurel and tanoak within 100m of the infection. Both imazapyr and glyphosate were used as post-treatments on stumps. The NRCS created a new sanitation protocol for dealing with SOD, and the board of forestry adopted a new emergency notice for SOD outbreaks to help control the pathogen's spread and help landowners offset the costs of management. While a great undertaking by many groups, unfortunately, the 100m buffer was not sufficient to contain the pathogen, and a suitable buffer size is still unknown. There were a few private landowners unwilling to cooperate, which prevents effective management. This effort was suitable to slow the spread and emphasizes that with various groups working together many trees can be protected. Valachovic et al. (2012) suggest that seasonal technicians, consistent crews, outreach to landowners, education efforts, and readily available funds will help there be appropriate, rapid, and more effective responses to SOD.

Conclusion

It is clear that collaboration and monitoring can have a significant impact in slowing the spread of *Phytophthora ramorum*, but efforts to expand monitoring, management, education, and funding must continue for management to be effective. There has been discussion for decades about how to monitor and manage the pathogen on different trees, scales, and ecosystems. There seems to be consensus in the scientific community about what is needed, and what is reasonable. Besides financial limitations and a defeatist attitude where it seemed that the infection was too widespread to manage it in California, it must be asked: what barriers exist that after decades of research and discussion there remain almost no policies in California to manage SOD? In the following sections, I argue that due to the high risk and high damage of SOD, mandatory management is ethical. Policies that incentivize dealing with the pathogen, and disincentivize apathy, should be created, and monitoring and management efforts expanded. I propose an agency should be created that has stewardship of the pathogen. I use an ethical framework to discuss under what conditions mandatory management is acceptable and how one can use the ethical driver of different landowners to discuss the importance, and responsibility, of managing *P. ramorum.* I then propose management considerations for southern Humboldt County, including incorporation of traditional ecological knowledge, expanding monitoring programs, and improvements to the management plan of Humboldt Redwoods State Park.

The Ethics of Sudden Oak Death Management

Before one discusses the management actions that should be undertaken, it needs to be discussed if mandatory management is ethical. Here, I argue that enforced management of sudden oak death is ethical under most circumstances. There are several arguments that can be used to conclude this, including both anthropocentric and nonanthropocentric viewpoints. First, I will discuss the many anthropocentric arguments that support mandatory management of *Phytophthora ramorum*, and then I will discuss nonanthropocentric arguments. I will conclude this section with a discussion on the core messages that can be used to talk about management with diverse stakeholders based on their presumed values and normative frameworks.

The Ethics of Mandatory Management: Anthropocentric Arguments

The first anthropocentric argument that can be used to support mandatory management concerns individual rights to goods, which includes ecosystem services such as clean air, clean water, recreation, and provisions, all of which have been previously discussed as being negatively affected by forests invaded by *P. ramorum*. Blackstone (1974) argues that each person has a right to a livable environment by "…being human and because a livable environment is essential to fulfill his human capacities…" If sudden oak death is allowed to perpetuate and propagate where people live and recreate, and the ecosystem services that humans are dependent on for subsistence, financial support, recreation, and clean goods degrade, then the environment becomes less livable. There is justifiable reason, then, to manage *P. ramorum* to maintain a livable environment for all people affected. Since some ecosystem services that forests provide have impacts on scales larger than just the local level, such as influences on the hydrologic cycle and climate regulation, making management mandatory on the regional level is also justified.

It is not only important to manage this pathogen to create a livable environment, or to "fulfill our human capacities" as Blackstone (1974) argued, but also to gain a sense of fulfillment. This is described by deep ecology, which focuses on the relationships between humans and nature. It describes life as interdependent and supports the idea that all life is united to the process of life through common goals. It does not consider humans superior to other species and it is intended to help people develop a more harmonious relationship with nature (Glasser 1995). This is reiterated by Partridge (1984) who claims that for humans to have fulfillment in life, we need things that are external and independent of us to enrich ourselves. Thus, nature has value because we value it. Even the aesthetics of nature can have instrumental value to us, through spiritual fulfillment and creative inspiration (Hargrove 1989). Existence value of a non-human organism or object can be of aesthetic value to humans, and so are worth protecting (G.E. Moore 1922; Hargrove 1989). As stated by Hargrove (1989) "…there would be no beauty at all, if it did not exist first and foremost in nature… as the wellspring of beauty." Management that preserves these values is then important to psychological and spiritual human health, as well as human rights to beauty.

Some may argue that mandatory management infringes on individual property rights. Since risks vary across land uses, some may not agree with it being forced on their property. In urban settings, direct social risks are higher than in wildlands, where diseased trees are more likely to cause personal and property damage. However, no matter where the disease occurs, there will be direct and indirect social risks, due to decreased recreational opportunities, reduced aesthetic values, and the degradation of ecosystem services. Allowing tanoak and bay laurel to become diseased and die is also a social risk in the case of cultural and heritage loss for indigenous individuals, which will be discussed in a later section. In wildlands, ecological, psychological, and spiritual risks may be greater than in urban settings, due to the greater impacts on ecosystem services and recreational values. Thus, no matter on what property type the pathogen invades, there are great social and ecological risks.

As discussed in J.S. Mill's *On Liberty* (1859) the government can rightfully interfere with one individual's liberties (a landowner's right to property) when that individual's liberties interferes with the liberties of others (other's access to ecosystem services and other rights). Since we know the risk of sudden oak death spread is high, and the potential damages socially, culturally, economically, and ecologically are high, mandatory management from the government via policy is appropriate and just to protect the liberties of other's – their property, their right to a livable environment, and other basic liberties that highly diseased environments have the potential to disrupt. This argument for mandatory management, even on private land, is also supported by Beatley (1989), who argues that being a responsible citizen means that private landowners must act to protect the larger community, not just their own interests. If their own interests interfere with the rights and freedoms of others, and they do not act, they are not behaving as responsible citizens, and there should be policy to ensure that the rights of others are protected from this selfish behavior. This extends to all types of landowners, including park managers, logging companies, and homeowners. All members of the community have a responsibility to protect their shared environment.

This concept is supported by Aldo Leopold's "land ethic" (1948). This philosophy is centered around the idea that humans are part of the world, not separate from it, so have an ethical obligation to protect the integrity of ecosystems. Thus, managing to protect forests from sudden oak death is justified from a Leopold ethic of land stewardship, especially considering that *P. ramorum* was introduced to this region by humans. Do we not have an obligation to manage the destruction that humans introduced (even if it was inadvertent)? While there is extensive information on the ethics of invasive species management, it is beyond the scope of this discussion. The question regarding the ethics of plant trade is also raised. Mainly – why has plant trade been prioritized over the health of ecosystems? However, that debate is also outside the realm of this discussion.

Returning to Leopold's land ethic, the potentially heavy management that would be required to manage *P. ramorum* is ethically justified not just from either a human or natural perspective, but from the intertwining of both. As Leopold states, "…a land ethic changes the role of *Homo sapiens* from conqueror of the land-community to plain member and citizen of it. It implies respect for his fellow-members, and also respect for the community as such." This touches on the concept of being a responsible citizen, and protecting the rights of others, as discussed above. Again, the different communities in this region have a responsibility to the shared environmental community to cooperate and practice respectful, thoughtful, and active, land stewardship.

Another argument is presented by Paul Taylor's (1981, 83, 84, 86) "bio-egalitarianism" which states that all creatures have intrinsic value. While this fits in to a nonanthropocentric argument, there are two key aspects of this ethic that should motivate human behavior. One, is the concept of nonmaleficence, which entails not causing harm. While harm has already been done from the introduction of this pathogen, the harm this pathogen causes to natural and human systems will continue to increase if there is no policy to manage its spread. The second concept relevant to human action presented by Taylor is restitutive justice, which aims to restore the past injustices done to ecosystems and non-human living organisms. *P. ramorum*'s presence in the United States, being introduced from international trade on imported plants, is the fault of humans. The deaths of millions of trees, the declined health of millions more, and the loss of ecosystem services that has been (and will continue to be) caused by *P. ramorum*, is then an injustice done to these ecosystems and creatures that policy and management can aim to correct.

The restitutive justice argument does not apply only to the plants and animals that have suffered from this pathogen's introduction, but in addressing the question if, and to what extent, the absence of vigorous, active monitoring and management represents environmental injustice to native tribes. Being a minority group, a disadvantage in expressing their interests already exists. And as described previously, many indigenous tribes have significant subsistence and spiritual relationships with tanoak. Has the absence of sudden oak death management then sacrificed a culturally important tree, thereby posing an injustice to indigenous members? Furthermore, the importance of tanoak to indigenous tribes is largely unknown to the public, representing another pathway by which ignorance has led to environmental injustice by focusing on the preservation of species (redwood and Douglas-fir) that western individuals value. Manning (1981) argues that a natural resource is a primary social good under Rawls' Theory of Justice (1971), and that primary goods include both resources and conditions. Thus, not implementing management that would preserve tanoak and the conditions that it thrives in, is unjust to indigenous individuals.

Rawls' Theory of Justice (1971) also supports the idea that slight inequality among groups may be acceptable in some circumstances, if the group that was least advantaged initially becomes better off in terms of goods, which includes environmental goods. So, if management improves the conditions and availability of a resource (tanoak, ecosystem services) to minority groups (which may include native tribes, individuals of lower income, and other ethnic minorities who do not have the economic or social power to influence policy), then mandatory management of sudden oak death is just.

Singer (1988) extends Rawls' (1971) theory about reasoners behind the veil of ignorance (individuals who have not yet been born or formed) to support ecosystem preservation. Singer (1988) discusses how those behind the veil do not know what type of entity they will be born as. They could be born into any religion, into any ethnicity, so in complete self-interest, a rational reasoner behind the veil of ignorance would choose to preserve culturally and religiously important resources, including the tanoak, because they might be born into this culture. Again, this supports the idea that *P. ramorum* management is just from the perspective of protecting indigenous rights.

One of the most important arguments for policy regarding mandatory management of *P. ramorum* regards the rights of future generations. First, the National Environmental Policy Act (NEPA 1969) explicitly states that protecting the environment for the sake of future generations is an important goal. Kavka (1978) argues that current generations have a moral obligation to uphold a good quality of life for future generations, and so should leave the same quantity and quality of a resource for future generations. This includes coastal redwood forests, their living and non-living parts, and their ecosystem services. Rawls' Theory of Justice (1971) also describes a "just savings principle" where current generations are responsible that institutions, including cultures, knowledge, technology, science, and skills, are protected for future generations. This means investing and saving in these institutions so that future generations have them, and this can extend to the environment as well. Current generations have a responsibility to invest in and save ecosystems so that they are present, and in good condition, for future generations. If current generations do not act to manage *P. ramorum*, then the coastal redwood resource, its conditions, and its individual parts will likely not be present and in good condition for future generations. The ecosystem services will be diminished, providing less food, materials, recreation, cultural values, and filtration benefits that human physical and mental health are dependent on. Thus, management of *P. ramorum* is just also to support the interests of future generations.

While Golding (1972) argues that current generations may not have strong obligations to future generations because they are not part of our "moral community," current moral communities may be sympathetic to future generations, so can form arrangements for the sake of future generations (Beatley 1989). Every individual and type of landownership will have different values (and intensity of caring about that value) for future generations. For example, a park's goal for future generations could be to maintain the aesthetic and recreational values, whereas some private loggers may want to pass a business down to their descendants. No matter the value, most parties involved in management will have some sort of stake or sympathy toward future generations. Even if current values are in conflict, interests in the future generation may provide a pathway for compromises in disease management. Since future generations are currently "behind the veil of ignorance" they have no way of claiming their interests. Current generations have a responsibility to maintain goods and institutions for them, for we do not know if they will value them more or less, and their options should be open (Rawls 1971; Goodin 1983).

Some may argue that extinction is natural, and perhaps sudden oak death should be permitted to run its course. However, since it is an introduced pathogen, and so is not naturally occurring in this area, this is a human mediated threat to species and ecosystems. There is no way to slow (and hopefully someday stop) the spread without heavy human influence, so those who are against anthropogenic interference in natural systems may be unintentionally supporting disease spread, thereby not behaving as responsible citizens by infringing on the rights of current and future generations, as well as both humans and non-humans. It is also important to note that doing nothing is still a choice and may not be "nothing" at all. A passive approach does not mean the pathogen no longer exists, it simply lets it run its course unhindered, which is, as argued here, unethical and irresponsible.

Importantly, Rolston (1988) emphasizes that the more irreversible an outcome is, the more careful the decisions should be made about it. Since *P. ramorum* spread and potential tanoak extinction will not be reversible, and there may be other unknown impacts, management should be taken. This respects current generations interests and needs of the site, as well as potential future generation interests. As Beatley (1989) argues, land ownership is a temporary right of use, a perspective that gains strength when considering human mortality, and that one-day future generations will own the land we now claim. Considering our land ownership as temporary emphasizes Beatley's (1989) argument that current generations have a responsibility to good land stewardship, especially for the sake of future generations.

Two other points should be discussed before moving onto the next section. One, regards the legal rights of trees. Christopher Stone (1972), in his book *Should Trees Have Standing?* argues for the legal rights of trees and natural objects, both living and non-living. Stone proposes that non-living and non-human living organisms have an entity that claims (or is appointed) guardianship over them to look after their legal interests and needs. Following this notion, an entity or agency that claims guardianship over the rights of tanoak, bay laurel, coast live oak, redwood, and other plants and animals impacted by this pathogen should be created to reside over their interests, support them in court, ensure that their interests are represented in policy, and confirm that appropriate management is taken. As reviewed in “Environmental Ethics and Planning” by Beatley (1989) to hold rights one must be able to cause legal action, have the harm of it considered during court proceedings for legal relief, and this relief must benefit it. An agency that takes guardianship over the non-human organisms impacted by *P. ramorum* can participate in legal settings for their interests.

An agency that claims guardianship in this way will have many benefits for humans, management, and non-humans, as discussed in the management recommendations section of this paper. One of these benefits for humans is the creation of more jobs. Hahn (1988) discusses how many environmental programs create trade-offs between environmental rights and jobs, which can cause barriers to environmental program success. In this case, however, more jobs will be created due to more individuals being needed for monitoring, implementing management (whether cutting, burning, or applying chemicals), working with communities, and facilitating communication. There will also be a need for political philosophers to aid with policy, more scientists to increase research, and other positions will open to bridge gaps between the public, science, policy, and management.

The Ethics of Mandatory Management: Non-anthropocentric Arguments

Beginning with the same claim by Blackstone (1974) used for anthropocentric arguments, I claim that Blackstone’s (1974) statement regarding a right to a livable environment extends to animals, for two reasons. One, animals may have essential functions in the food web and nutrient cycle that without a livable environment they cannot fulfill, and so will fail to fulfill their "animal" capacity, or function. Secondly, as described by Singer (1988), Rawls' Theory of Justice (1971) can be extended to preserve ecosystems, because those who are behind the veil of ignorance do not know if they will be born into a human or animal form. Thus, in complete self-interest, they would opt to support the interests of both humans and animals, knowing that if an environment is polluted or degraded they will feel the pain of poison, the sting of hunger, the fear of having no shelter. This is supported by Peter Singer (1985) who argues that if an animal is suffering, then there is no moral justification to not consider the suffering, and to not consider it equally as other beings. The potential devastation of *P. ramorum* could cause suffering for several animal species. And how much does a tanoak suffer while bleeding? It is then just to manage *P. ramorum* not just for humans to have access to a livable environment, and access to ecosystem services, but for the conservation of animal species dependent on the environment threatened by disease.

The concept of intrinsic value is supported by many other arguments, including Tom Regan's "right view" which states that all living creatures have inherent worth simply because they are living and experiencing life, they all have interests and desires. Ehrenfeld's (1981) "Noah Principle" reiterates existence value, as does Paul Taylor's (1981, 83, 84, 86) "bio-egalitarianism." Linking concepts of intrinsic value with Gaian theory, which describes earth as a closed functioning unit where each unit has feedbacks on the others, emphasizes the critical nature of sudden oak death management. What feedbacks occur regionally, nationally, and internationally due to highly diseased stands and tree mortality? What would occur with tanoak extinction? How would drastic forest changes impact the hydrologic cycle, soil formation, and soil stabilization? How would these factors alter animal habitat and food availability? Absence of vigorous sudden oak death monitoring and management accepts the loss of non-human organisms, and thus in some respect, denies their rights to life and intrinsic value.

According to Gaian theory each organism plays an essential role in earth's feedback system, and since this theory assigns nonanthropocentric instrumental value to these organisms, it demonstrates that they have worth outside of human interests. They have instrumental value to earth's systems (not just to humans), and have intrinsic value in that they do exist, they do experience life. Any being could be born as a tanoak or a ground squirrel, and thus their existence should be protected. This idea is echoed by Rolston (1988) who states that individuals have intrinsic value and are linked to others through instrumental values. Biocentric holism, as proposed by Westra (1994), takes this further, describing that the intrinsic value of the whole ecosystem should be put before the parts, or humans, thereby supporting a strong right to life that puts life support systems first. Thus, from a biocentric holism perspective, managing the coastal redwoods for sudden oak death is ethical because it puts the health of this life support system before the interests of the humans involved.

Now that it is established that policy, monitoring, and management of *P. ramorum* are essential for anthropocentric and nonanthropocentric reasons, issues arise regarding conflicting interests. There are several frameworks that may be used to solve these issues, but ultimately, they will need to be decided between the affected parties. VanDeVeer (1979) takes a two-factor egalitarian approach that ranks psychological capacities and types of interests to determine competing interests between humans and animals, with one factor being the degree of sentience of the organism and the other the type of interest. The ultimate conclusion is that even if one organism is considered psychologically superior to the competing organisms, a peripheral interest (like toys) cannot be prioritized over a basic interest (like food and water). Taylor (1986) has a Biocentric

Egalitarian Individualism framework for resolving competing interests between humans and natural systems. He proposes five principles to guide human interactions with non-humans, including appropriate self-defense, doing minimum wrong, restitutive justice, distributive justice, and ensuring proportionality of action (which is built from VanDeVeer's argument of basic, nonbasic, and serious interests).

In an interesting opposition, Baxter (1974) claims that environmental issues should be solved to human benefit. But still issues arise – which groups of humans are favored in a complex system of diverse interests? How can we possibly evaluate the psychological and spiritual suffering of a lost cultural or spiritual resource? How can that be compared to economic losses? Ecosystem service losses? And how can a just hierarchy be formed? These questions regarding current competing human conflicts will need to be resolved on the ground with the affected individuals, in an environment where open discussion and respect for varying perspectives is curated.

Values, Normative Frameworks, and Core Messages for Discussion

With mandatory management being ethical, it is important to understand how to discuss the importance of management with the various landowners. The discussion below is meant as a starting point – assumptions about the driving ethic are made from some literature, personal experience, and the personal experience of others. Thus, the ethic described is a broad category for each landownership and can be further broken down into more specific ethics. However, empirical studies will need to be done to determine precisely what these are, and this warrants further study. Furthermore, due to the variety of personalities, experiences, and perspectives, it is acknowledged that pluralities will exist. While broad generalities are made about groups, it is recognized that people are still individuals and will vary in their driving ethic. This discussion is meant to initiate ideas of how to discuss management across different values and normative frameworks, but in practice one will need to be aware of individualism and work specifically with a person or business's goals, instead of making assumptions.

Before meaningful discussions can be had, one must identify both the values and normative frameworks that motivates each landownership. Values tell what is important (the focus of the moral universe) to the stakeholder, and the normative framework describes what ought to drive human behavior. Values may range from anthropocentric to nonanthropocentric, and normative frameworks may range from care ethics to utilitarianism. Once these are identified, one can frame core messages for discussion that align with the stakeholder's value and behavioral motivation, so that the reason for sudden oak death management on their property is complementary to their value systems. Not only will it be important for agencies to understand how to communicate with stakeholders about how and why to manage for *P. ramorum*, if various stakeholders understand the drivers of others, collaboration between them may be more positive and constructive. The following discussion is summarized in Table 5.

Broadly speaking, the two groups whose values are non-anthropocentric are the Humboldt Redwoods State Park (HRSP) backcountry and Lolangkok Sinkyone. However, the HRSP lies in western ethics (ecocentric), whereas Lolangkok nature ethics derive from indigenous ethics (kincentric). Ecocentrism puts all the ecosystem, not just the parts with instrumental values to humans, as the focus of the moral community. Thus, the HRSP backcountry's focus is the entire redwood ecosystem, with values of naturalness and beauty. This leads to a normative framework that is focused on land stewardship, with preservation undertones. Useful core messages that complement ecocentric values and land stewardship motivations to encourage *P. ramorum* management include the preservation of natural beauty (since sudden oak death will reduce aesthetic values), protecting species' rights to existence (since SOD threatens many non-human organisms and lack of management allows this to occur), and the responsibility as stewards to preserve the redwoods for future generations. The non-anthropocentric values of the Lolangkok regard beauty, humans not being separate from nature, respect for all living things, and the intrinsic value of non-human organisms. While similar core messages may be used for Lolangkok discussions, since values are similar, it is important to develop those messages with tribal representatives instead of forcing their ethics into a western framework.

Interestingly, the HRSP frontcountry (which is located next to the park's main roads and has most of the facilities) seems to have different values and acts from a different framework than the backcountry (which includes preserved lands, degraded old logging areas, and some trails), as evidenced by differences in the management plan (California Department of Parks and Recreation, 2002). While this discussion focuses on the frontcountry of this large park, values in smaller urban and wild parks may be similar, and so one could potentially use similar messages for discussion with them.

The frontcountry has most of the main roads and recreational facilities, and the least amount of preserved area. Thus, the values are anthropocentric, with a focus on human happiness through access to recreation, aesthetics of the coastal redwood forests, and access to knowledge by learning about this ecosystem. The anthropocentric value supports stewardship with conservation undertones and utilitarian normative frameworks because management focuses on conserving the resource for continued human use, while promoting human happiness through recreational activities. The HRSP also receives money by charging camping and recreational fees, further supporting a utilitarian framework. Here, protecting the inherent natural beauty is a good core message to use for discussion, since continued human use and happiness of the system relies on maintaining its aesthetic beauty. This pairs with the other core message that compliments the stewardship and utilitarian frameworks – the responsibility as stewards to maintain the social, cultural, ecological, and economic values for both current and future generations. An ecosystem allowed to degrade diminishes all these aspects, thus the stewardship and utilitarian drivers would fail to support anthropocentric values.

Two major business types in this area are logging companies and agricultural businesses. As discussed in Bowcutt (2015) and earlier in this document, both have been major contributors to local economies since colonization in the late 1800's. Thus, for both stakeholders, primary values appear to be anthropocentric, focusing on monetary interests, human subsistence (for agriculture), providing quality products, and maintaining resource productivity (for logging). Both have stewardship and utilitarian frameworks for behavioral motivations. Stewardship arises from wanting to conserve the resource for continued use, and utilitarianism is evident through monetary uses and the production of resources. For both, core messages for discussion can focus on responsible resource use through ecosystem conservation, for the sake of current and future generations. If SOD infections are found on their properties, are not managed, and promote the direct and indirect consequences of plant dieback and disease, the stands they manage are likely to fail, or at least be degraded for an extended period of time. Not only will this negatively impact their personal monetary interests through reduced quality of products and decreased production, it may negatively impact local economies currently, as well as reduce the opportunity for future generations to utilize and supply these same products.

Plant nurseries also have anthropocentric values and utilitarian frameworks but depending on the size of the land (and whether the nursery focuses on indoor or outdoor materials), they may not have the stewardship responsibility. Anthropocentric values stem from monetary interests and promoting human happiness through plant care, and these are reflected in the utilitarian framework of promoting human interests, including their own. However, since *P. ramorum* was likely introduced via plant trade, which has also been a major mechanism of long-distance transport in the western United States, the core message for discussing pathogen management with nurseries is quite different from loggers, farmers, and ranchers. There are many ways the pathogen may transport from nurseries, which intense monitoring and management of nursery materials can prevent. These businesses have a responsibility to monitor and manage materials to prevent contaminated plants from entering households, entering wildlands through the urban/wildland interface, and from entering irrigation systems, which could cause infections on numerous property types. Furthermore, they have the responsibility to provide quality products to maintain business operations and customer satisfaction.

The following four stakeholders (homeowners, ecotourists, researchers, and politicians) are large groups that will likely have more variation in values and normative frameworks than the business or management-oriented stakeholders. These values and frameworks are based on personal experiences, the personal experiences of others, and synthesized from readings. Thus, when working with individuals in these groups it is particularly important to have specific conversations about their values and motivations. Presented are a few assumptions from personal experiences and readings and represents a potential avenue for discussion with these stakeholders.

From conversations about how homeowners often respond to plant disease on their property, their values seem to be biocentric. The moral community includes both humans and the biosphere, in contrast with ecocentrism which has a holistic focus on the ecosystem, and anthropocentrism which puts humans at the center of the moral community. Homeowners seem to be biocentric in that they care about the health of individual trees yet may also care about the tree in relation to property values and appearances. Thus, the normative framework may also vary, ranging from care and stewardship to utilitarianism. Care and stewardship arise from concern about the health of one's personal property, of disease on trees that one may have attachment to. Utilitarianism is evident in that sometimes plants and trees are placed on property for an instrumental value, and usually the limits to pathogen management on personal property are due to financial and resource limitations. Furthermore, both frameworks of care and utilitarianism may be present. If resources (money and labor) are available for individuals to access when infections are found on their property, then two core messages that may be used to motivate action are that of being of a caretaker and a responsible citizen. The caretaker message encourages the responsibility to nurture and protect one's own trees. The responsible citizen message focuses on preventing infections from spreading to neighboring properties, maintaining communities (the aesthetics, property values, and ecosystem services) and protecting ecosystems for current and future generations.

Ecotourism, or the vacationing to natural spaces, is a frequent activity in this area since the coastal redwoods are such a unique and beautiful ecosystem. Thus, ecotourists are important stakeholders in SOD discussions, even without holding property there. While there will be variations in why individuals travel to this area, a primary value seems to be anthropocentric, with the purpose of nature preservation being for continued human access to recreation, beauty, and knowledge. The normative frameworks, however, are quite different from the other stakeholders. One framework seems to be consequentialism, where the rightness/wrongness of ecotourism depends on the costs/benefits of ecotourism on the ecosystem, which includes pollution, inputs to local economies, and more. Another framework is the Eudamonist virtue ethic, where engaging in ecotourism promotes a life of flourishing, and allows people to pursue the potential for human excellence through psychological, spiritual, and/or knowledge fulfillment. Many individuals travel to natural areas to gain a sense of connectedness and wonder, but if it becomes too damaging to the system a responsible ecotourist will consider traveling elsewhere. Then, for ecotourists entering areas where plant disease either is present or may enter, a core message for discussion is one of responsible action. While visiting, they must act responsibly in the system, following guidelines to prevent long-distance transport of the pathogen. Responsible action promotes the preservation of the social, cultural, economic, and ecological values that initially tempted them to visit this area, allowing current and future generations to also have this experience.

Researchers encompass a large group of individuals who will vary in their values and motivations. Generally, it seems that values center on knowledge, and perhaps ecocentrism, where research is conducted to promote species and ecosystem health. The normative frameworks, then, may be deontological and/or stewardship. The deontological normative framework regards the duty to pursue scientific knowledge for knowledges' sake, as well as for the protection of ecosystem health. The stewardship framework is the responsibility to informed land management, and can be from a conservation, preservation, or care ethic. While some of the core messages described above may be used here, depending on personal connections to the landscape and what the stewardship focus is, a major discussion point regards promoting ecosystem health. Research should be conducted to better understand pathogen impacts, improve methods of management, develop new technologies, and improve upon old ones, with the goal of protecting trees, species, and ecosystem health for current and future generations. Continued research is an essential component for effective, long-term pathogen management. Thus, finding ways to motivate research in the face of what may seem like an impossible pursuit is a critical aspect of *P. ramorum* management.

Similar to the above groups, politicians are a vast group of people with various perspectives, and determining not just their personal beliefs, but who they represent, will be essential for creating adequate SOD management policies. Generally, it seems that politicians have an anthropocentric moral community, where they answer to human constituents, and are concerned about non-humans to the extent that they affect humans. The normative frameworks that extend from these values are pragmatic, where they do what is required to appease constituents and follow policies, as well as deontological, where action is based on upholding democratic principles. Their role in SOD management then becomes one of creating just and adequate policy. Variations on the core message can be created depending on where in the system they reside, who their primary constituents are, and what their personal values are. However, a core message for communicating with politicians focuses on how creating policy that provides resources for pathogen management promotes human happiness through protecting social, cultural, and economic values of natural resources, and maintains these resources for future generations.

As can be seen, while there are differences in values and normative frameworks within and among groups, there is one commonality in the core message intended to motivate management: future generations. When speaking about future generations, there are several frameworks that can be used, depending on the value of the landowner or stakeholder. If the value is about the welfare of future generations and their access to utilizable resources, then a consequentialist or utilitarian framework of discussion could be used. A deontological framework may be used if the primary concern regards upholding duties to, or the rights of, future generations. Virtue ethics and care ethics can also be useful for discussing future generations, if the concern is to exemplify responsible stewardship, or is driven by compassion, for future generations. From the previous discussion, it should be clear which framework to use for different landowners and stakeholders, and it may serve as useful tool when encountering variation within groups. Virtue ethics regarding future generations may be useful for HRSP, which has a clear focus on land stewardship, whereas utilitarianism and deontology may be more suitable frameworks for discussions with politicians and business owners. Care ethics may be the most complementary to the values of homeowners and ecotourists. Again, one must be careful not to generalize or assume people's values and normative frameworks in practice, and should use this discussion as a method for considering potential avenues of discussion regarding pathogen management, depending on the actual values and drivers of individuals.

Two Useful Frameworks for SOD Management Discussions

Beatley (1989) argues that people should "… develop their moral positions toward and about the environment through a deliberative and dialogue process…" Collaborative sudden oak death management has the opportunity to encourage such dialogue. Combined with the discussion above, this can help individuals define their own values and frameworks and better understand others. While it seems that most landowners and stakeholders do not take a more proactive approach to management due to resource and knowledge limitations, there have been times when resistance to management occurs. There are two frameworks that may be useful for discussion with resistant landowners, while also being useful for facilitating discussion between stakeholders. These two frameworks are Miller's (1982) "value as richness" and the combined Niebuhr-Rolston approach, proposed by Scoville (1995).

Miller's (1982) "value as richness" may be a good framework for discussion with resistant landowners, especially those with utilitarian frameworks and monetary interests. This ethic does not consider every single organism to have equal intrinsic value, so thus rejects Paul Taylor's bio-egalitarianism. This ethic states that while all things do have inherent value, that value is different for each species, depending on several factors. These factors are external and internal resources (richness), their developments and accomplishments, diversity and inclusiveness, harmony and integrity, and utility and generativity. This approach allows the comparison of a resource before and after management, and the relative values of different resources, to not only determine what the priority should be, but what management actions may be conducted. This framework can also be used from the perspective of a landowner. Is the resource in question (whether it be an individual plant or a landscape) providing higher value to the landowner than the utility it provides to other organisms?

A consequence of this framework is that it requires excluding humans from the discussion (the landowner cannot say that their inherent worth is greater than the resource in question because their potential is richer, and so have priority). Thus, this framework might not be suitable for entirely anthropocentric value systems. This framework focuses on valuation of nature: the tanoak, the redwood, the species dependent on them, their affect water quality, and more. It requires evaluating their richness (as resources) and their potential richness and determining their strengths. When one determines the focus of the landowner, evaluates their resources for richness and potential, and discusses their priorities, this theory of "value as richness" may be able to combine ecological and human goals. In essence, this theory supports the idea that humanistic and environmental ethics do not need to be in opposition (Miller 1982).

This framework is intended to "…[expand] humanism concerned with the further enrichment of human life and not just the curtailing of human interests for the sake of non-human welfare." For sufficient plant pathogen management, one must look beyond what services the land can provide humans. Miller (1982) excellently states "[t]he rest of nature has intrinsic worth, and indeed embodies values that humans do not, and thus is superior to humans in certain respects, its value is not confined to its service or spiritual sustenance for humans." While in personal agreeance with this statement, when using this framework for management purposes I suggest we not only consider the values and potentials of the ecosystem and its parts, but also consider what humans can provide the land, of which TEK is an essential part.

The other potentially useful framework for discussing management among and between stakeholders is the combined Niebuhr-Rolston approach, proposed by Scoville (1995). This theory combines Rolston's environmental ethics value theory (1988) with H. Richard Neibuhr's relational value theory (1970), to create a new way of thinking about ecological ethics, which considers intrinsic values as well as relationships between organisms. This approach puts the biotic community at the center of focus and recognizes that humans are part of the biotic community. Thus, humans can make ecologically reasonable decisions as members of that community, and through considering relational and contextual values. It is intended to link values with fact, and may address the is/ought fallacy, where it is thought that because something *is* happening means it *ought* to be happening. However, most would agree that just because *Phytophthora ramorum is* present in coastal redwood forests does not mean it *ought* to be there.

In the biotic community, there may be many centers of value, and this approach allows one to use relational and contextual concepts described by Niebuhr with Rolston's environmental ethics to take different perspectives. For example, when one takes the perspective of the tanoak (or even a whole ecosystem), the management of *Phytophthora ramorum* is considered a "good." This also makes policy that supports management a good. As Scoville (1995) states "…an environmental ethic in which the biotic community is the center of value will not focus solely on the preservation of a particular species or on the maintenance of diversity… but on maintaining the web of relationships that make up the component systems." This includes not just all the fungal and animal species that are also dependent on various plant resources in coastal redwoods, but also how humans function within this system, both with non-human and human components. Management that understands this and opens the discussion to consider these complicated webs may be more efficient in the long-term, while also supporting human relationships. Scoville (1995) comments that "…a nonanthropocentric ethic that can constructively dialogue with a prudential ethic will be better able to bring about actual change." By creating forums for discussion where landowners, stakeholders, and policy makers can understand the values and frameworks of others, and can consider humans as part of the center of value, not the only center of value, will provide the most productive opportunities for creating successful long-term pathogen management, from both an ecological and human perspective.

Proposed Management Strategies

Create a Responsible Agency

As discussed by Alexander and Lee (2010) in their assessment of pathogen management case studies, connections, scale, and building capacity are essential to effective management. Furthermore, they note that the lack of rigorous management of *P. ramorum* in California is largely due to no agency claiming responsibility for *P. ramorum* management. Since individuals and businesses do not receive state or federal funds, management is usually locally driven in California. Typically, when management actions are taken, it aims to protect high value or high-risk trees, reduce roadside hazards, and reduce fuel build-up (Alexander and Lee 2010). This leads to a very narrow management approach in California, which is ineffective for managing a pathogen with high sporulation and dispersal rates.

I propose that an agency that takes responsibility for *P. ramorum* management needs to be created. It will take "guardianship," as described above, of the landscape and the hosts it impacts. It will work closely with all collaborative agencies involved in monitoring and management, notify landowners when an infection is on their land, and when an infection is verified. It will serve as a bridge between the civilian level and different scales of government. It will discuss with landowners what the goal of their property is, and what management action(s) can be taken to best meet the property goal as well as manage *P. ramorum*. It will help homeowners petition to cover the cost of management on their property, which can be expensive for the average homeowner to cover, especially during times of economic hardship. As the overseer of the pathogen, it will assist in monitoring, management, communication, information, and help obtain resources so that management action can be taken. Not only will this agency be combating *P. ramorum* spread and damages, it will create many jobs, including those who work in the field conducting surveys, those who focus on education/outreach, lobbying, funding, and more. As the agency expands, it should include technological jobs, with the opportunity to improve GIS databases and SOD information systems.

Importantly, this agency will help petition local, state, and federal sources for funding so that funds are present to incentivize management when an infection is caught. Funds that are only dispersed in an emergency are insufficient to adequately and quickly manage stands invaded by *P. ramorum*. Funds must be readily available so action can be taken immediately, and landowners do not have to figure out how and where to ask for funds to manage their property. This agency will create a streamlined process for *P. ramorum* management by serving as a pathway for information, funding, and management resources.

Potential funding sources could be from the California National Park Service, California Department of Parks and Recreation, the United States Forest Service, Humboldt County, research grants, and donations. These departments may also be involved in conducting monitoring and management, along with volunteers, citizen scientists, university staff or students, and tribal members. As Alexander and Lee (2010) discuss, the success of pathogen management is greater on local scales. This agency will serve to bridge the different scales, working on the local level to help individuals and communities manage the pathogen, while also creating a bridge to higher scales of government to access funds and resources. In turn, as suggested by Alexander and Lee (2010), local governments should petition state and federal agencies for funding and labor when task forces as part of this agency find infections.

Furthermore, outreach and education need to be expanded. As identified by Crowley et al. (2019), while official advise sources (seminars, workshops, and tours) are useful for nonindustrial private forest landowners in making management decisions, unofficial advise sources (friends, family, neighbors, and personal experiences) are critical to not only decision making, but to management engagement. By providing more pathways for more community members to have knowledge regarding resources and appropriate management actions, the network of unofficial advice sources should increase, thereby also increasing engagement with pathogen management within and between communities. A section of this proposed agency will be dedicated to this purpose. Discussions at schools, offices, nurseries, and by request for special interest groups will be encouraged. They will work with Humboldt Redwoods State Park staff to host informational meetings and post information at campgrounds and visitor centers. These discussions and informational pamphlets will focus on preventive measures, but will also discuss what can be done once an infection is caught, how to report suspected infections (including on OakMapper and the

SOD mobile phone app), and who to contact with questions and for assistance. Importantly, awareness of symptoms needs to be raised, and photos with descriptions of these will be displayed to serve this purpose.

This agency will facilitate discussion with more stakeholders, which is important for social sustainability aspects of *P. ramorum* management, especially when it comes to determining how it will be managed, since many are against chemical treatments. Determining when and where these treatments are appropriate and legal will reduce opposition to management, particularly on private land. While Oregon took a more forceful approach to managing *P. ramorum*, this may not be possible (or ideal) in California. However, action will need to be taken against infected trees on people's property. Discussion with those landowners and/or incentivizing them (such as replacing the tree or providing a small check) will be important for cooperation and compliance with management. Table 1 can be used as a general reference for management goals across land types, and Table 5 can help identify what core messages to use for discussing management across different values.

In their article, Alexander and Lee (2010) identify the cooperation of various stakeholders as important to successful pathogen management. Stakeholders can range from homeowners, gardening groups, indigenous tribes, local leaders, arborists, tree care providers, private landowners, researchers, environmental activists, and more. All these groups may be able to assist with research, monitoring, and management. Having various stakeholders is essential since there will be many goals and cultural differences across different landownerships, so deciding management from the local level up to the regional level will identify the best management practices to pair with SOD management on different properties (Alexander and Lee 2010).

This reflects the community-based ecosystem management approach discussed by Gray et al. (2001), which links ecosystem and community health. It aims to be inclusive, including multiple voices and perspectives through all parts of the planning process. This approach also supports accessibility, inclusivity, transparency, and mutual learning (which requires respect and openness). It also supports adaptability, which allows for flexibility in management and the decision-making process based on changing needs and conditions as learned through communication and monitoring. By encouraging pathogen management (and thus land stewardship) between and among communities, promoting innovation in the private sector, and communicating across jurisdictions, involving various stakeholders creates a community-based ecosystem management approach that may increase management success ecologically and socially, build trust between groups and at different levels of government, and provide more pathways for obtaining resources necessary for management (Gray et al. 2001).

The collaboration of various stakeholders increases the sharing of knowledge and encourages positive interactions between and among groups, which also increases pathogen management success (Alexander and Lee 2010). It is important to identify the strengths of the community, build off them, and have positive interactions between groups to understand why management is important to each one. This can help people understand the cultural importance of tanoak to Native Americans, the timber value to private landowners, and more. Again, an agency that works with communities and is responsible for pathogen management can help identify local strengths, weaknesses, and the importance of management across land ownerships and land uses.

While this process may sound overwhelming to initiate, Gray et al. (2001) provide some suggestions of pathways that will promote successful community-based ecosystem management. This includes improving community capacity by creating trainings (which may also increase the network of unofficial advise sources), providing technical and financial resources, promoting innovation in the public and private sectors, linking civic and formal science to make information more accessible, ensuring that during the decision making and management process inclusivity, mutual learning, adaptability, transparency, and accessibility are focused on, understanding worker issues, promoting ecosystem workforces, and promoting laws and policies that support collaboration between businesses, rather than individual interests (Gray et al. 2001). With many aspects needing to be focused on, a responsible agency or large collaborative effort will encourage all these components to be considered, thereby increasing success of the program.

Not only will this agency create jobs, economic sustainability will be further encouraged through social and ecological sustainability. As mentioned previously, management actions that improve ecological sustainability will minimize the costs of managing other disturbances such as wildfires. It will prevent the pathogen from infecting the park and logging stands, thereby sustaining revenue from ecotourism and timber production. It will maintain property values as well as many regulating, provisioning, and supporting ecosystem services that could be costly to replace with technology or infrastructure.

It is also worth noting from Alexander and Lee's (2010) article that those who are more affluent are more likely to be involved with management due to having more connections, more money, and an understanding of how to get the attention of local officials. Those who are less affluent need help with resources, not just financially to combat the pathogen, but to access officials. Again, this emphasizes the importance of having a responsible agency to assist with this process, and in some cases take charge of it for the individual, who may not have the resources or knowledge to do so. As discussed in the Crowley et al. (2019) article, nonindustrial private forest landowners are more likely to be passive instead of active managers when they are unaware of where to access resources, including knowledge about active management, and when they do not have advice networks that provide information about risks and management. Cleary, education and accessibility to resources so that people know when, where, why, and how to manage SOD on their property is key to pathogen management success.

Further considering scale, Alexander and Lee (2010) discuss how it is important to identify differences between urban and wildland areas, and the urban/wildland interface. Urban areas will be easier to monitor and may be better monitored by locals. Wildlands may not only be overwhelming areas to work in, but may be owned by various stakeholders, so should have collaborations between them to combine the goals of these different organizations with management (Alexander and Lee 2010). For example, those concerned with water quality could also assist with stream bait monitoring. While resources are limited, a collaboration among stakeholders can be formed, providing the foundation from which an agency may be created.

Many of the suggestions for management are like integrated pest management (IPM) techniques, which may be a useful framework for initiating management of *P. ramorum*. IPM focuses on monitoring and assessment to make decisions about actual conditions. It sets a threshold where action against the pest (or in this case, pathogen) must be undertaken, and utilizes appropriate cultural, biological, chemical, and physical treatments to manage an outbreak. IPM also uses control and prevention techniques to manage outbreaks. While chemical treatments may be utilized, the goal of IPM is to effectively manage pests with the least amount of chemical introduction, as well as using chemicals that are considered less hazardous. In the case of *Phytophthora ramorum*, in some situations using biological controls outlined in IPM such as changing species composition and planting resistant hosts may be suitable management strategies. The agency (or initial collaboration) may reference IPM guidelines for pathogen management, using scientific literature to establish critical thresholds, consider non-chemical treatments, keep records, conduct monitoring, inspections, outline sanitation protocols, and more (UC IPM n.d.; EPA 2019; IPM Institute 2020).

Collaboration with Sinkyone

One of the most important aspects of improving social sustainability will be collaboration with the Sinkyone tribe. They have used tanoak for subsistence purposes and materials for millennium, thus including them in the protection of this tree and management of its pathogen is important for cultural and heritage preservation. A method proposed by Bowcutt (2013) to involve the Sinkyone is by asking them to create tanoak reserves. This could ensure that if *P. ramorum* causes high tanoak mortality in certain areas, that tanoak as a species will persist and could be replanted when the pathogen is no longer present in an area. This will serve to maintain an important cultural resource and offer a steppingstone for the Sinkyone to be more involved with management. Thus, tanoak reserves cared for by the Sinkyone may improve both ecological and cultural sustainability in both the short- and long-term. Historical indigenous burns may be an opportune way to increase Sinkyone involvement while encouraging the sustaining of culturally valuable practices and plants. As research into SOD resistances increases, the tanoak reserves may include individuals with natural resistances. Reserves could then be a source for tanoak replacements in cases of isolated infections, a method discussed and supported in IPM.

As described by Pierotti and Wildcat (2000), traditional ecological knowledge (TEK), "… is inherently multidisciplinary in that it links the human and the non-human…TEK may be useful in resolving a variety of stakeholders and interest groups in controversies over natural resource use, animal rights, and conservation." These authors go on to describe TEK as involving respecting non-humans, recognizing that bonds between humans and non-humans do exist, incorporating non-humans into ethics, and having the awareness that humans exist as part of the ecological system. Thus, while there are ecological practices that can benefit plants, animals, and humans through utilizing TEK, it also can serve as a method to address political and ethical behavior by intertwining the "…boundaries between philosophy, history, sociology, biology, and anthropology…" (Pierotti and Wildcat 2000). It involves a sense of place, and space, that exists outside of the temporal frameworks that western management often focuses on. In TEK, all things are connected temporally and spatially, and understanding these complex webs of relationships (between and among humans, between and among non-humans, and between humans and non-humans) will be important to understand for successful pathogen management. It will not just have great benefit to managing *P. ramorum* and its primary hosts over the landscape through time, but for maintaining positive and productive discourse between various stakeholders by having a "shared conceptual framework" (Pierotti and Wildcat 2000).

One method of TEK, indigenous fire stewardship (IFS), may be particularly useful for management. As discussed earlier, IFS can promote ecosystem health by reducing fuel loads and pest/pathogens, while also promoting cultural practices and knowledge (Lake 2019). While fire practices in this area were not developed with *P. ramorum*, there is still potential that it can help reduce contaminated litter, control bay laurel growth, and increase forest resilience indirectly through other benefits such as reducing fuel loads and drying plant materials. This is a yet unexplored method of SOD management, and the effects of fire, particularly IFS, on *P. ramorum* is worthy of future study. However, stating that IFS should be incorporated into management is much easier said than done. Lake et al. (2017) provide a framework that pairs key elements for applying traditional knowledge (TK) and western knowledge (WK) with how they complement management and research. This framework focuses on returning the use of TEK and IFS to land management by developing partnerships, key aspects that include trust building, sharing of knowledge, respectful communication, communication across stakeholders, and community awareness of fire benefits (Lake et al. 2017).

Monitoring and Management Recommendations

Early Detection

Once an infection is caught and treatments are made, monitoring should be conducted on the impacts of treatment at the forest stand level. Besides continued monitoring of pathogen symptoms, monitoring could include collecting data on soil moisture, compaction, stand regeneration, and species composition. This will be part of an adaptive management plan to ensure that the management actions taken are not negatively impacting the site, as well as to ensure that the appropriate management actions are utilized. Strategies may need to change depending on environmental conditions as well as both host and pathogen status.

To improve ecological sustainability, *P. ramorum* should be directly managed. Since once the pathogen establishes in a forest it is nearly impossible to eradicate, early detection is essential to protecting vulnerable species and forest stability (Valachovic et al. 2008). Early detection measures include targeted ground surveys, stream baiting, and using lateral flow devices (LFDs) to test for *P. ramorum* on site (Valachovic et al. 2008; Lane et al. 2007; Tomlinson et al. 2010). *P. ramorum* can travel up to 1 km in streams, so creating baits downstream from known infections can help monitor its spread to other locations (Davidson et al. 2005). Since stream baiting recovery rates are highly seasonal, the intensity of stream baiting can vary throughout the year, with a high intensity period in the peak period, which is February – June (Murphy et al. 2007). Streams that are frequently visited and have origins near infected areas should have priority monitoring for *P. ramorum*. While there has been an extensive stream baiting effort, with over 300 streams being monitored since infections were found in the early 2000's, this effort needs to be expanded (personal communication, Chris Lee, August 4, 2020). Monitoring should not just include high value sites or those with a high likelihood of being infected. Streams of intermediate value, moderate infection risk, and moderate visitation rates should also be monitored to slow the spread more effectively.

Once detected in a stream, individuals can go to that location, note trees for damage, and conduct an on-site LFD test. Results can be verified using real-time PCR (polymerase chain reaction) in a lab setting (Hughes et al. 2006). These methods should be able to determine with high certainty within 1 – 2 days if the pathogen is present in a new location. If found early, depending on the host and land ownership, the tree can be trimmed, removed, replaced, and/or treated with herbicides. However, experience identifying *P. ramorum* from stream baits in the lab requires a lot of training, and years of experience to do it quickly, since many *Phytophthora* species can be found on samples (personal communication, Chris Lee, August 4, 2020). This supports the idea of having an agency responsible for *P. ramorum*, since it would employ people for this purpose in the long-term.

Targeted ground surveys can be used in a similar way as stream baiting to monitor sites. For example, it is predicted that *P. ramorum* will move northward due to prevailing winds (Filipe et al. 2009). Locations with high densities of vulnerable hosts north of known infections can be visited by crews to monitor if and when *P. ramorum* infects a stand. Targeted ground surveys should be conducted near known and suspected infections frequently, whereas aerial surveys may only be necessary twice a year, due to how long it takes for aerial surveys to catch the disease. Another potential consideration for those conducting ground surveys is variation in spatial patterns in stands over time. Kelly et al. (2008) found that dead trees are initially highly clustered, but the cluster density of dead trees decreases overtime, even as mortality rates continue to increase. They also found that infected cohorts tend to appear in clusters away from the dead trees (Kelly et al. 2008). By evaluating the spatial pattern of mortality, crews who assess a potentially invaded stand may be able to determine how long the stand has been infected, and thus the appropriate severity of management actions.

Soils Management

Soils management has the potential to not only improve ecological sustainability, but social sustainability as well, by maintaining the health of the urban forest. Soils in this area are deep, moderately to well-draining, have high-runoff and low infiltration rates (SoilWeb n.d.). Slow infiltration rates, erosion and runoff may increase the distance *P. ramorum* disperses. Soil erosion due to urbanization may increase runoff, making it easier for the pathogen to spread. It may move downhill from the forest in surface runoff or soil water. If spores reach the river, the rate of transport greatly increases. Not only can soil water move the spores downhill, precipitation can pick up spores and transport them to the soil, where they will infiltrate or runoff. Furthermore, if rains or winds are strong enough, “splash” may transport the spores (DEFRA 2008).

The relatively high soil organic matter (SOM) may also impact *P. ramorum* by influencing soil water relationships. Fichtner et al. (2007) suggest that high OM increases soil moisture retention, which could promote *P. ramorum* survival. This same study found that if infected plant tissue falls to the forest floor, then soils may increase *P. ramorum* survival by acting as “inoculum reservoirs” (Fichtner et al. 2007). Light, prescribed ground fires may reduce the amount of contaminated surface litter. Furthermore, prescribed fires may indirectly help the forest resist and recover from *P. ramorum* infections through indirect benefits of fire, such as the release of stored nutrients and the creation of canopy gaps (personal communication, Chris Lee, August 4, 2020).

Canopy gaps increase the amount of sunlight available to the understory, thereby favoring understory growth, which may not favor SOD since smaller and younger trees are less susceptible to infections. Canopy gaps also reduce tree density and thus increase the distance SOD spores must travel to reach a suitable host. However, the benefits of canopy gaps depend on what species regrows, as discussed previously. While fires eliminate contaminated litterfall, smoke may dry out other contaminated plant materials, also disadvantaging *P. ramorum*.

P. ramorum can move and persist in soils, so increasing infiltration and reducing runoff might help minimize its movement to new areas, since it will travel downward into the soil instead of laterally (and potentially to new hosts). This may be especially important in urban areas where construction and other human activities increase soil erosion and compaction, further increasing runoff. To reduce runoff and increase infiltration, cities could use porous surfaces instead of concrete and plant more trees that are not susceptible to *P. ramorum* infections. Shoe washes could be installed at park exits, since spores of *P. ramorum* may be transported in soil on the soles of hiking boots (Davidson et al. 2005). This could help prevent long distance transport of *P. ramorum* to other locations.

Other management techniques to improve soil physical and biological properties should be undertaken, especially in cities. Reducing runoff and increasing infiltration could be done by planting more plants, especially ones with deep roots. However, this may increase OM and soil water retention, so if plants are used to meet runoff and infiltration goals, then plants that are not suitable host species for *P. ramorum* should be planted.

Water Management

Stream baiting is a critical part of monitoring *P. ramorum* spread, as discussed previously. However, there are other water management considerations, mainly for nurseries, which are the only businesses where inspections and management is mandatory. Chastagner et al. (2009) provide many useful recommendations for *P. ramorum* management in water that may come from nurseries, including installing biofilters to reduce the risk of contaminated water leaving the nursery and training employees on SOD symptoms. If there is standing water on a property, Chastagner et al. (2009) recommend treating it with algaecides. Waterways from nurseries should be monitored to help understand how *Phytophthora ramorum* transports from these systems into others, especially into forests and irrigation systems. The responsible agency can oversee monitoring waterways in cities and notifying landowners when the water they would use for irrigation may be contaminated.

Managing for Climate Change

Despite uncertainties in how coastal redwood forests will be affected by climate change, there certainly will be impacts. The effects will likely be exacerbated by current stresses and stresses that accrue over the next century. Thus, management to increase the resilience and resistance to climate change is important for protecting the forest not just from increased damage from disturbances, including *P. ramorum*, but also to preserve the full range of cultural and social values. Many species use these forests for refugia, so management considering climate change is important for preserving biodiversity and habitat for species that might be pushed out of their range due to climate change and more intense disturbance events.

Blom and Teraoka (2014) gathered stakeholders and managers to discuss strategies for managing redwoods with climate change. They identified roads, fragmentation, land-use, fire, fire management, invasive species, and climate change as primary stressors that need to be reduced to enhance redwood ecosystem health over the next century. Primary strategies to protect stands from stress included increasing connectivity of intact redwood forest patches to reduce fragmentation, improve roads, reduce stress from fire exclusion, and reduce stress from development. Other recommendations included increasing communication and redwood management coordination across the landscape and landownerships to improve conservation, restoration, and refuges (Blom and Teraoka 2014).

Although managers were not favorable to thinning mature redwood due to the creation of canopy gaps that increase the amount of flammable materials, thinning may be favorable in second growth forests to improve the growth of younger redwood, remove other unfavorable species, and remove SOD infected hosts (Blom and Teraoka 2014). However, some thinning and prescribed fires could be useful in infected old growth by removing contaminated materials.

Another anticipated impact of climate change is increased storm severity, which may not only increase the amount of SOD splash dispersal, it may increase runoff and erosion (Blom and Teraoka 2014). This supports the idea that roads should be improved to reduce extreme storm stress and decrease the ability of *P. ramorum* to transport during and after these events.

Blom and Teraoka (2014) support previous studies that *P. ramorum* management can be improved with increased communication and cooperation. Individuals need to communicate to all proper channels the timing and extent of infections so that it can be contained and controlled as quickly as possible, thereby protecting other locations. In particular, forest managers and private landowners need enhanced communication about management. Blom and Teraoka (2014) found that those who sell forest products want communication to have reassurance that management will not negatively impact their profits or economic viability, and managers with conservation goals want communication to ensure protection of high value areas. Tribal members wanted enhanced communication to ensure continued access to resources and the sustaining of culturally resources. A plan that combines all values and goals of stakeholders will ensure that communication and cooperation is incorporated into the plan, encouraging the sustaining of various values. If all stakeholders are involved in a monitoring and management program for climate change and SOD management, including potential assisted migration, site surveys, and pathogen treatment, the resistance and resilience of this ecosystem can be better preserved over the next century as external threats continue to cause ecosystem stress (Blom and Teraoka 2014).

Valachovic et al. (2017) found that thinning treatments have cobenefits for *P. ramorum* management and climate change mitigation. However, careful consideration of current site conditions must be noted before management occurs. They found an unexpected increase in mortality in Douglas-fir when thinning and prescribed fires were both conducted in an area, potentially due to unfavorable past and current site conditions. These treatments also showed differences in what shrubs and understory species regenerated, which may be important to consider if other invasive plants are already bordering the site. Herbicide treatments had higher fine woody debris and fuel bed depth than other treatments, indicating higher potential for hazardous fires. Prescribed fire reduced litter and duff depths, thus combining prescribed fire with other management practices can enhance protection from wildfires, reducing *P. ramorum* impacts. If these strategies allow tanoak to have greater volumes when they regrow, then tanoak may be able to store more aboveground live carbon, mitigating climate change (Valachovic et al. 2017).

In another study, Twieg et al. (2017) estimated tanoak basal area by the end of the century and the CO_2 sequestered in live tissue following bay laurel and tanoak stem density reduction treatments. All scenarios had benefits for tanoak size and CO_2 storage. After 100 years, tanoak basal area in thinned stands was predicted to be significantly higher than in untreated stands, storing an additional 6,017 – 23,624 metric tons of CO_2 in live biomass. Removing bay laurel and tanoaks before infection raised this amount. Since these treatments also avoid the increased wildfire severity and frequency caused by *P. ramorum* infections, these treatments also avoid CO_2 loss from forests due to wildfires (Twieg et al. 2017).

As discussed in an earlier section, it seems as if environmental conditions will become more favorable for *P. ramorum* as climate changes. However, wildfires may also increase. As it is yet unclear whether the moister winters or hotter, drier summers will have greater impacts on *P. ramorum* survival, the effects of climate change on SOD will need to be closely monitored over time to prepare for possible increasing rates of infection and mortality. How species move in response to climatic changes will also be important to monitor, because this may lead to an expansion of monitoring and management activities over time as host species ranges shift. Data on this should be collected and assessed in the adaptive management plan to ensure that the appropriate areas are being monitored. How *P. ramorum* will be affected by changing host ranges, and if the novel ecosystems will be a benefit or detriment to *P. ramorum*, is also unknown, but worthy of future study.

Management Actions and Goals

Besides being able to persist in the soil, *P. ramorum* can also survive on litter fall (Davidson et al. 2005). If detected in soil, litter fall, or in a location with a high amount of plant debris, prescribed burns could be conducted to remove potentially contaminated litter. *P. ramorum* prefers cool and moist conditions, so by drying and heating the soil, *P. ramorum* spores might be removed from the soil through prescribed surface fires. Prescribed fires would also reduce the likelihood of a severe wildfire occurring by reducing the amount of flammable fuels. Tree mortality due to *P. ramorum* is expected to increase the amount of flammable fuels in forests, so this strategy could minimize the ecological and economic impacts of both pathogen and wildfire disturbances (Valachovic et al. 2011). This provides an opportunity to work with indigenous tribes who may have historically used fires for land management purposes, thus providing a pathway to manage SOD, incorporate traditional ecological knowledge (TEK), promote inclusivity, and promote tribe collaboration with various aspects of management.

Recommendations for the amount of fungicides to inject or spray onto infected materials can be found in Garbelotto et al. (2009). Replacement of contaminated trees will depend on the goal of the property, funds available, and extent of the infection. For example, if a community has several infections, replacing the infected trees with California bay laurel or tanoak would not be appropriate due to their high susceptibility and sporulation capacities. Discussion with the property owner should determine what is replaced, with younger trees being cheaper and less susceptible to infection. While an old oak may be of high value to the property owner, it may not be possible to replace it with another old, large oak. A mixture of incentives may be necessary in some situations, either by replacing the tree with younger and/or different species as well as providing financial incentives for removing the high value tree. A potential disincentive to property owners who refuse to remove infected material on their property could be the responsibility to cover the costs of managing an infection on their neighbor's property if their own infected material is the source. Table 4 can be used as a reference for managers and landowners to assess the severity of management that needs to be taken on a property.

Methods to prioritize goals are offered in Valachovic et al. (2009) (Table 3). The authors suggest that the main goals could be to minimize property damage, protect important trees or a geographic location, and suppress spread. Once one asks what the goal of the forest is, and assesses the current site conditions including erosion, aesthetic values, and water quality, one can begin to think about how to manage it. What is the forest's ecology? What is the historical occurrence of disturbances? How will different disturbances favor different species and which species does the landowner want to favor? There are many combinations of actions that can be taken depending on the goal, but one must also assess available funds. The responsible agency should have a dialogue with the landowner to determine if they need help deciding what actions to take. Due to the many land types in the area, the management goals will be diverse. This may range from reducing ecosystem degradation due to urbanization and grazing, maintaining economic value of timber production, managing for disturbances, and/or managing for recreational values (Table 1).

If thinning is conducted, Cobb et al. (2012) found in their epidemiological model that in stands that have less than 60 tanoak per hectare and no neighboring host species, tanoak can persist despite residing in an invaded stand. Thus, thinning treatments should focus on reducing tanoak densities and removing bay laurel in infected stands. This will also increase the effectiveness of other treatments, such as surface burns and fungicide applications by reducing the density of susceptible and highly sporulating host species. In the case of thinning (or *P. ramorum* management on their property in general), if timber companies are concerned about job losses, loss of valuable products, and management costs, perhaps they are allowed a tax break or financial incentive to participate in research and management.

Alterations to Humboldt Redwoods State Park Current Management Plan

Besides working with the responsible agency to increase SOD symptom awareness by hosting talks and increasing the amount of available information about *P. ramorum* in the park, Humboldt Redwoods State Park needs to take more direct action in combating SOD. Stations where people can wash their shoes after hiking or camping, with the water being caught and filtered, can help reduce the chances of long-distance human-mediated transport. The park should also increase the amount of stream baiting and surveys being conducted to focus on prevention and early detection, instead of trying to manage infected stands when an invasion may already be well-established. Aerial surveys should be reduced to favor stream baiting and targeted ground surveys, since as discussed previously aerial surveys may notice infections at too late of a stage in the disease. The responsible agency can help train park staff in these surveys, and the agency will conduct their own surveys with permission in other locations in the case study area. Signs on trails or notices at trailheads can help awareness of symptoms while people are on their hike and encourage thoroughly cleaning clothes and shoes when done.

In the Humboldt Redwoods State Park general management plan, there is a trails plan that aims to increase visitor enjoyment and safety, create more trail links with surrounding lands, and protects the park's resources (California Department of Parks and Recreation 2002). Since *P. ramorum* can transport on the soles of hiker's boots, *P. ramorum* could be incorporated into the trails plan. This could be by adding notices at trail heads about symptoms to raise awareness, as well as a number to call if infected plants are seen. Shoe washes could also be installed at the ends of trails or the park exits, to minimize long distance transport of the pathogen on shoes.

The plan also notes needing improvements for recreational diversity, protection of cultural sites, protection of redwoods, campground improvements, facility improvements, and improved communications between the park, locals, businesses, and other stakeholders. It has different goals for the redwood natural reserve (primitive zone), backcountry (both non-mechanized and mechanized zones), frontcountry, transportation, and administration/operation zones. The frontcountry zone is where many of the trailheads, campgrounds, and proposed environmental education centers are, so may be the most vulnerable to human mediated transport of the pathogen. Management of *P. ramorum* may want to focus on the frontcountry, with some targeted ground surveys and stream baits in the backcountry (California Department of Parks and Recreation 2002).

The plan lists significant impacts of current uses on aesthetics, vegetation, wildlife, and cultural resources, with non-significant effects on noise pollution, earthquake risks, and soil erosion. A *P. ramorum* management plan would incorporate the things that are significantly impacted, so would improve their environmental plan. While mitigation impacts are listed, ranging from correctly timing construction to reduce social and ecological interference, reclassifying the park to have more protected areas, and conducting vegetation and wildlife impact surveys before projects progress, all these aspects could be severely impacted by *P. ramorum*, so it should be included in their management plan (California Department of Parks and Recreation 2002).

Adaptive Management

The created agency that is responsible for the pathogen and the Humboldt Redwoods State Park should create adaptive management plans. This means that as SOD management and monitoring increases, the frequency of plan review also increases. Effective adaptive management stems from continuous monitoring and assessment, and as stated previously, is a critical component of IPM that could be referenced for pathogen management. The review process will assess the results of monitoring and management actions, as well as the cost of implementation. Initially, reviews will need to be done yearly, but once the agency is well established so has had several years to analyze data, correct mistakes, incorporate new information, and increase stakeholder involvement, reviews may need to be done less frequently. Within the adaptive management plan, program costs should be assessed. This will help allocate sources to appropriate aspects of the program as infections are caught and managed. Besides evaluating program costs, the results of stream baits, lab tests, and the extent of education/outreach, the monitoring program should include an assessment of host mortality rates, rates of infections, soils data (such as moisture and compaction), tree growth rates, regeneration rates, and species composition changes.

This can help monitor how changing external conditions affects susceptible host species, coastal redwood forest ecosystems, and the pathogen over time, thereby informing the best management practices.

Conclusion

The plant pathogen *Phytophthora ramorum*, which causes sudden oak death, threatens the social, cultural, ecological, and economic integrity of southern Humboldt California. This area is home to Humboldt Redwoods State Park, which contains one of the largest coastal redwood reserves on the planet. Counties in central California failed to detect the pathogen early, leading to the mortality of millions of oaks and tanoaks, and causing millions of non-lethal foliar infections to form on over one hundred plant species. Shifts in forest structure and composition followed, reducing ecosystem stability and the loss of many ecosystem services, leading to irreversible consequences, and making eradication of the pathogen impossible. By utilizing early detection methods, such as targeted ground surveys, stream baiting, and on-site tests in the form of lateral flow devices (LFDs), *P. ramorum* can be detected before it is completely unmanageable.

Although it might be impossible to eradicate, that does not mean it is not important to contain it, to protect high value species and areas, and slow the spread to other locations. Using several ethical arguments, it has been discussed that it is ethical to force management, due to the high risk and threat *P. ramorum* poses to both human and natural systems. Determining values (the moral community) and normative frameworks (drivers of behavior) of different landowners and stakeholders will be useful for discussing the importance of pathogen management in a complementary way to the landowners' property goal.

There are still many uncertainties regarding *P. ramorum*, such as: do other tree species suffer mortality from *P. ramorum*, just on a longer time scale? How will climate change affect the range and reproduction of *P. ramorum*? How will the range of the most susceptible host species change with climate change? To what extent can integrating TEK help manage *P. ramorum*? How do the ethics of invasive species management correlate to *P. ramorum* management? How long can the pathogen be dormant in a forest before it causes an infection (i.e., how long can it be present in a stand before it is known)? How much can natural resistances slow the spread? Will it eventually hit a resistant or natural barrier? Why did it not arrive in the United States until the mid-1990's, although international trade started in the 1930's? Why and when did it originate? Understanding the historical spread and origin may provide insights into future changes and help prepare for different climate scenarios.

An agency needs to be created to take responsibility for pathogen management. This agency will have discussions with landowners, help them determine best management practices, aid them in finding resources to conduct management, and bring together various stakeholders from the local to regional level, all of which will increase the success of *P. ramorum* management in southern Humboldt County. Education and outreach programs can empower locals to identify the pathogen, helping early detection methods. Involvement of the Sinkyone tribe in monitoring, management, TEK utilization, and the creation of tanoak reserves can maintain their cultural bonds to tanoak and combat *P. ramorum* while strengthening social bonds with other stakeholders. If detected early, physical treatments (such as quarantine, cutting, and thinning) and chemical treatments may sufficiently slow the spread of the pathogen, if not contain it. Despite conflicting perspectives and the seeming hopelessness of combating *P. ramorum*, especially with the uncertainties of climate change, a large collaborative management effort can control this pathogen's spread. By bringing together many stakeholders, having sufficient resources ready to be utilized, and an agency whose only purpose is to assist monitoring and management of the pathogen, the preservation of the numerous social, cultural, economic, and ecological services provided by the coastal redwoods can be sustained.

Appendix I: Recommended Resources for Further Reading

Alexander, Janice and Chris A. Lee. 2010. “Lessons learned from a decade of sudden oak death in California: evaluating local management.” *Environmental Management* 46: 315 – 328.

Beatley, Timothy. 1989. "Environmental ethics and planning theory." *Journal of Planning Literature* 4(1): 1-32.

Blom, Ben, B. L. M., and N. P. S. Jason Teraoka. 2014. "Managing an ancient ecosystem for the modern world: coast redwoods and climate change."

Bowcutt, Frederica. 2015. *The Tanoak Tree: An Environmental History of a Pacific Coast Hardwood*. University of Washington Press.

Frankel, Susan J. 2008. “Sudden oak death and *Phytophthora ramorum* in the USA: a management challenge.” *Australasian Plant Pathology* 37: 19 – 25.

Garbelotto, Matteo and Douglas J. Schmidt. 2009. “Phosphonate controls sudden oak death pathogen for up to 2 years.” *California Agriculture* 63(1): 10 – 18.

Lee, Chris, Yana Valachovic, and Matteo Garbelotto. 2010. “Protecting trees from sudden oak death before infection.” *University of California Agriculture and Natural Resources Publication 8426.*

Miller, Peter. 1982. "Value as Richness: Toward a Value Theory for the Expanded Naturalism in Environmental Ethics." *Environmental Ethics* 4(2): 101-114.

Rizzo, David M., Matteo Garbelotto, and Everett M. Hansen. 2005. “*Phytophthora ramorum*: integrative research and management of an emerging pathogen in California and Oregon Forests.” *Annual Review of Phytopathology* 43: 309 – 335.

Scoville, Judith N. 1995. "Value theory and ecology in environmental ethics: a comparison of Rolston and Niebuhr." *Environmental Ethics* 17(2): 115-133.

Valachovic, Yana, Chris Lee, Jack Marshall, and Hugh Scanlon. 2009. “Forest treatment strategies for Phytophthora ramorum.” *Proceedings of the Sudden Oak Death Fourth Science Symposium Gen. Tech. Rep. PSW – GTR – 229*.

COMTF website: suddendeath.org

UC Cooperative extension: http://cehumboldt.ucanr.edu/Programs/Forestry/Sudden_Oak_Death/

APPENDIX II: FIGURES AND TABLES

Figure 1. Study site in southern Humboldt County, California. Includes the area between Redway, Phillipsville, Redcrest, and Honeydew. This creates a primary management focus on Humboldt Redwoods State Park while attempting to mitigate the pathogen's spread to other locations.

Figure 2. Map of confirmed isolations of *Phytophthora ramorum*, the range of host species the pathogen can infect, and counties with confirmed reports of *P. ramorum* in natural systems in California state (obtained from Frankel 2008).

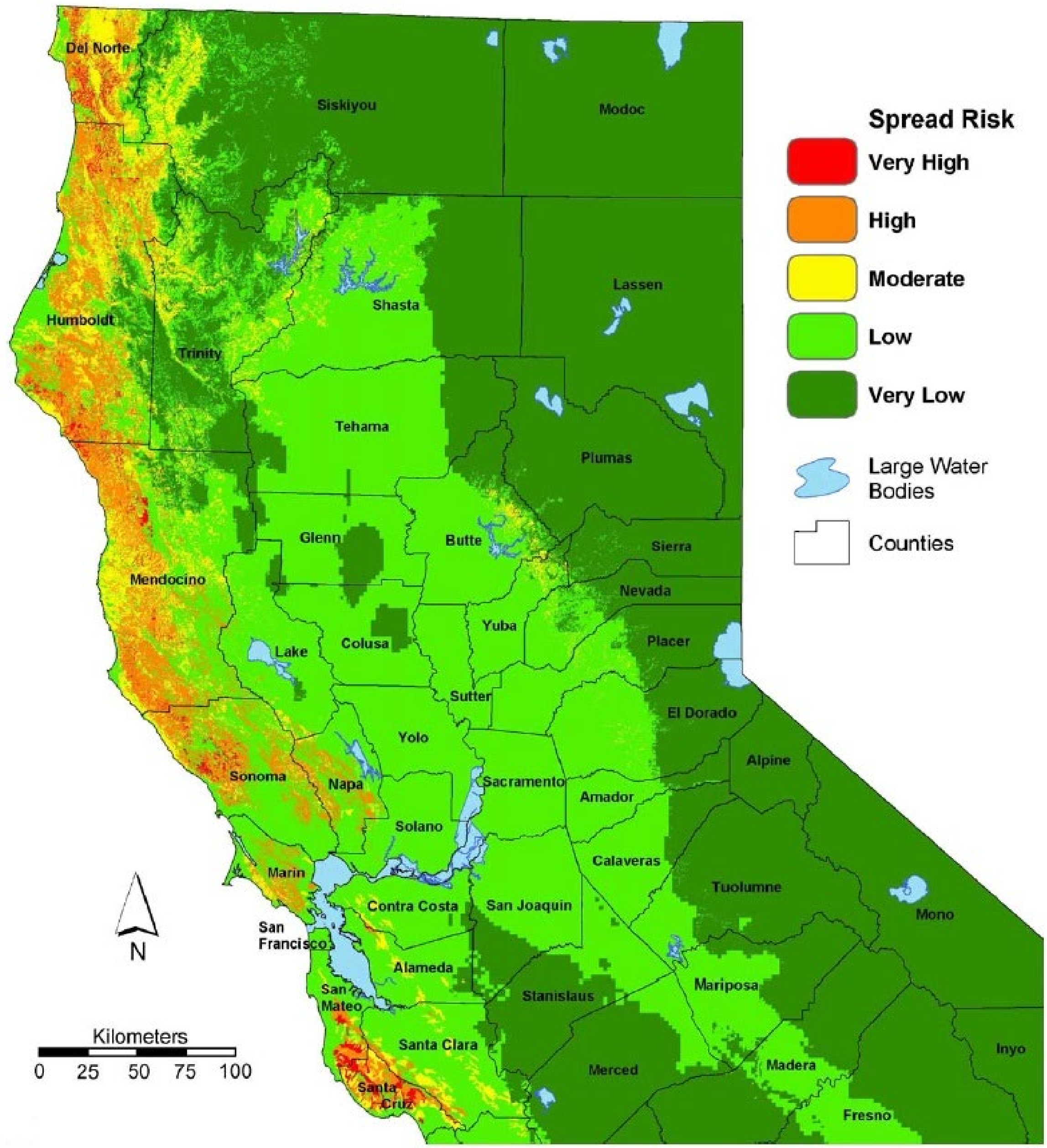

Figure 3. Map of the predicted spread risk of *Phytophthora ramorum* across California (obtained from Meentemeyer et al. 2004).

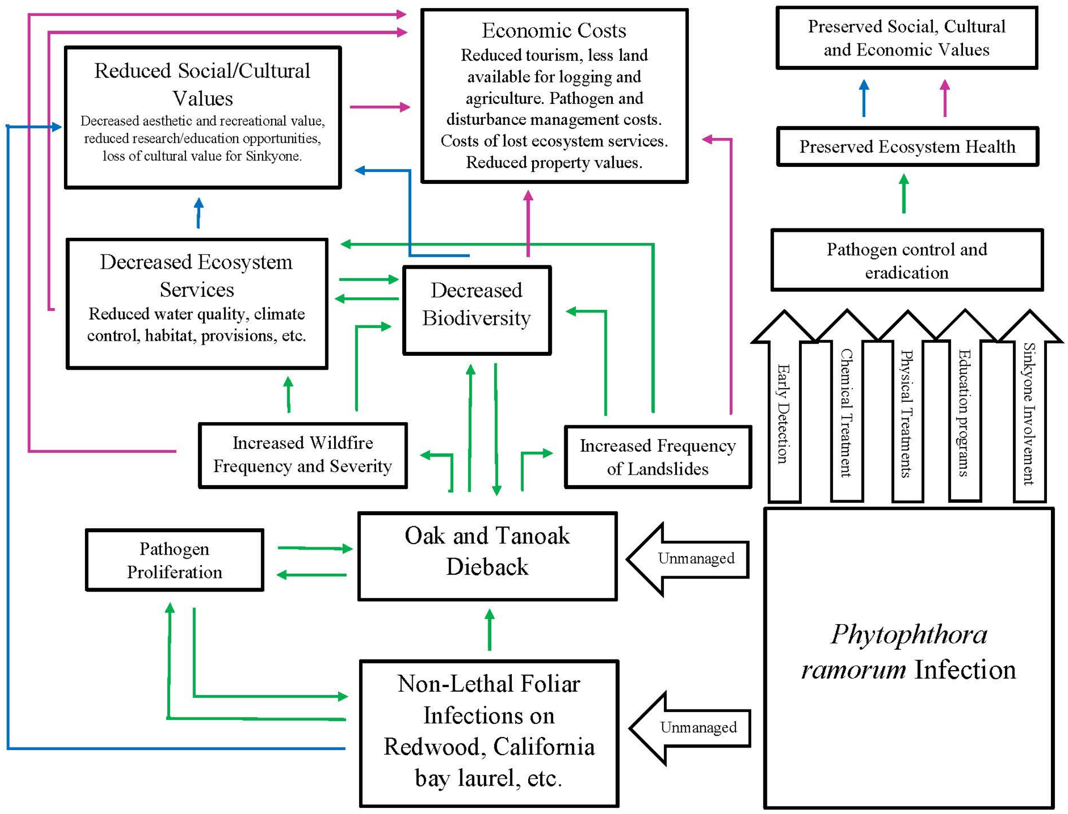

Figure 4. Diagram of interaction depicting pathways of managing *Phytophthora ramorum* infection and leaving it untreated. Quarantining or chemically treating the area can preserve ecosystem health, thereby maintaining the social/cultural, and economic values of southern Humboldt County. Failing to treat or manage the pathogen will have many negative consequences on social, cultural, economic, and ecological values due to the impacts of decreased biodiversity, decreased ecosystem services, and increased frequency of wildfires and landslides. Blue arrows indicate social/cultural impacts, green arrows indicate ecological impacts, and purple arrows indicate economic impacts.

Table 1. Matrix depicting the social, ecological, and economic impacts of different biological and anthropogenic systems in southern Humboldt County.

System Affecting Case Study Site	**Social, Ecological, and Economic Impacts**			**Management Goal**
	Social	**Ecological**	**Economic**	
Humboldt State Redwood Park	Provides recreation, education, and research opportunities. The park has historic and aesthetic value. Sinkyone have used tanoak as a source of food and materials for centuries.	Provides habitat and provisions to terrestrial species, improves water quality, mitigates soil erosion and flooding, sequesters carbon, improves air quality, and regulates local climate.	Tourism helps the local economy through park fees and supporting local businesses.	Use targeted ground surveys to mitigate pathogen spread in the forest. This will sustain recreational and aesthetic values; ecotourism; biodiversity; forest structure and composition; and ecosystem services.
Riparian Areas (Eel River, Bull Creek)	Provides recreation, education, and research opportunities. Riparian areas also have aesthetic value.	Provides habitat and provisions for aquatic species and water for plants and terrestrial organisms. Aquatic plants can enhance water quality through filtration.	Used for agricultural and municipal water, fishing, and promotes tourism.	Monitor riparian areas using stream baiting to minimize movement and track potentially vulnerable sites.
Disturbances (wildfires, landslides, pest/pathogen infections, invasive species)	Decreases recreational opportunities and creates loss of historic and aesthetic values. Reduced opportunities for research and education on vegetative and animal life, but increased opportunity to study disturbance regimes.	Decreases ecosystem services (reduces air and water quality, climate regulation, available habitat, and provisions).	Reduces tourism, land available for logging, cattle grazing, and recreation. Increases community costs due to management of disturbances and the reconstruction costs after a disturbance event.	Pathogen management will alter the severity and frequency of other natural disturbances by managing flammable fuel buildup and soil stability.

Roads	Provides access for researchers, tourists, and community members.	Splits the ecosystem, reducing ecosystem services and causing soil erosion.	Tourists and community members use roads to access desired areas, both who contribute to the economy by paying park fees, supporting businesses, having local jobs, etc.	Roads should be improved and monitored to reduce pathogen movement due to visitors. Washes and notices may be installed. Road improvement includes maintaining visitor access but reducing the impacts of habitat fragmentation.
Logging	Provides jobs for many community members.	Logging destroys habitats, reducing biodiversity and ecosystem services. It can increase air and water pollution and erode soil.	Provides income for many members of the community.	Monitor logging stands to prevent pathogen outbreak, maintaining the economic value of timber production.
Cattle grazing	Provides jobs for many community members.	Degrades natural habitats, reducing biodiversity and ecosystem services. It increases air and water pollution and erodes soil.	Provides income for many members of the community.	Degraded ecosystems are more vulnerable to other disturbances. Areas grazed by cattle should be monitored for symptoms of *P. ramorum* to minimize spread to nearby sites that may be susceptible.
Urban structures (buildings, parking lots)	Residential areas provide shelter for community members. Business buildings support jobs and parking lots make accessing areas easier.	Destroys natural habitats, reducing biodiversity and ecosystem services. Can increase air and water pollution and erode soil.	Urban structures may support the local economy through rent and mortgage payments. Parking lots and other structures have no clear economic value, but the removal would be costly.	Urban areas should incorporate soils and vegetation management to reduce pathogen movement and increase the urban forest's resilience to infection.

Table 2. Predicted analogous past and future climate periods for Humboldt County, California. All data was obtained from Burke et al. (2018) except for the "Historical" time period temperature difference, which was estimated from the IPCC AR5 (2014).

Future Year	Analogous Past Period	Temperature Difference
2020	Historical, 1940-1970 CE	0.2°C to 0.4°C warmer than preindustrial temperatures
2050	Mid-Holocene, ~ 6,000 years ago	0.7°C warmer than preindustrial temperatures

2100	Mid-Pliocene, ~ 3.3 – 3.0 million years ago	1.8°C to 3.6°C warmer than preindustrial temperatures
2200	Early Eocene, ~ 50 million years ago	13 °C ± 2.6°C warmer than late twentieth century temperatures

Table 3. Table of different *Phytophthora ramorum* management goals and treatment combinations, taken from Valachovic et al. (2009).

Goal	**Minimizing Property Impacts from Sudden Oak Death**	**Strategic Protection of Oak and Tanoak Islands, Old-Growth trees, or Particular Geographic Areas**	**Suppression of *Phytophthora ramorum* and Limitation of Spread**
Treatment	Dead tree removal¶	Manual removal of California bay laurel only[*,†]	Manual removal of bay laurel and tanoak (+/- prescribed underburning)[*]
	Reforestation	Agri-Fos® application[*,†,‡]	Modified fuel hazard reduction removal (+/- California bay girdling)[*]
	Maintain some tanoak with thinning (manual or by Agri- Fos®)¶	Combination of manual removal of bay laurel and Agri-Fos® application¶	Herbicide host removal (California bay laurel and tanoak)[*]
	Combination treatments to address site specific goals		

*Tested by Y. Valachovic and others in Del Norte, Humboldt, and/or Mendocino Counties
†Tested by T. Swiecki and others in Bay Area and surrounding coastal California area
‡Tested by M. Garbelotto, D.J. Schmidt, and others in Bay Area and surrounding coastal California area
§Tested by numerous researchers
¶Still untested

Table 4. Guidelines to determine the intensity of *Phytophthora ramorum* management required depending on distance to neighboring land, the proximity of the infected individual to other susceptible host species, what the infected species is, where the infection is found, the type of land use, and the object the infection is nearest. Management intensity increases as one moves from left to right.

Management Intensity →			
Proximity to Neighbors/Other Plots of Land			
> 300 m	200 m	100 m	< 50 m
Proximity of Infected Individual to Other Susceptible Host Species			
50 m	25m	< 10 m	< 1.5 m
Infected Species			
Low sporulating, low value species	Redwood	Coast Live Oak	California bay laurel or Tanoak
Location			
Urban Land	Suburban land	Urban/wildland interface	Wildlands
Type of Land Use			
Private land (Residential)	Private Land (Business)	Timberland	State Park
What is the Infection Closest to?			
Buildings and other city structures	Poor infrastructure (eroded soils, bad roads)	Streams, irrigation, water systems	Forest, host species

Table 5. The values, normative frameworks, and complementary core messages for discussing *Phytophthora ramorum* management across different landownerships and stakeholders.

Landowner or Stakeholder	**Value**	**Normative Framework**	**Core Messages for Discussion**
*‡Humboldt Redwoods State Park – Backcountry	Naturalness Beauty Ecocentric	Stewardship – preservation	Preserve inherent natural beauty Protect species' right to existence Responsibility as stewards to preserve redwoods for future generations
*‡Humboldt Redwoods State Park – Frontcountry	Anthropocentric – human happiness, access to knowledge, recreation, and aesthetic values	Stewardship – conservation Utilitarian – promote human happiness through recreational opportunities	Protect inherent natural beauty Responsibility as stewards to maintain social, cultural, natural, and economic values for current and future generations
*♦Logging Companies	Anthropocentric – monetary interests, providing quality products, maintaining resource productivity	Stewardship – resource conservation Utilitarian – monetary interests, product uses	Responsible resource use and conservation of ecosystems for current and future generation use
*Agricultural Businesses	Anthropocentric – monetary interests, human happiness, human subsistence	Stewardship – resource conservation Utilitarian – monetary interests, quality products	Responsible resource use and conservation of ecosystems for current and future generation use
**Nurseries	Anthropocentric – monetary interests, promoting human happiness through plant care	Utilitarian – promote human happiness (including own interests)	Responsibility to prevent contaminated materials from entering households, wildlands through the urban/wildland interface, and irrigation systems, and to maintain quality products for business and customers
**Homeowners	Biocentric – care about individual trees, trees in relation to property value and appearance	Care, Stewardship – personal property's health Utilitarian – financial limitations to property management	Caretaker – responsibility to nurture and protect one's own trees Responsible citizen – prevent spread to neighboring lands, maintain communities and their ecosystems for current and future generations, maintain aesthetics, property values, and ecosystem services
**▲Ecotourists	Anthropocentric – nature preservation for human	Consequentialism – "rightness" of ecotourism depends on the	Responsible action – follow guidelines to prevent long distance transport of pathogen to

	access to recreation, beauty, knowledge	costs/benefits of ecotourism on the system (pollution, local economics, etc.) Eudamonist Virtue Ethic – engaging in ecotourism promotes a flourishing life, allows people to pursue the potential for human excellence through psychological, spiritual, and knowledge fulfillment	preserve the social, cultural, economic, and ecological values for current and future generations
**♦Researchers	Knowledge Ecocentric – research conducted to promote species and ecosystem health	Deontological – duty to pursue scientific knowledge, for the sake of knowledge and for protecting ecosystem health Stewardship – responsibility to informed land management, can be conservation, preservation, or care	Conduct research to understand pathogen impacts, improve methods of management, develop new technologies, with the goal to protect trees, species, and ecosystem health for current and future generations
⸸♦Politicians	Anthropocentric – answering to human constituents, concerned about non-humans to the extent that they affect humans	Pragmatic – do what is required to appease constituents and follow policies. Deontological – upholding democratic principles	Policy that provides resources for pathogen management promotes human happiness by protecting social, cultural, and economic values of natural resources, and maintains resources for future generations
⸙Lolangkok Sinkyone	Non-anthropocentric – beauty, humans are not separate from nature, respect for all living things, non-human organisms have intrinsic value	Indigenous ethics - kincentric	Messages should be developed in dialogue/collaboration with tribal representatives.

*Information from mission statements.

- Humboldt Redwoods State Park: "The purpose of Humboldt Redwoods State Park is to preserve, protect, and perpetuate the outstanding natural and aesthetic values of the ancient redwood forests… Through careful stewardship, the solitude and grandeur of the park's cathedral-like forests, its inherent wilderness values, and significant cultural features shall remain unimpaired for the enjoyment of current and future generations." (https://www.parks.ca.gov/pages/1324/files/Environmental%20Draft.FINAL.sm.pdf)

- Humboldt Redwoods Company, LLC (logging): "Our commitment is to manage productive timberlands with a high standard of environmental stewardship, and also operate a successful business." (https://www.hrcllc.com/)

- Humboldt Grass-fed Beef: "A dedication to stewardship of the land, cattle and the natural resources provided by the uniqueness of our climate ensures that beef provided by Humboldt Grass-fed Beef is wholesome, healthy, and great tasting." (https://humboldtgrassfedbeef.com/)

ǂ Information obtained from the Humboldt Redwoods State Park management plans. The differences in management practices are the evidence for different values between the front and backcountry.

- Backcountry (including the primitive zone) focuses on preserving and protecting the forest, restoring old logged lands, and has some recreational uses. Frontcountry zone has most of the park's recreational facilities and is located near main roads. (https://www.parks.ca.gov/pages/1324/files/Environmental%20Draft.FINAL.sm.pdf)
**Information from personal experience (working with nurseries, working with researchers, being an ecotourist), and from the personal experience of others (primarily from Chris Lee (CAL – FIRE) and Susan Frankel (USFS PSW).

ⱡInformation from assumptions about policies that have been made, and those that have not. Some information from discussions with Chris Lee and Susan Frankel.

▲Information from Stark (2002), Wurzinger and Johansson (2006), Ballantyne and Packer (2013).

♦ Information from *The Foundations of Environmental Ethics* by Eugene C. Hargrove.

⸙Information obtained from readings by Frank Lake (USFS), Frederica Bowcutt (2013; 2015) and conversations with Chris Lee (CAL – FIRE).

APPENDIX III – SITE CHARACTERISTICS

Vegetation and Wildlife

The redwood forests of southern Humboldt County are highly diverse, with over one thousand plants listed in the CalFlora online database (National Park Service 2019). Among the most prevalent tree species are redwoods (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziesii*), tanoak (*Lithocarpus densiflorus*), madrone (*Arbutus menziesii*), Jeffrey pine (*Pinus jeffreyi*) and canyon live oak (*Quercus chrysolepsis*). There is also an abundant understory, primarily composed of rhododendron (*Rhododendron macrophyllum*), huckleberry (*Vaccinium* sp.), California bay laurel (*Umbellularia californica*), sword fern (*Polystichum munitum*), redwood sorrel (*Oxalis oregana*), salal (*Gaultheria shallon*), and azalea (*Rhododendron occidentale*).

Fauna in redwood ecosystems are also highly diverse with a wide variety of terrestrial, avian, and aquatic species. The most common terrestrial animals are ground squirrels, gray foxes, racoons, and black-tailed deer. Less common are black bears, mountains lions, and bobcats. Smaller organisms include banana slugs and snails (Humboldt Redwoods Interpretive Association n.d.). Dozens of bird species are supported by this ecosystem. There are many woodpecker species, finches, warblers, hummingbirds, owls, grouse, golden eagle, red-tailed hawk, bald eagle, flycatchers, goldfinches, sparrows, ravens, robins, wild turkey, jays, and osprey. Some species of migratory birds and anadromous fish require this site for only a portion of their life (Humboldt Redwoods Interpretive Association n.d.). Aquatic species are supported by Eel River and Bull Creek. The most common are lampreys, steelhead, Sacramento pikeminnow, Coho and Chinook salmon. River otters are also supported by this ecosystem but are not frequently seen (Humboldt Redwoods Interpretive Association n.d.).

Hundreds of species provide functional redundancy, which may help the forest resist stress and disturbances if one species decreases in abundance (Perry et al. 2008). However, there are a few key species that are essential to the food web and nutrient cycling, namely ground squirrels, black-tailed deer, and black bears. Ground squirrels disperse seeds and cones of many tree species. Black-tailed deer disperse seeds, maintain grass and small plant populations, and play a major role in nutrient cycling through the consumption and digestion of seeds, berries, twigs, grasses, and leaves (National Wildlife Federation n.d.). Black bears are opportunistic eaters, meaning that they eat birds, mammals, fish, insects, seeds, plants, and even garbage left by people in the park (National Wildlife Federation, n.d.). They assist nutrient cycling and provide top-down control on lower trophic levels.

Topography, Geology, and Soils

Redway is about 538' in elevation (Southern Humboldt Chamber of Commerce n.d.) However, nearby cities such as Weott, Redcrest, and Honeydew are between 300-400' above sea and the highest point of Humboldt Redwoods State Park is estimated to be a little over 3,000' above sea level, although most redwoods live below this level (U.S. Geological Survey 1981; Olsen et al. 1990). Aspect of slopes are SW/NE. Humboldt Redwoods State Park lies on the Mendocino Triple Junction where three tectonic plates meet, making it a seismically active area. These plates are the Gorda, North American, and Pacific plate. The plates have created steep slopes, which increases water erosion, thereby creating canyons and gorges (Fuller et al. 2015). These canyons and gorges create paths for water flow.

Most soils which redwoods survive on are from soft sedimentary rock (Olsen et al. 1990). The primary soil types in this site are Alfisols and Inceptisols. Slopes range from 2 – 110%. The soils are deep, moderate to well-draining, and have high runoff. Near Phillipsville and Redcrest, Entisols are present, which are deep and moderately well-draining. Soils within the more urbanized cities are considered "urban land" and do not have soils data (SoilWeb, n.d.) However, it is likely that soil within city limits are eroded due to compaction and construction. High runoff, low infiltration, and sloped topography may increase soil erosion.

Soil temperature ranges from 9°C – 16°C and are slightly to strongly acidic. The soils are isotic, meaning that they have higher pH-dependent charges than other soils and so are better able to bind phosphorous (Chiaretti et al. 2004). The slight acidity of the soil, and high precipitation, may lead to nutrient leaching. The isotic nature may prevent low phosphorous from being limiting. Soil organic matter (SOM) is about 75%, with decreases closer to city limits (SoilWeb, n.d.). Chemical inputs from gardening, construction, and trampling may negatively impact soil physical, chemical, and biological properties.

Rivers

Eel river is California's third largest watershed. It has more than 800 miles of river extending from Lake Pillsbury to the ocean. It has both state and federal funding to protect it from dams and pollution. It has four forks, with the south fork moving through redwood ecosystems. It is used for fishing and recreational purposes (National Wild and Scenic Rivers System, n.d.). A 14-mile-long tributary that connects with the south fork of Eel River, Bull Creek, cuts through Humboldt Redwoods State Park and is used for recreational purposes (U.S. Geological Survey 1981).

Disturbances

There are many anthropogenic sources of disturbance. Highway 254 and 101, smaller roads, trails, visitor centers, and public restrooms are in the park. Outside of the park there are scattered towns and cities. Rivers and a dense tree canopy may maintain connectivity in some areas, but larger highways, towns, and cities cause habitat loss and may reduce connectivity to the point of habitat fragmentation. There is ongoing timber production and cattle grazing in areas nearby, along the south fork of Eel River (Humboldt County Department of Community Development Services 2003). It does not directly affect the park but may indirectly through pollution.

Due to steep canyons, high precipitation rates, and seismic activity, landslides are common (Fuller et al. 2015). More common are wildfires, particularly in the dry months (late summer and early fall). It is predicted that due to climate change, wildfires will be less predictable, more frequent, and more severe (Humboldt County Government, n.d.). Estimations from Jolly et al. (2015) show that temperature and humidity in this site have remained stable since the 1970's. However, windthrow has increased and precipitation has decreased. Furthermore, fire season length has increased (Jolly et al. 2015). These data indicate that fire frequency is not changing, but that once fires ignite, they persist longer. Furthermore, fires from southern Oregon and California could drift to the site, influencing temperature, moisture content, carbon cycling, and aerosol-cloud interactions. Indirect impacts of disturbance from other areas may cause dimming or cooling effects at this site (Perry et al. 2008).

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