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Trends in plant virus epidemiology: Opportunities from new or improved technologies

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ABSTRACT

This review focuses on new or improved technologies currently being applied, or likely to be applied in the future, to worldwide research on plant virus epidemiology. Recent technological advances and innovations provide many opportunities to improve understanding of the way diverse types of plant virus epidemics develop and how to manage them. The review starts at the macro level by considering how recent innovations in remote sensing and precision agriculture can provide valuable information about (i) virus epidemics occurring at continental, regional or district scales (via satellites) and within individual crops (mostly via lightweight unmanned aerial vehicles), and (ii) exactly where to target control measures. It then considers recent improvements in information systems and innovations in modelling that improve (i) understanding of virus epidemics and ability to predict them, and (ii) delivery to end-users of critical advice on control measures, such as Internet-based Decision Support Systems. The review goes on to discuss how advances in analysis of spatiotemporal virus spread patterns within crops can help to enhance understanding of how virus epidemics develop and validate potentially useful virus control measures. At the micro level, the review then considers the many insights that advances in molecular epidemiology can provide about genetic variation within plant virus populations involved in epidemics, and how this variation drives what occurs at the macro level. Next, it describes how recent innovations in virus detection technologies are providing many opportunities to collect and analyse new types, and ever increasing amounts, of data about virus epidemics, and the genetic variability of the virus populations involved. Finally, the implications for plant virus epidemiology of technologies likely to be important in the future are considered. To address looming world food insecurity and threats to plant biodiversity resulting from climate change and rapid population growth, it is important that new and improved technologies that help understand and control epidemics of damaging plant viruses are adopted as smoothly and speedily as possible.

1. Introduction

The world is currently entering an exciting era of rapidly advancing technological innovation. This innovation is generating a new paradigm for plant virus epidemiology in which knowing what opportunities new or improved technologies can provide to improve understanding of plant virus epidemics, and ability to manage them, is of great importance. Such knowledge is critical because of: (i) the threat plant virus disease epidemics pose to world food security at a time of accelerating climate change and world population increase; (ii) increasing challenges to humankind's ability to control damaging virus epidemics arising from greater climate insecurity in a period when the worlds' ability to increase food production is projected to diminish, especially in drying mid-latitude regions; and (iii) the threat virus epidemics pose to plant biodiversity and the likelihood of mass species extinctions arising from the combined influences of climate change and humankinds' activities (e.g., Brooks et al., 2002; Tilman et al., 2002; Norse and Gommes, 2003; Anderson et al., 2004; Cline, 2007; Stern, 2007; Cooper and Jones, 2006; Canto et al., 2009; Jones, 2009; Jones and Barbetti, 2012).

Plant virus epidemics are multifaceted and highly diverse. Most involve tripartite pathosystems each component of which (virus, vector, and host) interacts with the environment (e.g. Thresh, 1974, 1980, 1981, 1982, 1983, 1986). New or improved technologies provide many opportunities to improve data collection efficiency and collect more diverse or completely new kinds of information. This process is changing plant virus epidemiology and virus disease management at both macro and micro scales. At the macro scale, it is revolutionising things like application of remote sensing and

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precision agriculture technologies, information system deployment, modelling and prediction ability, decision support capacity, analysis of spatiotemporal spread patterns, and overall understanding of factors driving epidemics (e.g., McBratney et al., 2005; Jones et al., 2010; Coutts et al., 2011; Bock et al., 2010; Mirik et al., 2011; Garrett, 2012). At the micro level, it is transforming what can be achieved by molecular epidemiology approaches, virus evolution studies and the latest virus detection procedures (e.g., Gibbs et al., 2008a; Adams et al., 2009; Boonham et al., 2009; Jones, 2009; Lecoq et al., 2011). This article focuses on the benefits new technologies provide that enable improvements in understanding plant virus epidemiology and management at both macro and micro scales.

2. Innovations in remote sensing and precision agriculture

Remote sensing involves gathering data about something without being in contact with it. Most remote sensing involves some form of electromagnetic radiation, such as heat or light. Standard aerial light photography from planes or helicopters flying overhead has often been used to determine the regional or local patterns of spread of plant virus epidemics (e.g., Hill and Walpole, 1989). However, light beyond the visible portion of the spectrum can reveal otherwise invisible virus symptoms. Spectral imaging allows collection of information the human eye fails to capture with its red, green and blue receptors. Thermal imagery refers to infrared imaging. Hyper-spectral images are ones in which each image contains a spectrum of light wavelengths. These images combine features of a spectrophotometer with the spatial information of an image. A multispectral image is one that captures image data at specific frequencies across the light spectrum. These wavelengths may be separated by filters or by using instruments sensitive to particular wavelengths. Hyper-spectral and muliti-spectral imagery both improve ability to differentiate diseased from healthy plants, and symptoms caused by different plant pathogens or pests (e.g., West et al., 2003; Steddom et al., 2005; Bock et al., 2010; Prabhakar et al., 2012). Combined use of aerial and ground-based remote sensing maximises precision and accuracy of disease assessment and quantification (e.g. Steddom et al., 2005). When aerial remote sensing is used, imagery is normally captured by satellites, manned aircraft or helicopters, or unmanned aerial vehicles (UAV's). Precision agriculture has been defined as "that kind of agriculture that increases the number of correct decisions per unit area of land per unit time with associated net benefits" (McBratney et al., 2005). A major benefit it can provide is in allowing geo-referenced areas identified within a crop by remote sensing to be targeted selectively with chemical sprays or fertilizer applications using geographic information system (GIS) or global positioning systems (GPS) based-precision farming equipment (e.g., Zhang et al., 2002; McBratney et al., 2005).

Uses of remote sensing in plant virus epidemiology and management include:

- Providing improved understanding of the spatiotemporal dynamics of epidemics.
- Providing advanced warning about epidemics, and monitoring ongoing epidemics over time at continental, regional, district and within-field levels.
- Helping distinguish virus resistant from susceptible germplasm lines.
- Minimising both the cost of applying chemicals and damage to the environment by making possible targeted chemical spraying to remove virus infection foci or localised arthropod virus vector infestations within crops. Such targeted chemical sprays involve use of herbicides to kill virus-infected plants (thereby removing them as within-crop sources of infection for further spread) or pesticides to kill localised vector populations.

Bawden (1933) found that infrared film revealed some types of otherwise invisible virus symptoms while others appeared using black and white film sensitive to visible light. The difference was explained by differences in the spectral characteristics of the virus symptoms. Colwell (1956) used the spectral properties of healthy and *Barley yellow dwarf virus* (BYDV; genus *Luteovirus*, family *Luteoviridae*)-infected cereal crops to predict the most appropriate film and filter combinations to reveal BYDV symptoms. Ausmus and Hilty (1971) found that *Maize dwarf mosaic virus* (genus *Potyvirus*, family *Potyviridae*)-infected maize leaves had significantly smaller reflectivities than healthy maize leaves. Chaerle et al. (1999) used thermal imagery of tobacco leaves inoculated with *Tobacco mosaic virus* (genus *Tobamovirus* family, *Virgaviridae*) to reveal that spots of elevated temperature confined to the site of infection increased in intensity from 8 h before the onset of necrotic local lesions, and remained detectable as a halo around subsequent ongoing necrosis. Martin et al. (1999) quantified chlorotic leaf areas by using a digital image capture device to differentiate between degrees of *Maize streak virus* (genus *Mastrevirus*, family *Geminiviridae*) resistance in different maize genotypes that were indistinguishable using other symptom assessment approaches. Steddom et al. (2003) used hyper-spectral leaf reflectance and multi-spectral canopy reflectance to differentiate *Beet necrotic yellow vein virus* (BNYV; genus *Benyvirus*, family unassigned)-infected from healthy sugar beet plants. Prediction accuracies were 89% (leaf spectra) and 88% (canopy reflectance), suggesting remote sensing can facilitate detection of sugar beet rhizomania disease. Workneth et al. (2009) used a hand-held radiometer that measured reflectance at 555 nm to quantify grain yield loss due to *Wheat streak mosaic virus* (WSMV; genus *Tritimovirus*, family *Potyviridae*) infection along transects in wheat crops. There were significant cross-correlations between yield and the intensity of reflectance values associated with presence of WSMV-infected plants. Chávez et al. (2009) used multi-spectral reflectance imagery and spectro-radiometry to reveal presence of early *Potato yellow vein virus* (PYVV; genus *Begomovirus*, family *Geminiviridae*) symptoms in potato plants before chlorotic symptoms became visible to the naked eye. Reflectance in the blue region (450–495 nm) revealed symptoms earlier than reflectance in the near infra-red region (>750 nm). Subsequently, Chavez et al. (2010) improved the diagnostic power of their remote sensing methodology by applying multifractal analysis and wavelet transformation to spectroradiometrical data from PYYV-infected and healthy potato plants.

The 'space race' of the 1960s resulted in a rapid increase in orbiting satellites. Military surveillance satellite technology enabled development of land observation (Landsat) satellites. These satellites provide systematic and repetitive observations of the earths' surface with sensors covering multiple regions of the electromagnetic spectrum. The images are archived for future study. However, problems associated with their use have included low resolution imagery, cloud cover and infrequent timing (Steddom et al., 2005). Their low resolution images proved more suited to identifying virus-diseased crops on a continental, regional or district scale than to providing detailed within-crop information. Mirik et al. (2011) used False colour composite Landsat 5 Thematic Mapper (TM) images to map wheat crops with high incidences of WSMV infection in two counties in the Texas Panhandle region, USA. This was done over two crop years in which WSMV was common. Early season images were used to prepare a normalised disease vegetation index (NVDI) image. This NVDI image was then used to mask non-wheat surface components in the TM image. Maximum likelihood classifier (MLC) is a classification procedure for identifying spectrally similar areas on an image. Using MLC, an image was produced from the masked TM image that was colour coded to separate wheat crops into irrigated healthy, irrigated diseased, rainfed healthy and rainfed diseased categories (Fig. 1). The overall