Strategies for Control of Sudden Oak Death in Humboldt County—Informed Guidance Based on a Parameterized Epidemiological Model[1]

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Introduction

The outbreak of sudden oak death (SOD) in Humboldt County, California is geographically isolated from the wider epidemic in central California. This situation offers an opportunity for containment, but also poses a danger of massive spread of *P*. *ramorum* (the pathogen that causes SOD) through the vast forest stretch that extends from Redway, southern Humboldt County, to Curry County, Oregon, due to favorable host and environmental conditions. There is a consensus on the need to implement a systematic strategy to manage *P*. *ramorum* in Humboldt County in order to reduce the local impacts (ecological, social, and economic) of the disease and to prevent further northward spread of the pathogen. While lessons can be learned from the extensive control efforts that have been implemented in Curry County, there is uncertainty as to which strategy to employ and as to what level of control is attainable in Humboldt County given the current size of the focus, limited resources available, and range of public opinion with regard to different options. In order to guide strategic planning, we forecast the epidemiological feasibility and risk of failure for a set of control scenarios. We do this for a period of 5 to 10 years using a mathematical model that represents the stochastic dispersal and transmission of *P*. *ramorum* on the local host landscape. The model is parameterized via Bayesian MCMC estimation of pathogen spread from aerial survey data. We consider control strategies and combinations thereof, starting in 2009 (together with scenarios to explore "what if control had been started earlier"). Four main control strategies are considered: (1) removal of inoculum in the area of the disease focus, (2) removal of inoculum away from the disease focus and ahead of symptoms, (3) aerial spraying with Agri-Fos® on a large scale, and (4) a host-free zone near to the van Duzen River. The results suggest that the large size of the Redway focus and potential for long-distance dispersal of *P*. *ramorum* pose considerable challenges to containment, but that local control in this focus or early containment of new, smaller foci are attainable. The insight provided by this study is relevant to other regions of California as effective control measures are probably optimally designed at a regional scale.

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Humboldt Epidemic

While the first cases of *P. ramorum* occurred in central California in the mid 1990s (Rizzo and others 2005), the first reports of *P. ramorum* infection in Humboldt County date from 2002. Since then the affected area in Humboldt County has grown at an increasing rate with significant mortality among tanoak (*Lithocarpus densiflorus*) and oak (*Quercus*) species over an estimated thousands of acres. The spread of disease has been predominantly northward of the initial focus near Redway and Garberville, probably due to prevailing winds. So far, only moderate, localized control measures have been applied in the county with evidence that these might have had an impact at the scale of the treated individuals and plots (Valachovic and others 2005, 2008).

Epidemiological Model and Control Scenarios

We have developed a probabilistic, spatially-explicit metapopulation model for the transmission dynamics of *P. ramorum* in the local host landscape; the main outcomes are risk maps of the probability of infection. The model's resolution is a 250 m by 250 m cell representing a mixed-host stand. Each cell's host composition, susceptibility, and infectivity are determined by the CALVEG GIS database (Meentemeyer and others 2004). At each time, each cell can be in one of the following four classes: susceptible; infected and asymptomatic (or cryptic); infected and symptomatic, and therefore detectable; or removed if host culling is in operation. Removed cells can be re-colonized via host re-sprouting or re-invasion. Infected cells can transmit inoculum to susceptible cells according to a dispersal-kernel function of relative distance. The model was parameterized using tanoak mortality data from aerial surveys in the Redway area between 2004 and 2007. We applied Bayesian Markov chain Monte Carlo estimation to infer the time and location of the index case (near Redway) and the rate and spatial scale of transmission, and to choose among candidate dispersal kernels (a long-tailed power-law fitted the data considerably better than a negative-exponential). We considered the following alternative control strategies:

1. Monitoring in a pre-determined area about once per year and removal of inoculum in detected symptomatic stands comprising host culling or herbicide treatment and pile burning (Valachovic and others 2008).
2. Agri-Fos® aerial spraying applied on a large scale (Kanaskie and others 2009) to provide temporary protection of hosts (for example, tanoak) and prevent northern spread. Treatment is applied in a strategy mixing of inoculum removal "at the origin" and, with the same frequency, spraying "ahead of symptoms" in low-density population areas.
3. A host-free "barrier" (Valachovic 2005) located near the Van Duzen River (Phillip Cannon, U.S. Department of Agriculture, Forest Service, Pacific Southwest Region, personal communication) to prevent northern spread.

We concentrated on a region approximately 85 km long from south to north containing the initial focus nearer the southern edge. For implementation of control and definition of northern invasion, we divided this region into three areas: **Area 1** (containing the focus, for "control at the origin"), **Area 2** (north of the focus and predicted to contain little disease if any in 2009, for "control ahead of symptoms"), and **Area 3** (predicted not to be infested in 2009 and to be protected from invasion). Areas 1 and 2 have the same size. The "barrier," located at the northern edge of Area

2, extends from east to west, is 5 km wide from north to south, and is hypothetically managed such that it remains host free.

Predicted Natural Spread

The epidemic front (defined as the region where the probability of invasion ranges between 95 percent and 5 percent) is forecast to advance northward at a speed of 7 to 8 km/year (but more slowly before 2006 when the focus was small at the scale of a unit cell). In 2009, the epidemic front is predicted to be between 25 and 35 km north of Redway (near the estimated initial focus), between Miranda and the Van Duzen River. These predictions rely on data that include 2 years with high spring rainfall and favorable spread, so it is possible that future estimates including data from 2008 and later would yield a slower rate of spread, although recent years have coincided with the La Niña weather cycle and the (warmer and wetter) El Niño cycle is expected to resume soon. The results therefore suggest a fairly rapid northern spread of *P. ramorum* in the medium and long term in the absence of large impact interventions.

Predicted Impact of Control Strategies Starting in 2009

Sustained removal of inoculum on a smaller scale than the size of the focus is effective locally (as indicated by a drop in the local **basic reproductive number** from > 10 to < 1 per infected host), but fails to contain northern spread due to continuing cryptic infection. Sustained removal on a larger scale than the size of the focus – either by increasing the control area or through early monitoring and rapid treatment – can provide local control and contain growth of the focus for several years. Agri-Fos® large-scale spraying can protect effectively and contain further spread for many years (depending on coverage and efficacy) if applied early and repeatedly ahead of the epidemic front. A 5 km-wide host-free barrier is ineffective in containing the Humboldt County focus as inoculum builds up and is able to jump over, at least under topographic and weather conditions analogous to those near Redway. Therefore, the currently large size of the Humboldt County focus and the long-distance dispersal of *P. ramorum* imply that, although it is in theory possible to eliminate the focus, the scale, nature of the treatment, and coordination needed to do so would make it unfeasible. However, the model suggests it is possible to control new, small foci through early detection, culling, and protection ahead of infection. This study relies on the currently limited epidemiological data and knowledge of the pathogen's biology. These findings are relevant to local control of *P. ramorum* in northern California and to areas of central California where the pathogen is at early stages of establishment or has not yet invaded.

Literature Cited

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