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Analysis of Moko disease propagation on plantain (*Musa* AAB Simmonds) through a model based on system dynamics

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Abstract Plantain represents one of the principal sources of income for Colombian farmers, besides being an important aspect of the national culture. Plantain is part of the daily diet for different social levels. Nevertheless, its production is threatened by diseases that have devastated entire crops and have forced many families to change their agricultural occupation. Moko (*Ralstonia solanacearum* phylotype II race 2) is one of the diseases that over time has caused considerable loses and continues to bring major phytosanitary problems to the region. The easy transmission of the pathogen makes it necessary to implement methodologies that help to limit the epidemic spread of the disease. In order to improve our understanding of the propagation of the disease through the plant's developmental stages and contribute to establishing better targeted control measures, this paper proposes a population simulation mathematical model, which seeks to interpret the dynamics of Moko disease, bearing in mind the influence of the plant's developmental cycle. We investigate the implementation of disease prevention on the population of susceptible and infected plants over time. The model has a good fit to the field data. The simulations, using the parameters estimated, showed that early elimination of infected plants is important to reduce disease incidence. It is also important to implement strategies to prevent the spread of the bacteria, which translates to a smaller probability of infection in any state.

Keywords Plantain crop · Mathematical modelling · *Ralstonia solanacearum* · Prevention · Quindío

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Introduction

Plantain crops are among the production systems of great socioeconomic relevance in Colombia and in the department of Quindío. Due to the fruit's nutritional content, it has become part of the daily family

diet and has been the economic support of families from different social levels. Hence, it is cultivated in most of the country's territory, with Quindío being one of large producers (Grajales-Amorocho and Muñoz-Loaiza, 2021a, 2021b). Currently, the plantain crop is considered the department's most productive crop (Akinro et al., 2012).

Plantain is a rhizomatous grass whose terminal bud produces the inflorescence. Each plant produces successively a series of clusters, each from a side shoot. The principal developmental stages include (i) appearance of shoots or rootstalks, (ii) growth in the vegetative phase, (ii) flowering and fructification (Tixier et al., 2004). The crop develops at its own rhythm and does not follow a synchronous cycle. Therefore, at a given moment, a plantain crop consists of a population of individual plants derived from plant shoots in various stages of development. The optimal mean temperature for crop development is 30 °C and a precipitation < 100 mm per month. When these conditions change and the crop is exposed to climatic extremes, production decreases and the probability increases of the spread of diseases like Moko (Okolie et al., 2019).

Moko is a disease caused by the bacterium *Ralstonia solanacearum* phylotype II race 2 (Fegan & Prior, 2006), which after entering the plant, creates obstructions in the xylem, limiting the flow of water towards the aerial parts, leading to symptoms such as wilting and yellowing of younger leaves, producing a milky-white exudate that accumulates on the surface of freshly cut stems, rhizomes, or rootstalks, rotting or non-uniform ripening of fruits,, and, eventually, killing the plant (Flórez & Agudelo, 2019; Denny, 2006).

Currently, Moko disease has no recovery treatment and is limited to preventive measures, excessive use of pesticides, and eradication of diseased plants (Grajales-Amorocho & Muñoz-Loaiza, 2021a, 2021b). Nonetheless, through measures of good agricultural practice, it is possible to sustain the crop and reduce infection sources. To improve control methods, it is important to elucidate the dynamics of the disease – considering the crop's developmental stages and the effect of prioritizing the application of prevention and control strategies to avoid an increase in infection foci. Mathematical models are a useful tool to identify the efficacy of disease control methods (Brunetti et al., 2020) and, thus, provide support in decision making in possible future scenarios of increased incidence of the disease.

Mathematical models have been used principally to predict the disease dynamics in humans, but these are also used in diseases in plants (Cunniffe et al., 2015). Mew models have been proposed for plantain crops (Agouanet et al., 2021). Among the studies focused on this crop, the emphasis has been on diseases, like *Xanthomonas*, Sigatoka, and in some cases for Moko disease (Jeger et al., 2018).

Grajales-Amorocho and Muñoz-Loaiza (2021a, 2021b) evaluated prevention strategies for plantain Moko disease incidence, using a population simulation model with nonlinear ordinary differential equations. They studied the effect of various disease prevention scenarios on the population of susceptible and infected plants over time. The authors found that with early elimination of infected plants, the disease tends to be controlled, while when infected plants are eliminated later on in the disease cycle the disease persists over time. They corroborated the effect through sensitivity analysis. In terms of costs, they demonstrated the existence of combinations of prevention strategies under different scenarios that resulted in the lowest costs.

Grajales-Amorocho et al. (2022) evaluated – through mathematical models – the effect of reseeding with infected rootstalk. These authors presented a population simulation model with disease control, and studied its effect on the population of susceptible and infected plants, and associated economic loses over time. They found that replanting infected rootstalk strongly increases the disease incidence and production costs, causing higher economic loss. The authors argue that prevention strategies and elimination of infected plants should be implemented to maintain a reasonable amount of susceptible plants over time and control the population of infected plants, in addition to causing lower economic loss.

Moreover, Mapinda et al., 2022 modified a mathematical model for the transmission dynamics of the banana *Xanthomonas* wilt (BXW) disease, including some control measures. The authors modeled the banana population (susceptible, asymptomatic infectious, and symptomatic infected) and the vector insect population and developed a mathematical model that interprets the dynamics of the disease, seeking to control BXW disease. They performed numerical simulations to examine the impact of participatory community education programs, elimination of soil bacteria, elimination of the diseased pseudo-stalk and evaluated control strategies for vertical transmission. Their

results show that community and participatory agricultural education programs, as well as timely elimination of infected plants and soil bacteria, reduce the number of secondary infections drastically.

In addition, Agouanet et al. (2021) proposed a mathematical model considering two reproduction means of the pathogen spores and a time delay related to incubation to assess the dynamics of the banana black leaf streak disease The basic reproduction number $\mathcal{R}_o$ was estimated for the system considering the production of sexual and asexual spores, with and without time delay. The results showed that the system's stability depends not only on the incubation period.

The purpose of this study was to broaden our understanding of the transmission of the pathogen and its interaction with different control strategies. We consider the relevance of the developmental stages in the spread of disease in order to support more-specific decision making that contributes to the crop's sustainable management.

Materials and methods

Field work

The field work was conducted over 12 months in a plantain crop located in the farm El Guadualito, in the La Esmeralda township of the municipality of Pueblo Tapao, Montenegro in the department of Quindío, Colombia. One hectare was defined and all the plants therein were marked (Fig. 1); the initial state of the crop recorded. Assessments were done every 15 days, bearing in mind the variable amount of susceptible and infected plants in each of the plant's developmental stage (vegetative, flowering, or fructification), plants in state of fructification eliminated through harvest, plants eliminated due to disease, and the number of new rootstalks per plant.

This methodology was implemented to study the effect of the plant's developmental state on disease transmission, given that – according to Tapiero et al., 2007 – spread of the bacteria that causes the Moko disease takes place more efficiently from the acorn, which is the flowering stage. The assessments were done bi-weekly because Douglas (2012) found that the symptoms of the bacteria may be manifested 15 days or one month after reaching the plant.

The epidemiological model and the plant's development cycle

A simulation model is presented with nonlinear ordinary differential equations, which describes the dynamics of the plantain Moko disease defined by the following assumptions:

- The plantain plant's development cycle is considered in the vegetative, flowering, and fructification phases.

Fig. 1 Plants from the plantain crop marked for the research

- The flowering phase and fructification phase are considered in a single state.
- Infected plants are considered in each developmental stage of the plant.
- The elimination rate of plantain plants in the fructification phase due to harvest is considered.
- Infected reseeding is considered in the vegetative phase.
- Uninfected plantain plants in the vegetative phase become infected with a constant probability per time unit.
- The infected plants contribute to bacterial transmission.
- The maximum capacity of plants in the study region is included.

Variables and parameters of the model

The following variables and parameters were defined:

- $x_1(t) \equiv x_1$ is the number of susceptible plantain plants in the vegetative phase.
- $x_2(t) \equiv x_2$ is the number of susceptible plantain plants in the flowering phase and in the fructification phase.
- $x_3(t) \equiv x_3$ is the number of infected plantain plants in the vegetative phase.
- $x_4(t) \equiv x_4$ is the number of infected plantain plants in the flowering phase and plants infected in the fructification phase.
- $y(t) \equiv y$ number of susceptible plantain plants in fructification phase eliminated through harvest.
- $y_e(t) \equiv y_e$ is the number of infected plantain plants in the flowering phase eliminated due to having the disease.

The parameters of the model are.

- γ : constant reseeding rate
- k : load capacity (maximum population) of plantain plants in the study region
- β : probability per time unit of transmission of infection from plants infected in the vegetative phase to susceptible plants in the flowering or fructification phases
- σ : probability per time unit of transmission of the infection from plants infected in the flowering or

fructification phases to susceptible plants in the flowering or fructification phases;
- δ : rate of infection of susceptible plants in the vegetative phase
- α : rate of susceptible plants in the vegetative phase that change phase
- ϵ : rate of elimination through harvest of susceptible plantain plants
- π : rate of development of infected plants in vegetative phase that develop into infected plants in the flowering phase.
- h : Fraction of the planting material that is infected.

The prevention controls are:

- g : fraction of infected plantain plants in the fructification phase, eliminated
- f : fraction of susceptible plantain plants that receive prevention of bacterial infection.

Figure 2 shows the compartments diagram for the plantain Moko infectious process, considering the plant's development cycle.

Deduction of the model's differential equations

In accordance with the flow diagram in Fig. 1, the rate of change of the population of susceptible plants in vegetative phase with respect to time is determined by the reseeding flow $(1 - h)\Gamma$ where Γ indicates the number of rootstalks replanted as dependent on the maximum capacity of plantain plants $\left(1 - \frac{\sum_{i=1}^{4} x_i}{k}\right)$ minus the term αx_1 that indicates the number of susceptible plantain plants in the vegetative phase that become flowering plants. The term δx_1 expresses the number of susceptible plantain plants in vegetative phase that are infected. This gives the differential equation

$$\frac{dx_1}{dt} = (1 - h)\Gamma - \alpha x_1 - \delta x_1. \tag{1}$$

The differential equation,

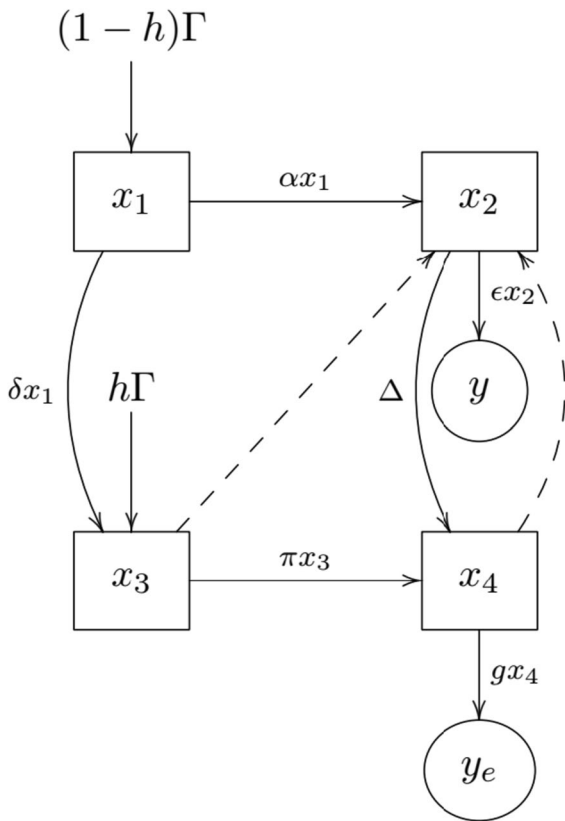$$\frac{dx_2}{dt} = \alpha x_2 - \epsilon x_2 - \Delta. \tag{2}$$

Fig. 2 Diagram of the plantain Moko propagation dynamics, including its development cycle with $\Gamma = \gamma \left(y + y_e \right) \left(1 - \frac{\sum_{i=1}^{4} x_i}{k} \right)$ and $\Delta = (1-f)x_2 \frac{\beta x_3}{\sum_{i=1}^{4} x_i} + (1-f)x_2 \frac{\sigma x_4}{\sum_{i=1}^{4} x_i}$

$$\frac{dx_3}{dt} = \delta x_1 + h\Gamma - \pi x_3. \tag{3}$$

Finally, the density of the population of infected plants in the fructification phase is affected by infected plants in vegetative phase that become fructificatious plants and by the new cases of infected plants in the flowering phase or fructification given by Δ, while this population decrease through elimination through harvest. The foregoing is expressed through the following differential equation

$$\frac{dx_4}{dt} = \pi x_3 + \Delta - g x_4. \tag{4}$$

The differential equations for y and y_e are given by

$$\frac{dy}{dt} = \epsilon x_2, \tag{5}$$

$$\frac{dy_e}{dt} = g x_4. \tag{6}$$

Results and discussion

Uncontrolled model fit to real data

To fit the model, we used Nonlinear Least Squares Regression, programmed in MATLAB using the first-order Runge–Kutta method that permits solving the system of differential equations. To estimate the model parameters that permit the fit to the data, the lsqcurvefit subroutine was used, which allows solving non-linear curve fitting problems by means of least squares. This fit methodology is also used by Heathcote & Nicholls, 1990; Pan et al., 2014; Pandey et al., 2020; Ramírez Carvajal et al., 2020.

The following optimization problem was considered:

$$\begin{cases} minimize\ z(\overline{\omega}) = \sum_{i=1}^{n} \left(\overline{X}_i - X(t, \overline{\omega}) \right)^2, t_1 \le t \le t_n \\ \qquad Subject\ to\ X = \dot{f}(t, X, \overline{\omega}) \\ \qquad\quad with\ X(0) = \overline{X}_1 \end{cases}$$

where $\overline{X}$ represents the vector of real data and $\overline{\omega}$ the vector of parameters of the system of differential

Describes the rate of change of the density of susceptible plants in the flowering or fructification stage. The susceptible plantain plants in the fructification stage are eliminated through harvest at a constant rate ϵ and due to the bacterial transmission from infected plantain plants to susceptible plantain plants in the fructification phase $\Delta = (1-f)x_2 \frac{\beta x_3}{\sum_{i=1}^{4} x_i} + (1-f)x_2 \frac{\sigma x_4}{\sum_{i=1}^{4} x_i}$.

The rate of change of the population of plants infected in the vegetative phase, $\frac{dx_3}{dt}$, is equal to the flow of susceptible plantain plants in the vegetative phase that acquire the bacteria at a rate δ, plus the fraction h of rootstalks infected in the replanting material minus the plantain plants infected in the vegetative phase that become frutificatious

equations to be estimated to obtain the minimum sum of the residual squares, $\overline{\omega} = (\beta, \sigma, h, f, \alpha, \gamma, \delta, \pi)^T$.

The method to estimate $\overline{\omega}$ is based on the Levenberg–Marquardt algorithm, which uses a mixture of the gradient descent algorithm and the Gauss–Newton algorithm to determine the values of the parameters that minimize $z(\overline{\omega})$ (Ranganathan, 2004).

Figure 3 shows the fit of the model solution to the data collected. The optimized parameter values are:

$$\overline{\omega} = (\beta, \sigma, h, f, \alpha, \gamma, \delta, \pi, \vartheta)$$
$$= (0, 0.8757, 0.0019, 0.1243, 0.3383, 0, 0.0278, 0, 1)$$

To determine the goodness of fit for the model, the R^2 coefficient is determined; this coefficient permits quantifying how reliable the parameter values are estimated for the model. For its interpretation, it is relevant to indicate that its value is within the interval from 0 to 1 and the closer the value of the coefficient is to 1, the better the fit of the model to the data. The R^2 coefficient for nonlinear fits is defined as (Malkina-pykh, 2019).

$$R^2 = \frac{\sum_i \widehat{y}_i^2}{\sum_i y_i^2}$$

where $\widehat{y}_i$ are the data with estimated values and y_i are the real or collected data. For this specific case, $R^2=$

0.9952, indicating according to Malkina-pykh, 2019 the reliability of the fit.

Simulations of the model

The simulations of the model were carried out in MATLAB, using the values of the parameters and values from initial populations.

With the values obtained in estimating the parameters, the simulations were conducted varying the conditions of the prevention strategies (f) and elimination of infected plants (g). The population of susceptible plants in the vegetative state x_1 increases with increasing fraction of plants prevented to become infected, as shown in Fig. 4. The number of susceptible plants reaches approximately 400 if 80% of the infections is prevented and 10% of the infected plants are eliminated before harvest. The figure demonstrates similar behavior when implementing both strategies in equal proportions and when implementing g in greater proportion. A decreased population of susceptible plants was observed over time if none of the strategies is implemented.

These findings agree with that that shown by Ramírez et al., 2020 who found that implementing good agricultural practices for plants considered healthy at first glance, avoids the onset of new diseases and, hence,
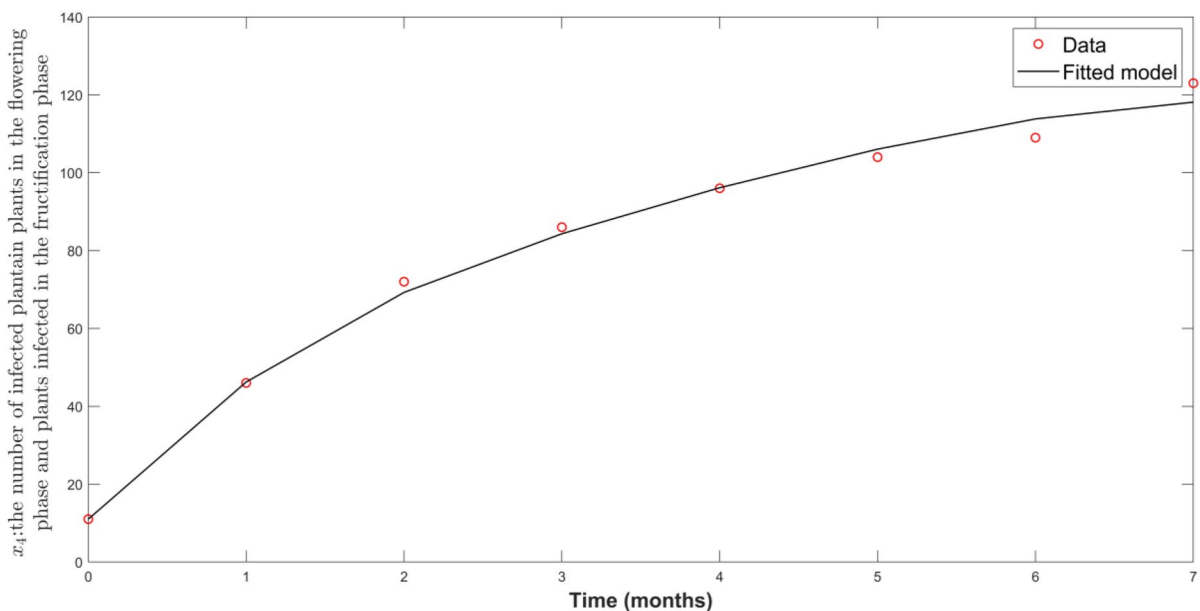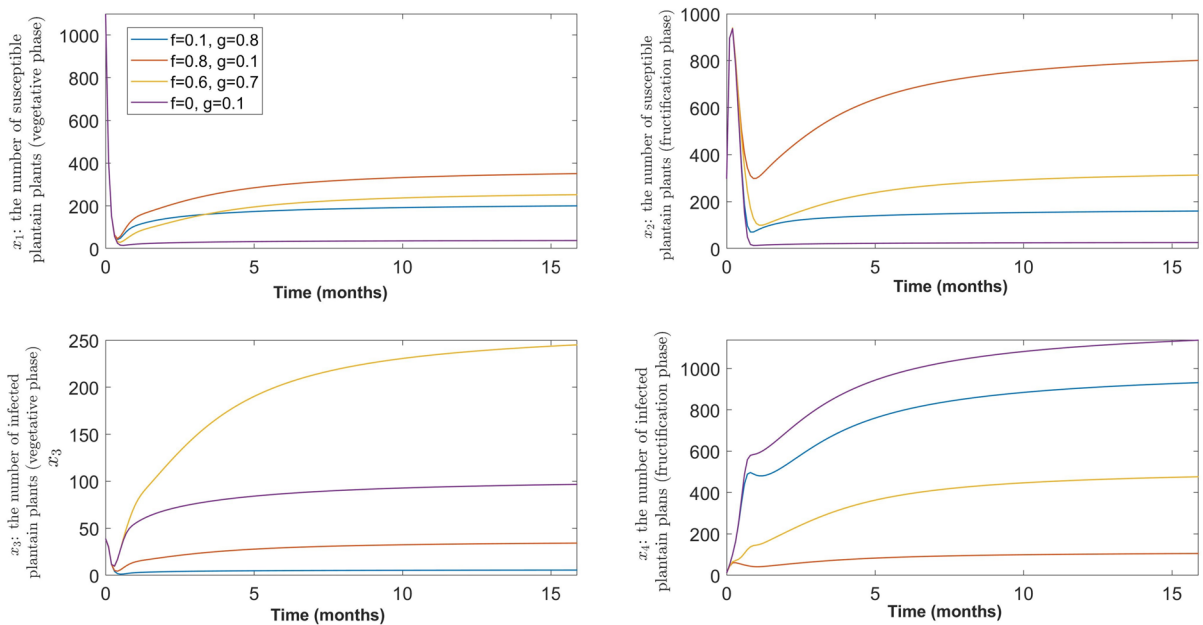

Fig. 3 Fit of the model

Fig. 4 Behavior of the population of susceptible and infected plants in flowering and fructification stage

the spread of those already existing. When plants in the vegetative state are already infected, it is important to implement early elimination, as shown in Fig. 4, where the population of x_3 tends to decrease if g is increased. These results agree with that published by SENASICA (2019) who states that to avoid the increase of foci of disease caused by bacteria in the plantain crop, early elimination of these foci is essential.

The population of susceptible plants during the flowering and fructification stage, x_2, behaves similar to that of plants susceptible during the vegetative state where increasing densities are observed when the infection prevention strategy is implemented.. However, the population of infected plants, x_4, shows a noticeable increase to approximately 1,000 plants if both disease control strategies are not implemented. Early elimination of infected plants is important to reduce the disease. Implementing the infection prevention strategy has a larger effect on the density of susceptible plants than implementing the early removal strategy.

Conclusions

A system of nonlinear differential equations was developed that describes the transmission of Moko disease caused by *Ralstonia solanacearum* in the plantain crops, considering its developmental cycle and characteristic parameters of disease transmission. Control strategies, such as the prevention strategies and elimination of infected plants were included in the model.

Considering the mathematical model and the data collected in the field. The model was fitted to the data with Nonlinear Least Squares Regression, which was solved through the Levenberg–Marquardt algorithm, allowing estimation of the different values of the parameters. The parameter values obtained, show that the propagation of the disease in the flowering phase and in the fructification phase (σ) plays a larger role compared to the propagation of the disease during the vegetative phase (β).

In a plantain crop infected with Moko disease, early elimination of infected plants is an important practice to control the disease. However, weed pruning, tool and footwear disinfection, and selection of rootstalks for planting are prevention strategies that decrease the likelihood of infection in any stage and avoids the spread and increase of infection foci.

program, and the Group on Mathematical Modeling in Epidemiology (GMME).

Data Availability The data that support the findings of this study are available on request from the corresponding author.

Declarations

Disclosure statement The authors found no possible conflicts of interest.

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