Journal of Environmental Management 92 (2011) 1292–1302

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Predicting the economic costs and property value losses attributed to sudden oak death damage in California (2010–2020)

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ARTICLE INFO

Article history:
Received 14 June 2010
Received in revised form
11 December 2010
Accepted 17 December 2010
Available online 9 January 2011

Keywords:
Natural disaster
Emerging infectious disease
Invasive species
Phytophthora ramorum

ABSTRACT

Phytophthora ramorum, cause of sudden oak death, is a quarantined, non-native, invasive forest pathogen resulting in substantial mortality in coastal live oak (*Quercus agrifolia*) and several other related tree species on the Pacific Coast of the United States. We estimate the discounted cost of oak treatment, removal, and replacement on developed land in California communities using simulations of *P. ramorum* spread and infection risk over the next decade (2010–2020). An estimated 734 thousand oak trees occur on developed land in communities in the analysis area. The simulations predict an expanding sudden oak death (SOD) infestation that will likely encompass most of northwestern California and warrant treatment, removal, and replacement of more than 10 thousand oak trees with discounted cost of $7.5 million. In addition, we estimate the discounted property losses to single family homes of $135 million. Expanding the land base to include developed land outside as well as inside communities doubles the estimates of the number of oak trees killed and the associated costs and losses. The predicted costs and property value losses are substantial, but many of the damages in urban areas (e.g. potential losses from increased fire and safety risks of the dead trees and the loss of ecosystem service values) are not included.

1. Introduction

Invasive species are non-indigenous animals, insects, plants, and pathogens that can degrade natural and managed habitats and have adverse economic impacts. There are approximately 50,000 invasive species in the United States and this number is increasing (Pimentel et al., 2005). In the U.S. alone, damage and control costs of invasive species are estimated at more than $138 billion annually (Pimentel et al., 2005). However, most damage and control costs of invasive species are based on unpublished reports, and more analyses of the economic costs based on theory and scientific research are needed.

Phytophthora ramorum, cause of sudden oak death, is a non-native forest pathogen resulting in substantial mortality in coastal live oak (*Quercus agrifolia*) and several other oak and closely related tree species on the Pacific Coast of the United States (Meentemeyer et al., 2008a). The disease was discovered in the California counties of Marin and Santa Cruz in the mid 1990s (Rizzo and Garbelotto, 2003). The pathogen was first identified in 2000, and sudden oak death (SOD) has reached epidemic levels in many coastal mixed evergreen forests along the California coast and in a few locations in southwestern Oregon (Vaclavik et al., 2010). As of September 2009, in the U.S., SOD infestations have been observed in fourteen counties in California (Fig. 1) and one county in Oregon. The Big Sur eco-region alone has been estimated to contain more than 225,000 standing dead forest trees in 2005 because of SOD (Meentemeyer et al., 2008a).

The sudden oak death pathogen appears to be a generalist species that has the potential to spread and kill oak trees throughout much of the United States (U.S. Government Accountability Office, 2006). The SOD pathogen causes both lethal and non-lethal infections in

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doi:10.1016/j.jenvman.2010.12.018

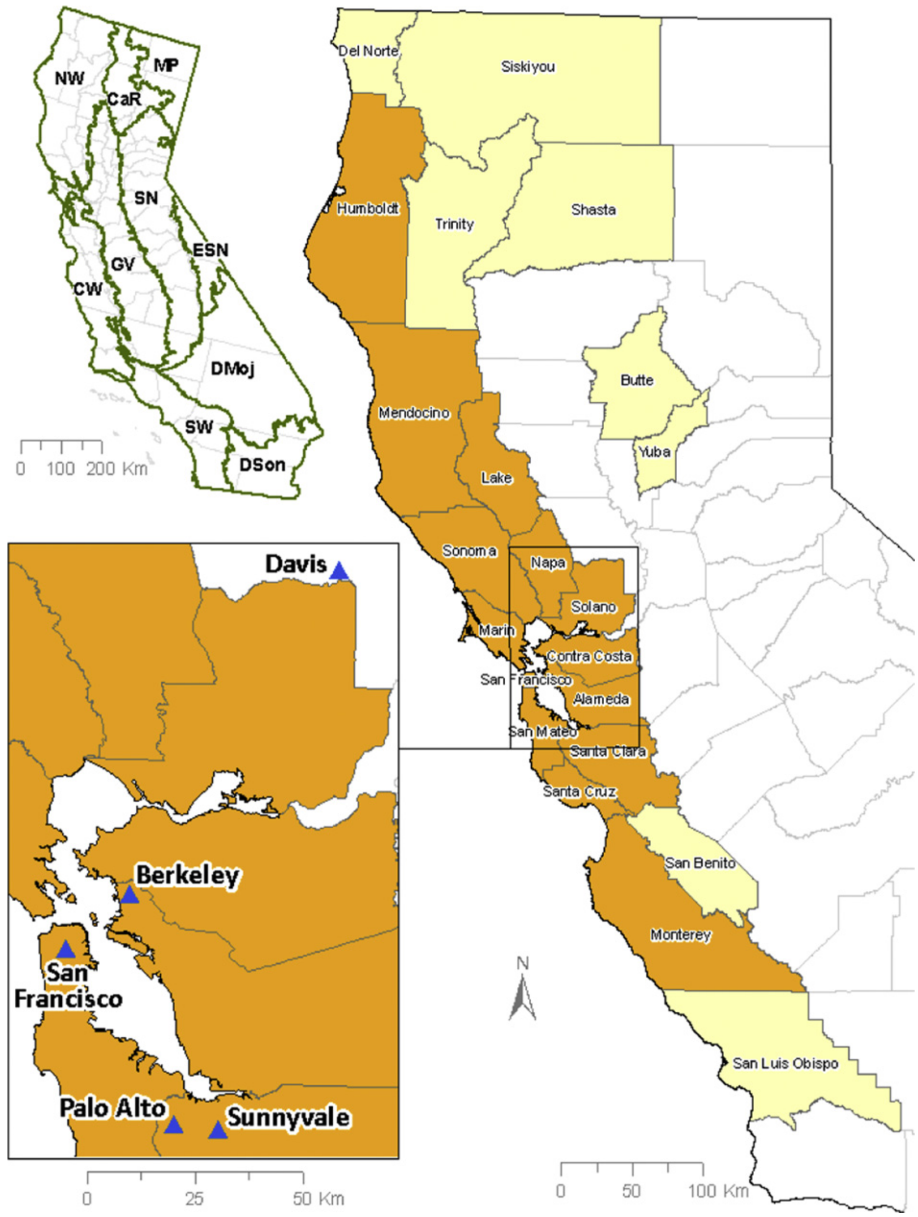

Fig. 1. Study area with California counties known to be infested by Sudden Oak Death in January 2010 (orange) and those predicted to be infested by 2020 (tan). The top-left map shows the mapping zones (NW-Northwestern California, CW-Central Western California, SW-Southwestern California, GV-Grand Central Valley, CaR-Cascade Range, MP-Modoc Plateau, SN-Sierra Nevada, ESN-Eastern Sierra Nevada, DMoj-Mojave Desert, Dson-Sonoran Desert) and the inset shows the cities with tree inventory information we used to estimate oak density.

plants. The lethal form of the disease infects the branches and stems of several ecologically important tree species including tanoak (*Notholithocarpus densiflorus*), coast live oak (*Q. agrifolia*), canyon live oak (*Quercus chrysolepsis*), California black oak (*Quercus kelloggii*), and Shreve's oak (*Quercus parvula var. shrevei*). Except for tanoak, these tree species are unlikely to transmit the disease to other host plants. In contrast, foliar hosts develop a different form of the disease; infected leaves and twigs of these species produce inoculum spores that can transmit the disease among hosts (Davidson et al., 2005).

More than twenty plant species in California and Oregon have been identified as foliar hosts, in particular California bay laurel (*Umbellularia californica*) and tanoak (Sansford et al., 2009). The potential for these foliar hosts to readily support *P. ramorum* growth and the pathogen's ability to disperse in wind-blown rain (Davidson et al., 2002), the broad geographic range of the host species (Meentemeyer et al., 2004), and the ability to infect and kill ecologically important oak species makes this emerging disease a serious threat to many forest ecosystems (Rizzo and Garbelotto, 2003).

In response to the threat of expanded extensive tree mortality posed by the sudden oak death, federal, state and local agencies and foreign governments have imposed quarantines to restrict the movement of nursery and forest plants, conduct surveys to detect new infestations, and support education and outreach, disease management, and research. These programs are costly, yet there is a limited economic literature on the expenditures and losses from the damage, especially in developed areas. While the SOD pathogen is found most commonly in forests, much of the economically quantifiable damage caused by the disease occurs on developed land because oaks are a valued community tree on streets, and in parks, and yards.

Table 1
Developed land and canopy cover in U.S. Census Communities and in all land in the study area.

California Counties	U.S. Census Communities		All land	
	Developed land (ha)	Canopy cover (ha)	Developed land (ha)	Canopy cover (ha)
Alameda	48,200	807	68,100	2,270
Butte	12,000	2,030	24,600	4,080
Contra Costa	46,800	3,590	64,600	4,750
Del Norte	1,580	184	12,500	5,360
Humboldt	9,300	1,880	30,500	10,000
Lake	4,930	327	17,400	2,460
Marin	13,100	2,180	20,300	4,300
Mendocino	2,710	234	45,600	17,200
Monterey	2,570	198	67,800	5,080
Napa	3,720	360	13,200	1,290
San Benito	6,710	18	16,300	606
San Luis Obispo	22,100	804	53,100	2,520
San Mateo	44,700	3,930	37,800	5,060
Santa Clara	40,400	657	90,700	4,270
Santa Cruz	32,800	4,240	22,500	5,180
Shasta	11,400	1,060	32,300	5,160
Siskiyou	2,900	283	39,000	10,800
Solano	21,500	611	28,600	646
Sonoma	15,200	1,260	45,100	5,730
Trinity	3,410	712	22,100	8,430
Yuba	3,380	598	9,200	966
Total	349,410	25,964	761,300	106,158

Some studies have forecast economic impacts of other invasive forest species, such as Kovacs et al. (2010) and Sydnor et al. (2007) for emerald ash borer (*Agrilus planipennis* Fairmaire) and Haight et al. (2010) for oak wilt (*Ceratocystis fagacearum*). Kovacs et al. (2010) predict that from 2009–2018 the emerald ash borer infestation will encompass 25 states and result in the treatment, removal, and replacement of more than 17 million ash trees within communities with a mean discounted cost of $10.7 billion. Sydnor et al. (2007) estimate the emerald ash borer could result in removal and replacement costs of $1.0–$4.2 billion in Ohio communities. Haight et al. (2010) predict that 76–266 thousand oak trees will become infected with oak wilt in the next decade in Anoka County, Minnesota, with discounted removal cost of $18–60 million.

Assessing the potential economic impacts of SOD is important in understanding the current and potential impacts of the pathogen, for evaluating the benefits of efforts to eradicate or slow the spread of SOD, and for investing in research and management. In 2008, state and federal governments spent about $10 million on regulatory, survey and detection, outreach and education, method and research investment on SOD (S. Frankel, personal communication, 2009). We estimate the discounted cost of tanoak and oak treatment, removal, and replacement and the discounted property value losses in developed communities in California by simulating the spread of SOD infestation over the next decade (2010–2020) and calculating the associated costs and property values losses.[1]

2. Methods

The study area (Fig. 1) includes the counties of California we predict will have oak mortality from the SOD pathogen by 2020. The next decade (2010–2020) was chosen for our analysis because, for a time frame of more than a decade, human caused dispersal of the pathogen may have significantly altered the study area, and for a time frame less than a decade, the analysis is susceptible to periodic changes in the intensity of the disease. Projecting the SOD infestation, costs, and property value losses further than a decade would require assumptions that are difficult to justify. The methodology for estimating the discounted cost of oak treatment, removal, and replacement follows the approach taken by Kovacs et al. (2010), and the methodology for estimating property value losses follows the approach developed in Aukema et al. (2010). Our approach to estimating the discounted costs and losses of the dead and dying oaks has three primary components. First, we estimate the number of oak trees on developed land. Next, we predict the communities that will be infested with SOD over a 10-yr horizon. Finally, we predict the number of trees affected in response to the infestation and compute the total discounted costs and losses.

Table 2
Developed land, canopy cover, and oak/tanoak (*Quercus* spp., *Notholithocarpus densiflorus*) density for selected cities and regions in California.

Areas	Developed land (ha)	Canopy cover (ha)	Oak trees per ha developed land	Oak trees per ha canopy cover
Cities				
San Francisco	11,392	422	0.14	10.24
Berkeley	2,547	259	1.59	15.63
Davis	2,284	168	0.77	10.49
Sunnyvale	5,055	–	1.81	–
Palo Alto	3,381	261	2.68	34.72
Mean	4,629	266	1.4	17.77
Region				
Marin County, CA	14,493	3,173	17.71	80.91
Sonoma County, CA (*Notholithocarpus densiflorus*)	45,141	5,727	–	88.10

2.1. Estimating the number of oak trees

We estimate the number of oak trees on developed land in U.S. Census-defined communities, geographic areas defined by jurisdictional or political boundaries and included in the U.S. Census definitions of places (census-designated place, consolidated city, and incorporated place).[2] We use a digital map of communities developed from the 2000 U.S. Census by the U.S. Forest Service for an assessment of urban and community forests as part of the Forest and Rangeland Renewable Resources Planning Act of 1974 (Nowak and Greenfield, 2008). Communities cover 546 thousand ha in our 10.4 million ha study area.

Communities are defined as places of established human settlement and may include both developed and undeveloped land within their boundaries. We estimate numbers of oak trees on developed land within communities because these oak trees will likely be the highest priority to treat, remove, and replace. We identify developed land using the 2001 National Land Cover Database (NLCD 2001). The NLCD 2001 is a raster-based land cover classification derived from satellite imagery and consistently applied with a 30 × 30 m resolution over the United States (Homer et al., 2007). The NLCD 2001 has four developed land cover classes based on the percentage of impervious surface and vegetation cover (Homer et al., 2004), and these four land classes cover 260 thousand ha of the 546 thousand ha of community land in our study area (Table 1).[3] We also report the area of tree canopy cover in the developed portions of communities based on NLCD 2001. Tree canopy covers about 9% (23,897 ha) of developed land.

[1] This does not include the costs of other adverse impacts of the pathogen, property damage from falling trees or fire, costs to industry due to market loss or treatment costs, increased management costs for sanitation, and direct losses of nursery stock.

[2] For detailed definitions, see http://www.census.gov/geo/www/cob/pl_metadata.html.

[3] For detailed information, see http://www.mrlc.gov/nlcd.php.

It is important to note that the U.S. Census contains a geographic definition of urban area based on population density in census blocks and block groups, which differs from our definition of community. U.S. Census-defined urban areas and communities may overlap but they are not congruent (see Nowak and Greenfield, 2008 for examples in the northeastern U.S.). We use communities as geographic units in this study because communities have geopolitical boundaries and people within these jurisdictions may organize and manage their oak trees in response to SOD infestation as a group.[4]

The numbers of oak trees on developed land in communities are estimated using forest inventory information for five cities (Table 2) that we obtained from web sites, publications, and personal communication with city foresters (Kovacs, 2009; Maco et al., 2005; Maco et al., 2004; Nowak et al., 2001). The inventory information includes estimates of the total number of oak trees within city boundaries, including trees on public and private lands. For each city, we divide the number of oak trees by the area of canopy cover on developed land to obtain an estimate of oak density (Table 2, right-hand column). Across the five cities, average oak density is 18 trees per ha of tree cover with a range of ten trees per ha in San Francisco to thirty-five trees per ha in Palo Alto.

The forest inventory information for cities is the basis for estimating numbers of oak trees on developed land within communities. First, we divide the study area into mapping zones (Fig. 1, top-left map). The mapping zones are from the NLCD 2001 and represent areas of relatively homogenous landform, soil, vegetation, and spectral reflectance (Homer et al., 2004). Then, we assign each city or region to a mapping zone and compute average oak density (trees per ha cover) for the zone (Fig. 1, inset).[5] If inventory information for a particular zone is not available, we use the oak density of the nearest zone. Finally, we multiply the average oak density times the area of tree cover on developed lands in communities to estimate number of oak trees in the mapping zone.

Since the cost of managing oak trees in areas of SOD pathogen infestation depends on tree size and land use, we also estimate the number of oak trees by size class and land use in the developed portion of communities in each mapping zone. The tree inventories for the cities of Berkeley and Palo Alto include estimates of all trees in non-residential areas for several diameter classes, and the city of Palo Alto includes estimates of all trees in residential areas for several diameter classes. The percent of developed land that is residential and non-residential comes from the zoning map for the city of Berkeley (City of Berkeley, 2009).[6] From this detailed inventory information, we compute oak density (trees per ha cover) for residential and non-residential areas over three tree diameter classes (2.5–30 cm, 30–61 cm, and > 61 cm) (Table 3). Because most of the city tree inventories only include estimates of numbers of oak trees, we use the relative oak tree densities across land use and size classes in Berkeley and Palo Alto to estimate oak tree densities by land use and size class in each of the other cities.

[4] A small number of "communities" may be historical or special-use districts that no longer have formal geopolitical boundaries.

[5] For example, if forest inventory information is available for three cities in a mapping zone, the average oak density of the three cities is the oak density for the zone.

[6] The zoning map for Berkeley is at the Department of Planning and Development web-site http://www.ci.berkeley.ca.us/ContentDisplay.aspx?id=6356. There is limited information about the proportions of residential and non-residential land in communities; though compared to the city of Palo Alto, we believe these proportions are similar to other communities in our study area. Communities not in a large metropolitan area may have a higher proportion of residential land.

Table 3
Oak (*Quercus* spp.) density by land use and diameter class for the California cities of Berkeley and Palo Alto.

Land use	Percent of developed land[a]	Oak trees per ha cover	Oak trees per ha cover by diameter class		
			2.5–30 cm	30–61 cm	>61 cm
Residential[b]	0.60	15.5	3.9	7.8	3.9
Non-residential[c]	0.40	21.6	11.7	6.8	3.1

[a] The percent of developed land that is residential and non-residential is based on the zoning map for Berkeley.
[b] This is based on the tree inventory for the city Palo Alto.
[c] This is based on the tree inventories for the cities of Berkeley and Palo Alto.

2.2. Predicting SOD mortality

Predicting the number of oak trees that die each year from SOD is a two-step process. First, we predict when during the interval 2010–2020 oak mortality begins in each community. Once oak mortality begins, we apply a fixed annual mortality rate to tally oak mortality during the remainder of the time horizon.

To predict when oak morality begins in each community, we use the results of a spatio-temporal, stochastic epidemiological model of SOD infection spread (Meentemeyer, 2009; Meentemeyer et al., 2011). The model predicts the number of infected host units in 250-m grid cells in weekly intervals. The model accounts for environmental heterogeneity by partitioning California into 250-m grid cells containing multiple susceptible and infected host units, which are subject to variable weather conditions through time. The total number of host units in each 250-m cell is mapped as the composite abundance of *P. ramorum* host species, weighted by susceptibility and capacity for inoculum production (Meentemeyer et al., 2004; Vaclavik et al. 2010).

Pathogen spread within and between grid cells is driven by local weekly weather conditions, host density, forest phenology, and a dispersal kernel that describes spatial spread. Stochasticity influences three epidemiological processes in the model: a) inoculum production at a given location, b) the possibility that inoculum is dispersed between locations, and c) the chance of infection following dispersal to a susceptible location. The model assumes that infection of location (cell) j during week t occurs as a Poisson process of rate $\phi_{jt} = \sum_i \psi_{ijt}$ where ψ_{ijt} is the rate of spread from an infected location i to location j during week t. The contribution of infection from location i to location j is modeled as:

$$\psi_{ijt} = \beta(\chi_t(f_i)m_{it}c_{it}I_{it})\left(\chi_t\left(f_j\right)m_{jt}c_{jt}S_{jt}/N^{\max}\right)K\left(d_{ij};\alpha_1,\alpha_2,\gamma\right)/d_{ij}, \quad (1)$$

where $\chi_t(f_j)$ is the phenological variable, equal to 1 if cells of forest type f_j can infect and be infected at time t and 0 otherwise; m_{jt} and c_{jt} are space- and time-dependent weather conditions; I_{it} and S_{jt} are the number of infected and susceptible host units at time t in cells i and j; N^{max} is the maximum number of host units in any site; $K(d_{ij};\alpha_1,\alpha_2,\gamma)$ is a stochastic dispersal kernel for movement of inoculum over distance d_{ij} estimated using scale parameters α_1, governing the scale of short-range movement; α_2, governing the long-range movement; and γ, governing the proportion of spore units that are locally dispersed; and β controls the rate of stochastic spore production (Meentemeyer, 2009; Meentemeyer et al., 2011).

To apply the spread model, the spatial distribution and abundance of susceptible hosts is composited to produce a 250-m grid cell host competency index map (Meentemeyer et al., 2004), which is then scaled to an integer values ranging 0–100. The moisture suitability index, scaled 0–1, represents the number of days in week t with precipitation greater than 2.5 mm, and a temperature suitability index, also scaled 0–1, represents the temperature dependence of *P. ramorum* inoculum production and was calibrated using data concerning effects of seven temperature treatment levels (Davidson et al., 2005). The weather condition indices were also mapped for each week at the 250-m resolution via spatially interpolated estimates of daily precipitation and mean daily temperature (Hunter and Meentemeyer, 2005). The scale parameters for the local and long distance dispersal are based on records of the presence and absence of the disease obtained from i) aerial surveys in Humboldt county (Valachovic et al., 2008) and ii) all known *P. ramorum* positive locations confirmed by the California Department of Food and Agriculture (Meentemeyer et al., 2008b) and maintained by the California Oak Mortality Task Force (COMTF; Kelly and Tuxen, 2003). Parameters for dispersal (α_1, α_2, γ) and inoculum production β are estimated using Markov chain Monte Carlo (MCMC) techniques (e.g. Gilks et al., 1996).

The model was initiated by introducing a single infested host into each of three susceptible locations in central western California (Fig. 1) on January 1, 1990, based on the current understanding of invasion history (Mascheretti et al., 2008, 2009; Rizzo et al., 2005). Then, we made 1000 simulations of pathogen spread and infection from 1990 to 2020. From these simulations, we computed the average infection density in each cell at the beginning of each year between 1990 and 2020.

The average infection densities in 250 m cells are used to determine when oak mortality begins in each community in the period 2010–2020. First, we overlaid the grid of cells with a digital map of communities and computed summary statistics of infection density in each community, including the mean, maximum, and the sum of the predicted infection density.

Then, we multiplied the statistics by the proportion of the community that is susceptible to infection. Finally, we compared the statistics to predetermined thresholds and assumed that tree mortality begins when the all three statistics exceed their thresholds.

The thresholds for mean, maximum, and sum of infection density were determined using model projections of infection density and observations of oak mortality in 14 counties between 1990 and 2010. Using model projections of infection density, we computed summary statistics for each county at the beginning of each year from 1990 to 2010. Then, we noted the year in which oak mortality was first observed in each county from a chronology of SOD-related oak mortality compiled by COMTF and expert opinion (COMTF, 2009; D. Rizzo, personal communication, July 22, 2009).[7] Finally, we selected the highest level of each county-level statistic from the years in which oak mortality was first observed. The resulting thresholds for the mean, maximum, and the sum of the predicted infection density are 0.002, 0.012, and 0.084, respectively.

When the projections of mean, maximum, and sum of infection density exceed their thresholds in a community, we assume that the oak mortality commences and proceeds at a constant rate for the remainder of the horizon. In the following paragraphs, we explain how we estimated the extent of infected woodlands within counties, and annual mortality rates for coast live oak and tanoak from observations of oak mortality in infected woodlands.

We used aerial surveys of oak mortality in 2002 from the U.S. Forest Service Forest Health Protection program to determine the extent of infected woodlands in four counties (U.S. Forest Service, 2010). Marin and Santa Cruz counties, with known SOD-related tree mortality since 1995, have 6% to 10% of the area of the county generally infested by 2002. Sonoma and Monterey counties, with known SOD-related tree mortality since 1999, are 1% to 3% generally infested by 2002. Based on these observations, we assume that, when oak mortality becomes noticeable, 5% of its area is generally infested.

Generally, SOD infested areas appear in patches; some oak woodlands and tanoak forests may be heavily infected while an adjacent valley may show no signs of the infection. For example in the Big Sur eco-region, Meentemeyer et al. (2008a) observed 8% of the oak woodlands and 36% of the tanoak forests to be infected as of 2005, and in eastern Sonoma County Meentemeyer et al. (2008c) found that 16% of the oak woodlands were infected as of 2006. McPherson et al. (2002) observed intensification of SOD in areas of Marin County with 35% and 16% in 2000 followed by 38% and 19% in 2001 of the oak woodlands, respectively. In tanoak forests, McPherson et al. (2002) observed increases in infected areas of 40% in 2000 to 55% in 2001. Based on these observations of the patchiness of SOD infection within a generally infested area, we assume that, when oak mortality begins in a community, 1% of the community's area is covered by infested coast live oak forest and 2% of the area is covered by infested tanoak forest.

The annual rate of *P. ramorum* mortality in infested coast live oak woodlands has been shown to range between 2% to 5% per year (Maloney et al., 2005; Meentemeyer et al., 2008a; McPherson et al., 2002) with up to 6% per year in tanoak forests (Maloney et al., 2005; Meentemeyer et al., 2008a). Adjusting these mortality rates by our assumptions of the area proportions of infected coast live oak and tanoak forests within counties, we assume a 0.04% per year mortality rate for coast live oak (based on an infected area of 1% and a rate of mortality of 4%) and a 0.1% per year mortality rate for tanoak (based on an infected area of 2% and a rate of mortality of 6%).

2.3. Estimating the costs of SOD damage

Once oak mortality from the SOD pathogen begins in a community, we assume that a homeowner or community tree manager maximizes the present value of net benefits associated with each oak tree by choosing among four actions—1) do nothing, 2) remove, 3) remove and replace, or 4) treat with a fungicide and by trimming or removing California bay laurel trees, to prevent injury from SOD (Kovacs et al., 2010).[8] The optimal action from an economic perspective is to remove and replace smaller oak trees (<45 cm diameter for homeowners and <61 cm diameter for tree managers) with non-susceptible species and treat larger oak trees.[9] Larger oak trees have high value that can be sustained through time with treatment. Conversely, it is better to remove and replace small oak trees to hasten the benefits of longer-living replacement trees and avoid the cost of treatment. Because of the patchy nature of SOD invasions, we assume that 5% of the large trees of a community, those within the generally infested area, are treated when oak mortality from the SOD pathogen is first observed in the community.

Many communities and homeowners have been observed to "do nothing" when their oaks trees are killed by the SOD pathogen (S. Frankel, personal communication, April 23, 2010). This choice of no action usually occurs within the interior of large parks or on the

[7] Except for Marin and Santa Cruz counties, where large numbers of tanoaks are first observed dying in 1995, the SOD chronology refers to the date of confirmation of the SOD pathogen in a county by the California Department of Food and Agriculture.

[8] The model assumes that 40% of the treated trees still become infected (Garbelotto 2010; Garbelotto and Schmidt 2009).

[9] The decisions are optimal according to the model, but a number of factors, for example sentimental attachment, uncertainty surrounding the effectiveness of the treatment, or a limited budget for tree removal and replacement, could result in a different decision by homeowner or tree manager.

Table 4
Management costs estimated for homeowners and community managers based on oak tree diameter at breast height (DBH; 1.4 m aboveground). Costs estimates are from arborists in Marin County, California (Alexander et al. 2009; A. Mammone, personal communication, April, 29, 2010).

Landowner	Costs ($/tree)			
	Remove	Remove and replace	Treat	
			Pruning Bay Laurel	Fungicide
	Tree size = 2.5–30 cm in DBH			
Homeowner	$850	$1250	$315	$27
Community	$640	$940	$291	$25
	Tree size = 30–61 cm in DBH			
Homeowner	$1,250	$1,750	$700	$60
Community	$940	$1,340	$583	$50
	Tree size = >61 cm in DBH			
Homeowner	$2,400	$3,000	$1,167	$100
Community	$1,800	$2,300	$875	$75

lots of exurban dwellings where human contact with infected oaks is more limited. To account for this, we estimated no action is taken to treat, remove, and replace oak trees on twenty percent (City of Berkeley, 2009) of non-residential land within communities (park, institutional, and industrial land) and thirty percent (San Mateo County, 2009) of residential land outside communities (low-density exurban dwellings). The costs of removal and replacement depend on tree size, with community managers paying slightly less than homeowners (Table 4). Removal and replacement costs come from arborists (Alexander et al., 2009; A. Mammone, personal communication, April 29, 2010) and represent the costs of managing 15 cm, 45 cm, and 76 cm diameter trees.[10] The replacement trees recommended by arborists include the valley oak (*Quercus lobata*) and interior live oak (*Quercus wislizenii*) since these oaks are not susceptible to infection by SOD and support more wildlife than forests without any oaks. Treatment to prevent injury from SOD commonly involves: a) spraying or injecting a systemic fungicide directly into the trunk of the tree, and b) removing or pruning of California bay laurels. A fungicide with phosphites AGRI-FOS® amended with the surfactant Pentrabark™ prevents infection and injury from SOD for two years (Garbelotto and Schimct, 2009). In California, bay laurel is the most common foliar host plant for SOD pathogen and reducing their contact with oaks, by removing or pruning them, may lower the risk of transmission to neighboring oaks (Swiecki and Bernhardt, 2008b). To calculate the treatment costs (Table 4), we combine together the costs of the fungicide and the bay laurel pruning (Alexander et al., 2009) and assume that retreatment by the fungicide is required every two years and that the bay laurel pruning is for a 30–61 cm size tree.

Based on the predicted spread of the SOD pathogen from the spread model, the annual discounted treatment, removal and replacement costs take place over the 10-yr horizon. Larger trees (>45 cm diameter for homeowners and >61 cm diameter for tree managers) are treated by trimming bay laurel immediately and applying a fungicide every other year until the end of the 10-yr horizon. Smaller trees (<45 cm diameter for homeowners and <61 cm diameter for tree managers) are removed and replaced at the time of mortality. For homeowners, half the oak trees in the tree diameter size class 30–61 cm are treated, and the other half are removed and replaced. The annual treatment, removal, and replacement costs are discounted to the present with a 2% real discount rate.[11]

2.4. Estimating property value losses of SOD damage

We calculate property value losses to homeowners from SOD by finding the sum of: a) the net present value of the reduction of property value of having a dying tree on the property for the number of years the dying tree is on the property, and b) the net present value of the reduction of property value of having reduced tree canopy on the property for the number of years the property has reduced tree canopy:

$$\text{Property value loss} = P*H*\theta*\left\{\frac{DV_1}{r}*\left(1-\frac{1}{(1+r)^{T_1}}\right)+\frac{DV_2}{r}*\left(1-\frac{1}{(1+r)^{T_2}}\right)\right\} \quad (2)$$

where P is the median value of a single-family home, H is the number of homes with oak tree canopy, θ is the proportion of oak trees removed or treated from the previous section,[12] DV_1 is the percentage discount to home price of having a dying tree on a property, T_1 is number of years a dying tree is on the property, DV_2 is the percentage discount to home price of having reduced tree canopy on the property,T_2 is the number of years the property has reduced tree canopy, and r is the 2% real discount rate.

The median value of a single-family home by county comes from the Census.[13] The number of homes with oak tree canopy is the product of the number of homes with tree canopy and the proportion of homes with oak tree canopy. The number of homes with tree canopy comes from the NLCD land base for tree canopy on developed land in communities, the proportion of land that is residential, and the number of homes per hectare of developed land (Marin County, 2009; San Mateo County, 2009). The proportion of homes with oak tree canopy is the product of the oak density (oak trees per hectare developed land) and the inverse of the number of homes per hectare of developed land.

The percentage discount to home value of having a dying tree on a property and the number of years the dying tree is on the property, based on hedonic property price studies, is the discount of 5% for three years (Holmes and Smith, 2008; Holmes et al., 2006; Huggett et al., 2008; Kovacs et al., in press). After the three-year period, most of the dead and dying trees are presumably removed from an infected area, but the resulting reduction in tree canopy causes an additional discount to the property, estimated from hedonic property price studies at 0.5% (Anderson and Cordell, 1988; Sander et al., 2010; Netusil et al., 2010). After ten years of this discount, we assume a replacement tree provides comparable tree canopy.

2.5. Sensitivity analysis

U.S Census-defined communities are places of established human settlement, yet urban development also exists outside

[10] Removals alone can cost from $500 to $5,000 depending upon the proximity of the tree to structures and the level of difficulty involved in its removal. Ray Moritz, a consulting arborist in Marin County, estimates a $3 million/year increase in work for tree companies in Marin County (Frankel, 2003). Communities have lower costs of oak removal and treatment than individual homeowners because the Department of Public Works owns equipment for regular tree maintenance. Also, the cost of tree removal and treatment depends on tree size. We estimate costs for communities and for three tree sizes based on proportions from the EAB cost calculator for Indiana (http://www.entm.purdue.edu/EAB/).

[11] Howarth (2009) observes that the future benefits of a public good, such as the removal and replacement of a dead oak tree, should be discounted at a rate close to the market rate of return for risk-free financial assets.

[12] The homes with oak trees being treated may also experience property value discounts because the oak tree is perceived to be at risk of infection.

[13] The home value, which is the average for the period 2005 to 2007 for California, is converted into 2009 dollars.

community boundaries (Nowak and Greenfield, 2008). To account for development outside communities, we expand the land base to include all developed land as defined by the NLCD 2001. The developed land classes in the NLCD 2001 have been used extensively to estimate land cover associated with urban development (e.g., Brown et al., 2005, Burchfield et al., 2006). In the sensitivity analysis, we estimate the number of oak trees on developed land both inside and outside communities. We include forest inventory information from two regional studies of oak resources (Table 2). From the oak tree density of China Camp State Park and proportion of oak trees on residential and non-residential land from the tree inventories for Berkeley and Palo Alto (Kelly et al., 2008; Kovacs, 2009), we estimate a coast live oak density of 81 trees per ha cover for the County of Marin. Swiecki and Bernhardt (2008a) measured tanoak tree density (*N. densiflorus*) in forested plots along roads in Sonoma County, and we estimate 88 trees per ha cover outside communities.[14]

We assume that oak trees on developed, residential land outside communities will be treated or removed and replaced in response to SOD infestation in the same fashion as trees inside communities; however, trees on developed, non-residential land[15] will not be managed in response to SOD and incur no cost tabulated for this study.[16] The proportion of residential land on developed land, outside of the communities, is based on the general and housing plans for San Mateo and Marin Counties (Marin County, 2009; San Mateo County, 2009).[17] With these assumptions, we determine how this larger land base affects the discounted cost of oak treatment, removal, and replacement and property value losses.

3. Results

We estimate 734 thousand oak trees grow on developed land within communities in the study area (Table 5), ranging from 545 oak trees in San Benito to 127 thousand oak trees in Santa Cruz. The county with the largest oak population (Santa Cruz) has a large amount of canopy cover on developed land (4,240 ha) and high oak density (35 trees per ha cover). The county with the smallest oak population (San Benito) has a small amount of canopy cover on developed land (18 ha).

3.1. SOD infestation

We predict that the area of SOD infestation will steadily expand from its current distribution in 2009. Newly infested counties occur primarily on the perimeter of the existing area of infestation. By 2020, the infestation is predicted to cover most of the northern part of the state, and one county further south. An example of the simulated progression of the SOD infestation is shown in Fig. 2. Note that the infestations predicted to occur in Butte and Yuba counties result from the expansion of existing SOD infestations in the northern most counties of the state.

Table 5
Estimated number of oak and tanoak trees in developed areas of communities and number of oak trees that are either replaced, removed, or treated under the SOD infestation. The sensitivity analysis shows the result of expanding the land base to include all developed land as defined by the National Land Cover Database 2001.

California Counties	Base case		Sensitivity analysis	
	Oak trees	Oak and tanoak trees treated or removed	Oak trees	Oak and tanoak trees treated or removed
Alameda	24,277	376	36,931	582
Butte	44,973	238	58,574	307
Contra Costa	107,910	1,672	117,966	1,836
Del Norte	5,557	86	50,240	812
Humboldt	56,737	878	126,949	2,018
Lake	9,881	153	28,329	453
Marin	66,072	1,022	84,313	1,318
Mendocino	7,076	109	153,159	2,483
Monterey	5,961	92	48,076	777
Napa	10,902	169	18,963	300
San Benito	545	7	5,618	79
San Luis Obispo	24,181	292	38,996	478
San Mateo	118,309	1,833	127,996	1,991
Santa Clara	19,759	306	50,966	813
Santa Cruz	127,383	1,974	135,535	2,106
Shasta	23,536	164	50,676	350
Siskiyou	6,284	65	75,981	792
Solano	2,804	57	2,834	58
Sonoma	37,973	587	76,554	1,214
Trinity	21,531	333	88,093	1,414
Yuba	13,281	93	15,710	109
Total	734,932	10,508	1,392,460	20,289

3.2. Cost and property value losses of SOD damage

Over the 10 year period, the discounted cost of treating, removing, and replacing oak trees on developed land in communities is $7.5 million, and the discounted property value losses is $135 million (Table 6). A majority of the cost is incurred by removing and replacing small oak trees on residential land. The larger of mid-sized oaks are treated which is less expensive than being removed and replaced. For comparison, although this would never occur, if all 734 thousand oak trees on developed land in communities are assumed to be removed and replaced or treated at once, the total cost is $729 million, nearly one hundred times our estimate, and the property value loss is $8.3 billion, more than sixty times our estimate. The difference reflects our prediction that one-hundredth of the 734 thousand oak trees in study area communities will be treated or removed and replaced in the 10-yr horizon and our assumption that costs and losses incurred later in the horizon are discounted.

Roughly 1% of the oak trees on developed land in communities (10.5 thousand) are treated or removed and replaced over the 10-yr horizon (Table 5). Counties have similar proportions of oak trees that are treated or removed and replaced, except for slightly lower proportions for the counties infested later in the 10-yr horizon (Butte, Shasta, Siskiyou, and Yuba), and slightly higher proportions for counties infested at the beginning of the 10-yr horizon (Alameda, Contra Costa, Monterey, San Mateo, Santa Clara, and Santa Cruz). Counties with high property value losses are those with high home values and with more than seven hundred oak trees predicted to be treated or removed and replaced early in the study period (Marin, San Mateo, Santa Cruz, and Sonoma). Since the property values discount from dying trees of 5% might not be applicable to all housing markets in California, property value losses are calculated for a standard deviation downward at 3% and upward at 7% (Kovacs et al., in press). Property value losses are $93 million on the low-end and $178 million on the high-end. Sensitivity of property value

[14] Few communities have suitable habitat for tanoaks (Meentemeyer et al. 2004). Thus, the mortality of tanoaks has limited influence on the discounted costs except for the exurban developed land outside of communities in northern California counties.

[15] This is the 2001 National Land Cover Class for "Developed, Open Space." These are areas where impervious surfaces account for less than 20% of total cover. This includes large-lot single-family housing units, parks, and golf courses (MRLC, 2009).

[16] Some oaks near power lines or other valuable structures on non-residential land may be removed, which incurs costs not included in this study.

[17] We estimate that the proportion of residential land on developed land, the average of San Mateo and Marin counties, is 0.28.

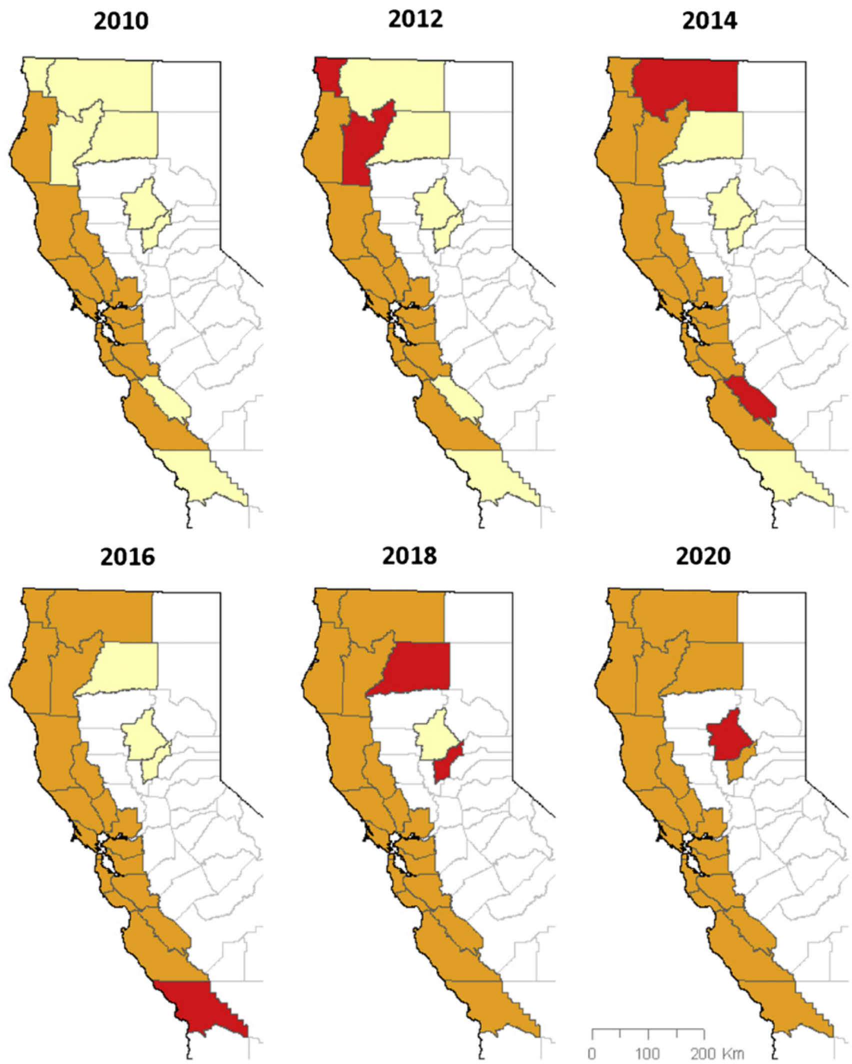

Fig. 2. A simulation of *P. ramorum* distribution in California counties from 2010 to 2020. Red counties are newly invaded, orange counties became infested in prior years, and tan counties are not yet infested. These maps represent the average of 1000 stochastic simulations.

losses to the discount assumption indicates that more studies of the effect of dying trees on property values are needed.

Further details of the discounted costs by land use and tree size are shown in Table 7. Most of the discounted costs are on residential land and for the removal and replacement of oaks. Homeowner costs per tree for removal, replacement, and treatment on residential land are higher than tree manager costs per tree on non-residential land. Large oaks in residential areas warrant the costly pruning of neighboring bay laurel, but homeowners only treat large trees within the small generally infested area. When the fungicide treatment is not effective, the removal and replacement of the large oaks contribute to the discounted costs.

3.3. Sensitivity analysis

Expanding the land base to include all developed land as defined by the NLCD 2001 more than doubles the estimate of number of oak trees from 735 thousand to 1.4 million (Table 5). Using the larger land base, we estimate that the number of oak trees treated or removed and replaced in response to the SOD infestation (20.3 thousand) is almost twice as many as we estimated using developed land within U.S. Census-defined communities (10.5 thousand). Much of this increase is attributable to the tanoak that is plentiful in the northern California counties. Similarly, the discounted cost of treatment, removal, and replacement ($14.9 million) and property value losses ($350 million) for all developed land is almost twice the estimate of the discounted cost ($7.5 million) of treatment, removal, and replacement and more than twice the property value losses ($135 million) on developed land within communities.

We note that the proportion of oak trees that are treated or removed and replaced in the sensitivity analysis is roughly the same as the proportion of oak trees treated or removed and replaced in the base case. This is the case even though non-residential trees on developed land outside communities are not treated or removed and replaced in response to infestation.[18] The additional oak trees treated, removed and replaced are the tanoaks which are much more prevalent on land outside of communities. The sensitivity analysis demonstrates that estimates of the number of oaks and cost of SOD damage are dependent on the data source and definition of the land base.

[18] We assume oaks on non-residential land outside of communities do not influence properties since the trees are not sufficiently close to dwelling structures to have an effect on properties. The optimal action is "do nothing" since any other actions yield no benefits and is costly. 30

Table 6
Estimated costs of treatment, removal, and replacement of oak trees and the property value losses under the SOD infestation. The sensitivity analysis shows the result of expanding the land base to include all developed land as defined by the National Land Cover Database 2001.

California Counties	Base case			Sensitivity analysis		
	Oak and tanoak trees treated or removed	Cost (2010 $ thousands)	Property value losses (2010 $ thousands)	Oak and tanoak trees treated or removed	Cost (2010 $ thousands)	Property value losses (2010 $ thousands)
Alameda	376	$265	$4,693	582	$411	$13,200
Butte	238	$170	$421	307	$220	$848
Contra Costa	1,672	$1,178	$20,400	1,836	$1,294	$27,000
Del Norte	86	$61	$384	812	$578	$3,084
Humboldt	878	$626	$5,509	2,018	$1,438	$26,500
Lake	153	$163	$901	453	$482	$6,802
Marin	1,022	$729	$17,800	1,318	$940	$35,100
Mendocino	109	$78	$927	2,483	$1,768	$22,800
Monterey	92	$65	$1,206	777	$552	$30,700
Napa	169	$120	$2,100	300	$213	$7,547
San Benito	7	$7	$80	79	$76	$2,675
San Luis Obispo	292	$257	$2,240	478	$423	$7,007
San Mateo	1,833	$1,291	$29,200	1,991	$1,403	$37,500
Santa Clara	306	$216	$4,379	813	$577	$28,400
Santa Cruz	1,974	$1,390	$28,000	2,106	$1,485	$34,200
Shasta	164	$134	$425	350	$286	$2,071
Siskiyou	65	$61	$192	792	$740	$2,430
Solano	57	$33	$7,472	58	$33	$7,902
Sonoma	587	$419	$7,004	1,214	$865	$32,000
Trinity	333	$237	$1,903	1,414	$1,008	$22,500
Yuba	93	$75	$249	109	$89	$401
Total	10,508	$7,574	$135,484	20,289	$14,882	$350,666

Table 7
Discounted removal, replacement, and treatment cost (2010 $ thousands) of the predicted SOD infestation for homeowners and community managers based on oak tree diameter at breast height (DBH; 1.4 m aboveground).

Land use	Diameter class (cm)			Total
	2.5–30	30–61	>61	
Residential	$3,554	$1,739	$1,625	$6,919
Non-residential	$242	$133	$280	$655
Total	$3,796	$1,873	$1,905	$7,574

4. Conclusions

Our estimate of the discounted cost of treatment, removal, and replacement in response to SOD infestation over a 10-yr horizon from 2010–2020 is $7.5 million and the discounted property value losses is $135 million. Since the cost of treating, removing, and replacing all the 734 thousand oak trees on developed land in communities at once is $729 million and the property value loss is $8.3 billion, a valuable oak resource is clearly at risk. The predicted costs and property value losses are substantial, but a full accounting of the damages in urban areas would include the potential losses from increased fire and safety risks of the dead trees and the loss of ecosystem service values.

In addition to the land base assumption that we tested in the sensitivity analysis, other assumptions may affect our estimates of treatment, removal, and replacement costs and property value losses. Our cost estimates are based on the assumption that homeowners and community foresters manage oak trees to maximize present value of tree benefit net management cost, and the best actions are either treatment or removal and replacement. If homeowners or community foresters have cost constraints or place lower values on oak trees than we assume, fewer oak trees than we predict will be treated or removed and replaced, and we overestimate homeowner and tree manager costs. If oak trees block views or home buyers are not aware of SOD, property values may not be discounted when an oak tree dies, and we overestimate property value losses.

Our results are based on a simplifying projection of the results of a stochastic, spatially-explicit, model for the spread of *P. ramorum* in California. We identify three simplifying assumptions in particular that could be relaxed individually or collectively in future research to investigate the effects of uncertainty and disease dynamics on the cost-effectiveness of disease control. The first concerns the way we identify the time at which mortality first affects oak trees within a particular community. The approach has the benefit of parsimony and is sufficient to derive initial estimates for the economic costs and property value losses attributed to sudden oak death damage in California. We use three estimators for the time of arrival of the epidemic based upon the mean, the maximum and the sum of the infected density within a community. Although these are derived from stochastic simulations, by relying on the three summary statistics, this effectively 'washes-out' some of the stochasticity from the epidemiological model. This effect is likely to be most pronounced at the edge of an infection front, and the largely deterministic spread dampens long distance movements and imposes mainly nearest-neighbor spread of threshold-exceeding communities (see Fig. 2). Secondly, we assume that once a community is infected, oak mortality occurs at a constant rate, rather than being driven by the level of *P. ramorum* infection. Finally the effects of control activity are decoupled from the epidemiological model: control(s) applied after the pathogen arrives in a particular spatial location (i.e. spraying with fungicide and/or cutting bay laurel) do not affect the rate of pathogen spread.

Previous work has examined optimal control strategies for the control of sudden oak death by removal of infected hosts and the effects that removal has on the epidemic development (Ndeffo and Gilligan, 2009). Other work identified optimal strategies for the balance of expenditure on detection of SOD compared with control under fixed budgets (Ndeffo and Gilligan, 2010). Each of these analyses necessarily involved simplification of the epidemic models, reducing the models to sympatric meta-populations in which the sub-populations comprised the spreader species (bay laurel) and the target (oak) species. The analyses were motivated for control in relatively small areas, such as the China Camp State Park. The current paper considers much larger, statewide strategies but without the feedback of control on the dynamics of infection. This feedback matters in local dynamics and may affect larger-scale dynamics at the margin of disease spread and incursion into new areas. Future work will therefore analyze the interplay of optimal control strategies and disease dynamics at the larger-scale of this paper.

The USDA Animal and Plant Health Inspection Service (APHIS) and the state plant pest regulatory agencies monitor and regulate potential pathways for artificial movement. We did not attempt to specifically model long distance dispersal of *P. ramorum* caused by humans, and as a result, we do not predict the establishment of outlier populations. To the extent that the establishment of outlier SOD pathogen populations increases the rate at which counties become infested, our model underestimates the progression of spread and the discounted costs and property value losses.

A systematic sample of community forests throughout the study area and the number of homes with oak trees in a community is needed to obtain statistically sound estimates of the number and size of oak trees on residential and non-residential lands and the number of homes potentially affected. While estimates of oak abundance in communities for which tree inventory data are available appear robust, expanding those numbers to places without tree inventories, as we do here, should be viewed with some caution because inventories are only available from a limited number of communities and do not represent a random sample. The discounted costs represent resources that could be devoted more productively elsewhere in the economy, and the property value losses are net losses to society from the invasion of the SOD pathogen. Other net losses to society (e.g., the nursery industry and forest ecosystem service value losses) not considered in this study also need to be counted.

Non-native insects (e.g., emerald ash borer) and pathogens (e.g., *P. ramorum*, cause of sudden oak death) continue to invade forests of the United States and cause significant economic damage, including costs borne by residential property owners and municipal governments (Aukema et al., 2010). Quantifying the impacts and costs of biological invasions is critical to informing strategies for prevention, management, and research. Our approach to estimating the economic impacts of a non-native forest pathogen involves the projection of pathogen spread throughout its potential range and economic damage on developed land. Our framework is highly flexible and potentially useful for other non-native forest insects and pathogen.

Acknowledgements

The authors are grateful to David Nowak and Eric Greenfield, U.S. Forest Service Northern Research Station for sharing digital maps of U.S. Census-defined communities and data for 2001 NLCD developed areas and tree cover. Janice Alexander, UC Cooperative Extension, Marin County and Susan J. Frankel, U.S. Forest Service Pacific Southwest Research Station provided guidance on the spread and infestation of SOD, management practices for the treatment of oaks, and tree inventory information for cities and regions. Thomas Holmes and Jeffrey Englin helped in the development of the arborist survey for Marin County. We thank Christopher Gilligan, Nik Cunniffe, and Alex Cook for invaluable input to the development and testing of the spatio-temporal epidemiological model. The authors also acknowledge the support of the USDA Forest Service Pacific Southwest Research Station and the National Center for Ecological Analysis and Synthesis. R.K. Meentemeyer and T. Vaclavik were also supported by a grant from the National Science Foundation (EF-0622677).

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