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Carbon sequestration and emissions mitigation in paddy fields based on the DNDC model: A review

Shan Yin [a,c,d,e,1], Xianxian Zhang [b,f,1], Junyao Lyu [a,c,d], Yuee Zhi [a,e], Feng Chen [g], Longqin Wang [h], Chunjiang Liu [a,c,d,e,*], Sheng Zhou [b,f,**]

[a] School of Agriculture and Biology, Shanghai Jiao Tong University, 800 Dongchuan Rd., Shanghai 200240, China
[b] Eco-Environmental Protection Research Institute, Shanghai Academy of Agricultural Sciences, 1000 Jinqi Rd, Shanghai 201403, China
[c] Shanghai Yangtze River Delta Eco-environmental Change and Management Observation and Research Station, Ministry of Education, 800 Dongchuan Rd, Shanghai 200240, China
[d] Shanghai Urban Forest Ecosystem Research Station, National Forestry and Grassland Administration, 800 Dongchuan Rd., Shanghai 200240, China
[e] Key Laboratory for Urban Agriculture, Ministry of Agriculture and Rural Affairs, 800 Dongchuan Rd., Shanghai 200240, China
[f] Shanghai Engineering Research Centre of Low-carbon Agriculture (SERCLA), 1000 Jinqi Rd, Shanghai 201403, China
[g] Shanghai Chongming Modern Agricultural Park Management Committee, 2 Chongming Beishougeng Rd, Shanghai 202163, China
[h] Shanghai Songlin Food (Group) CO. LTD, 2268 East Rongle Rd, Shanghai 201613, China

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ABSTRACT

The DeNitrification–DeComposition (DNDC) model is a process model with a series of carbon and nitrogen biogeochemistry in agro-ecosystems. It incorporates the driving factors of the ecological environment and aims to simulate the carbon and nitrogen cycle in the terrestrial ecosystem. Furthermore, the model can be applied effectively in a paddy ecosystem. Based on an investigation and literature review, this study summarized and analyzed the impact of agricultural practices such as water management, fertilizer application, and straw incorporation on greenhouse gas emissions and soil carbon storage. After years of improvement, the DNDC model can presently be used effectively to evaluate the carbon sequestration and emissions mitigation potential of various agricultural practices. However, the related details of scientific processes of agricultural management, such as biochar incorporation and plastic mulching in paddy fields, should be added or modified and combined with experimental cases of actual agricultural practices to complete the calibration of the model, provide theoretical support for its promotion, and establish a reliable method of evaluating carbon sequestration and emissions mitigation in paddy fields.

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* Correspondence to: C. Liu, School of Agriculture and Biology, Shanghai Jiao Tong University, 800 Dongchuan Rd., Shanghai 200240, China.
** Correspondence to: S. Zhou, Eco-Environmental Protection Research Institute, Shanghai Academy of Agricultural Sciences, 1000 Jinqi Rd, Shanghai 201403, China.
E-mail addresses: chjliu@sjtu.edu.cn (C. Liu), zhous@outlook.com (S. Zhou).
[1]These authors have contributed equally to this work.

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1. Introduction

The agricultural ecosystem provides the food people require and also crucially carries carbon (C) and nitrogen (N) in the C and N cycle. The ecosystem is affected by numerous natural and human factors, such as soil, climate, crops, and agricultural practices. All these factors are connected to each other through substance and energy exchange, forming a complex biogeochemical system. However, because of human activities, the agricultural ecosystem is a critical source of non-carbon dioxide (non-CO_2) greenhouse gases (GHGs), which account for 56% of anthropogenic emissions of non-CO_2 GHGs (IPCC, 2014). Methane (CH_4) emissions from the global agricultural ecosystems are 3.22×10^6 Gg CO_2-eq yr^{-1} and nitrous oxide (N_2O) emissions are 5.99×10^6 Gg CO_2-eq yr^{-1} (FAO, 2020). Paddy fields are vital parts of an agricultural ecosystem, and their harvest area accounts for 23% of the total area of cereal crop cultivation worldwide (FAO, 2020). Because of prolonged flood water management, soil has been maintained in an anaerobic reduction condition during rice growing seasons, which provides favorable conditions for CH_4 production. CH_4 emissions from paddy fields account for 18% of emissions from agricultural sources (FAO, 2020). In addition, the application of N fertilizer, water-saving irrigation, and certain other agricultural practices promote N_2O emissions from paddy fields. Annual N_2O emissions in China are approximately 33 Gg N, accounting for 14% of the emissions from agricultural soils (Aliyu et al., 2019). Furthermore, the improvement of the C storage of paddy fields is crucial in mitigating global warming. The C storage of upper paddy soil (0–30 cm) in China is 1.6 Pg C, and the C sequestration potential is 0.9 Pg C (Qin et al., 2013). Therefore, when stabilizing rice production, the adoption of agricultural practices that increase the C pool content of paddy soil and reduce GHG emissions (C sequestration and emissions mitigation for short) is a crucial measure for coping with global climate change.

To accurately assess the impact of agricultural practices on the C sequestration and emissions mitigation potential of paddy ecosystems, understanding the C and N cycle of paddy ecosystems is crucial. Much basic data has been accumulated through field observation and simulation experiments for understanding the scientific process of the C and N cycle in terrestrial ecosystems. With the continuous improvement of science and technology as well as the deepening awareness of the C and N cycle's mechanisms, scientists have begun to develop models to quantify and predict the substance flow of ecosystems. Among them, the process-oriented model, based on the biogeochemical process of C and N dynamic migration, collects the key processes and their control factors in the agricultural ecosystem. The process-based model can effectively expand the scope of analysis from limited site experiments to unlimited scales in time and space and also provide a practical method for quantitative measurements of the C and N cycle in the agricultural ecosystem.

At present, a series of process models are recommended in IPCC guidelines for national GHG inventories, including the Century, RothC, CH4MOD, and DNDC-Rice (originating from the DNDC model) models. The DNDC model, developed by Li et al. (1992), has been used in various countries and regions to simulate the C and N cycle in agricultural, wetland, forest, and grassland ecosystems. In a paddy ecosystem, the DNDC model is mainly used to evaluate soil C and N dynamics and GHG emissions. After years of development, the DNDC model can perform simulations effectively and its efficacy has been recognized by numerous researchers.

Based on a series of biogeochemical processes, the DNDC model combines ecological driving factors, environmental factors, and corresponding physical and chemical processes to study the C and N cycle in the terrestrial ecosystem. In the past few decades, many scholars have jointly used and developed the DNDC model, adding new submodules and biogeochemical process formulas and parameters. The function of the model has been continually expanded, forming multiple forms such as Manure-DNDC, DNDC-online model, which can be used to evaluate C and N dynamics, GHG emissions, nonpoint source pollution, GHG economic benefits, and other data (Gao et al., 2014; Gilhespy et al., 2014; Jiang et al., 2017), and it has been widely verified and applied worldwide. This review mainly introduces the research progress regarding the DNDC model in evaluating the effects of agricultural practices on C sequestration and emissions mitigation in paddy ecosystems.

2. Biogeochemical process of the DNDC model

The DNDC model is composed of an input interface, biogeochemical field, and core process. Users input the environmental driving factors (including meteorological data, soil parameters, crop parameters, and agricultural practices) of the target ecosystem through the input interface. The target environmental characteristics are used to build the biogeochemical field and to transform the driving factors into driving forces of chemical element movement. The core process determines the biogeochemical reactions before finally completing the calculation and simulation of C, N, and moisture in the ecosystem. In the book *Biogeochemistry: Scientific Basis and Model Method* (Fig. 1), Li (2016) elaborated the detailed submodules and processing mechanism process of the model and also discussed the scientific basis and calculation process supporting the model.

2.1. Soil climate

DNDC model can be used to simulate the gas from soil, such as CO_2, CH_4, N_2O, NH_3, etc. The formation of CO_2, CH_4, and N_2O in soil is mainly the result of soil microbial activities, which are impacted by soil environment. Therefore, correct simulations of soil climate, including soil temperature, moisture, pH, and electrical potential (Eh) and related substrate concentration, are critical for tracking GHG emissions.

The model uses the parameters of heat transfer rate, specific heat capacity, and thermal conductivity of soil to calculate soil temperature layer by layer and balances the relationship of input water and output water to calculate the soil moisture of each layer. In the paddy ecosystem, the key to simulating CH_4 and N_2O emissions accurately is to combine soil temperature, water dynamics, and gas flux. To fit the model to a cold and snowy environment, the rain–snow submodule was modified and agricultural snow cover model (snowMAUS) was embedded in the DNDC model, enabling it to more effectively simulate the effects of rain and snow on soil temperature and moisture (Cui and Wang, 2019). The DNDC-Rice model improved the simulation of soil leakage and evapotranspiration and it calculates the soil water content layer by layer in an hourly step, alters the soil water content with the parameters of irrigation time and duration, and defines the water leakage rate (leakage to the 50-cm-deep soil layer at 1 mm day^{-1} rate), thereby implementing the dynamic simulation of water in continuous flooding and alternating dry–wet treatment (Katayanagi et al., 2012). To

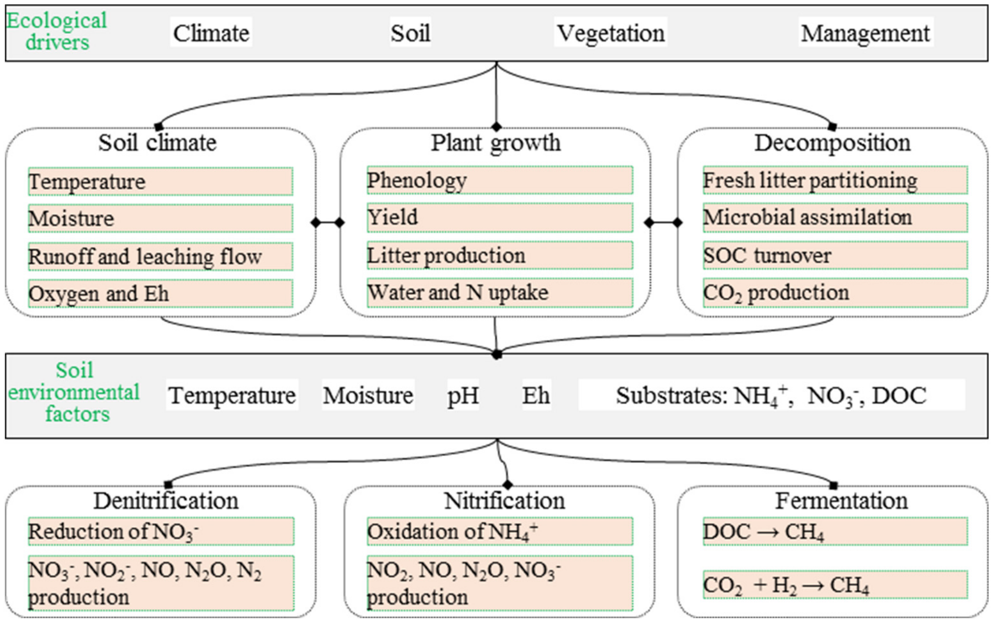

Fig. 1. Structure of the DNDC model (Li, 2016).

accurately simulate the GHG emissions of paddy fields in India, Pathak et al. (2005) increased the leakage rate of certain reaction substrates in soil in the model, such as dissolved organic carbon (DOC) and nitrate. The results of the optimized model greatly reduced CH_4 emissions at the high leakage point but had no effect on those at the low or medium leakage point.

2.2. Plant growth

Plant growth is closely related to the dynamics of C and N in the terrestrial ecosystem, which is also the basic step for the DNDC model to correctly simulate the dynamics of C and N in the soil–crop–atmosphere cycle. To accurately simulate crop growth, the model developers established crop submodules and integrated relevant crop growth models, such as the simple empirical equation, PnET (Photosynthesis-Evapotranspiration), EFEM (Economic Farm Emission Model), NEST (Northern Ecosystem Soil Temperature), and general crop model MACROS (Modules of an Annual CROp Simulator) (Zhang et al., 2002; Li et al., 2004; Zhang and Niu, 2016).

The optimized model can simulate the daily growth of crops, the absorption of soil water and N elements by crops, the potential productivity of crops, the growth of crops under the conditions of water and nutrient constraints, and the DOC of a reaction substrate transported into soil by plant root secretions (Fig. 2). Furthermore, the optimized model can track the circulation of C, N, and water in the ecosystem during plant growth. It uses nine crop parameters (maximum biomass production; biomass fraction of grain, leaf, stem, and root; biomass C/N ratio; annual N demand; thermal degree days for maturity; water demand; N fixation index; optimum temperature; and vascularity) to define rice plant and simulate the daily growth and potential productivity of rice. The DNDC model calculates the stress index of water and N to evaluate the absorption of soil water and N by crops. The DOC of a reaction substrate transported to soil by plant root secretion is calculated to track the circulation of C, N, and water in the ecosystem during rice growth. At present, crop parameters in the DNDC model mainly come from observed values in North America and China. Users can use the default values or create their own simulated crops. Katayanagi et al. (2013) verified the N balance in the DNDC-Rice model using rice crop parameters in Japan. The results indicated that the observed values of

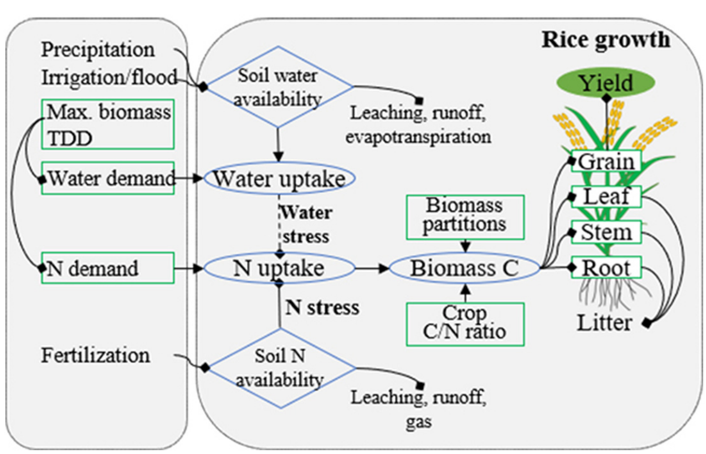

Fig. 2. Rice growth submodel in DNDC.

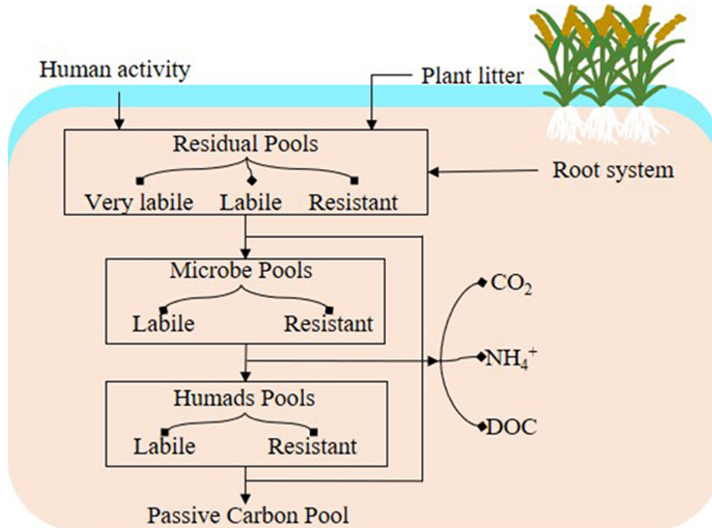

Fig. 3. Carbon dynamics in DNDC model.

grain, stem, and root biomass were consistent with the simulated values (root-mean-square error [RMSE] = 13, 16, and 7%, respectively), but the leaf area index, leaf biomass, and leaf N content were overestimated (RMSE = 125, 60, and 37%, respectively), mainly because of the overestimation of rice N absorption and leaf N assimilation.

2.3. Carbon dynamics

Soil organic carbon (SOC) content is a crucial indicator of soil fertility. In DNDC model, soil organic carbon residues in agro-ecosystem divide into 4 major pools: residues, microbe, humads, and passive carbon (Fig. 3). Each pool has 2 or 3 sub-pools with specific default decomposition rates, which affected by soil temperature, soil moisture, soil texture and substrate concentration, etc. SOC is utilized by plants and microorganisms and finally participates in the C and N cycle. The accumulation of crop residues, manure, biochar, and microbial residues in paddy soil constitutes a critical source of soil's SOC pool. According to their physical and chemical properties, exogenous carbon sources are allocated to different subpools of SOC with default decomposition rates. The decomposition process is affected by many factors, such as organic matter type and soil texture (Li, 2016). The DNDC model can accurately simulate SOC and its dynamic change under specific climates (R^2 = 0.96) and can also complete long-term estimation (Zhang and Shao, 2017; Ku et al., 2019).

2.4. Greenhouse gas emissions

The production and consumption of CO_2, CH_4, and N_2O in soil occur through different redox reactions (decomposition, nitrification/denitrification, and methane production) (Fig. 4). Eh determines whether a reaction can occur. The model constructs the "anaerobic balloon," uses the Nernst equation to calculate Eh in the system, and then uses Eh to judge which redox reaction should occur. The balloon uses the Michaelis–Menten equation to quantify the kinetic effect of substrate concentration on the reaction rate, realizing the conjugate calculation of the thermodynamics and kinetics of the redox reaction generated by GHGs. Moreover, the model defines the interior of the balloon as a relatively reduced soil microarea and the exterior as an oxidized one and allocates

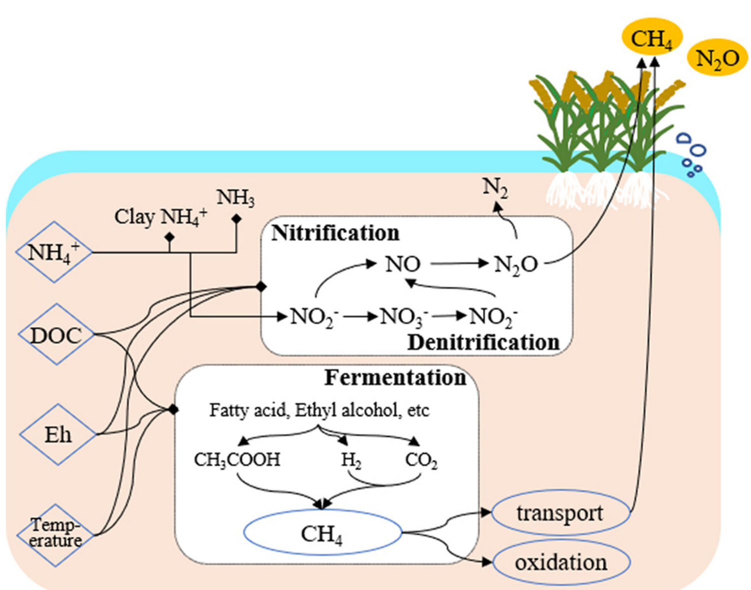

Fig. 4. The process of greenhouse gas emissions in DNDC model.

the reaction substrate (such as DOC, NH_4^+, NO_3^-, and O_2) to the interior and exterior of the balloon proportionally to produce reduction or oxidation reactions, respectively. The DNDC model calculates the consumption and concentration changes of DOC, O_2, NO_3^-, NO_2^-, NO, N_2O, Mn_4^+, Fe_3^+, SO_4^{2-}, and H_2 in various reactions to track the changes of CO_2, CH_4, and N_2O (Li et al., 2004).

Because of the special water management mode of paddy fields, the soil water fluctuates frequently between states of saturation and unsaturation, and the range of Eh variation can be from +650 to −350 mV. CH_4 and N_2O can only be produced under specific Eh conditions (CH_4, −300 to −150 mV; N_2O, 200 to 500 mV) (Li, 2016). In the model, O_2, NO_3^-, Mn^{4+}, Fe^{3+}, and SO_4^{2-} are added as electron acceptors and H_2 and DOC are used as electron donors to more effectively track the change of soil Eh, determine the reaction rate of each oxidation/reduction reaction, and calculate the generation and consumption of CH_4 and N_2O (Fumoto et al., 2008; Katayanagi et al., 2012).

3. Carbon sequestration and emissions mitigation of paddy fields

The DNDC model employs the climate, soil, crop, and agricultural management of the ecosystem as the environmental driving factors; constructs the soil biogeochemical field, including temperature, moisture, pH, Eh, and substrate concentration; adopts the biogeochemical process in the C and N cycle as the core process; and finally, completes the dynamic simulation of the C and N cycle of the ecosystem. The DNDC model combines agricultural practices such as crop growth, water management, fertilizer management, and tillage. After agricultural practices are input, the change of the biogeochemical field in the model affects the C and N cycle in the system, thereby affecting the C sequestration and emissions mitigation effect of the paddy ecosystem (Fig. 5). In a paddy ecosystem, agricultural practices affect the C and N cycle and have a critical impact on its C sequestration and emissions mitigation potential (Table 1).

3.1. Carbon sequestration potential of a paddy ecosystem

3.1.1. Effect of exogenous carbon addition on the carbon sequestration potential of a paddy ecosystem

Agricultural practices are the main reason for SOC change. SOC change is induced by two processes: (1) the consumption of SOC by microorganisms through heterotrophic respiration and (2) the addition of exogenous C. The model calculates the daily change in SOC storage by calculating the C output (soil respiration and DOC leaching) and C input (such as straw return, plant litter, and manure input) of soil daily and accumulates the daily change in SOC storage to obtain the annual change (Li, 2016).

Exogenous C input, such as straw return, manure input, or biochar application, can promote the accumulation of soil SOC. Yan et al. (2011) found that the average organic C content in the surface soil (0–20 cm) of cropland in China increased from 11.95 g kg^{-1} during 1979–1982 to 12.67 g kg^{-1} during 2007–2008, with an average annual growth rate of 0.22%. Based on the Geographic Information System (GIS) database of soil properties and agricultural management systems, the C sequestration of farmland soil for the next 30 years was estimated. The estimations revealed that the soil in East Sichuan is in a state of continuous C sequestration under current management practices (Zhang and Shao, 2017). The main reason is the increase of crop yield and exogenous C caused by straw return, which is an effective measure for soil C sequestration. With the increase of the straw return proportion in China, SOC will continue to increase; however, the decomposition rate of straw left on the surface is higher than that of straw buried in the soil, which is not conducive to the accumulation of SOC. Adding tillage methods and the amount of straw return to the model can help simulate and evaluate the effect of different depths of straw return on C sequestration.

Without straw return or manure application, the SOC of a paddy field will continue to decrease. Fresh straw return and decomposed straw manure application can increase soil SOC content by 9% and 11%, respectively (Ku et al., 2019). Manure application can promote the increase of soil SOC content mainly because its decomposition rate is lower than that of fresh straw. The combined simulation results of DSSAT crop model and the DNDC model indicate that soil SOC stock can be increased by 28% with the combined application of chemical fertilizer and manure (Naher et al., 2020). When straw and other biomass are cracked into biochar, their properties become stable and they are beneficial for C sequestration when applied to cropland. Stable biochar can fix more C in the soil. A meta-analysis revealed that biochar could significantly increase the SOC content of farmland surface soil (Liu et al., 2016). In the model, biochar is classified into inert C pools with low decomposition rates. However, biochar contains some easily decomposable components, and its stability varies depending on the source. Therefore, determining how to use the model to evaluate the C sequestration potential of soil after biochar application remains to be completed.

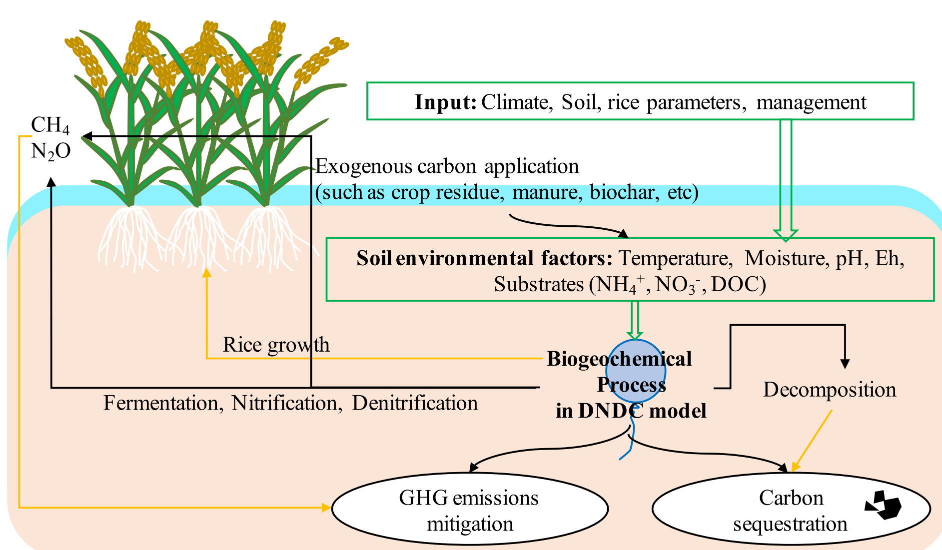

Fig. 5. DNDC application in GHG C sequestration and emissions mitigation in paddy fields.

Table 1
Statistics for evaluating the performance of DNDC model for rice yield, GHG emissions, and carbon stock in paddy fields over the past 10 years.

Location	Agricultural management	Variation	Statistical index	Aims	Reference
Shanghai, China	Organic+inorganic fertilizer	CH_4 N_2O	R^2: 0.76, ME: 0.71 R^2: 0.71, ME: 0.67	Spatial scale, GHG mitigation	(Zhao et al., 2020)
Punjab, India	Fertilizer management	SOC	R^2: 0.78	Spatial scale, C sequestration	(Singh and Benbi, 2020)
Zhejiang, China	Fertilizer management	Rice yield CH_4 N_2O	R^2: 0.88, rRMSE: 0.12 Similar pattern Similar pattern	IPCC scenarios, GHG mitigation	(Chen et al., 2020)
Zhejiang, China	Fertilizer management	Rice yield SOC content	R^2: 0.90, ME: 0.75 R^2: 0.71, ME: 0.75	Spatial scale, C sequestration and GHG mitigation	(Zhu et al., 2019)
Jiangxi, China	Land use change	CH_4 N_2O	R^2: 0.80– 0.89 R^2: 0.16– 0.71	GHG mitigation	(Zhao et al., 2019a)
Shanghai, China	Rotation system	Rice yield CH_4 N_2O	R^2: 0.96, ME: 0.70– 0.86 R^2: 0.88, ME: 0.41– 0.56 ME: −0.23 to −7.88	Spatial scale, GHG mitigation	(Zhang et al., 2019b)
Heilongjiang, China	Traditional management	CH_4	R^2: 0.89, ME: 0.87	Spatial scale, IPCC scenarios, GHG mitigation	(Nie et al., 2019)
Iksan, South Korea	Straw incorporation	Rice yield SOC	ME: −5.5– 0 ME: 0– 0.37	Time scale; C sequestration	(Ku et al., 2019)
Jianghan Plain, China	Rotation system	CH_4 N_2O	R^2: 0.92– 0.93, RAE: 8.29– 15.31% R^2: 0.85– 0.98 RAE: 12.13– 16.42%	Spatial scale, GHG mitigation	(Zou et al., 2018)
China	Traditional management	Rice yield	RAE: 0– 8.14%	Spatial scale, GHG mitigation	(Tian et al., 2018)
Shandong, China	Traditional management	SOC content	R^2: 0.48– 0.94, ME: 0.35– 0.83	Spatial scale, C sequestration	(Chen et al., 2018)
Red River Delta, Vietnam	Traditional management	CH_4	R^2: 0.95	Spatial scale, IPCC scenarios	(Torbick et al., 2017)
Central Thailand	Traditional management	Rice yield CH_4	R^2: 0.99 R^2: 0.96	Spatial scale, IPCC scenarios, CH_4 mitigation	(Minamikawa et al., 2016)
Beijing, China	Fertilizer management	SOC content	R: 0.45– 0.78	C sequestration	(Li et al., 2016)
Henan, China	Fertilizer management	SOC content	R: 0.41– 0.73	C sequestration	(Li et al., 2016)
Japan (Hokkaido, Tohoku, Hokuriku, Kanto, Tokai-kinki, Chugoku-Shikoku, Kyushu-OKinawa)	Water management	CH_4	R: 0.85– 0.89	CH_4 simulation	(Katayanagi et al., 2016)
Jiangsu, China	Water management	N_2O	R: 0.48– 0.79	N_2O simulation	(Hou et al., 2016)
Shanghai, China	Fertilizer management	Rice yield CH_4 SOC stock	R^2: 0.89 R^2: 0.87 R^2: 0.76	C sequestration and GHG mitigation	(Gao et al., 2016)
Gimje, South Korea	Water management	CH_4	ME: 0.24– 0.65	CH_4 mitigation	(Chun et al., 2016)
China (Hunan, Chongqing, Guangxi, Shanghai, Jiangsu, Heilongjiang)	Water and nitrogen management	Rice yield CH_4 N_2O	R^2: 0.79– 0.84 Similar pattern Similar pattern	Spatial scale, GHG mitigation	(Chen et al., 2016)
Califonia, USA	Direct-seeded rice system	Rice yield CH_4 N_2O	R^2: 0.30– 0.78 R^2: 0.85 R^2: 0.31	GHG mitigation	(Simmonds et al., 2015)
Tai-Lake region, China	Traditional management	SOC content	R: 0.2– 0.5	Spatial scale	(Zhang et al., 2014)
Jiangsu, China	Traditional management	N_2O	R^2: 0.89	Model performance	(Wu and Zhang, 2014)
China	Traditional management	SOC content	R: 0.40– 0.99	Spatial scale, C sequestration	(Xu et al., 2012a)
Sanjiang Plain, China	Fertilizer management	CH_4	R^2: 0.85– 0.91, ME: 0.84– 0.87	Spatial scale, CH_4 simulation	(Zhang et al., 2011)

Note: R^2, coefficient of determination; ME, Nash–Sutcliffe index of model efficiency; rRMSE, relative root mean square error; RAE, relative absolute error.

3.1.2. Effect of tillage practices on the carbon sequestration potential of a paddy ecosystem

In addition to the application of exogenous C, the long-term use of plowing tillage, rotary tillage, and other traditional tillage methods in the agricultural ecosystem has effects on soil mineralization, thereby affecting SOC accumulation. No-tillage practices can fix C by reducing the disturbance of soil and the decomposition rate of the C pool. However, according to the results of the DNDC model, the potential of no tillage for soil C sequestration is highly limited. In Jiangsu, China, the soil C sequestration potential at 0–30 cm soil depth under reduced tillage, no tillage, and combined tillage (reduced tillage and 30% straw incorporation), was quantitatively estimated, which indicated that the application of reduced tillage and no tillage could increase the accumulation of SOC in some paddy fields, and combined tillage had twice potential for C sequestration than in reduced tillage (Xu et al., 2012b). Site experiment and model simulation results in Ningxia and Hunan province also showed that the effect of no tillage combined with straw return on soil C sequestration was superior to that of no tillage only (Huang et al., 2012). However, some studies have confirmed that no tillage practices lead to soil hardening and affect soil aeration and crop yield (Pittelkow et al., 2015). Therefore, comprehensive consideration is required when assessing the C sequestration potential of tillage practices.

3.2. Greenhouse gas emissions mitigation potential of a paddy ecosystem

3.2.1. Effects of water management measures on the emissions mitigation potential of a paddy ecosystem

CH_4 is produced by methanogenic bacteria using soil humus, rice root exudates, soil microbial residues, and organic materials as substrates. In the root exudation area (around the root) or soil micro-oxidation area, some CH_4 is oxidized to CO_2 and H_2O by methanotrophic bacteria, and some CH_4 that is not oxidized is discharged into the atmosphere through rice plants, bubbles, and liquid diffusion. The model builds a module based on an anaerobic balloon, which can effectively implement and stimulate CH_4 and N_2O emissions in flooded paddy fields.

Flooded paddy fields are a critical source of CH_4 emissions, and the key to reducing such emissions is to optimize water management. Mid-season drainage not only inhibits the ineffective tillering of rice through water stress but also reduces CH_4 emissions through promoting the oxidation of CH_4. Compared with continuous flooding, mid-season drainage can significantly reduce the total CH_4 emissions from paddy fields by 36% to 77% (Zou et al., 2005; Wang et al., 2012b). Li et al. (2004, 2005) used the DNDC model to evaluate the potential of paddy emissions mitigation in China, and their results indicated that mid-season drainage water management could reduce CH_4 emissions by 4.2–4.7 Tg CH_4-C yr^{-1} while increasing N_2O emissions by 0.13–0.20 Tg N_2O-N yr^{-1} from paddy fields in China. Compared with the practice of single drainage, multiple drainage can further reduce CH_4 emissions during rice growth (Sander et al., 2016), which is consistent with simulation results of the model (Minamikawa et al., 2016). Compared with flooding, single and multiple drainage in 2051–2060 reduced CH_4 emissions by 21.9–22.9% and 53.5–55.2%, respectively, under the RCP4.5 scenario (Minamikawa et al., 2016).

In addition, the DNDC model can define numerous water management modes. This enables the simulation analysis of GHG emission scenarios under various types of water management to effectively predict their emissions mitigation potential in time and space scales. After parameterizing two rice varieties, namely M206 (a high-yield and semi-dwarf variety) and Koshihikari (a traditional variety), Simmonds et al. (2015) simulated the grain yield and CH_4 and N_2O emissions of rice under different N loads and water management types with water-seeding and dry-seeding cultivation. The results indicated that DNDC could distinguish the rice yield of the two varieties and reproduce the CH_4 emission dynamics under different management scenarios. Water-saving irrigation management, such as controlled irrigation and alternate wetting and drying, can significantly reduce CH_4 emissions but may also promote N_2O emissions (Zhou et al., 2020). Field experiment and model evaluation results revealed that alternate wetting and drying effectively reduced CH_4 emissions during rice growing seasons but also simultaneously stimulated N_2O emissions; furthermore, the comprehensive global warming potential (GWP) was only one-third of that under flooding management (Katayanagi et al., 2012). The model could also effectively simulate the dynamics of CH_4 emission peak values in the rice–dry crop rotation system, which was basically consistent with field observation results (Zhang, 2013; Chun et al., 2016).

3.2.2. Effect of nitrogen management on emissions mitigation potential of a paddy ecosystem

Chemical N fertilizer and manure provide the substrate source for soil nitrification and denitrification microorganisms, which is the most critical factor affecting N_2O emissions. The global annual N_2O emissions from the application of chemical N fertilizer and manure were 2.0 ± 0.8 Tg N and 0.6 ± 0.4 Tg N, respectively (Li and Ju, 2020). The N_2O emissions caused by the field fertilization practice accounted for 33% of total N_2O emissions. The continuously increasing amount of fertilizer being applied has been the main reason for the global N_2O emissions increase. Many studies have confirmed that soil N_2O emissions increase linearly or exponentially with the increase of N application (Shcherbak et al., 2014; Wang et al., 2018).

To reduce the application amount of N fertilizer, improve the utilization rate, and reduce the N_2O emissions of cropland soil, many scientists have summarized a concept and technology based on the optimization of N management called the 4Rs: right fertilizer rate, right application time, right place, and right source. The submodule of N application in the model includes factors such as the type, amount, time, and mode of application, which provide a foundation for the estimation of the impact of 4R technology on GHG emissions.

Based on DNDC model, the simulated value of crop yield was fitted the measured value well in rice-wheat rotation system under different N application, which reflected the relationship between crop yield and N application; when N fertilizer application reached 60% of the conventional amount, the increase in N no longer promoted a significant increase in crop yield, whereas the comprehensive greenhouse effect decreased by 43% compared with the conventional practice (Li, 2012). After the rice varieties were parameterized by Simmonds et al. (2015), the model could reproduce the CH_4 emission dynamics under different amounts of N fertilizer and different flooding times. The results of DNDC estimation indicated that GHG emissions could be reduced without affecting the crop yield through reducing the amount of N applied based on the current amount. At present, a large potential exists for reducing the use of chemical N fertilizer in China. The paddy yield will be stabilized when the amount of N fertilizer is reduced by 0.88 Tg per year. In the main rice growing regions of China, such as Jiangsu, Yunnan, Guizhou, and Hubei provinces, GHG emissions can be reduced by as much as 40% through N fertilizer reduction (Chen et al., 2016).

3.2.3. Effect of exogenous carbon addition on the emissions mitigation potential of a paddy ecosystem

The reasonable addition of exogenous C can affect CH_4 emissions in paddy fields. Numerous studies have shown that all types of exogenous C, such as straw, green manure, and organic manure, provide rich substrates for methanogens and can significantly promote CH_4 emissions from rice fields (Wang et al., 2012b; Zhou et al., 2020). Compared with no exogenous carbon addition, manure input and straw incorporation enhanced CH_4 emission per unit of rice yield significantly, with 54% and 107% increase respectively (Zhao et al., 2019b). Straw return or manure application can suddenly increase the content of soil organic matter, but it will be gradually decomposed by soil microorganisms, providing a rich substrate for methanogens and other microorganisms. The model constructed the effect of environmental conditions on microbial decomposition activity, which can accurately reproduce the biogeochemical process of exogenous C addition.

In addition, CH_4 emissions increased significantly under the scenarios of high straw return and manure application (Wang et al., 2012a). The results of model simulations and field experiments indicated that N_2O emissions were affected by straw return amount, return type, and return depth. Returning straw to the field after incineration resulted in significantly higher N_2O emissions than returning to the field directly (Chen et al., 2015). After the indices of alfalfa and broad bean were parameterized in the DNDC model, the observed values and simulated results of Gao et al. (2016) revealed that the application of alfalfa and broad bean straw during rice growing season significantly increased CH_4 emissions, and the effect of broad bean straw was greater than that of Alfalfa straw. In different rice rotation systems, the GHG emission of a rice–Chinese milk vetch rotation system was lower than that of a rice–wheat rotation system (Zhang et al., 2019b). However, the model cannot accurately express the effect of biochar treatment on CH_4 and N_2O because no specific input parameter exists for biochar in the model (Wang, 2013).

3.2.4. Effect of coupling agricultural practices on the emissions mitigation potential of a paddy ecosystem

In actual rice production, the pairing of water and fertilizer and other agricultural practices is often used to stabilize the yield and reduce GHG emissions. A reduction in N application by 15.7% would not reduce rice yield in China, and the combination of shallow irrigation and appropriate fertilization could reduce GHG emissions by 34.3% while increasing the rice yield by 1.7% (Chen et al., 2016). The most effective measures for GHG emission mitigation in paddy fields are upland rice cultivation > shallow irrigation > use of ammonium sulfate instead of urea or ammonium bicarbonate > medium-term sun drying > straw return in nonrice-growing season > application of slow-release fertilizer > continuous flooding irrigation (Li et al., 2006). Tian et al. (2018) paired the DNDC model with the DSSAT model and Agro-Ecological Zone model to evaluate the balance relationship between GHG emissions and yield under Chinese rice-planting conditions. The simulation results showed that CH_4 and N_2O emissions could be reduced while the yield was guaranteed under the double management measures of mid-season drainage and balanced fertilization. The DNDC model can also be used to analyze the N balance and N use efficiency of paddy fields under different irrigation, fertilization, and controlled drainage conditions. When water-saving irrigation is applied and the amount of N applied does not exceed 180 kg N ha^{-1}, the soil N pool of paddy field is loss (54.7––127.6 kg N ha^{-1}). Except for shallow irrigation–deep storage–medium level N application and shallow irrigation–deep storage–high N application, the N deficit of controlled drainage treatment was greater than that in conventional drainage treatment. The combination of shallow irrigation, deep storage, medium level N, and controlled drainage was the optimal water and fertilizer treatment mode (Liu and Shao, 2013).

The application of plastic mulching cultivation technology can solve the problem of winter irrigation of paddy rice in northwest China, and it is also a crucial form of agricultural management for CH_4 emission mitigation. Compared with continuous flooding, plastic mulching could significantly reduce CH_4 emissions by 86% while maintaining rice yield (Zhang et al., 2013). Moreover, compared with a field without mulching, the soil climate of a field with mulching was significantly different, mainly with respect to field evapotranspiration, heat exchange, and soil aeration, which affected the soil temperature and moisture, microbial activity, and gas diffusion emissions. Many studies have modified and optimized the mulching submodule of the DNDC model (Han et al., 2014; Zhang et al., 2019a; Zhou et al., 2019). The model can simulate the soil temperature and moisture accurately under different mulching density scenarios. However, few studies have been conducted on GHG emissions simulation under the condition of paddy field mulching.

In addition, cultivating and selecting varieties with excellent drought resistance and high yield play crucial roles in water saving and emissions mitigation. In recent years, China has developed a new variety of cultivated rice, namely water-saving and drought-resistant rice (WDR), which differs from lowland and upland rice varieties. WDR has the characteristics of high-yield and high-quality rice and the water-saving and drought-resistant properties of upland rice. When irrigation was reduced by 50%, the yield and quality of WDR were the same as those of traditional rice (Luo, 2018). When irrigation was reduced by 70%, its CH_4 emissions decreased by 51–77% while the yield remained relatively stable (Sun et al., 2016). The emergence of WDR combines the advantages of the high yield of lowland rice and low water demand of upland rice. The water demand, root exudates, and root oxygen secretion ability differ from those of conventional lowland rice, resulting in the specificity of GHG emissions and N loss. How to make more effective use of the DNDC model to evaluate its potential in paddy field emissions mitigation is one of the directions for model improvement and optimization.

4. Conclusion

It is critical to recognize the potential of C sequestration and emissions mitigation in paddy fields for dealing with global climate change. Many studies have made numerous achievements in case studies of C sequestration and emissions mitigation. Since the establishment of the DNDC model, researchers worldwide have used their field data to verify and correct the model, which has caused the continual increase of its credibility and continual expansion of its functionality and scope. The model can now be used in various terrestrial ecosystems to predict crop growth, soil C and N dynamics, GHG emissions, and N loss.

After modification and calibration, the model has been applied to the assessment of GHG emissions and the SOC sequestration potential of C sequestration and emissions mitigation measures such as straw return, water management, and N reduction. Moreover, it is necessary to further analyze the effects of various management measures—such as straw return to the field, biochar application, and water management from flooding to water-saving irrigation—on the comprehensive potential of C sequestration and emissions mitigation in paddy fields; thus, the timing for exogenous C application and water management can be arranged and the C sequestration and emissions mitigation potential of this measure can be maximized.

With the aggravation of environmental problems and the improvement of agricultural practices, expectations for the prediction function of the model are increasing. In the future, it will be necessary to evaluate the comprehensive effects of various farmland measures on SOC change, GHG emissions, food security, and ecological environments. How to make more effective use of the DNDC model to serve the low-C production of rice from the point to regional scale as well as how to establish a reliable prediction and evaluation system under agricultural practices and climate scenarios are the development trends for the model's application.

CRediT author statement

Shan Yin: Conceptualization, Writing - Original Draft; **Xianxian Zhang**: Conceptualization, Writing - Original Draft; **Junyao Lyu**: Writing - Original Draft; **Yuee Zhi:** Investigation, Resources; **Feng Chen**: Investigation, Resources; **Longqin Wang**: Investigation, Resources; **Chunjiang Liu**: Writing - Review & Editing, Project administration; **Sheng Zhou**: Writing - Review & Editing, Project administration.

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