Commentary

When prevention fails. Towards more efficient strategies for plant disease eradication

Pathogen exclusion through quarantine is the most effective strategy for plant disease prevention. However, phytosanitary measures usually restrict the movement of forest and agricultural goods, which may conflict with trade interests. In fact, increased trade in commodities has been associated with more frequent biological invasions in recent decades (Hulme, 2009). In this issue of *New Phytologist*, Hyatt-Twynam *et al.* (pp. 1317–1329) compare strategies for the eradication of emerging plant disease epidemics. Using the example of citrus canker, caused by the bacterium *Xanthomonas citri* subsp. *citri*, in residential areas in Florida (USA), the authors compare three strategies judged by the estimated number of citrus trees eliminated. The classic constant radius removal turned out to be less efficient than the proposed variable radius, and risk-based strategies, which incorporate more mathematical complexity and epidemiological background knowledge. Results were robust to changes in the parameters, dispersal kernel formulations, or host distribution databases.

'Hyatt-Twynam et al. *demonstrate that including epidemiological knowledge is critical to improve the efficacy and efficiency of eradication strategies.'*

As in other disciplines, simulation models are important for informing plant-disease management because they allow exploration of the potential consequences of different intervention strategies. Simulation models are particularly useful in plant-disease eradication, because risk managers typically must decide on a strategy at the very early stages of the epidemic, when data are scarce (Parnell *et al.*, 2015). With recent advances in computational power, complex spatio-temporal models for eradication can now be approached in a Bayesian framework, permitting the inclusion of prior information gathered from expert knowledge and previous studies. Bayesian inference also allows posterior probabilities to be obtained with an explicit representation of uncertainty, which can be very useful in the decision-making process (Keith & Spring, 2013).

This article is a Commentary on Hyatt-Twynam *et al.*, **214**: 1317–1329.

Plant-disease eradication programs

When referring to plant-disease eradication, the image of a burning pile of trees usually comes to mind (Fig. 1). However, in plant pathology, eradication has been defined in a broader sense, as the appropriate disease-control action when a pathogen has breached the exclusion barrier, but is not yet widely distributed or well-established (Maloy, 1993). In addition to plant removal and burning, other techniques have also been used for plant-disease eradication, such as burying, pruning, defoliation, composting, soil-fumigation and biofumigation, solarization, steam sterilization and vector control.

Eradication aims to eliminate or reduce the primary inoculum and may also be used as a holding action until disease resistance or other control measures can be deployed. In some situations, eradication is used only at the borders of an infested area to create a 'cordon sanitaire' and avoid further pathogen spread. Such an approach was taken, for example, against the cocoa swollen shoot disease, caused by *Cacao swollen-shoot badnovirus*, in Ghana and the olive quick decline syndrome, caused by the bacterium *Xylella fastidiosa*, in south-eastern Italy (Maloy, 1993; Martelli *et al.*, 2016).

Historically, eradication of plant diseases had been attempted even before pathogens were recognized as their causal agents. Empirical observations indicated that the 'blast' of cereals was most severe in the vicinity of barberry bushes; hence, in 1660, France issued a regulation requiring the destruction of barberry plants in wheat-growing areas and similar measures were later passed in the United States (Ebbels, 2003). It was not until 1865 that barberry

Fig. 1 Eradication of pear trees affected by fire blight, caused by the bacterium *Erwinia amylovora*, in Zaragoza, Spain. Courtesy of Miguel A. Cambra, CSCV, Zaragoza.

was discovered as an alternate host of the fungus *Puccinia graminis*, the causal agent of stem rust of wheat.

Hyatt-Twynam *et al.* evaluate their simulation models using the citrus canker disease as a case-study, which is actually one of the most significant examples of plant-disease eradication. In South Africa, the disease was found on 33 farms and on 24 of them, entire orchards, or blocks of affected trees, were destroyed, amounting to 44 735 lost trees after the onset of the eradication campaign in 1918. All nurseries in the infested area were also destroyed (Doidge, 1929). The eradication was effective and apparently no further outbreaks of citrus canker have been reported in South Africa up to now.

In Florida (USA), citrus canker was first noticed around 1912 and since then has gone through a series of eradications, introductions and re-emergences resulting in millions of trees removed at a cost of about one billion USD. This was the largest plant-disease eradication program to date, but the campaign was finally halted after hurricanes in 2004 and 2005 disseminated the pathogen state-wide, with an estimated area potentially impacted by eradication of 68 676 ha (Gottwald & Irey, 2007). As with other invasive alien species (Pluess *et al.*, 2012), the case of citrus canker illustrates how the spatial extent of an epidemic dramatically affects the chances of eradication, which are highest at the very early stages of disease outbreak.

Stakeholder acceptability of eradication campaigns

In their article, Hyatt-Twynam *et al.* obtained the lowest number of removed trees with a risk-based eradication strategy, but indicated that the complexity of this strategy might make it less transparent to stakeholders. By contrast, a variable control radius strategy could be easier for stakeholders to accept. As Hyatt-Twynam *et al.* point out, stakeholder acceptability merits careful attention when designing eradication strategies. Historically, eradication programs have been controversial, generating strong public opposition that has delayed or even halted interventions. Furthermore, stakeholders perceive costs and benefits differently, based on their interests, knowledge, value systems, and perception.

As in the case-study of Hyatt-Twynam *et al.*, plant disease outbreaks were frequently initiated in residential areas associated with infected plants in private gardens and backyards. In this scenario, the views of the stakeholders are usually highly polarized depending on how they will be affected by the disease. For instance, plant removal may be highly effective for disease eradication, but may be opposed by residents who perceive little benefit, particularly when plants are cryptically infected and, therefore, asymptomatic. Indeed, a recent national survey conducted in the UK on the public acceptance of tree health policies, indicated that felling only affected trees was greatly favored over the removal of all susceptible trees (Fuller *et al.*, 2016).

Social scientists recognized that eradication can be accomplished only if all stakeholders, including lay-public, cooperate and contribute through positive interactions (Marzano *et al.*, 2015). The need for effective public outreach and education has been widely recognized, and indeed some pest eradication programs have dedicated up to one-third of their budget to communication. A misinformed or ill-informed public may fail to differentiate sound science from mere beliefs, fostering conspiracy theories or other radical arguments (Liebhold *et al.*, 2016), as observed in the recent *X. fastidiosa* outbreak in south-eastern Italy (Abbot, 2015). Furthermore, eradication campaigns generally operate in a crisis-mode, which does not facilitate balanced communication among all the parties involved.

Although the role of socio-economic factors in eradication success has been recognized, such considerations are understudied and rarely reported. Moreover, emotional and aesthetic values, cultural traditions and natural heritage are difficult to monetize and, therefore, often excluded from economic cost-benefit models. More active interactions among epidemiologists, economists, and social scientists could, therefore, improve the efficacy of plant-disease eradication programs.

Diagnostic tests and remote sensing to enhance plant-disease eradication

To obtain accurate predictions of potential disease spread, simulation models usually require data on the actual prevalence of infected plants, including those cryptically infected that are asymptomatic but can be infectious (Thompson *et al.*, 2016). Cryptic infections with relatively long incubation periods are frequent in vascular tree diseases, such as the olive quick decline. Increasingly, accurate and rapid diagnostic tests are available for many plant pathogens and can be used both in the laboratory and in

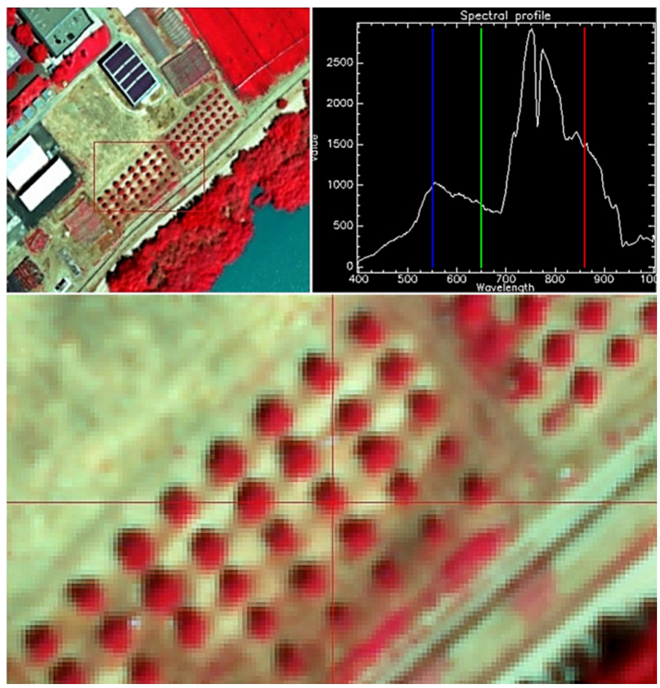

Fig. 2 Hyperspectral image acquired from an airborne platform. The spectral profile extracted from each pixel and from entire tree crowns (top right) are used for the calculation of stress indicators related to tree physiological status and disease severity levels. Courtesy of the Laboratory for Research Methods in Quantitative Remote Sensing (QuantaLab), IAS-CSIC, Cordoba, Spain, http://quantalab.ias.csic.es.

the field (De Boer & López, 2012). Indeed, improved diagnostic tests have been recognized as a key contributing factor in the eradication program of black Sigatoka disease of banana, caused by the fungus *Mycosphaerella fijiensis*, in Australia (Henderson *et al.*, 2006).

However, the representativeness of diagnostics relies strongly on proper sampling design, both at the field, and at the individual plant, level. For instance, in cryptically infected trees, the analysis of only a few clustered leaves might return a negative diagnostic test even from an infectious individual. With diagnostic tests, large spatial extent and fine resolution can only be achieved through extensive testing at relatively high cost, which may be unfeasible in some situations. Besides diagnostic tests, the use of remote sensing to map the distribution of plant diseases has evolved considerably during the last three decades and can be performed at different scales, depending on the area to be monitored as well as the spatial and spectral resolution required (Martinelli *et al.*, 2015).

Sensors used for this purpose, such as multispectral, hyperspectral, and thermal cameras, can measure the electromagnetic energy emitted or reflected by plants at different wavelengths (Fig. 2). The reflectance measured is influenced by various structural and leaf biochemical constituents of the plants, such as leaf area, water content, chlorophyll and nitrogen concentration, and other pigments that are rapidly affected under stress conditions. Additionally, fluorescence emission and canopy temperature can be quantified from remote sensing imagery, which are directly linked with plant photosynthesis and transpiration rates and used for the early detection of diseases. Often, healthy and diseased plants have different characteristic spectral signatures, allowing the detection of the physiological and biochemical effects of the early stages of infection.

At the leaf and plant level, spectral information can be gathered at high spatio-temporal resolution, and accessed quickly from hand-held devices, or by using sensors mounted on regular agricultural vehicles. Today, lowering prices and miniaturization make unmanned aerial systems (UASs) increasingly popular for fast stand-level monitoring. However, their autonomy and payload are still limited compared with manned aircraft, and legal regulations limit operations beyond line-of-sight. Therefore, manned aircraft remain the only alternative to obtain maps at larger scales, with optimum spatial and spectral resolution, for the early detection of disease outbreaks (Calderón *et al.*, 2015). In this context, available satellite imagery provides global coverage at lower spatial and spectral resolutions, which are still useful for the detection of affected plants at an advanced stage of disease severity.

Following earlier successes and failures in plant-disease eradication (Maloy, 1993), Hyatt-Twynam *et al.* demonstrate that including epidemiological knowledge is critical to improve the efficacy and efficiency of eradication strategies. The rapid development of enhanced remote sensing techniques for monitoring plant disease at its early stages could allow relatively large areas to be surveyed with high spectral and spatio-temporal resolution. As in dynamic crop models, simulation models for plant-disease eradication may assimilate these epidemiological data in order to obtain more accurate predictions of potential spread and, therefore, inform on more targeted interventions.

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