RESEARCH ARTICLE

Developing Yield Prediction model for Grapes under Climatic Scenario Along with Disease Management

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ABSTRACT

Crop development and yield are both influenced by the weather. A generic agro-climatic yield prediction model for grape is created and analytically solved in this research. In the field of mathematical biology, this model is valuable for research scholars, faculty members, and academics. To acquire the final form of the yield prediction model, an asymptotic analysis is performed. Climate, disease, and grape yield are all dependent parameters in the model creation process. Independent characteristics include infection rate, disease incidence, seasonality rate, and removal rate of grape production per harvest period. The model is also examined, with parameters estimated using field data from GRS during the period 2015-2021. On concentration curves, the impacts of various parameters are discussed. This model's stability analysis is also explained. The obtained analytical solution is found to be in satisfactory agreement with the numerical and stability studies.

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INTRODUCTION

Grape is one of the most commercially important crops in the world; it has a fairly good source of minerals like calcium, phosphorus, iron and vitamins like B_1 and B_2. Moreover, the juice is mild, laxative and acts as stimulant for kidneys. It is one of the most ancient crops known to humans. Grapes vines were originally a temperate fruit crop, which is grown successfully under tropical conditions. Unripe grapes are used to treat sore throats, and dried grapes are used against constipation and thirst. Round, ripe, sweet grapes are used to treat a wide range of health problems including cancer, cholera, smallpox, nausea, eye infections, skin, kidney, and liver diseases.

Climate has a profound influence on vine growth, productivity and quality of fruits. Of the factors contributing to the successful cultivation of grapes, climate ranks first. The weather parameters viz., sunlight, rainfall, and humidity also influence the quality development of the fruits.

Downy Mildew (*Plasmopara viticola*) is known as one of the most important vineyard diseases in Tamil Nadu because it has the capability to develop and spread very quickly and cause large crop losses in certain areas according to the weather conditions [1]. Farmers must make decisions about whether or not to spray downy mildew and also how frequently to spray and which agrochemicals to use [2]. A good understanding of the stage is needed in incidence and conditions of congenial for the incidence and development of the disease. The efficacy and mode of action of fungicides help the effective management of any disease, particularly downy mildew.

Some mathematical models are developed to provide short-term and field-scale predictions of DM epidemics resulting from infections caused by *P. viticola* sporangia in Switzerland, France, Austria,

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Germany, and Italy [3-10]. These models are developed by using a common database of previous publications.

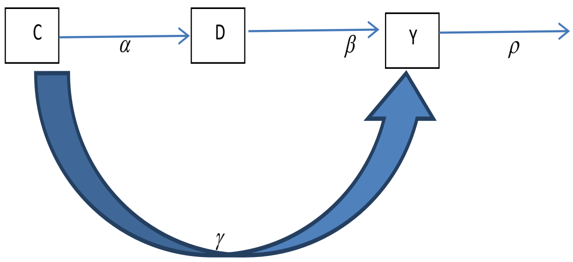
Christopher *et al*. have reformulated the SIR model with host response to infection load for a plant disease [11]. Daniele *et al*. [12] have developed the model for temporal dynamics of brown rot spreading in fruit orchards. Jeger *et al*. [13] have developed a generic modelling framework to understand the dynamics of foliar pathogen and bio-control agent (BCA) populations in order to predict the likelihood of successful bio-control in relation to the mechanisms involved. Abdul Latif has formulated the induced resistance to plant disease using a dynamical system approach [14]. Mario de la Fuente has compared different methods of grapevine yield prediction in the time window between the fruit set and version [15]. Rory Ellis et al. [16] have developed the Bayesian growth model to predict the yield for grapes by using simulation. A dynamic model for *Plasmopara viticola* primary infections on the grapevine was elaborated according to a mechanistic approach by Vittorio Rossi [17]. A generic mathematical model that incorporates the elicitor effect to combat disease infection was initially introduced by Abdul Latif [18]. Manisha S. Sirsat [19] obtained the predictive model for each phenology that predicts yield during the growing stages of grapevine and identifies highly relevant predictive variables by machine learning technique. Recently, a prediction model has been developed for the Godello cultivar, one of the preferential autochthonous white cultivars in the Northwest Spain Ribeiro Designation of Origin vineyards, by means of aerobiological, meteorological and flower production analysis by Estefania Gonzalez-Fernandez [20]. More recently, Kadbhane et al. [21] have developed the grape yield (ACGY) model under a climate change scenario using multiple linear regression analysis.

Most of the previous yield prediction models using secondary data, the model obtained in a particular district based on data, cannot apply to other districts. But, this proposed yield prediction model for grapes is generic for all districts.

According to the literature survey, there are many yield-estimating models that can be used to estimate the yield of wheat, rice, maize, sorghum, sugarcane, etc. However, for grapes, there are no models available for estimation without secondary data. So far, no models have been reported for the estimation exactly of grape yield in Indian terrain. The present study aims at developing an agro-climatic grape yield prediction model for the study area in the Theni district based on current and future climate data. However, to the best of our knowledge, till date no general model and analytical results for the concentration of climate, disease and yield of grape as a function of infection rate, disease incidence, seasonality rate and removal rate of grape yield loss per harvest time. The obtained analytical solution in comparison with the numerical and stability analysis is found to be in satisfactory agreement. In addition, the basic reproduction number for the yield prediction model for grape is obtained.

MATERIAL AND METHODS

In the development of the yield prediction model, temperature, relative humidity, rainfall, and rainy days etc., are all considered climate domain characteristics. Climate is affected by indirectly for grape yield; disease is affected by directly grape yield. Figure 1 shows the agro-climatic disease grape yield model schematic diagram used to define the situation for the real-life assumption of the theoretical outcome



The parameters from the domain γ is the seasonality rate, β is the disease incidence, α is the infection rate and ρ is the removal rate of yield loss per harvest time. It is considered in the development of the agro-climatic grape yield prediction model using the asymptotic analysis. The basic form of the model is indicated below:

$$\frac{dC}{dt} = -\alpha CD - \gamma C \tag{1}$$

$$\frac{dD}{dt} = \alpha CD - \beta D \tag{2}$$

$$\frac{dY}{dt} = \beta D + \gamma C - \rho Y \tag{3}$$

The corresponding initial conditions are:

$$C(0)=C^{*};D(0)=D^{*},Y(0)=Y^{*} \quad (4)$$

where C is the concentration of climate, D is the concentration of disease, Y is the concentration of yield, t is the time in days, α is the infection rate for grape, β is the disease incidence rate for grape, γ is the seasonality rate, ρ is the removal rate of grape yield loss per harvest time, using HPM to find the solution of the equations (1-3) is

$$J=\begin{pmatrix}-\alpha D-\gamma & -\alpha C & 0\\ \alpha D & \alpha C-\beta & 0\\ \gamma & \beta & -\rho\end{pmatrix}$$

At an equlibrium point

$$J=\begin{pmatrix}-\gamma & -\beta & 0\\ 0 & 0 & 0\\ \gamma & \beta & -\rho\end{pmatrix}$$

$$C(t)=C^{*}e^{-\gamma t}-\frac{\alpha C^{*}D^{*}}{\beta}e^{-\gamma t}+\frac{\alpha C^{*}D^{*}}{\beta}e^{-(\beta+\gamma)t}+\left(\frac{\alpha^{2}C^{*2}D^{*}}{\beta\gamma}-\frac{\alpha^{2}C^{*2}D^{*}}{(\beta+\gamma)}-\frac{\alpha^{2}C^{*}D^{*2}}{2\beta^{2}}\right)e^{-\gamma t}-\frac{\alpha^{2}C^{*2}D^{*}}{\beta\gamma}e^{-(\beta+\gamma)t}$$
$$+\frac{\alpha^{2}C^{*2}D^{*}}{(\beta+\gamma)}e^{-(\beta+2\gamma)t}+\frac{\alpha^{2}C^{*}D^{*2}}{\beta^{2}}e^{-(\beta+\gamma)t}-\frac{\alpha^{2}C^{*}D^{*2}}{2\beta^{2}}e^{-(2\beta+\gamma)t} \quad (5)$$

$$D(t)=D^{*}e^{-\beta t}+\frac{\alpha C^{*}D^{*}}{\gamma}e^{-\beta t}-\frac{\alpha C^{*}D^{*}}{\gamma}e^{-(\beta+\gamma)t}+\left(\frac{\alpha^{2}C^{*2}D^{*}}{2\gamma^{2}}-\frac{\alpha^{2}C^{*}D^{*2}}{\gamma\beta}+\frac{\alpha^{2}C^{*}D^{*2}}{(\beta+\gamma)}\right)e^{-\beta t}$$
$$-\frac{\alpha^{2}C^{*2}D^{*}}{\gamma^{2}}e^{-(\beta+\gamma)t}+\frac{\alpha^{2}C^{*2}D^{*}}{2\gamma^{2}}e^{-(\beta+2\gamma)t}+\frac{\alpha^{2}C^{*}D^{*2}}{\gamma\beta}e^{-(\beta+\gamma)t}-\frac{\alpha^{2}C^{*}D^{*2}}{(\beta+\gamma)}e^{-(2\beta+\gamma)t} \quad (6)$$

$$Y=Y^{*}e^{-\rho t}+\left(\frac{\gamma C^{*}}{\gamma-\rho}+\frac{\beta D^{*}}{\beta-\rho}\right)e^{-\rho t}+\frac{\gamma C^{*}}{\rho-\gamma}e^{-\gamma t}+\frac{\beta D^{*}}{\rho-\beta}e^{-\beta t} \quad (7)$$

LOCAL STABILITY ANALYSIS

Equilibria:

An equilibrium point is a point at which variables of a system remain unchanged over time. An equation (1) – (3) possesses the equilibrium $\left(\frac{\beta}{\alpha},0,\frac{\beta\gamma}{\alpha\rho}\right)$ and the system is stable at this equilibrium point. If the system is at stable steady state and is perturbed slightly off the steady state, then the system will return to the steady state. Therefore, small fluctuations in crops will not destroy the equilibrium and it would expect to observe such equilibrium in nature. In this way, the stability typically determines physically viable behavior. It is now determined that the behavior of equations (1)-(3) near the equilibrium point finds the linearization at the equilibrium. Jacobian matrix is needed to assess.

Eigen values of the Jacobian matrix are $\lambda_1=0,\lambda_2=-\rho,\lambda_3=-\gamma$. In our system, $\mathrm{Re}(\lambda_i)\le 0$ so the given system is stable. It is clear to see that the system (1)-(3) has disease-free equilibrium $\left(\frac{\beta}{\alpha},0,\frac{\beta\gamma}{\alpha\rho}\right)$. Let $X=(C,D,Y)^{T}$, then the system (1)-(3) can be written as $X'=F(X)-V(X).$

where,

$$F(X)=\begin{bmatrix}0\\ \alpha CD\\ \beta D\end{bmatrix} \text{ And } V(X)=\begin{bmatrix}\alpha CD+\gamma C\\ \beta D\\ -\gamma C+\rho Y\end{bmatrix}$$

The Jacobian matrices of $F(X)$ and $V(X)$ at the disease-free equilibrium points are respectively.

Let,

$$F = \left\langle J(F(X)) \right\rangle_{\left(\frac{\beta}{\alpha},0,\frac{\beta\gamma}{\alpha\rho}\right)} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \beta & 0 \\ 0 & \beta & 0 \end{bmatrix},$$

$$V = \left\langle J(V(X)) \right\rangle_{\left(\frac{\beta}{\alpha},0,\frac{\beta\gamma}{\alpha\rho}\right)} = \begin{bmatrix} \gamma & \beta & 0 \\ 0 & \beta & 0 \\ -\gamma & 0 & \rho \end{bmatrix}$$

Then, $V^{-1} = \frac{1}{\rho\beta\gamma}\begin{bmatrix} \beta\rho & -\beta\rho & 0 \\ 0 & \rho\gamma & 0 \\ \beta\gamma & -\beta\gamma & \beta\gamma \end{bmatrix}$ and

$$FV^{-1} = \frac{1}{\rho\beta\gamma}\begin{bmatrix} 0 & 0 & 0 \\ 0 & \rho\beta\gamma & 0 \\ 0 & \rho\beta\gamma & 0 \end{bmatrix}$$

Stability can be analyzed using direction filed, numerical method in figure 9. Thus, $R_0 = spectrum(FV^{-1}) = 1$ the given system is globally stable. It has formulated a yield prediction model and investigated the dynamical behaviors. It has also obtained the basic reproduction number, R_0 which plays a crucial role. By constructing Lyapunov function, it proves the global stability of the equilibria: when the basic reproduction number is less than or equal to one, all solutions converge to the disease-free equilibrium that is disease dies out eventually.

NUMERICAL SOLUTION

The model formulation of the equation is numerically solved to test the accuracy of this analytical method. Eqs. (1-3) are numerically solved using Matlab software, a programme that may be used to solve initial value problems. A complete MATLAB application for numerical simulation is included in A. The comparison confirmed that the numerical results match visually and tabular analytical results extremely well. For using field-level data during the period 2015-2021 (in Table 2), the seasonality rate, the disease incidence, the infection rate and the removal rate of yield loss per harvest time are obtained and applied in the given analytical result. There is no significant difference in error % between the numerical and analytical results.

VALIDATION RESULT

In this study, we also propose a survey of grapes growing areas for incidence of downy mildew from 2015 to 2021. A total of fifteen vineyards were selected for the collection of disease incidence levels. The observations on the disease incidence were collected twice a week from the selected grapes vineyards. The results of the survey conducted on grapes showed that downy mildew was a major disease than other diseases especially 0-60 days after forward (fruit) pruning. The daily weather parameters were collected in Grape Research Station, Theni district, Tamil Nadu. The daily weather data are taken on average to form year-wise weather data. The weather parameters like Maximum and Minimum Temperature, Relative humidity and Rainfall were purposively used in the study. The incidence, intensity of downy mildew disease and yield at the field level during 2016-2020 were assessed. Using this field level data, the proposed model can be validated and the results are presented in figure 2.

RESULTS AND DISCUSSION

Eqs. (5-7) are the new analytical expressions of the climate, disease and yield as a function of the seasonality index, the disease incidence, the infection rate and the removal rate of yield loss per harvest time. The concentration of a species is determined by the varying relative rates of infection rate, disease severity as well as effective seasonality rate. The concentration of $C(t), D(t)$ and $Y(t)$ involved in the infection rate, seasonality index and diseases severity with respect to the time in days from the agro-climatic grape yield model and compared with numerical results in Fig. 2. From the figure, it is observed that the concentration of climate is increasing when disease is automatically increasing and other concentration yield becomes zero at initial time. Due to longtime, the concentration of climate is decreasing when the disease is automatically decreasing at the same time the concentration of yield is increases. The concentration profile is equal to steady state when time in days ($t \geq 1$). The effects of seasonality index C^* on concentration of climate as a function of time (days) with $D^* = 0, Y^* = 0, \alpha = 23.98, \beta = 24.04, \gamma = 90$ are shown in Fig. 3. As it increases, the concentration of climate decreases.

Fig. 4 shows the effects of infection rate on the concentration of disease as a function of time (days) using Eq. 6, where it is observed that the concentration of disease increases when the infection rate increases. Fig. 5 demonstrates quantitatively the effects of the seasonality rate parameter on the concentration of yield as a function of time in days. At low time, the effect of decreasing seasonality rate on the concentration yield is shown to reduce the yield concentration.

Fig. 6 shows the infection rate versus year for grape using the estimation parameter. Grape is one of the important fruit crops in India and it was cultivated in several parts of India. In Tamil Nadu particularly Cumbum Valley, Theni district having peculiar climatic condition which favors five crops in two years. The present study was conducted to data on downy mildew infection rate for future disease severity prediction. Data on infection rate revealed that 2017-18 had the highest infection rate (28.02 %), followed by 2016-17 having a score of 24.57 %. Among the different year 2019-20 had the lowest infection rate (20.95 %). The difference in infection rate might be due to varietal characters leaf area, climatic conditions (temperature, rainfall, relative humidity, wind speed etc.), and infection rate and control measures.

Fig. 7 represents the disease intensity in grapes under Cumbum valley condition was continuously observed from 2016-2020. The disease intensity in grapes on various years exhibited the significantly difference. The disease intensity was peak at 2016-17 thereafter it was decreased and reached lowest disease intensity (1.51) in 2018-19. During 2019-20 the disease intensity was increasing trend and having a value of 1.55. The variation in disease intensity might be due to leaf area, climatic condition (temperature, rainfall, relative humidity, wind speed etc.), infection rate and control measures.

Fig. 8 shows the three-dimension space on the concentration of climate for varying effective seasonality rate and infection rate. The concentration of climate is independent of both α and γ but is a function of C^* where reduces the concentration of climate. Fig. 9, the concentration of disease varies with infection rate and disease incidence for large value of t. In this regime, the concentration of disease increases with increasing infection rate when $\beta < 10$.

In figure 10, the disease incidence β is extremely high, when the concentration of yield asymptotically reaches a constant value regardless of γ, but it depends on α. It can be concluded that the concentration of yield increases, when the seasonality index and disease incidence slightly decrease. Analytical expression of climate, disease and yield are compared with simulation results in Table 1. The maximum relative error between numerical simulations with the analytical result for the developed model is obtained 0.2832%. Stability analysis is carried out for the developed model using the parametric Jacobian transformation method. Based on the obtained results of the mathematical tests, the developed yield prediction model (Eq.5-7) is recommended for its use to estimate the grape yield. Further, phase portraits, for both linear and non-linear system can be predicted or analyzed using algebraic method. In figure 11, is easy to see that the globally stable state and the both upper and lower are positive state are stable nodes.

Appendix A

MATLAB Program for the Numerical Solution of Nonlinear Differential Eqs. (13-15).

```
function main
options= odeset ('RelTol',1e-6,'Stats','on');
%initial conditions
C=33;
D=0.0001;
Y=0;
Xo = [C, D, Y];
tspan = [0,0.5];
xspan = [0,100];
tic
[t, X] = ode45(@TestFunction, tspan, Xo, options);
toc
figure
plot (t, X (:1), t, X (:2), t, X (:3))
ylabel('x')
xlabel('t')
return
function [dx_dt] =TestFunction (t, x)
a=23.98;
b=24.04;
r=90;
dx_dt (1) =-a*x (1) *x (2)-r*x (1);
dx_dt (2) =a*x (1) *x (2)-b*x (2);
dx_dt (3) =b*x (2) +r*x (1);
dx_dt = dx_dt';
return
```

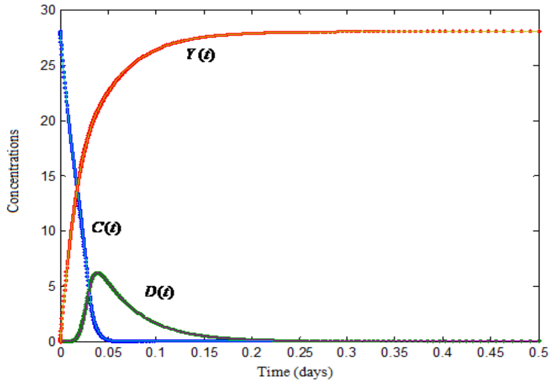


Figure2. Concentrations for $C(t), D(t)$ and $Y(t)$ versus time in days for $C^* = 33, D^* = 0, Y^* = 0, \alpha = 23.98, \beta = 24.04, \gamma = 90, \rho = 0.2.$ The dotted line represent the numerical results and solid line represents the analytical results.

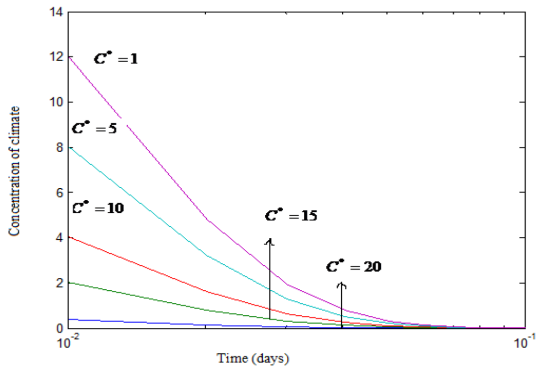


Figure 3. Effects of seasonality index C^* on concentration of climate as a function of time (days) with

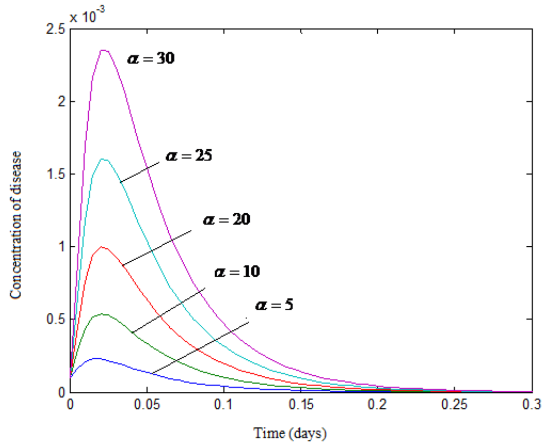


Figure 4. Effects of infection rate α on concentration of disease as a function of time (days) with $C^* = 33, D^* = 0, Y^* = 0, \beta = 24.04, \gamma = 90.$

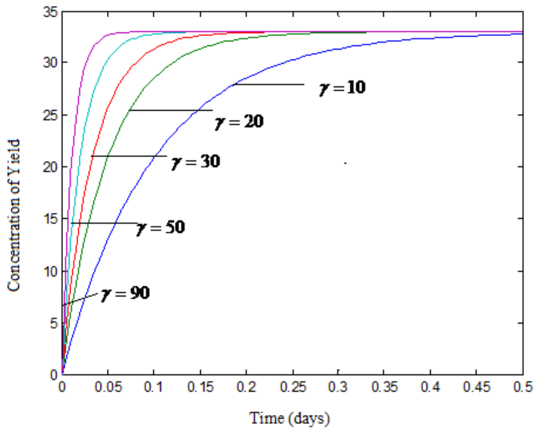


Figure 5. Effects of effective seasonality rate γ on concentration of yield as a function of time (days) with $C^* = 33, D^* = 0, Y^* = 0, \alpha = 23.98, \beta = 24.04, \rho = 0.2.$

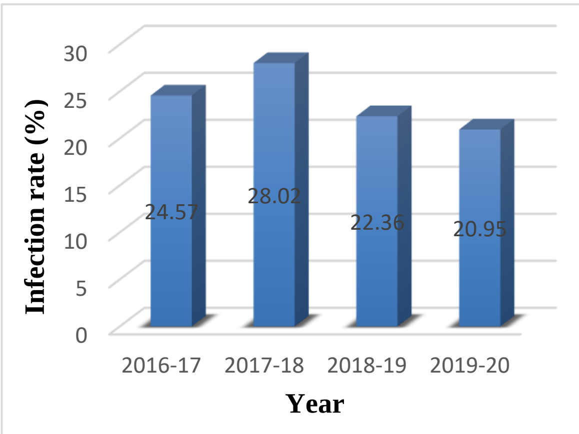


Figure 6: Infection rate as a function of year 2016-2020 influence of climatic condition for grape cultivation in Theni district

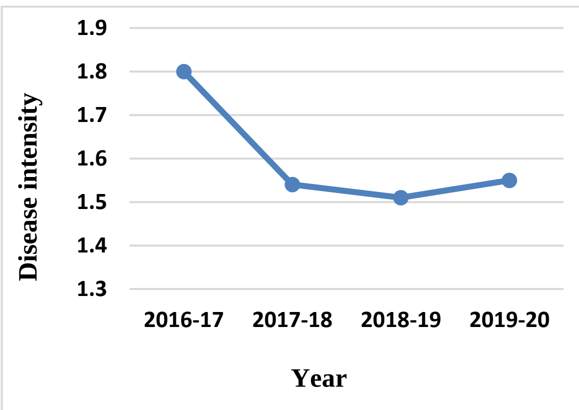


Figure 7: Disease intensity as a function of year 2016-2020 influence of climatic condition for grape cultivation in Theni district

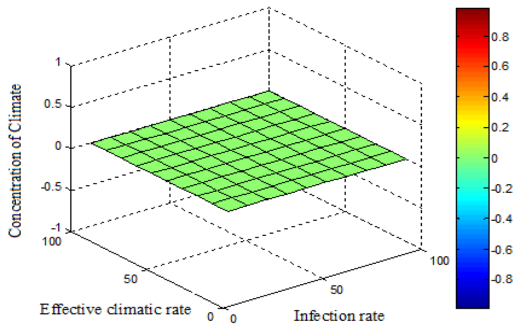


Figure 8. Effects of disease incidence β on concentration of climate for varying effective seasonality rate and infection rate for $C^* = 33, D^* = 0, Y^* = 0.$

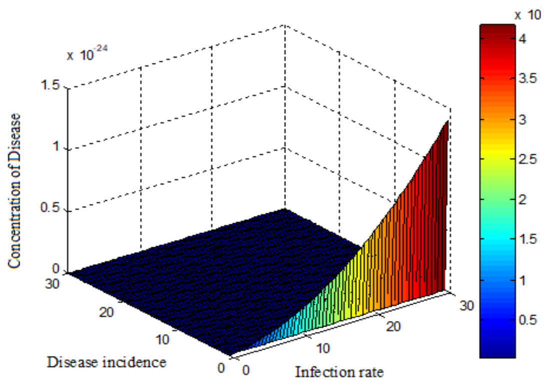


Figure 9. Effects of effective seasonality rate γ on concentration of disease for varying infection rate and disease incidence for $C^* = 33, D^* = 0, Y^* = 0.$

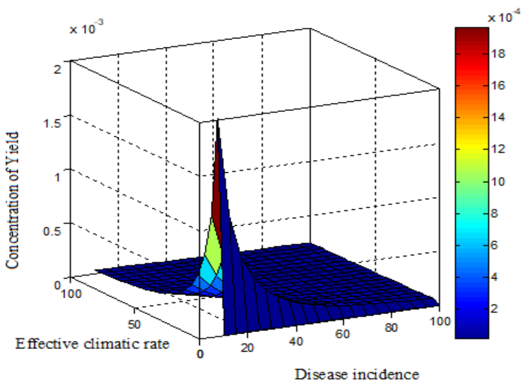


Figure 10. Effects of infection rate α on concentration of yield for varying effective seasonality rate and disease incidence for $C^* = 33, D^* = 0, Y^* = 0, \rho = 0.2.$

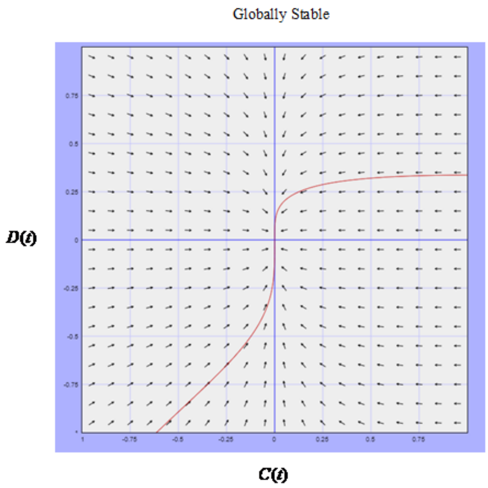


Figure 11. A sketch of the phase plane of the climate disease yield prediction system. Arrows represent the direction of the phase flows of matter through the system.

Table1.Comparison of analytical result with numerical result for Concentrations $C(t), D(t)$ and $Y(t)$ for experimental values of parameter $C^{*}=33, D^{*}=0, Y^{*}=0, \alpha=23.98, \beta=24.04, \gamma=90, \rho=0.2.$

t	Concentrations $C(t)$			$D(t)$			$Y(t)$		
	This work	Simulation	Error %	This work	Simulation	Error %	This work	Simulation	Error %
0	28.0000	28.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.1	0.00311	0.00312	0.3215	1.6140	1.6150	0.0620	26.3900	26.3800	0.0379
0.2	0.1473	0.1475	0.1358	0.1473	0.1476	0.2037	27.8500	27.8501	0.0004
0.3	0.0120	0.0121	0.8333	0.0121	0.0122	0.8264	27.9900	27.9902	0.0007
0.4	0.0052	0.0052	0.0000	0.00521	0.0052	0.1919	28.0000	28.0000	0.0000
0.5	0.0001	0.0001	0.0000	0.00241	0.00242	0.4149	28.0000	28.0000	0.0000
	Average error %		0.2151	Average error %		0.2832	Average error %		0.0065

Table 2: Experimental values of the parameters from Grape research station and surrounding villages at Theni district during the period 2015-2021.

S. No	Parameters	Experimental value
1.	Infection rate (α)	23.98 %
2.	disease incidence (β)	24.04%
3.	seasonality rate (γ)	90%
4.	removal rate of grape yield per harvest time (ρ)	0.2 to 0.6%
5.	Disease concentration at initial time (D^{*})	0
6.	Yield concentration at initial time (Y^{*})	0
7.	Climatic concentration at initial time (C^{*})	33^{0}c

Conclusion

Previously, studies related to mathematical analysis and modeling on grapes and climatic elements in Tamil Nadu have been seen as scanty. But a number of general studies have been made on different aspects of grapes but none of them has focused adequately on the mathematical model studies. In this paper, we present the results of the investigation undertaken on grapes diseased, climatic effect and yield as a function of infection rate and disease intensity and disease incidence with respect to observation days. The obtained results have a good agreement with that numerical result and stability analysis. It is established that the global dynamics are completely determined by the basic reproduction number. If ≤ 1, then the disease-free equilibrium is globally asymptotically stable. Therefore, the given system of equations of the model is globally stable. Based on the obtained results of the developed yield prediction model, it is recommended for its use to estimate the grape yield. Also, a valuable tool for predicting crop yields a few years ahead of time.

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Ethics statement

No specific permits were required for the described field studies because no human or animal subjects were involved in this research.

Originality and plagiarism

We assure that we have written and submitted only entirely original works.

Consent for publication

All the authors agreed to publish the content.

Competing interests

There were no conflicts of interest in the publication of this content.

Data availability

All the data of this manuscript are included in the MS. No separate external data source is required.

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