Article

Modeling the dynamics of methane emission from rice paddies and livestock populations and its effects on global warming: A comparison of model with data

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Abstract
The rice paddies and livestock populations are the largest anthropogenic sources of methane emissions in the atmosphere causing global warming. In this paper, a nonlinear mathematical model is proposed and analysed to study the effect of methane emissions on global warming by considering four dependent variables, namely, the cumulative biomass density of rice paddies, the cumulative density of livestock populations, the atmospheric concentration of methane emitted from rice paddies, livestock populations as well as natural sources and the average global warming temperature of near earth's atmosphere. In the modeling process, it is assumed that both the cumulative densities of rice paddies and livestock populations follow logistic models with their respective growth rates and carrying capacities. The livestock populations are assumed to be partially dependent on rice paddies for food. Further, the livestock populations are assumed to be harvested for meat and leather. The growth rate of methane concentration in the atmosphere is assumed to be proportional to the cumulative density of rice paddies as well as of livestock populations. This growth rate also increases with a constant rate from natural sources but it decreases with a rate proportional to its concentration in the atmosphere due to various factors. The growth rate of global warming temperature is assumed to be proportional to the increased level of methane concentration in the atmosphere from its equilibrium value. It is also assumed that this temperature decreases with a rate proportional to its enhanced level from its equilibrium value caused by various natural factors such as rain fall, reforestation, etc. The model is analyzed by using stability theory of ordinary differential equations and computer simulation. The analysis shows that as the emissions of methane from rice paddies and livestock populations increase, the global warming temperature increases considerably from its equilibrium level. The percentage increase in global warming temperature with the corresponding increase in methane concentration is determined from the model and compared with the available data in the literature. The comparison is found to be very satisfactory. The numerical simulation confirms this result.

Keywords mathematical model; methane; rice paddies; livestock populations; global warming; stability analysis.

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1 Introduction

One of the most important problems that our society faces today is global warming due to greenhouse gases. The most abundant greenhouse gases are carbon dioxide, methane, nitrous oxide, etc. The elevated level of methane in the Earth's atmosphere which is about 16% of all greenhouse gases is a matter of great concern due to its large impact on climate change. It is produced mainly due to production processes of rice paddies and farming processes of livestock populations (Ramanathan and Feng, 2009; Seiler et al., 1984). Rice production contributes approximately 5-19% of the total global methane emissions into the atmosphere and livestock populations contribute approximately 33% of global anthropogenic methane emissions. It has been observed that the worldwide rice production is responsible for nearly 20% of global anthropogenic CH_4 emission (Cao et al., 1996). It has been predicted that increasing demand of rice for food to millions of people in the world can further enhance CH_4 production contributing more than 80% of its emission in the atmosphere (Zhang et al., 2011). It has been estimated that China has to increase its rice production up to 20% by 2030 to ensure the food security to its increasing population (Peng et al., 2009). Thus, a continuous increase in rice production is one of the main reasons for increase of CH_4 in the atmosphere.

The farming of livestock populations is one of the other reasons in developing countries due to increasing demand of products such as meat, milk, etc. The livestock populations produce significant amount of methane directly via enteric fermentation and indirectly via manure management which is affected by various factors including the animal size, age, growth rate, type and quality of feeds, genetics, environmental temperature, etc., (Johnson and Johnson, 1995; Shibata and Terada, 2010). Animals release CH_4 into the atmosphere by exhaling the gas mainly through the mouth and nostrils (Chagunda et al., 2009). The CH_4 emission from manure depends on the physical characteristics of feces (shape, size, density), climate (temperature and humidity), etc (Gonzalez-Avalos and Ruiz-Suarez, 2001). As a mitigation option, the ageing and unproductive livestock populations can be killed for meat and leather.

It is noted here that very few studies have been conducted to study the increase of global warming temperature due to methane caused by rice paddies and livestock populations simultaneously (Goyal and Shukla, 2018; Misra and Verma, 2013; Misra and Verma, 2017; Shukla et al., 2015). Therefore, in this paper, a non-linear mathematical model is proposed and analyzed to study the increase of average global warming temperature caused by emissions of methane due to production processes of rice paddies and farming of livestock populations simultaneously. The focus in this paper is also to compare the model prediction with data published in literature (Butler and Montzka, 2018; Dlugokenck, 2018; Petz, 2018).

2 Mathematical Model

To model the problem mentioned above, let $B(t)$ be the cumulative biomass density of rice paddies, $C_a(t)$ be the cumulative density of livestock populations, $C(t)$ be the atmospheric concentration of CH_4 and $T(t)$ be the global warming average atmospheric temperature over its equilibrium T_0. In the modeling process, the following concepts are used.

(i) The growth rate of cumulative biomass density of rice paddies which is assumed to grow logistically is depleted bilinearly by the cumulative density of livestock population.

(ii) The growth rate of cumulative density of livestock population is also assumed to follow logistic model and it increases with the cumulative density of rice paddies bilinearly but it decreases with a rate proportional to its density.

(iii) The growth rate of methane concentration in the atmosphere is assumed to be directly proportional to cumulative density of rice paddies and livestock populations. It also increases with a constant rate caused by natural factors but its decrease is proportional to its concentration in the atmosphere.
(iv) The growth rate of global warming temperature is assumed to be directly proportional to the increase of methane concentration in the atmosphere from its equilibrium concentration C_0. But it decreases with a rate proportional to its enhanced level in the atmosphere.

Keeping the above considerations, the following four dimensional nonlinear mathematical model is proposed to study the effect of methane emissions on global warming,

$$\frac{dB}{dt} = sB\left(1-\frac{B}{L}\right) - s_1 BC_a \tag{1}$$

$$\frac{dC_a}{dt} = (r-r_0)C_a - \frac{rC_a^{\ 2}}{K_a} + r_{a1}BC_a \tag{2}$$

$$\frac{dC}{dt} = Q_0 + \lambda_1 C_a + \lambda_2 B - \lambda_0 C \tag{3}$$

$$\frac{dT}{dt} = \theta(C-C_0) - \theta_0(T-T_0) \tag{4}$$

where $C_0 = \dfrac{Q_0}{\lambda_0}$ and $B(0) \geq 0,\ C_a(0) \geq 0,\ C(0) \geq C_0 > 0,\ T(0) \geq T_0 > 0$

In Eq. (1), the growth rate of the cumulative biomass density, B, of rice paddies is governed by a logistic equation where s and L are its intrinsic growth rate and the carrying capacity respectively. The constant s_1 is the depletion rate coefficient of biomass density of rice paddies, B, due to livestock populations. In the second equation of the model, the cumulative density of livestock populations, C_a, is governed by a logistic equation where r and K_a are its intrinsic growth rate and the carrying capacity respectively. The constant r_{a1} is the growth rate coefficient of livestock population, C_a, due to use of rice paddies (i.e. $r_{a1}BC_a$). Also r_0 is the depletion rate coefficient of livestock populations due to harvesting for meat, leather, etc. This can be thought of a mechanism for mitigation option. In the third equation, the emission rate of methane is considered to be directly proportional to the respective cumulative biomass density of rice paddies and livestock populations. The constants λ_1 and λ_2 are the emission rate coefficients of methane due to the cumulative density of livestock populations (i.e. $\lambda_1 C_a$) and the cumulative biomass density of rice paddies (i.e. $\lambda_2 B$) respectively. The constant Q_0 is emission rate of methane due to natural sources and λ_0 represents its natural depletion rate coefficient. In the last equation, the average atmospheric temperature over its equilibrium i.e., $(T-T_0)$ is assumed to be proportional to the increased level of methane concentration from its equilibrium (i.e., $\theta(C-C_0)$), θ being its growth rate coefficient. The constant θ_0 is the natural depletion rate coefficient of atmospheric temperature.

In the following, we analyze the model (1) - (4) for which a lemma is needed as stated below.

Lemma The region of attraction for all solutions of model (1) - (4) initiating in the positive octant is given by the set,

$$\Omega = \left\{ (B, C_a, C, T) : 0 \leq B \leq L,\ 0 \leq C_a \leq \frac{K_a}{r}(r_a + r_{a1}L),\ C_0 \leq C \leq C_m,\ 0 \leq T \leq T_0 + \frac{\theta}{\theta_0}(C_m - C_0) \right\}$$

where $r_a = r - r_0 > 0$ and $C_m = \dfrac{Q_0 + \lambda_1 \dfrac{K_a}{r}(r_a + r_{a1}L) + \lambda_2 L}{\lambda_0}$.

The model (1) – (4) is analyzed under the assumption $s > s_1 C_a$ (for all values of C_a).

3 Equilibrium Analysis

The system (1) – (4) has four equilibria, namely,

(1) $E_0(0, 0, C_0, T_0)$

(2) $E_1\left(0, K_a, \dfrac{Q_0 + \lambda_1 K_a}{\lambda_0}, T_0 + \dfrac{\theta \lambda_1 K_a}{\theta_0 \lambda_0}\right)$

(3) $E_2\left(L, 0, \dfrac{Q_0 + \lambda_2 L}{\lambda_0}, T_0 + \dfrac{\theta \lambda_2 L}{\theta_0 \lambda_0}\right)$

(4) $E^*(B^*, C_a{}^*, C^*, T^*)$

The existence of E_0, E_1 or E_2 is obvious. We prove the existence of $E^*(B^*, C_a{}^*, C^*, T^*)$ as follows,

Existence of $E^*(B^*, C_a{}^*, C^*, T^*)$

The equilibrium $E^*(B^*, C_a{}^*, C^*, T^*)$ is obtained by solving the following set of equations

$$s\left(1 - \frac{B}{L}\right) - s_1 C_a = 0 \tag{5}$$

$$r_a - \frac{rC_a}{K_a} + r_{a1}B = 0 \text{ where } r_a = r - r_0 > 0 \tag{6}$$

$$Q_0 + \lambda_1 C_a + \lambda_2 B - \lambda_0 C = 0 \tag{7}$$

$$\theta(C - C_0) - \theta_0(T - T_0) = 0 \tag{8}$$

Solving Eqs. (5) and (6), we get

$$B = \frac{L}{s}(s - s_1 C_a),\ s > s_1 C_a \tag{9}$$

$$C_a = \frac{r_a + r_{a1}L}{\left(\dfrac{r}{K_a} + r_{a1}L\dfrac{s_1}{s}\right)} = C_a{}^* > 0 \tag{10}$$

Using Eq. (10) in Eq. (9), we get

$$B^* = \frac{L}{s}(s - s_1 C_a^*),\text{ provided } \quad s > s_1 C_a{}^* \tag{11}$$

From Eq. (7), we have

$$C^* = \frac{(Q_0 + \lambda_1 C_a{}^* + \lambda_2 B^*)}{\lambda_0} \tag{12}$$

From Eq. (8), we have

$$T^* = T_0 + \frac{\theta}{\theta_0}(C^* - C_0) \tag{13}$$

Thus, the equilibrium $E^*(B^*, C_a{}^*, C^*, T^*)$ exists uniquely.

Variations of T with different parameters

Using Eqs. (9) and (10) in Eq. (7), we have

$$Q_0 + \lambda_1 \frac{r_a + r_{a1}L}{\left(\frac{r}{K_a} + r_{a1}L\frac{s_1}{s}\right)} + \lambda_2 \frac{L}{s}\left(s - s_1 \frac{r_a + r_{a1}L}{\left(\frac{r}{K_a} + r_{a1}L\frac{s_1}{s}\right)}\right) - \lambda_0 C = 0 \tag{14}$$

Variation of T with λ_1

Differentiating equation (14) with respect to λ_1, we have

$$\frac{dC}{d\lambda_1} = \frac{r_a + r_{a1}L}{\lambda_0\left(\frac{r}{K_a} + r_{a1}L\frac{s_1}{s}\right)} > 0$$

Since $\frac{dC}{d\lambda_1} > 0$, therefore, from $\frac{dT}{d\lambda_1} = \frac{dT}{dC}\frac{dC}{d\lambda_1}$ we have $\frac{dT}{d\lambda_1} > 0$

This implies that temperature T increases as the rate of concentration C of CH_4 increases due to cumulative biomass density of livestock populations.

Variation of T with λ_2

Differentiating Eq. (14) with respect to λ_2, we have

$$\frac{dC}{d\lambda_2} = \frac{L}{\lambda_0 s}\left(s - \frac{s_1(r_a + r_{a1}L)}{\left(\frac{r}{K_a} + r_{a1}L\frac{s_1}{s}\right)}\right) > 0 \tag{15}$$

as, $s - \frac{s_1(r_a + r_{a1}L)}{\left(\frac{r}{K_a} + r_{a1}L\frac{s_1}{s}\right)} > 0$,

From Eq. (10), we have $T = T_0 + \frac{\theta}{\theta_0}(C - C_0)$

Differentiating this with respect to C, we have

$$\frac{dT}{dC}=\frac{\theta}{\theta_0}>0 \tag{16}$$

Now $\dfrac{dT}{d\lambda_2}=\dfrac{dT}{dC}\dfrac{dC}{d\lambda_2}$

Using Eqs. (15) and (16), we have, $\dfrac{dT}{d\lambda_2}>0$

This implies that temperature T increases as the rate of concentration C of CH_4 increases due to cumulative biomass density of rice paddies.

Similarly, we can show

$$\frac{dC}{dr_0}<0 \text{ and } \frac{dT}{dr_0}<0 \tag{17}$$

These conditions show that the concentration C of CH_4 and the average temperature T decrease as r_0 increases.

4 Stability Analysis

4.1 Local stability

By computing Jacobian matrix corresponding to the model system (1) – (4), it can easily be checked that

(1) $E_0(0,0,C_0,T_0)$ is a saddle point unstable manifold in $B-C_a$ plane and stable manifold in $C-T$ plane.

(2) $E_1\left(0,K_a,\dfrac{Q_0+\lambda_1 K_a}{\lambda_0},T_0+\dfrac{\theta\lambda_1 K_a}{\theta_0\lambda_0}\right)$ is a saddle point, unstable manifold in B –direction and stable manifold in C_a-C-T plane.

(3) $E_2\left(L,0,\dfrac{Q_0+\lambda_2 L}{\lambda_0},T_0+\dfrac{\theta\lambda_2 L}{\theta_0\lambda_0}\right)$ is a saddle point unstable manifold in C_a – direction and stable manifold in $B-C-T$ plane.

Now we proceed to determine the local stability of $E^*(B^*,C_a^*,C^*,T^*)$.

The Jacobian matrix of the system (1) – (4) about E^* is

$$J(E^*)=\begin{bmatrix} -\frac{s}{L}B^* & -s_1 B^* & 0 & 0 \\ r_{a1}C_a^{\ *} & -\frac{r}{K_a}C_a^{\ *} & 0 & 0 \\ \lambda_2 & \lambda_1 & -\lambda_0 & 0 \\ 0 & 0 & \theta & -\theta_0 \end{bmatrix}$$

It is noted that one eigenvalue of above Jacobian matrix is negative and others are given by the following characteristic equation,

$$z^3 + c_1 z^2 + c_2 z + c_3 = 0$$

where, $c_1 = \frac{s}{L}B^* + \frac{r}{K_a}C_a{}^* + \lambda_0$

$$c_2 = \lambda_0 \frac{r}{K_a}C_a{}^* + \lambda_0 \frac{s}{L}B^* + \frac{r}{K_a}\frac{s}{L}B^* C_a{}^* + r_{a1} s_1 B^* C_a{}^*$$

$$c_3 = \lambda_0 \frac{s}{L}\frac{r}{K_a}B^* C_a{}^* + \lambda_0 r_{a1} s_1 B^* C_a{}^*$$

Since $c_1 > 0, c_2 > 0, c_3 > 0$ and $c_1 c_2 - c_3 > 0$. By using Routh Hurwitz criteria, we note that E^* is locally asymptotically stable without any condition.

Now we study the nonlinear stability analysis of E^*.

4.2 Nonlinear stability

Consider a positive definite function

$$U = m_1\left(B - B^* - B^* \log\frac{B}{B^*}\right) + m_2\left(C_a - C_a{}^* - C_a{}^* \log\frac{C_a}{C_a{}^*}\right)^2 + \frac{1}{2}m_3(C - C^*)^2 + \frac{1}{2}m_4(T - T^*)^2$$

where m_1, m_2, m_3 and m_4 are positive constants to be chosen suitably.

Differentiating U with respect to $'t'$ we get

$$\frac{dU}{dt} = \frac{m_1}{B}(B - B^*)\frac{dB}{dt} + \frac{m_2}{C_a}(C_a - C_a{}^*)\frac{dC_a}{dt} + m_3(C - C^*)\frac{dC}{dt} + m_4(T - T^*)\frac{dT}{dt}$$

Putting the values of derivatives from model system (1) – (4) and simplifying, we get,

$$\frac{dU}{dt} = -m_1\frac{s}{L}(B - B^*)^2 - m_2\frac{r}{K_a}(C_a - C_a{}^*)^2 - \lambda_0 m_3(C - C^*)^2 - m_4\theta_0(T - T^*)^2$$

$$+ (m_2 r_{a1} - m_1 s_1)(B - B^*)(C_a - C_a{}^*) + m_3\lambda_2(B - B^*)(C - C^*)$$

$$+ m_3\lambda_1(C_a - C_a{}^*)(C - C^*) + m_4\theta(C - C^*)(T - T^*)$$

After some algebraic manipulations and by choosing,

$$m_1 = 1, m_2 = \frac{s_1}{r_{a1}}, m_3 < \left(\frac{2}{3}\lambda_0\right)\min\left(\frac{s}{\lambda_2{}^2 L}, \frac{2s_1 r}{\lambda_1{}^2 r_{a1} K_a}\right) \text{ and } m_4 < \frac{4}{9}\left(\frac{s\lambda_0{}^2\theta_0}{\lambda_2{}^2\theta^2 L}\right)$$

it is noted that $\frac{dU}{dt}$ is negative definite. Thus, E^* is nonlinearly asymptotically stable without any condition.

5 Numerical Analysis

To validate the analytical findings, we perform numerical simulation of the model system (1) – (4) with respect to $E^\bullet$ for different values of parameters. For that the system (1) – (4) is integrated numerically with the help of MAPLE 18 using the following values of various parameters.

$Q_0 = 70,\ \lambda_0 = 0.1,\ r = 0.5,\ K_a = 20000,\ L = 10000,$

$r_{a1} = 0.0000004,\ r_0 = 0.005,\ \lambda_1 = 0.004,\ \lambda_2 = 0.003, \theta = 0.0003$

$\theta_0 = 0.2,\ s = 0.3,\ s_1 = 0.0000001,\ C_0 = 700,\ T_0 = 13.4$

The equilibrium values of different variables in E^* are obtained as,

$B^* = 9933.470214,\ C_a{}^* = 19958.93553,\ C^* = 1796.361528,\ T^* = 15.044542$

The eigenvalues of the Jacobian matrix corresponding to E^* are -0.20000, -0.10000, -0.49893 and -0.29804. Since all the eigenvalues are negative, the interior equilibrium E^* is locally asymptotically stable.

To present nonlinear stability of E^* for the model system (1) – (4) in $B - C_a - T$ plane, trajectories with different initial starts have been plotted in $B - C_a - T$ plane as shown in Fig. 1. It is apparent from Fig. 1 that all trajectories approach the equilibrium E^* showing that the equilibrium E^* is nonlinearly stable for these set of parameters.

To visualize the variation of model variables with different set of parameters, these are plotted in Figs. 2 – 8. In Figs. 2 – 3, the concentration C of methane and average atmospheric temperature T with time t for different values of r_0, the depletion rate coefficient of livestock population due to harvesting, are plotted which show that C and T decrease as r_0 increases. From Figs. 4 – 5, it is noted that the concentration C of methane and average atmospheric temperature T increase as λ_1 increases. In Figs. 6 – 7, the concentration C of methane and average atmospheric temperature T with time t is plotted which show that C and T increase as λ_2 increases. From these graphs it is concluded that methane concentration decreases with harvesting of livestock populations but increases with the increase in the biomass density of rice paddies as well as increase in livestock populations.

In Fig. 8, the percentage increase of the atmospheric average temperature with the percentage increase in methane concentration is shown for the data taken for model analysis and compared the same with real experimental data, (Butler and Montzka, 2018; Dlugokenck, 2018; Petz, 2018). The model analysis shows that the methane concentration has increased 162.28 percent which is approximately equal to the experimental data (165.63%). An increase of about 13.67% in methane concentration results an increase of 1% in average atmospheric global warming temperature.

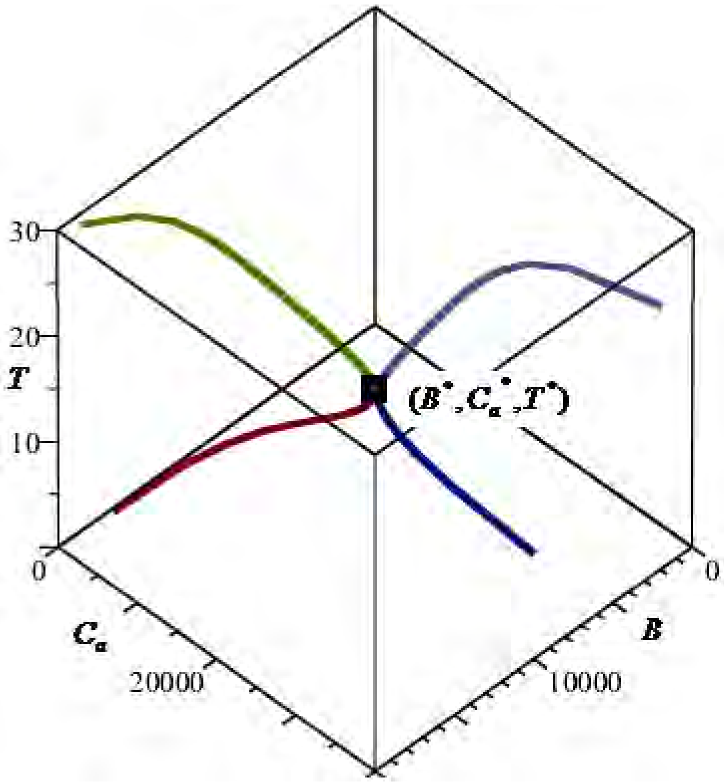

Fig. 1 Nonlinear stability in $B - C_a - T$ plane.

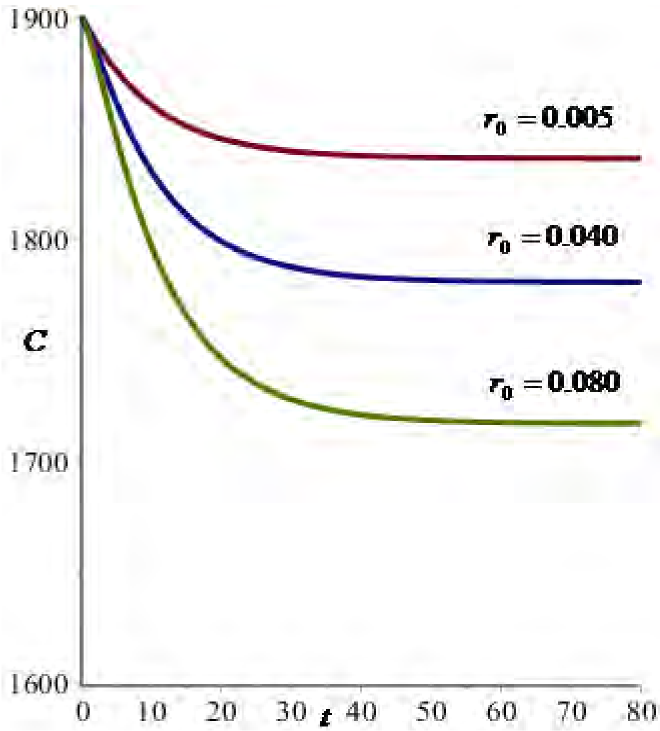

Fig. 2 Variation of methane concentration C with time t for different values of r_0.

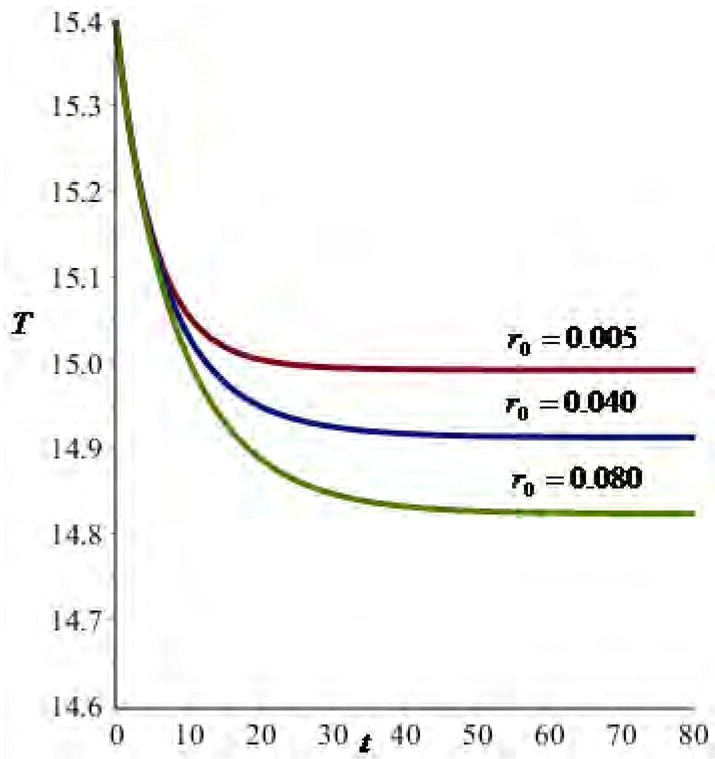

Fig. 3 Variation of temperature T with time t for different values of r_0.

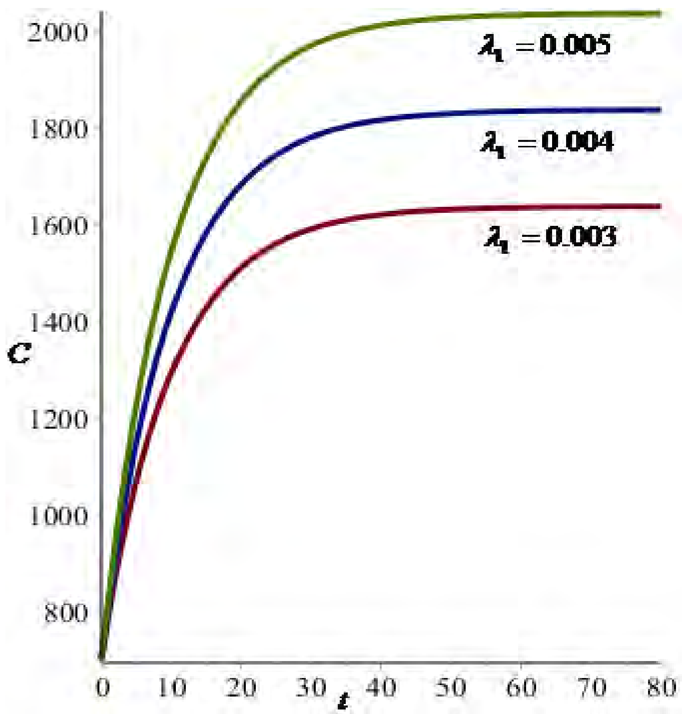

Fig. 4 Variation of methane concentration C with time t for different values of λ_1.

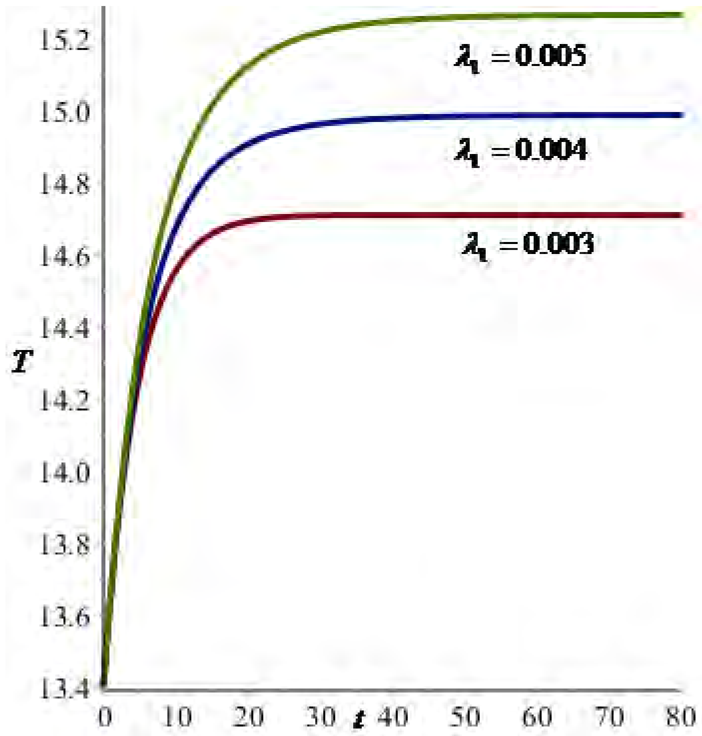

Fig. 5 Variation of temperature T with time t for different values of λ_1

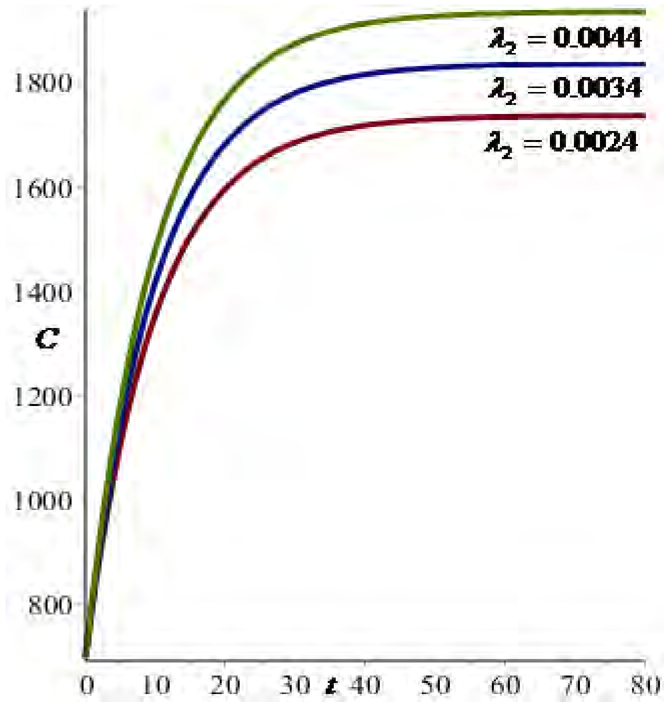

Fig. 6 Variation of methane concentration C with time t for different values of λ_2.

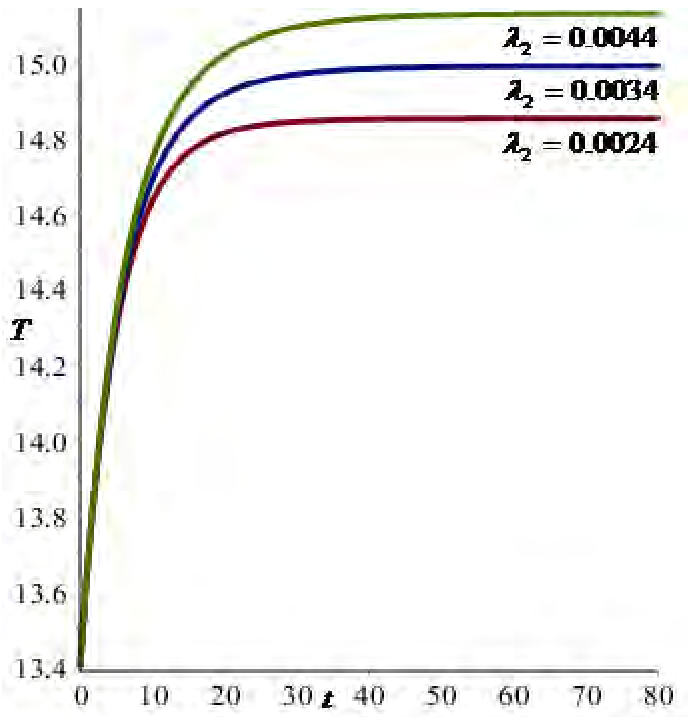

Fig. 7 Variation of temperature T with time t for different values of λ_2

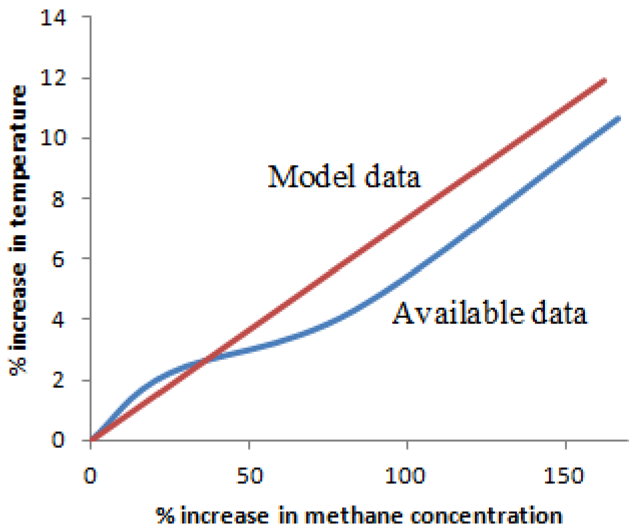

Fig. 8 Variation of percentage increase in temperature $\left(= \dfrac{T - T_0}{T_0} \times 100\right)$ with respect to percentage increase in methane concentration $\left(= \dfrac{C - C_0}{C_0} \times 100\right)$

6 Conclusion

In this paper, a nonlinear mathematical model has been proposed to study the effect of methane emissions on global warming temperature caused by rice paddies and livestock populations. In the modeling process, the four dependent variables, namely, the cumulative biomass density of rice paddies, the cumulative density of livestock populations, the atmospheric concentration of CH_4 and the average atmospheric temperature have been considered. The growth rates of cumulative biomass density of rice paddies and the cumulative density of livestock populations have been assumed to be governed by logistic models with their respective growth rates and carrying capacities. It has also been assumed that the growth rate of the cumulative density of rice paddies decreases due to its use by livestock populations. The concentration of CH_4 is considered to be proportional to the cumulative biomass density of rice paddies as well as the cumulative density of livestock populations. Further, the growth rate of cumulative density of livestock populations decreases due to harvesting for meat and leather. The increase in the global warming temperature has been assumed to be proportional to the increased level of concentration of CH_4 in the atmosphere from its equilibrium value.

The proposed model has been analyzed by using stability theory of ordinary differential equations and numerical simulations. It has been shown, analytically and numerically, that as the concentration of methane emission increases with time due to increasing growth rates of the cumulative density of rice paddies and livestock populations, the global warming average temperature increases. However, due to harvesting of livestock populations, the global warming temperature decreases. It has also been shown from the model analysis that for an increase of about 13.67% in methane concentration, the increase in average atmospheric temperature has been found to be of 1%. This result is compared with real experimental data and has been found to be very satisfactory.

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