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Modelling the effects of awareness-based interventions to control the mosaic disease of *Jatropha curcas*

Fahad Al Basir[a], Konstantin B. Blyuss[*,b], Santanu Ray[a]

[a] Systems Ecology & Ecological Modeling Laboratory Department of Zoology, Visva-Bharati University, West Bengal 731235, India
[b] Department of Mathematics, University of Sussex, Falmer, Brighton BN1 9QH, UK

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ABSTRACT

Plant diseases are responsible for substantial and sometimes devastating economic and societal costs and thus are a major limiting factor for stable and sustainable agricultural production. Diseases of crops are particular crippling in developing countries that are heavily dependent on agriculture for food security and income. Various techniques have been developed to reduce the negative impact of plant diseases and eliminate the associated parasites, but the success of these approaches strongly depends on population awareness and the degree of engagement with disease control and prevention programs. In this paper we derive and analyse a mathematical model of mosaic disease of *Jatropha curcas*, an important biofuel plant, with particular emphasis on the effects of interventions in the form of nutrients and insecticides, whose use depends on the level of population awareness. Two contributions to disease awareness are considered in the model: global awareness campaigns, and awareness from observing infected plants. All steady states of the model are found, and their stability is analysed in terms of system parameters. We identify parameter regions associated with eradication of disease, stable endemic infection, and periodic oscillations in the level of infection. Analytical results are supported by numerical simulations that illustrate the behaviour of the model in different dynamical regimes. Implications of theoretical results for practical implementation of disease control are discussed.

1. Introduction

Constantly increasing global energy demands have significantly raised the need for stable alternative fuel sources. One the most prominent types of alternative energy is the biofuels that are produced from oils of a variety of plants, many of which can be grown in a sustainable manner even in harsh environmental conditions. Among various candidates for the mass production of biofuel, *Jatropha curcas* has recently emerged as a strong contender, due to its high content of 27–40% of triglycerides (Achten et al., 2007; Sahoo et al., 2009), and the fact that this plant can be grown even in drought conditions, on arid, salty and sandy soils, it requires minimum cultivation efforts and produces first harvest in just 18 months. Moreover, the reported levels of oil production from Jatropha plants are higher than those of soybean (the main source of biodiesel in the US), sesame, sunflower, castor and rapeseed from plantations of the same size (Jongschaap et al., 2007). The Jatropha plant originated in Central America and Mexico, but has subsequently spread to Africa, Latin America and South-East Asia. Importantly, the Jatropha plant does not compete with other food crops, and beside being a source of biofuel, it also proves to be an effective phytoremediator, carbon sequester, and soil erosion controller (Mangkoedihardjo and Surahmaida, 2008; Pandey et al., 2012).

A major challenge for the sustainable large-scale growth of the Jatropha is plant disease (Alabi et al., 2011; Strange and Scott, 2005; Thresh, 2003), most often a mosaic disease caused by one of the viruses in the *Begomovirus* family (Gao et al., 2010; Kashina et al., 2013; Narayana et al., 2007; 2006) that is transmitted by the whitefly *Bemisia tabaci* (Bedford et al., 1994). The effects of this disease include mosaiced, reduced and distorted leaves, blistering, as well as stunting of diseased plants. Low density of *Jatropha curcas* is known to facilitate fast transmission of mosaic disease (Fauquet and Fargette, 1990), and the disease transmission is affected by environmental conditions such as temperature and humidity, with heavy rainfalls significantly limiting the spread of whiteflies (Fargette et al., 1994). The virus is transmitted from infected plants to uninfected vectors, and from infected vectors to uninfected plants. Once the vectors acquire mosaic virus from infected plants, they are able to pass it on to other uninfected plants within 48 h (Fargette et al., 1994).

Various strategies have been developed to mitigate the negative effects of mosaic disease (Ahohuendo and Sarkar, 1995; Seal et al.,

* Corresponding author.
E-mail address: k.blyuss@sussex.ac.uk (K.B. Blyuss).

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2006; Thresh and Otim-Nape, 1994). These include vector control in the form of insecticidal soaps (Butler et al., 1993; Thresh and Cooter, 2005), as well as application of nutrients to the soil. Insecticidal soaps are sprayable organic insecticides that can be used on a variety of plants, fruit and vegetables, to a degree that these products can be safely consumed after normal washing. Their insecticidal action consists in blocking the spread of whitefly-borne infection by reducing the number of eggs being laid, as well as preventing adults from flying, thus minimizing the disk of further disease transmission. Insecticidal soaps have already proved to be effective in reducing pest infections of cottonseed and cowpea (Butler and Henneberry, 1990; Oparaeke et al., 2006). Another effective approach for control of mosaic disease is the use of nutrients that can reduce disease burden by providing disease tolerance or resistance of plants to pathogens (Dordas, 2009; Graham, 1983; Graham and Webb, 1991; Pennazio and Roggero, 1997; Singh, 1970). Plant nutrition is an essential component of sustainable agriculture, as in most cases it is more cost-effective and also environmentally friendly to control plant disease with the adequate amount of nutrients without the use of pesticides. Once the level of disease is reduced to an appropriate level, it can be further controlled by other cultural practices or conventional organic biocides, making this approach not only successful, but also less expensive. There are several examples of efficient disease control through manipulation of soil nutrient concentration, which can be achieved by modifying either nutrient availability, or nutrient uptake (Huber and Graham, 1999).

Most effective strategies for control of plant disease include a combination of different approaches, as in integrated pest management (Khoury and Makkouk, 2010; Klerkx et al., 2010; Schut et al., 2014). It should be noted, however, that a successful implementation of a large-scale crop disease containment and prevention program can only be achieved subject to adequate level of population awareness and cooperation (Khan et al., 2013; Schumann and D'Arcy, 1999). This would not only improve the uptake of cultivating a particular crop by farmers, but also would facilitate their engagement in improving crop performance and disease control (Bellec et al., 2012). Farming awareness campaign in Malenadu region in India helped educate farmers on the serious risks that pesticides pose both to the human health and to the environment, and to encourage proper use of pesticide to minimise their negative effects (Kumar et al., 2012; Yang et al., 2014). Similar approach was used in Indonesia, where dedicated farmer field schools were used to disseminate information about sensible farming practices that resulted in improved cost-effectiveness and reduced unnecessary use of pesticides (Braun et al., 2000; Feder et al., 2004a; 2004b). In the particular case of cultivating Jatropha plants for the purpose of developing additional income from biofuel, major information campaigns in Kenya by various NGOs, community-based organisations and private investors, have led to the large-scale adoption of *J. curcas* by farmers (Mogaka et al., 2004). Mali has designed a dedicated governmental Strategy for Biofuels Development aimed at promoting *J. curcas* as a sustainable development tool (Favretto et al., 2015). In Burma, the national campaign for biodiesel production took off on an unprecedented scale in 2005, with funds, farm lands and labour being diverted to growing Jatropha (World Rainforest Bulletin, 2008). From the perspective of responding to mosaic disease, proactive involvement of farmers has proved very effective in improving disease control and subsequently increasing crop yields (Chipeta et al., 2016; Moses, 2009).

A number of mathematical models have looked at effects of population awareness on control of infectious diseases (Agaba et al., 2017b; Cui et al., 2008; Funk et al., 2010; Manfredi and d'Onofrio, 2013; Misra et al., 2011a; 2016). Time delay associated with response to disease awareness has also been shown to play a significant role in determining disease outcome and design of appropriate control measures (Agaba et al., 2017a; 2017c; Greenhalgh et al., 2015; Zuo et al., 2015). In terms of modelling the effects of awareness on control of mosaic disease in *J. curcas*, Al Basir et al. (2017) analysed a model with a separate compartment for aware population, and assumed that removal of infected plants and infected vectors occurs at a rate proportional to the number of aware individuals. Al Basir and Roy (2017) studied the effect of roguing, i.e. removing of infected plants, at a rate proportional to the overall number of infected plants, with a time delay to account for the time it takes to observe the infection and take action. Without making it explicit, effectively this represents the response of farmers through their delayed awareness of mosaic disease affecting Jatropha plants. Roy et al. (2015) have analysed a model of mosaic diseased and used significant similarities between mosaic infections of cassava and Jatropha plants to parameterise their model and investigate the impact of continuous and pulse spraying strategies for the application of insecticidal soap to eliminate vector population. Venturino et al. (2016) have considered the same problem with continuous spraying from the perspective of optimisation theory and showed how an optimal strategy can be developed that minimises the use of insecticide, while achieving the aim of controlling the spread of mosaic disease.

In this paper we consider the spread of mosaic disease in a Jatropha plantation, with disease control being implemented through the application of insecticides and nutrients depending on the level of population awareness about the disease. The awareness is assumed to have a contribution from direct observation of plant infection by farmers, and another input from global awareness campaigns. The outline of this paper is as follows. In the next section we derive the mathematical model of mosaic disease of Jatropha plants and discuss its basic properties. Section 3 is devoted to analysis of stability and bifurcation of different steady states of the model. In Section 4, we supplement analytical results by numerical computation of bifurcation diagrams, as well as numerical solution of the model to illustrate different dynamical regimes. The paper concludes in Section 5 with the discussion of results and future research.

2. Model derivation

We consider a population of plants that can become exposed to a mosaic disease spread by a whitefly vector. Plant population is divided into healthy, latently infected, and infected plants, to be denoted as x, l and y, respectively. Healthy plants are assumed to reproduce logistically with a growth rate r and a carrying capacity K. It is assumed that once whiteflies infect a healthy plant, it becomes latently infected, i.e. it is incubating the disease but does further contribute to new infections. Rather than explicitly model the process of transfer of infection from plants to vectors, we instead focus directly on the population of infected vectors, whose size is denoted by v, and assume that the rate of growth of infected vectors is proportional with a constant b to the number of infected plants, from which they can acquire the infection. Begomoviruses that cause mosaic disease are known to be *circulative-persistent viruses* (Czosnek et al., 2017), which means that once the whitefly vectors become infected, they will remain infectious for the rest of their lifetime (Holt et al., 1997; Jeger et al., 2004). The reason for this is that when whiteflies feed on infected plants, they ingest the virus contained in the plant sap with their stylets, and subsequently the virus crosses the filter chamber and the midgut to be then translocated into the primary salivary glands (Czosnek et al., 2017; Jackson and Chen-Charpentier, 2017). When these vectors then feed on healthy plants, virus particles circulating in the whitefly saliva will enter these plants and start infection in them.

With these assumptions, the basic host-vector model for the dynamics of mosaic disease takes the form