Investigations of methane emissions from rice cultivation in Indian context

Shalini Anand\textsuperscript{a,\*}, R.P. Dahiy\textsuperscript{a}, Vikash Talyan\textsuperscript{a}, Prem Vrat\textsuperscript{b}

\textsuperscript{a}Centre for Energy Studies, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India
\textsuperscript{b}Indian Institute of Technology Roorkee, Uttranchal 247667, India

Received 20 March 2004; accepted 25 October 2004
Available online 2 December 2004

Abstract

The increasing demand of the growing population requires enhancement in the production of rice. This has a direct bearing on the global environment since the rice cultivation is one of the major contributors to the methane emissions. As the rice cultivation is intensified with the current practices and technologies, the methane fluxes from paddy fields will substantially rise. Improved high yielding rice varieties together with efficient cultivation techniques will certainly contribute to the curtailment of the methane emission fluxes. In this paper, the system dynamic approach is used for estimating the methane emissions from rice fields in India till the year 2020. Mitigation options studied for curtailing the methane emissions include rice production management, use of low methane emitting varieties of rice, water management and fertilizer amendment. The model is validated quantitatively and sensitivity tests are carried out to examine the robustness of the model.

© 2004 Elsevier Ltd. All rights reserved.

Keywords: Global warming; Greenhouse gases; Methane emission; Mitigation options; Rice fields; System dynamics

1. Introduction

Methane gas present in the atmosphere substantially affects the radiative budget of the Earth (Wassmann et al., 2000; Aulakh et al., 2001) and has predominant impact on the global warming in comparison to the other greenhouse gases. There are several sources of methane emission leading to its build up in the atmosphere. Among them rice fields are considered to be the important contributors (Mitra et al., 1999) where large quantity of methane is generated. Rice-cultivated area is steadily increasing all over the world to meet the food requirement of the growing world population.

Flooding of rice fields cuts off oxygen supply from the atmosphere to the soil, which leads to anaerobic fermentation of organic matter in the soil, resulting in the production of methane (Ferry, 1992). Thus, flooded rice fields provide congenial environment for methane production and are considered to be a major anthropogenic source for biogenic methane. The emission of methane from rice fields is dependent on several factors such as water management, amendment of organic and inorganic fertilizers, rice varietal characteristics and soil environment (Mitra et al., 1999).

India is the second largest country in the world in terms of population and is one of the important rice-producing countries. Rice fields of India can be classified as irrigated, rainfed, deepwater or upland. Deepwater means the paddy plants are immersed at least 50–100 cm in water. Most of the rice is grown on wetlands (irrigated, rainfed and deepwater); only 15% of the cultivated area is under uplands. The upland rice fields are not considered a source of methane emission because they are not flooded for sufficient time. Wetland rice fields have been identified as one of the major sources of methane emission. Methane emission from wetland rice cultivation is expected to increase due to the likely intensification of rice cultivation in the coming decades.

Considerable research work is in progress to devise options for mitigating methane emissions from the rice fields (Lu et al., 2000; Singh et al., 2003). In this paper, we...
present System Dynamics (SD)-based simulation system for temporal projection of overall methane emissions from rice cultivation in India. Implication of different policy options is analysed for evaluating their contribution to reduction of methane emissions. The System Dynamics (SD) methodology has been used to work out a model for scenario building, conducting policy experiments and making the projections. A causal-loop structure is constructed by involving the rice demand, production, methane emissions, accumulation and mitigation policy options. A detailed flow diagram is developed and dynamo equations for each element in the diagram are incorporated in the model. Estimations are made for methane emissions under different scenarios over a period of 20 years.

2. System dynamics approach

System dynamics is a computer-aided approach for analysing and solving complex problems with a focus on policy analysis and design. In management and social systems (Mohapatra et al., 1994), policy-makers and researchers have extensively used system dynamics methodology and conducted policy experiments. A detailed description of the system dynamics methodology is given in Sterman (2000). The SD approach has been applied to a number of studies related to environment; environmental impact assessment analysis (Vizayakumar and Mohapatra, 1991, 1993), solid waste management (Mashayekhi, 1993; Karavezysis et al., 2002), analysis of greenhouse gas emissions and global warming (Vrat et al., 1993; Anand et al., 2003), water resource planning (Ford, 1996), environmental planning and management (Guo et al., 2001; Guneralp and Barlas, 2003) and many more situations.

System dynamics model is developed by establishing a causal-loop relation between the components associated with the model in the form of a causal-loop diagram. Then a flow diagram is constructed and the dynamo equations are added to the model. In system dynamics model, the simulations are essentially time-step simulations. The model takes a number of simulation steps along the time axis. The dynamics of the system is represented by

\[ \frac{dN(t)}{dt} = kN(t) \]

which has a solution

\[ N(t) = N_0 \exp(kt) \]

where \( N_0 \) is the initial value of the system variable, \( k \) is a rate constant (which affects the state of the system and \( t \) is the simulation time).

3. Rice cultivation model

Flow diagram and corresponding formulation of SD modelling equations are formulated for the rice cultivation model, which involve interactions among a number of system components. The model is based on cause-loop diagram shown in Fig. 1. This illustrates the dynamic nature of inter-relationships among components of the model, their interactions leading to amplification of emissions and control measures (policies), and mitigation adaptation applied towards such changes. Each arrow of the causal-
loop diagram indicates the influence of one element on the other. The influence is considered positive (+) if an increase in one element causes an increase in another, or negative (−) in the opposite case.

The area under rice cultivation needs to be increased up to certain extent with the growing population; causing enhanced methane emission and environmental risk. In the causal-loop diagram developed for the rice cultivation model, relevant mitigation options to curtail the methane emission are taken into account. These are maintaining a balance between rice demand and production, an effective water management, shifting to alternate low methane emitting varieties of rice. In addition, fertilizer amendment scenario is simulated. With the application of the policy options, the level of methane

Fig. 2. Flow diagram for rice cultivation model. Subsystem diagrams are: (a) rice production subsystem, (b) area under rice cultivation subsystem, (c) methane production subsystem.
emission should go down constituting a self-stabilising, feed back loop.

A flow diagram is useful for showing the physical as well as information flows in the system dynamics model. Fig. 2 shows the details of the flow diagram developed for analyzing the rice cultivation sector. Intricacies of the mutually interacting processes are also delineated in the flow diagram.

Stocks, flows and auxillary variables form the main building blocks of SD model. Stocks symbolised by a rectangular box in Fig. 2 represent level or state variables. They account for accumulation in the system. A double-lined arrow with valves representing physical flows, controlled by a flow rate, indicate change in the value of flows. Stocks in a dynamic system in turn influence the values of flows. A single line is for showing information flow. A cloud represents source and sink of the structure and the cloud symbol indicates infinity and marks the boundary of the model.

The information from the level variables to the rate variables is transformed by a third variable called auxiliary variable, represented by circles. The diamonds represent constants, which do not vary over the run period of simulation. A constant is defined by an initial value throughout the simulation. There is switch control with which the initial values of constants, auxiliaries and levels can be changed and selection can be made between alternative strategies. To avoid confusion in the diagram, repeated variables are represented in the form of snapshot variables (frame-like structures).

Flow diagram is divided into three subsections: section (a) represents rice production subsystem where production of rice is projected; section (b) represents area under rice cultivation subsystem and section (c) represents a flow diagram for the methane emission subsystem. The policy options related earlier for the methane mitigation are also incorporated in the model.

The modelling details of three subsystems are described in the following sub sectors.

3.1. Rice production subsystem

Rice production, represented in Fig. 2(a) is affected by the rate of rice productivity and the area under rice cultivation. The area under rice cultivation and increase in the yield of rice per million hectare of rice-cultivated area are taken as level variables. Rice production is obviously linked to its demand, which is calculated on the basis of per capita consumption. This needs information about population, and the population is considered as a level variable. Its variation obviously depends on the rate of population growth. Area under
wetland rice cultivation, which is responsible for methane generation, is computed under this head. The dynamo equations used to account for the scenarios in this subsystem are:

\[
\begin{align*}
\text{Population} &= \text{Population} + (\Delta t \times \text{Population\_growth\_rate}) \\
\text{Population\_growth\_rate} &= \text{Population\_growth\_multiplier} \times \text{Population} \\
\text{Rice\_consumption} &= \text{Population} \times \text{Percapita\_consumption} \\
\text{Rice\_production} &= \text{Increase\_yield} \times \text{Area} \\
\text{Increase\_yield} &= \text{Increase\_yield} + (\Delta t \times \text{Rate\_yield}) \\
\text{Area} &= \text{Area} + (\Delta t \times \text{Rate\_of\_area\_growth}) \\
\text{Rate\_of\_area\_growth} &= \text{Area} \times \text{Area\_rate} \\
\text{Here we generate alternate policy scenarios by the use of switch function. The switch is defined as 1 for the baseline scenario and the switch equal to 2 for the alternate scenario of maintaining rice production equal to that required for rice consumption.} \\
\text{Rate\_of\_area\_growth} &= \text{Area} \times \text{Conditional\_rate} \\
\text{Conditional\_rate} &= \text{IF (Switch\_\_1=1, Area\_rate1, Strategy)}
\end{align*}
\]
Strategy=IF (surplus_gap>0, Area_rate, Area_rate1) where, Area_rate=0; Area_rate1=0.008

Similarly, yield is also altered by switch function when scenarios are generated for fertilizer amendment and cultivating low methane emitting varieties of rice.

3.2. Area under rice cultivation subsystem

The wetland area obtained under rice production subsystem is further divided into irrigated, rainfed and deepwater area. Irrigated area is subdivided into continuously irrigated, singly intermittent aeration irrigated and multiple intermittent aeration irrigated area shown in Fig. 2(b). Rainfed area is subdivided into continuous rainfed and drought-prone rainfed area. These are in conformity with the usual practices adopted for the rice cultivation (IPCC, 1996). All these options are auxiliary variables and have different percent area constant. The above-mentioned wetland areas have different potential for methane emission depending upon the water management situation. Effective alternate water management options (described in detail under Section 4) are also studied under this subsystem.

In addition, emissions of methane are dependent on the variety of rice cultivated. We have developed a scenario for the emissions of methane when alternate varieties of rice with low methane emission potential are cultivated in the intermittently irrigated area with interrupted irrigation. The use of alternate varieties is called ‘cultivars variation’.

3.3. Methane production subsystem

In this subsystem represented in Fig. 2(c), the accumulation of methane is simulated and is taken as a level variable. There is a dynamic balance between the inflow from rate of methane accumulation and the out flow from the rate of methane decay. Initial value of the methane level is taken as 0 Tg. The rate of methane accumulation is taken as the total of methane emissions from the respective wetland areas. The lifetime of methane in the atmosphere is expected to be 12 years (IPCC and WGI, 1995). In the model, we have considered the rate of methane decay to be equal to its production rate 12 years ago. Methane accumulation is, therefore, modeled using a delay function. Here we have used pipeline delay. Pipeline delay can be understood as a pipe in which water is entering at one end and would come out from the other end with a time delay needed in traveling along the length of the pipe. Methane is entering into the atmosphere with a given rate and is going out or is undergoing decay with the same rate, but with a delay time of 12 years. This leads to the following equations for calculating the rate of methane emission and methane accumulation:

Total_rate_CH4_emissions=Area*Scaling factor for the particular area*Emission constant

Accumulation=Accumulation+(dr*Accumulation rate)−(dr*Decay rate)
Accumulation rate=Total_rate_CH4_emissions
Decay rate=DELAYPPL(‘InputVar’, ‘DelayTime’, ‘Initial’)
where, InputVar=Accumulation rate; Delaytime=12; Initial=0

4. Scenario generation

The data for area under rice cultivation in India for the fiscal year 1999–2000 is taken from the ninth Five-Year Plan (Government of India, 1997, 2001–2002). The year 2000 is taken as the base line year when the population of India was 1014 million and was increasing at a growth rate of 1.62%. Following the projections given in the ninth Five-Year Plan, the population growth rate is stepped down to 1.57%, 1.50%, and 1.44% by the use of STEP function for the model simulations. The total rice consumption in the year 2000 is obtained taking into account 77 kg per capita consumption. The other applicable parameters for the base year are: area under rice cultivation 44.36 million hectares and the annual growth rate in the area 0.8%; and rice productivity 1.913 tonnes/ha giving the total production of 84.87 million tonnes. Rice is cultivated on 85% wetland area and the remaining area comes under upland cultivation. The wetland area is subdivided in irrigated (62.35%), rainfed (30.59%) and deep-water area (7.06%). In the irrigated wetland rice area, 30.18% is continuously irrigated and 69.82% is intermittently irrigated; 62.2% of the intermittently irrigated wetland rice production area is under single irrigation intermittent aeration and 37.8% is under multiple intermittent aeration; and 32.69% of the rainfed area is continuously rainfed and 67.31% is drought prone. The percentage division among different types of areas indicated is taken from IPCC (1996) for the Indian water regimes. The current and future rate of methane emissions are calculated from the corresponding area distribution and the methane accumulation in the

<table>
<thead>
<tr>
<th>Rice growing areas</th>
<th>Seasonally integrated methane emission factors (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS</td>
<td>RPM</td>
</tr>
<tr>
<td>Continuous irrigation area</td>
<td>10</td>
</tr>
<tr>
<td>Single Intermittent irrigation area</td>
<td>5</td>
</tr>
<tr>
<td>Multiple Intermittent irrigation area</td>
<td>2</td>
</tr>
<tr>
<td>Continuous rainfed area</td>
<td>8</td>
</tr>
<tr>
<td>Drought prone rainfed area</td>
<td>4</td>
</tr>
<tr>
<td>Deep water area</td>
<td>8</td>
</tr>
</tbody>
</table>
atmosphere is then projected. The methane emission factors integrated seasonally taken from IPCC (1996) and their alternatives used in our analysis are listed in Table 1.

Policy options are stipulated for scenario building to curtail the methane emission. All the alternate options used to build various scenarios are made effective from the year 2006. The scenarios considered are: baseline scenario, rice production management, water management, cultivar variation and fertilizer amendment. The conditions for the baseline are already specified, whereas in the rice production management scenario efforts are made to balance the product and consumption. For the water management, two scenarios are adopted, i.e. scenario 1: continuously irrigated area is subjected to single intermittent irrigation, and scenario 2: the total irrigated area is subjected to multiple intermittent irrigation. In the study of alternate cultivars, the low methane emitting varieties of rice with methane emission potential of 22.85 kg/ha (Mitra et al., 1999) are considered under intermittent irrigation condition. On the other hand, water management is applied to the otherwise continuously flooded area. This scenario is then made equivalent to the intermittent irrigation while analyzing the reduction in the methane emission with the application of alternate cultivars in these areas. It is worth mentioning here that the alternate cultivars also contribute to the increase productivity, thereby lowering the area under rice cultivation.

The share of rice in the total food chain can obviously be ensured with the application of adequate quantities of fertilizers to the high yielding varieties/hybrids. Tiwari (2002) has projected the rice productivity required for India in the year 2006–2007, 2012 and 2020 to be 2.45, 3.0 and 3.69 tonnes/ha, respectively. Yields of nearly 10 tonnes/ha can be obtained through site-specific nutrient management involving the use of 250–150–150–40–5 kg N–P₂O₅–K₂O–S–Zn/ha (Pathak, 2000).

We have developed a scenario to study the impact of nitrogen fertilizer (urea) on the methane emissions and yield of rice for continuously irrigated and continuously rainfed water regimes. It is assumed with the addition of urea, methane emissions on an average increase by 1.75 times and yield increases by 25% (Rath et al., 1999; Singh et al., 1999; Ghosh et al., 2003). This is incorporated in the model from the year 2006. It may be pointed out that the application of ammonium sulphate emits lower methane than that from urea (Ghosh et al., 2003). Sulphate addition through ammonium sulphate has been advocated for the mitigation of methane from rice cultivation (Denier van de G. et al., 2001). In the present study, the impact of scenarios taking ammonium sulphate and other fertilizers are not simulated, as there is not sufficient Indian data available for quantifying the effect of fertilizers on the yield.

5. Model validation

Validation of the system dynamics model is necessitated to establish sufficient confidence in the model on some
Fig. 4. Variation of population with growth rate multiplier.

Fig. 5. Variation of methane emissions with area under rice cultivation.
chosen criteria suitable for the system under study (Forrester, 1976; Sahay, 1987).

5.1. Historical validation of the data

For the purpose of the study, population variable is selected. Data for the year 1990 is incorporated in the model and projections are made for the year 2001. Model results are comparable along with the actual values, as shown in Fig. 3.

5.2. Structural verification test

In the model, the methane decay rate is matched with the emission rate maintaining a life cycle of 12 years. In this case, the model is structurally validated as is evident from Fig. 10 for the entire time span, showing a bend for the year 2012.

5.3. Dimensional consistency test

The dimensional consistency is ensured in writing the model equations.

6. Sensitivity analysis

Sensitivity tests basically ascertain whether or not minor shifts in the model parameters can cause shift in behaviour of the model. Once the robustness of the model is ensured, the model can be used for policy making (Forrester, 1961; Mohapatra et al., 1994). As already discussed, the methane emissions and its accumulation is affected by factors like population, land under cultivation, increase in yield per hectare of rice and lifetime of methane in the atmosphere. Sensitivity of the model to these parameters is clearly reflected as is described in the following section.

6.1. Impact of population on rice demand

Population has a major impact on the demand of rice, which in turn, is the prime determinant of the area under rice cultivation and the ultimate methane emissions from that much area. It is evident from Fig. 4 that population of the country jumps to 1421.80 millions from the projected figures of 1364.50 millions by the year 2020 due to a slight change in the population growth rate multiplier. The growth rate multiplier is used as a step function with values of 1.63%, 1.7%, 1.76% for the year 2001–2006, 2006–2011 and 2011–2018, respectively.

6.2. Impact of area under rice cultivation on methane emissions

It is observed that a minor increase in the area rate under rice cultivation from 0.8% to 1% will emit an additional 0.10 Tg/year of methane. This is over and above the projected emissions of 2.57 Tg/year by the year 2020 (Fig. 5).
6.3. Impact of methane lifetime on its accumulation in the atmosphere

Lifetime of methane in the model is represented by a delay period of 12 years. Whatever amount of methane that enters into the atmosphere, the same is assumed to decay after 12 years. As seen in Fig. 6, the accumulation of methane varies from 19.84 to 30.20 Tg on variation in delay period of decay rate from 8 to 15 years, confirming the sensitivity of the model to this parameter.

7. Results and discussion

In the year 2000, area under rice cultivation in India was 44.36 million hectares (Government of India, 2001–2002). This area was distributed among continuously irrigated, intermittently irrigated, continuous rainfed, drought prone rainfed and deep-water as mentioned in Section 4. With the known emission factors given in Table 1 for these areas, the distribution of methane emissions for the baseline scenarios (BS) is included in Table 2. Total of the emissions from
different types of the areas, work out to 2.19 Tg/year for the base year 2000. As expected, the emissions from the drought prone rainfed and deep-water rice producing areas are less. Intermittent drying and flooding periods during the rice cultivation on the drought prone rainfed areas cause reduction in the methane emissions.

Estimates of Parashar et al., 1996 ranging from 2.7 to 5.4 Tg/year are higher than those of our model. In their study, they have classified paddy-harvested area into continuously flooded or irrigated, intermittently flooded or rainfed, deep-water and upland area with no further classification of continuously irrigated area. In our study, we have classified irrigated area into continuously flooded and intermittently irrigated area with a subdivision of intermittently irrigated area into single intermittent and multiple intermittent irrigation. Methane emission potential of intermittently irrigated area is less as compared to the continuously irrigated area. In addition, seasonally integrated factors used in our study, for the baseline scenario are for the fields without any organic fertilizer. The recent global estimates of methane emissions from rice cultivation are in the range of 30–50 Tg/year (Neue and Sass, 1998). Our estimates from rice cultivation in India during the year 2000 give 2.19 Tg/year, contributing only 4.38–7.31% to the global emissions.

The Indian population estimated from our model is projected to reach 1,364.50 million by the year 2020, as is shown in Fig. 7. Rice production obtained from the SD analysis is shown in Fig. 8 and it is expected to reach 120.96 million tones in the year 2020. This will over shoot its projected consumption of 105.07 million tonnes. To achieve this production, the area required for rice cultivation has to be raised steadily to 52.02 million hectares. Increase in area under rice cultivation is also shown in Fig. 8. With alternative scenarios, however, the situation will change as discussed in the subsequent sections. Obviously, the demand of rice is linked to the population growth. In the overall economic plans of the country, some surplus production for exports is also desirable. For the increased production of rice, area under rice production should also be increased which, however, will contribute to the enhanced emissions of methane. Production should, therefore, be carefully planned taking into account the various factors for the speedy economic growth.

The methane emissions from the rice-cultivated area shown in Fig. 9 indicate that in year 2020, 2.57 Tg/year, i.e. total of 29.30 Tg will be added to the atmosphere by this time. Fig. 10 shows a steady increase in methane accumulation till the year 2012. Thereafter, the rate of increase diminishes since in the elimination of methane from the atmosphere 12 years of its lifespan is incorporated in the model.

![Fig. 8. Increase in the rice production, consumption and area under rice cultivation over a period of 20 years.](image-url)
7.1. Rice production management

The projections of consumptions and production of rice for the year 2020 are 105.10 and 120.96 million tonnes, respectively, giving a surplus of 15.86 million tonnes. Though the surplus production is beneficial for the export promotion and will make a modest contribution to the economic growth of the country, this will, however, be with a price tag on the environment. Under such a scenario, methane emissions are at the rate of 2.57 Tg/year adding 29.30 Tg to the stock of methane. When a policy option of producing rice at a rate, which is sufficient for meeting the consumption requirement of increasing population, is applied, the projections for the area required by 2006 will be 46.63 million hectares. It would stabilise to this area (10.55% reduction) by the year 2020, with no further increase in area under rice cultivation. The rate of methane emissions will be 2.29 Tg/year adding 27.59 Tg to the stock of methane in the atmosphere.

7.2. Water management

Aerating the soil during the flooding periods with altered water management leads to decrease in the methane production rate from the soils. Since methanogens require highly reducing conditions, aerating the soils arrests the development of reducing conditions in the soils and enhances the methane oxidation, which leads to a decrease in methane production level and ultimately to a total decrease in the methane emissions. Thus, proper drainage during the growing season could be a promising mitigation strategy that should not affect yields substantially. Accordingly, the rate of methane emissions are observed to reduce by 16.31% (2.15 Tg) and 40.28% (1.55 Tg) for the water management scenarios 1 and 2, respectively, with the respective addition of 24.59 and 17.66 Tg to the atmosphere by the year 2020.

7.3. Cultivars variation

Rice plants serve as a medium for the transfer of methane from the anaerobic soil layer to the atmosphere. More than 90% of methane fluxes from rice soils are mediated by rice plants (Holzapfel-Pschorn et al., 1985). Variability in plant architecture, metabolic activity and gas transport potential among different rice cultivars could be a reason for the variation in methane efflux from the paddy fields. In addition, the rice cultivars differ in their ability to transport oxygen to the rhizosphere (Kludze et al., 1993). This is known to induce changes in the redox potential of rice.

Fig. 9. Rate of cumulative methane emissions for the baseline scenario (BS), rice production management scenario (RPM), water management scenario 1 (WM1), water management scenario 2 (WM2), cultivars variation scenario (CV) and fertilizer amendment scenario (FA).
rhizosphere (Flessa and Fisher, 1992). A higher oxidation status in the soil–root interface may stimulate methane oxidation, thereby reducing the source strength of methane in the rhizosphere region available for emission through rice plants.

There could be substantial reduction in methane emissions if low methane emitting variety of rice is adopted along with the water management on the continuously irrigated area and intermittently irrigated area. From the year 2006 of incorporation of this policy in the model, the rate of methane emissions get stabilised to 1.07 Tg/year and thus the accumulation by the year 2020 comes to 12.82 Tg. Reductions in methane emissions are due to the increased area under alternate low methane emitting varieties with intermittent irrigation. This will not only reduce the methane emissions, but also increase the yield up to 6 tonnes/ha (Mitra et al., 1999). Increased yield of rice leads to increased production from less area thus restricting further increase in the emissions. With the increase in yield rice production comes to surplus level from the existing area under rice cultivation. There is, therefore, a scope of decreasing methane emissions by cutting down the area under rice cultivation under this scenario.

7.4. Fertilizer amendment

The nitrogenous fertilizer is seen to have a positive effect on the methane emissions. The applied fertilizers may help to increase methanogenesis by supplying methanogens with nitrogen for their metabolism. The fertilizers also have a positive effect on the quantity of biomass associated with paddy plants. This may increase rhizo deposition of carbon compounds, which may enhance methanogenesis. Further, as the rice plants serve as a conduit for methane transport from the soil to the atmosphere, increased volume of the biomass provides more of gaseous transport (Nouchi et al., 1990).

Our model shows that with the application of fertilizer methane emissions increase to 3.17 Tg/year for the year 2006 and will remain constant by the year 2020. The reason behind this is that the addition of urea fertilizer has enhancing effect on the yield. Increase in the per hectare yield amounts to the reduction in area for rice cultivation for a given quantity of rice. Thus, the methane emissions under such a scenario will be curtailed. Methane emissions in Tg/year and methane accumulations in Tg for the baseline scenario and for the other alternative scenarios studied are shown in Figs. 9 and 10.
8. Conclusion

A system dynamics model for simulation of methane emissions from rice fields is developed. The model is used to obtain trends and estimates for a time span of 20 years under different scenarios. Possible strategies to mitigate the methane emissions from this sector are suggested and analysed. Methane emissions from rice fields are dependent on the quantity of rice produced, varieties of rice, flooded area under rice cultivation and fertilizer amendment. Baseline scenario for methane emissions and its accumulation in the atmospheric pool is generated. In the baseline scenario, the rate of methane emissions is projected to reach 2.57 Tg/year over the next 20 years, adding 29.30 Tg to the atmosphere. Reductions in the surplus production of rice, the use of alternate low methane emitting varieties of rice, effective water management will reduce the methane emissions.

Acknowledgements

The authors (SA) and (VT) thank the Indian Institute of Technology Delhi and University Grants Commission, respectively, for the award of fellowship. Thanks are also due to Mr. Naresh Kumar for general assistance during the course of work.

References


