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Numerical analysis of the source-sink alternation of composite global warming potential of the paddy ecosystem in the Yangtze Delta

LIU Jiandong (刘建栋)[1], ZHOU Xiuji (周秀骥)[1] & YU Qiang (于 强)[2]

1. Chinese Academy of Meteorological Sciences, Beijing 100081, China;
2. Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

Correspondence should be addressed to Liu Jiandong (email: liujiandong2001@263.net)

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Abstract By coupling the biogeochemical model with plant ecological model, a model was established to reveal the principle of the composite global warming potential transformation in the paddy ecosystem. Validation of the model with the observed data indicated that the model can simulate both the crop growth processes and emissions of CH_4 and N_2O accurately. Some numerical analyses were made to identify the impacts of different fertilizer application on assimilation of CO_2 and emissions of CH_4 and N_2O, and the transformation principle of the composite global warming potential. Based on the results of the numerical analysis, the source-sink alternation of composite global warming potential in the paddy ecosystem was discovered, and some new conceptions of fertilizer index such as maximum-sink fertilizer, zero-emission fertilizer are put forward in this paper. The fertilizer scheme for Yangtze Delta was proposed to provide the important scientific basis for a sustainable agriculture in this region.

Keywords: paddy ecosystem, global warming potential, numerical simulation.

The three important greenhouse gases, namely CO_2, CH_4 and N_2O[1,2], participate in the process of carbon and nitrogen cycling in the paddy field simultaneously. CO_2 is assimilated by rice through photosynthesis, which means the paddy field is the sink of CO_2[3]. On the other hand, the CH_4 and N_2O emit from paddy field with the biogeochemichal process of carbon and nitrogen cycling, which means the paddy field is the important emission source of CH_4 and N_2O[4,5]. The principle of composite greenhouse effect of these three gases and their transformation becomes an important but unknown scientific question.

The demand for food in the world is increasing in recent years, which might result in the fertilizer enhancement. More applied fertilizer increases more CO_2 assimilation in the ecosystem, but it also results in more emissions of CH_4 and N_2O[4,5]. In order to mitigate the greenhouse gases effectively, it is very important for scientists to couple the biogeochemichal model with plant ecological model, and to reveal the impacts of different fertilization on the composite greenhouse effects of these three gases by numerical analysis. In this research, a comprehensive numerical model was established by coupling the biogeochemical model DNDC[6,7] with crop growth model[8,9], and the composite warming potential of CO_2, CH_4 and N_2O in the paddy ecosystem was analyzed with this model.

1 Establishment of the model

The model is composed of 5 submodels, including crop growth, soil water movement, transformation of carbon and nitrogen in soil and farming practices (fig. 1). Crop growth process is controlled by the development stage model, and it is accumulated by the numerical integration. This process is influenced by the stress of water and nitrogen in soil. Soil water movement includes surface runoff, saturated infiltration, unsaturated drainage, diffusion, evaporation, plant transpiration and water absorption by roots. Soil organic carbon is divided into three active pools and a passive pool, and each active carbon pool includes two or three sub-pools. Soil carbon produces CO_2 under aerobic conditions or CH_4 under anaerobic conditions. During decomposition of residues, the carbon is either released as CO_2 or incorporated into microbial biomass. As microbes die and their biomass decomposes, the carbon will be partitioned to CO_2, new microbial biomass and labile humads. Some carbon will be transferred from labile humads to resistant humads, and to passive carbon pool. The soil organic nitrogen pool is corresponding to the soil organic carbon pools according to the C/N ratio. Plant root and straw and manuring are the sources of soil organic nitrogen. Soil organic matter decomposition will release the nitrogen to inorganic form, and ammonium will be oxidized to nitrate through nitrification. Both ammonium and nitrate can be absorbed by the plant. Under anaerobic conditions, nitrate is subject to denitrification and produces N_2O and N_2. Fertilization includes date, depth, amount of nitrate, ammonium, ammonia and urea. The fertilizer is mixed uniformly from the indicated depth, and added directly to the respective soil nitrogen pools. The main process can be calculated as follows.

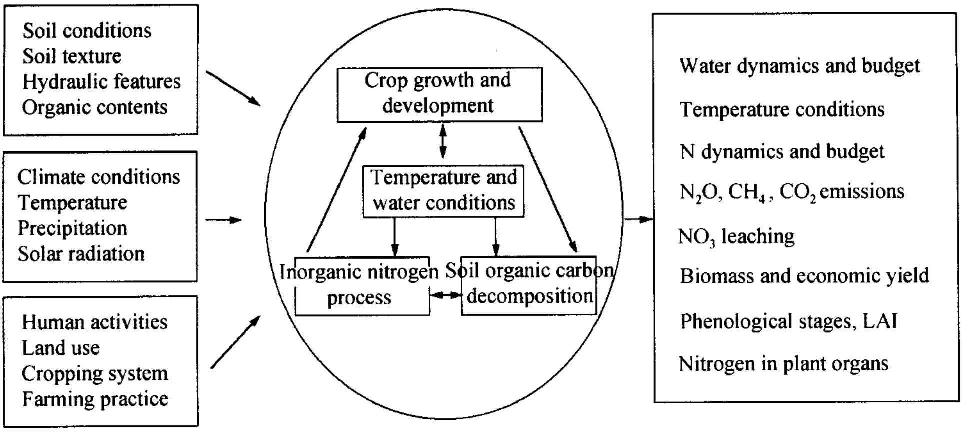


Fig. 1. The structure and the basic components of the model.

1.1 Simulation of crop growth

Crop model includes the development stage, photosynthesis, respiration, and assimilation partitioning. The total daily photosynthesis P_0 ($kgCO_2hm^{-2}d^{-1}$) is simulated as

$$P_0 = \min(W_s, N_s)\times\int_0^{D_L}\int_0^{L} P(Lc,t)\mathrm{d}L\mathrm{d}t\ , \tag{1}$$

where W_s and N_s are factors influencing photosynthesis by the stress of water and nitrogen, D_L is the daylength, L is the leaf area index of the canopy, $P(Lc, t)$ is photosynthesis rate($\mathrm{kgCO_2hm^{-2}d^{-1}}$) of per leaf area at the time t, Lc is leaf area index in a layer. P_0 was estimated with Goudriaan three-point integration method[8]. The photosynthesis of the crop is affected by the stress of water and nitrogen in soil, and connected with water movement underground and the carbon and nitrogen cycling. Respiration and partitioning are calculated according to the method put forward by Penning de Vries[9]. The maximum photosynthesis rate and extinction coefficient of canopy are two important parameters in this sub-model, which can be determined through iteration based on the observed data. The default values of these two parameters are 40 $\mathrm{kgCO_2hm^{-2}h^{-1}}$ and 0.6[9].

1.2 Transformation of soil carbon

Soil organic carbon is divided into three active pools and a passive pool, and each active carbon pool includes two or three sub-pools. The decomposition of each pool in each layer is simulated independently with first-order kinetics[6,7].

$$\frac{\mathrm{d}C_i}{\mathrm{d}t} = m_{Ci}\times m_{Ni}\times m_{Ti}\times m_{Mi}\times m_{Li}\times K_i\times C_i\ , \tag{2}$$

where C_i is the content of carbon pool i($\mathrm{kghm^{-2}L^{-1}}$), i represents carbon pools, m_{Ci}, m_{Ni}, m_{Ti}, m_{Mi} and m_{Li} are the effects of soil clay adsorption, soil C/N ratio, temperature, soil moisture and tillage on decomposition. K_i is the specific decomposition rate of carbon pool i. The process of CO_2 emission is considered to be a source driving process in the model, and CH_4 is produced under anaerobic conditions. Soil redox potential (E_h) is a critical index for CH_4 production and oxidation.

$$\Delta E_h(L) = \begin{cases} 100\times[0.5\times A_r\times F_r/D(L) - 5\times T(L)/D(L) - 0.4\times F(E_h)](\text{flooding}), \\ 100\times\{0.5\times A_r\times F_r/D(L) + 0.5 + 2\times[1 - W_f(L)]\}\qquad(\text{no flooding}), \end{cases} \tag{3}$$

where $\Delta E_h(L)$ is daily variation of redox potential in soil layer L, A_r is plant aerenchyma index, F_r is the fraction of root in layer L, $D(L)$ is the depth of the layer L, $T(L)$ is daily decomposition in layer L, $W_f(L)$ is water moisture in layer L, and $F(E_h)$ reflects the effects of general oxidization[6].

$$F(E_h) = \begin{cases} 1 & (E_h \geq 0), \\ 1/(1 - 0.05\times E_h) & (E_h \leq 0). \end{cases} \tag{4}$$

Net methane production is the difference between methane production, oxidation and emission.

$$\Delta C = P_C - O_C - E_C\ , \tag{5}$$

where ΔC is the daily variation of CH_4 in the soil layer. P_C, O_C and E_C are daily production, oxidation and emission of CH_4, which can be calculated based on Cao et al[11]. The parameters in this sub-model are based on the observation results of Sigren et al.[10].

1.3 Transformation of soil nitrogen

Nitrification is simulated by[6]

$$R_N = \begin{cases} D_N \times H / 0.03 \times [1 - \exp(-K_{35} \times f_{\mathrm{T}})] \times f_{\mathrm{SW}} \times f_{\mathrm{PH}} & \text{(no flooding),} \\ D_N \times H / 0.03 \times [1 - \exp(-K_{35} \times f_{\mathrm{T}})] \times f_{\mathrm{Eh}} & \text{(flooding),} \end{cases} \tag{6}$$

where R_N is the daily amount of NH^+_4 nitrified to NO^-_3($kgNhm^{-2}L^{-1}d^{-1}$), D_N is the concentration of NH_4^+, K_{35} is the nitrification rate at 35℃, H is the sum of microbial biomass and humads, f_T, f_W, f_P and f_E are effects of temperature, soil moisture, pH and E_h on nitrification[6]. Under anaerobic conditions, denitrification is the dominant process. The growth rates of denitrifiers, which depend on the concentrations of carbon and N oxides, are calculated with a double-nutrient-dependent Michaelis-Menten-type growth pattern[6]

$$U_N = U_{\max} \times \frac{S_C}{K_C + S_C} \times \frac{N_x}{K_N + N_x}, \tag{7}$$

where U_N is the relative growth rate of the denitrifiers, S_C and N_x are soluble carbon and nitrogen in soil, respectively. K_C and K_N are half-saturation values of soluble carbon and N oxide. $U_{\max}$ is maximum growth rate. The crop absorption of nitrogen depends on the demand of nitrogen for growth and the capacity of nitrogen supplied by soil and root. Soil organic nitrogen is connected with the soil carbon pool according to the ratio of carbon and nitrogen.

The emission rate of N_2O E_N is related to the soil water moisture conditions and the adsorption coefficients of the gases in soil, it can be expressed as [6,7]

$$E_N = \begin{cases} H_N \times P_i & \text{(no flooding),} \\ 0.01 \times H_N \times (A_r + T/100) & \text{(flooding),} \end{cases} \tag{8}$$

where H_N is the N_2O content in soil, A_r is plant aerenchyma index, T is soil temperature. P_i is a medial variable, which can be expressed as

$$P_i = 0.017 + (0.025 - 0.0013 \times f_l) \times (1 - W_f) \times 2^{T/20}, \tag{9}$$

where f_l is the soil clay content related factor

$$f_l = 2 \times C_l / 0.63, \tag{10}$$

where C_l is the soil clay content. The parameters in this sub-model were set according to the DNDC and its computer code[6,7,12].

2 Validation of the model

The processes of CH_4 emissions from paddy field in the Suzhou region[5] is simulated in fig. 2(a), and the principle of CH_4 emissions in the whole growth period was revealed by the model fairly well. N_2O emissions were observed in Changshu region in 1999. The 900 $kghm^{-2}$ NH_4HCO_3 was used as base fertilizer on 18th June, transplanting was on 20th June, and 750 $kghm^{-2}$ top application was used on 28th July. The process of N_2O emissions was also simulated accurately by the model (fig. 2(b)). The accumulated dry matter of rice in different growth periods was observed from 1993 to 1994 in Changde agrometeorological station in Hunan. The comparison of simulated data and observed data is showed in fig. 2(c), which indicates that the trend of the simulation result is consistent well with that of the actual growth process. Since the essentials of crop growth are the process of CO_2 assimilation through photosynthesis, the correctness of the simulation results of crop growth indicates that CO_2 assimilation can be also simulated accurately with the model. It is credible to reveal the principle of crop growth and emissions of greenhouse gases based on the numerical analysis with the model.

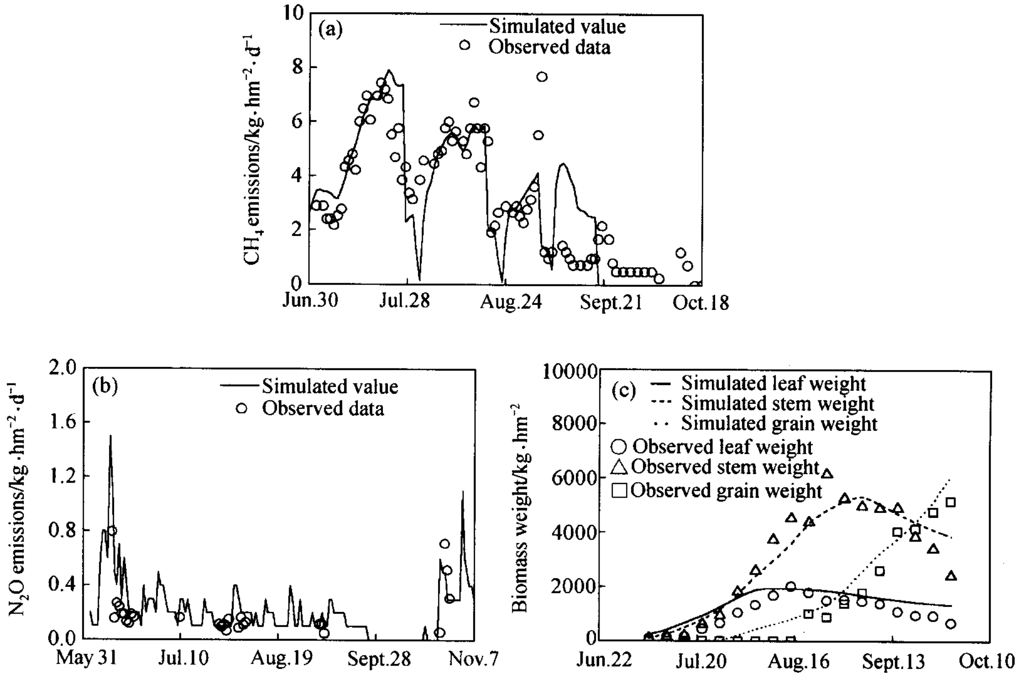


Fig. 2. Simulation of rice growth process, CH_4 emissions and N_2O emissions. (a) CH_4 emissions in Suzhou, 1995[5], (b) N_2O emissions in Changshu, 1999, (c) Rice growth process in Changde, 1994.

3 Numerical analysis

Crop growth and greenhouse gases emissions are influenced by many factors such as crop varieties, meteorological conditions, fertilizer and tillage[13,14]. The objective of this study is to reveal the impact of fertilizer on yields and greenhouse gases emissions, so all apart from fertilizer should remain unchanged in the numerical analysis. The scenario for the simulation was input to the model before numerical analysis. Single rice in Suzhou region is simulated, with flooding on 15th June, transplanting on 18th June, first drainage from 22nd July to 28th July, second drainage from 12th August to 18th August, drainage on 13th October and harvest on 31st October. The rice straw was used as base fertilizer on 15th June, and NH_4HCO_3 was used as top fertilization in jointing stage. This is a kind of general farming practice in the local area. Because both of the maturing and fertilizer are used in the rice ecosystem, the value of fertilizer equivalent is adopted as fertilizer unit. The fertilizer equivalent was defined as follows: The fertilizer equivalent 0 represents none of mature and fertilizer, and fertilizer equivalent 1 represents 500kghm^{-2} rice straw plus 20kgNhm^{-2} NH_4HCO_3 fertilization, the rest may be deduced by analogy, so fertilizer equivalent N represents N times 500kghm^{-2} rice straw plus 20kgNhm^{-2} NH_4HCO_3.

The composite effect of greenhouse gases is the focus in this study, so the greenhouse effects were used uniformly for comparison. According to definition of GWP (Global Warming Potential) put forward by IPCC (International Panel of Climate Change)[1,2], at 20-year time scale, the greenhouse effects for different gases can be calculated as[1,2] (i) Assuming CO_2 of soil respiration is E_s, its GWP G_s can be expressed as $G_s = E_s \times 1$; (ii) Assuming the CO_2 of crop respiration is E_p, its GWP G_p can be expressed as $G_p = E_p \times 1$; (iii) Assuming the CH_4 emission is E_c, its GWP G_c can be expressed as $G_c = E_c \times 63$; (iv) Assuming the N_2O emission is E_N, its GWP G_N can be expressed as $G_N = E_N \times 270$; (v) Assuming the assimilated CO_2 is E_r, its GWP G_r can be expressed as $G_r = E_r \times 1$. The composite GWP of paddy ecosystem G_w is defined as $G_w = G_s + G_p + G_c + G_N - G_r$.

3.1 Analysis of the principle of GWP variation during crop growth periods

The numerical analysis results showed that the GWP of N_2O emissions and crop respiration CO_2 is two orders of magnitude lower than that of the CH_4 emissions and assimilated CO_2 when fertilizer equivalent equals 0. GWP of soil respiration is also much lower than that of CH_4 emissions and assimilated CO_2. The composite GWP of paddy ecosystem mainly depends on the GWP of CH_4 emissions and assimilated CO_2. It can be seen clearly in fig. 3(b) that there are source-sink alternations of composite GWP during crop growth period. When the GWP of CH_4 emission is higher than that of the assimilated CO_2, the paddy ecosystem becomes source of the GWP, otherwise it becomes sink of the GWP.

Both GWP of assimilated CO_2 and that of the CH_4 emissions increase when the fertilizer equivalent increases to 4, but the increasing magnitude of GWP of assimilated CO_2 is higher than that of the CH_4 emissions, which reinforced the greenhouse sink function of paddy ecosystem (fig. 3(c)). When the fertilizer increases to 10, the increased magnitude of GWP of CH_4 emissions is higher than that of the assimilated CO_2, and source function of GWP of the paddy ecosystem becomes stronger. In fact, the photosynthesis decreases rapidly in the later period of the growing season under fertilizer equivalent 0 condition, because the organism demanded for the crop growth can only be supplied from the soil. The nitrogen stress becomes very small when the fertilizer equivalent increases to 4, which results in the photosynthesis increasing obviously in the middle and late growth period, as the nitrogen demanded for crop growth can be supplied adequately from nitrogen fertilization. But if the fertilizer goes on increasing, the increased magnitude of assimilation CO_2 will become smaller, because the photosynthesis reaches the saturation status. There is also a maximum fertilizer for CH_4 emissions, but because fertilizer 10 is much lower than that maximum value, the CH_4 emission increased obviously with more fertilizer application.

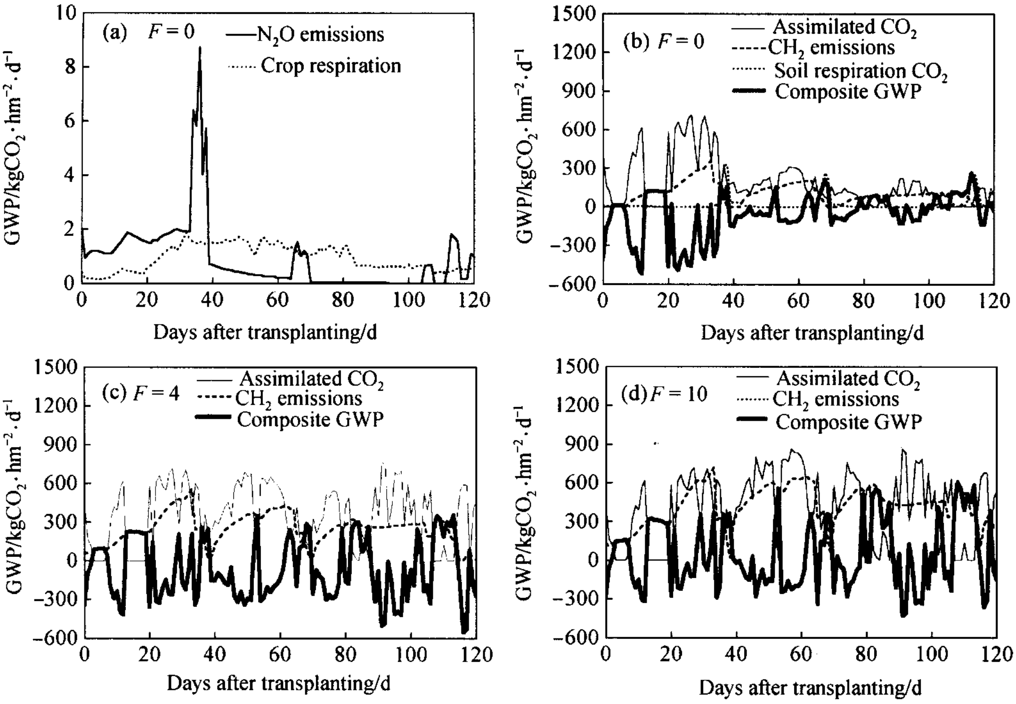


Fig. 3. Transformation of GWP (Global Warming Potential) in rice growth periods. (a) GWP of crop respiration of CO_2 and N_2O emissions, (b), (c) and (d) show the GWP of assimilated CO_2 and CH_4 emissions and the composite GWP when the fertilizer equivalent equals 0, 4 and 10 respectively. F expresses fertilizer equivalent.

3.2 Numerical analysis of the principle of GWP in the whole growth period

The composite behavior of GWP of paddy ecosystem in the whole growth period is much more important. The meteorological factors in Suzhou region in 1995 were input to the model, and the different fertilizer equivalents from 0 to 10 were input to the model as different scenarios, which reflected 11 paddy fields with the same other conditions except for fertilizer equivalent in 1995. Then rice yield and the composite GWP can be calcutated correspondingly under the different fertilizer schemes by accumulating the daily GWP during growth period. The composite GWP of the whole growth period is chiefly determined by the GWP of the assimilated CO_2 and CH_4 emissions.

Both the GWP of crop assimilated CO_2 and that of the CH_4 emissions increase with fertilizer application enhancement, but the variation forms are different. There is an obvious phenomenon that the response of photosynthesis to the fertilizer application changes according to the “reward decrease principle”. There is only little increase of photosynthesis with more fertilization application when the fertilizer equivalent reaches 3 to 4. On the contrary, the CH_4 emissions increase quickly with fertilizer equivalent increasing, since even fertilizer equivalent 10 is much lower than the maximum fertilizer of CH_4 emissions. Then the composite GWP of paddy ecosystem reduces with fertilizer application enhancement at the fertilizer range from 0 to 3.5, as the increased magnitude of greenhouse effect of assimilated CO_2 exceeds that of the CH_4 emissions. On the other hand, the composite GWP increases with fertilizer application enhancement when the fertilizer equivalent exceeded 3.5, as the increased argument of greenhouse effect begins to become lower than that of the CH_4 emissions (fig. 4(d)).

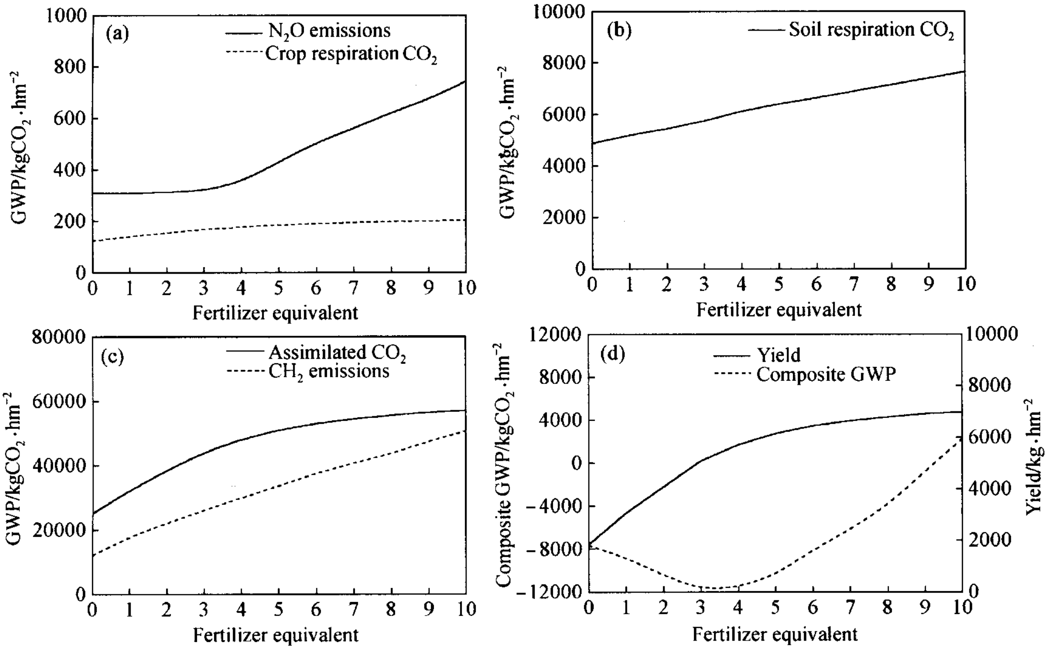


Fig. 4. Impacts of fertilizer on rice yield and GWP. (a) GWP of N_2O emissions and crop respiration of CO_2, (b) GWP of soil respiration of CO_2, (c) GWP of assimilated CO_2 and CH_4 emissions, (d) variation of yield and composite GWP with fertilizer equivalent.

The paddy ecosystem becomes the maximum sink of GWP with fertilizer equivalent 3.5, so this fertilizer equivalent is defined as the maximum-sink fertilizer, and the yield with maximum-sink fertilizer is defined as the maximum-sink yield. The yield with the maximum-sink fertilizer is not the highest yield, but the increase magnitude of the yield will reduce rapidly if the fertilizer equivalent exceeds the maximum-sink fertilizer, so the maximum-sink fertilizer is the optimum fertilizer from the environmental point of view. The composite GWP of the paddy field escalates with fertilizer equivalent increasing if the fertilizer exceeds the maximum-sink fertilizer. The composite GWP becomes 0 when the fertilizer equivalent reaches 9.0, which is a turning point from sink of GWP to the source of GWP in the paddy field. The fertilizer equivalent at this point is defined as zero-emission fertilizer, and the corresponding yield is defined as zero-emission yield. The fertilizer should be in the range between zero-sink fertilizer and zero-emission fertilizer from the environmental agriculture point of view.

3.3 Numerical analysis of the impacts of meteorological factors on maximum-sink fertilizer and zero-emission fertilizer

Both the crop yield and greenhouse gases emissions are affected by the meteorological conditions. In order to reveal the impacts of meteorological conditions on fertilizer index, the daily meteorological data from 1951 to 1995 in Suzhou region were input to the model to simulate the impact of fertilizer equivalent on yield and greenhouse gases emissions under different meteorological conditions, with the same scenario as 1995.

The numerical analysis results under three different meteorological conditions in 1965, 1975 and 1985 showed that the response of both crop yield and greenhouse effect changes greatly even under the same fertilizer conditions, which resulted from the variations of meteorological conditions (fig. 5). It is identified by the numerical analysis that different meteorological conditions are obviously affecting the maximum-sink fertilizer and zero-emission fertilizer. Fig. 5(d) shows the relationship between crop yields and composite GWP under four different meteorological conditions, which indicats clearly that the composite GWP decreases with crop yield increasing when the crop yield is lower. Whereas the composite GWP increases rapidly with crop yield enhancement when the crop yield reaches the maximum-sink yield. Though there are great differences among the variation curves under different meteorological conditions, this kind of variation principle is changeless under different meteorological conditions.

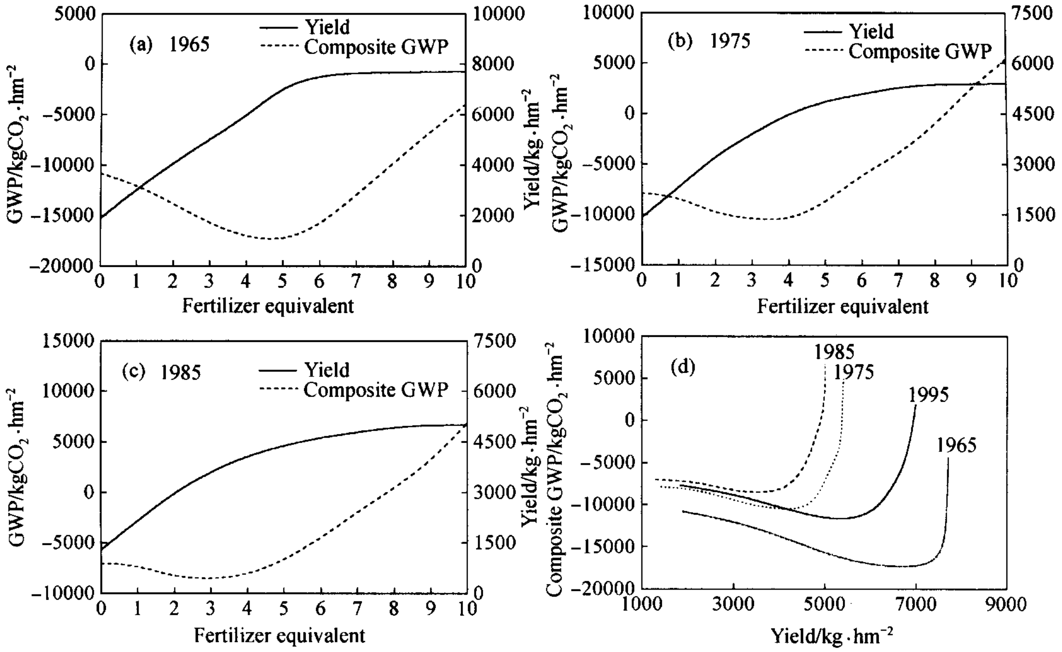
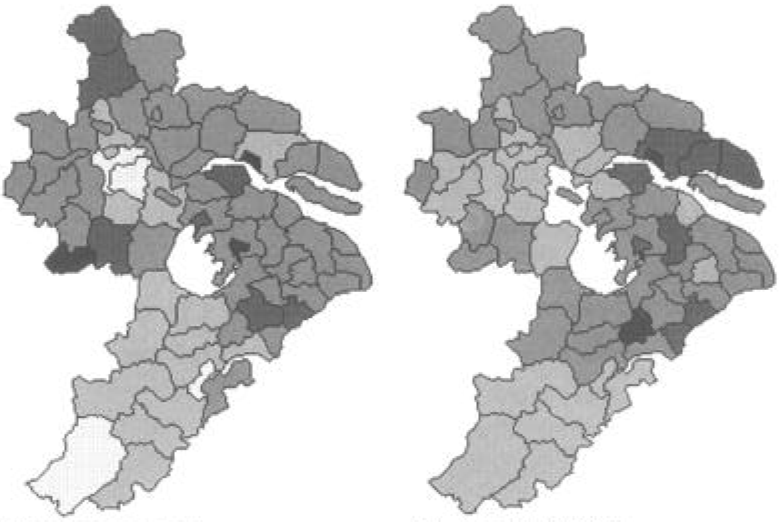


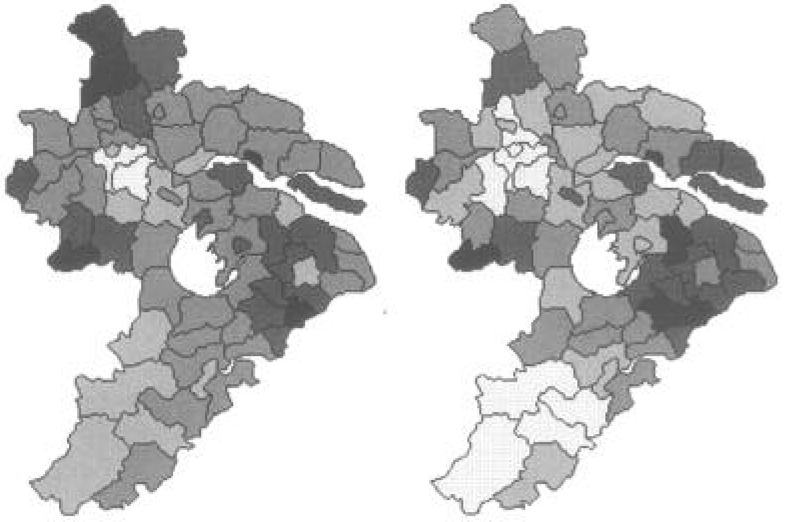
Fig. 5. Impacts of fertilizer on yield and composite GWP under different meteorological conditions. (a), (b) and (c) show the yield and composite GWP changing with fertilizer equivalent under three different meteorological conditions in 1965, 1975, and 1985, (d) shows the composite GWP variation with yield under different meteorological conditions.

4 The optimum fertilization scheme for the Yangtze Delta

The fertilization scheme for the Yangtze Delta is given in fig. 6 under the soil conditions and the average climate conditions, including the distribution of maximum-sink fertilizer, the maximum-sink yield, zero-emission fertilizer and zero-emission yield. In the opinion of the theory, it is the optimum scheme if the maximum fertilizer is applied in all regions. But more fertilizer application is demanded for enhancing the crop yield in some regions because of the pressure of the great volume of population, therefore zero-emission fertilizer and zero-emission yields were



(a) Fertilizer equivalent (b) Yield/10^3kg · hm^{-2}



(c) Fertilizer equivalent (d) Yield/10^3kg · hm^{-2}

Fig. 6. Distribution of fertilization index and corresponding yield in the Yangtze River Delta. (a) Maximum-sink fertilizer, (b) maximum-sink yield, (c) zero-emission fertilizer, (d) zero-emission yield.

also given in the scheme. Compared with the actual fertilizer application at moment, the fertilizer application in the south part of Jiangsu Province and northeast part of Zhejiang Provinece is somewhat higher. The fertilizer application in some areas exceeds the Maximum-sink fertilizer already. The crop yield index and fertilizer scheme can be applied at the range from maximum-sink yield to the zero-emission yield according to the different development demands in different regions.

5 Conclusions

(1) A numerical model was established by coupling the carbon and nitrogen cycling process with crop growth process. Validation of the model with observed data showed that both the carbon and nitrogen cycling and crop growth can be simulated accurately. Numerical analysis results showed that the composite GWP of the rice ecosystem mainly depends on the GWP of CH_4 emissions and crop assimilation of CO_2. The phenomena of source-sink of composite GWP of the paddy ecosystem in crop growth period were firstly revealed by numerical analysis.

(2) The numerical analysis results showed that the composite GWP decreases with fertilizer equivalent increasing when the fertilizer equivalent is lower. The composite GWP increases quickly with fertilizer equivalent increasing when the fertilizer equivalent is higher enough. The equivalent corresponding to the maximum sink of GWP is defined as the maximum-sink fertilizer, and the yield with maximum-sink fertilizer is defined as the maximum-sink yield. The fertilizer equivalent point that the composite GWP equals 0 is defined as zero-emission fertilizer, and the corresponding yield is defined as zero-emission yield.

(3) The maximum-sink yield under average climate conditions can reach a high yield ranging from 4500 $kghm^{-2}$ to 15000 $kghm^{-2}$ in the Yangtze Delta. This means that the high production can be provided with lower greenhouse gasses effect in the paddy ecosystem by the optimum fertilizer scheme, and resources can be exploited harmoniously with environmental production ultimately.

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