MINISTRY OF NATURAL RESOURCES AND ENVIRONMENT

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METHANE AND NITROUS OXIDE EMISSIONS FROM CROP CULTIVATION IN THE RED RIVER DELTA

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LIST OF SCIENTIFIC ARTICLES OF THE AUTHOR RELATED TO THE THESIS

1. **Bui Thi Thu Trang**, Mai Van Trinh, Đinh Thai Hung, Vu Thi Hang (2021), *Research on the trend of N_2O emissions from maize cultivation soil in Dan Phuong, Hanoi*, Journal of Plant Protection, Plant Protection Research Institute, ISSN 2354-0710, No. 5.

2. **Bui Thi Thu Trang**, Mai Van Trinh, Bui Thi Phuong Loan, Vu Thi Hang, Đinh Quang Hieu, Luc Thi Thanh Them, Đang Anh Minh (2021), *Research on methane (CH_4) và and nitous oxide (N_2O) emissions from four paddy soil types in the Red river Delta*, Journal of Climate Change Science, Vietnam Institute of Meteorology, Hydrology and Climate Change, ISSN 2525-2496, No. 18, pp. 45-57.

3. **Bui Thi Thu Trang**, Chu Sy Huân, Mai Van Trinh và Đinh Thai Hung (2021), *Research on the sensitivity of parameters and calibrates DNDC model for calculating emissions from paddy rice cultivation activities*, Vietnam Journal of Science and Technology, ISSN 1859-4794, Vol. 63, No. 6, pp. 11-17.

4. **Bui Thi Thu Trang**, Mai Van Trinh, Đinh Thai Hung, Quang Thi Thuong Thuong, Phan Thu Tiep, Hoang Thi Trang, Đang Ngoc Tu (2021), *Research on greenhouse gas emissions from wet rice cultivation activities in Thinh Long town, Hai Hau district, Nam Dinh Provice,* Journal of Climate Change Science, Vietnam Institute of Meteorology, Hydrology and Climate Change, ISSN 2525-2496, No. 17, pp. 48-59.

5. Chu Sy Huân, Mai Van Trinh, Cao Viet Ha, Bui Thi Phuong Loan, Vu Thi Hang, Đinh Quang Hieu, Đao Thi Minh Trang, **Bui Thi Thu Trang** (2020), *Study on greenhouse gas emission of rice soils in Thai Binh province*, Vietnam Journal of Agricultural Sciences, ISSN 1859-0004, No. 1, pp. 113-122.

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8. **Bui Thi Thu Trang**, Mai Van Trinh, Le Thi Trinh, Nguyen Thi Hoai Thuong (2018), *Assessment some calculation models of greenhouse gas in agro-ecosystems*, Journal of Science on Natural Resources and Environment, Hanoi University of Natural Resources and Environment, ISSN 0866-7608, No. 19, pp. 27-37.

INTRODUCTION

1. Rationale

Greenhouse gas (GHG) emissions in production, or agriculture, in particular, have become a global problem. Significantly, it can be mentioned that Vietnam, one of the countries, depends on agricultural production as a prominent citizen's livelihood. The agricultural industry is not only heavily affected by climate change but also causes emissions.

Although the National GHG inventory has been implemented three times from 1994, Vietnam's GHG inventory calculation still mainly uses the emission factors according to Method 1 of the IPCC (IPCC, 1996). These factors do not differ in topography, climate, soil, crops, and crop intensification. However, the precise quantification of GHG emissions from rice and other crops is complex because of spatial variations in climate and soil, crops, and farming practices.

As a result, the application of a mathematical model in quantifying GHG emissions is a possible solution to meet both technical requirements and emissions calculation for space and time with high and stable accuracy due to the monitoring and measuring of GHG emissions in the field is very complicated and requires many resources (equipment, funds, and human resources). The DeNitrification- DeComposition (DNDC) model is a tool widely applied in calculating GHG emissions from agroecosystems in the world and is gradually gaining attention in Vietnam. This model allows to forecast the amount of carbon retained in the soil, the loss of nitrogen, and the emission of greenhouse gases such as CO_2, CH_4, N_2O from agroecosystems by day (Mai Van Trinh, 2013).

From the above analysis, the thesis named *"Methane and nitrous emissions from crop cultivation in the Red River Delta"* was selected for implementation.

2. Research objectives

- Determine the amount of GHG emissions from annual rice and upland crop cultivation in the Red River Delta.

- Establish GHG emission maps for annual rice and upland crop areas according to the Red River Delta's different climate and soil conditions.

3. Subject, scope and activities of the research

3.1. Subject of the research

Conduct research on rice, maize, and annual upland crops; main soil types: fluviols, infertile gray soil, solonetz soil, thionic soil in the Red River Delta; greenhouse gases: methane (CH_4) and nitrous oxide (N_2O) emissions from wet rice soils and nitrous oxide (N_2O) emissions from annual maize and upland crops in the Red River Delta.

3.2. Scope of the research

- Spatial scope: The thesis was conducted in the Red River Delta, in which specific observations and measurements in the field were carried out in Thanh Tri and Soc Son districts, Hanoi city; Hai Hau and Nghia Hung districts, Nam Dinh province; Thai Binh city, Kien Xuong district, Vu Thu district, and Tien Hai district, Thai Binh province; Nam Sach district, Hai Duong province; and fluvisols growing maize of the Red River in Dan Phuong district, Hanoi city.

- Time range: From January 2016 to October 2020.

3.3. Research activities

To achieve the research objectives, the following main contents were implemented:

(1) Study overviews of research on GHG emissions in crop production in Vietnam and the world;

(2) Develop a methodology to calculate the amount of CH_4, N_2O from annual rice and upland crops according to different climate and soil conditions in space;

(3) Study the current situation and evolution of CH_4 and N_2O emissions from rice grown at the monitoring areas in Thanh Tri districts (Fluviols) and Soc Son district (Infertile gray soil), Hanoi city; Hai Hau district (Fluviols and Solonetz soil), and Nghia Hung district (Solonetz fluviols), Nam Dinh province; Thai Binh city (Fluviols), Vu Thu district (Fluviols), Kien Xuong district (Thionic soil) and Tien Hai district (Solonetz soil), Thai Binh province; Nam Sach district (Fluviols), Hai Duong province; and maize is grown on fluviols of the Red River in Dan Phuong district, Hanoi city;

(4) Establish a set of input data to serve the calculation of GHG emissions by space: meteorological data, map of current land use, land map, complex map of meteorology, soil, and land use;

(5) Study the operating mechanism of the DNDC model, assess the sensitivity of the parameters, adjust and verify the model for GHG emission calculation for researched crops in the Red River Delta;

(6) Research on GHG emissions for plant species and research scope.

4. Thesis statement

(1) GHG emissions vary spatially, depending on different climatic conditions, soil types, crops, and farming practices (water and fertilizers management), and their distribution can be quantified.

(2) The rate of GHG emissions changes over time, growth stages of crops, environmental factors such as temperature, precipitation, evapotranspiration, water regime, pH, fertilizer regime, etc.

(3) GHG emissions are calculated accurately for every point in space when data on climate, soil, crops, farming activities, and especially monitoring data in the study area are available.

5. Original contributions of the thesis

Firstly, the thesis clarified that GHG emissions (CH_4 and N_2O) depend on the following objects: type of soil, cultivation method, sub-climate in space and time;

Secondly, modeling and spatial analysis methods were applied to calculate GHG emissions for all points in the study area based on the proven monitoring data on soil, meteorology, crop types, and farming methods from representative points;

Thirdly, the thesis synthesized the calculation results of GHG emissions at the experimental sites and completed quantifying GHG emissions in space based on spatial and temporal data on climate, soil, crops, farming methods, and modeling tools, GIS. From there, GHG emission distribution maps for the whole Red River Delta were established.

6. Scientific and practical contributions of the thesis

6.1. Scientific contributions

Besides the succession and mechanism of methane (CH_4) and nitrous oxide (N_2O) emissions at the growth stages of rice grown on fluviols, infertile gray soil, solonetz soil, thionic soil, these of nitrous oxide (N_2O) emission at the growth stages of maize grown on fluviols of the Red River were also studied.

The calculation method and research results of GHG emissions for annual rice and upland crop areas in the Red River Delta with different meteorological and soil conditions were provided and presented on maps.

From analyzing the sensitivity of the DNDC model in detail for correction, a set of standard parameters of the model for GHG emission calculation was found. This can be handy for future studies to inherit without repeating the research, saving many resources and filling the gaps in knowledge of GHG emission modeling in agriculture.

The calculation method can be inherited and perfected for calculating and establishing emission distribution maps for other agricultural production areas based on the study area's climate, soil, crops, and farming practices. Additionally, the time range and method development of new research for other study areas are able to reduce.

6.2. Practical contributions

Results on emission calculation and distribution of greenhouse gas emissions on the Red River Delta's annual rice and upland crop areas were provided.

The emission calculation and distribution results can be used to inventory greenhouse gas emissions. Moreover, the built solutions can reduce greenhouse gas emissions for crop production in the Red River Delta.

7. Structure of the thesis

The thesis consists of the following main parts:

Introduction;

Chapter 1: Overview of greenhouse gas emissions from crop cultivation;

Chapter 2: Methodology of the research;

Chapter 3: Research results on greenhouse gas emissions from annual rice and upland crop cultivation in the Red River Delta;

Conclusion and recommendations; References.

Chapter 1. OVERVIEW OF GREENHOUSE GAS EMISSIONS FROM CROP CULTIVATION

1.1. Overview of greenhouse gas emissions

Regarding the mechanism of formation and release of CH_4, N_2O, and CO_2, soil microorganisms play a vital role in most terrestrial ecosystems. Environmental factors affecting the growth of microorganisms are soil oxygen content, soil water content, soil temperature, mineral N content, organic matter, pH value, etc. Besides, some farming activities can, directly and indirectly, impact CH_4 and N_2O emissions from the soil, such as tillage, organic fertilizer, nitrogen fertilizer, etc. The amount of CH_4 and N_2O produced in the soil can be much more significant than the actual emissions to the atmosphere (Neue, 1994). They can be further transformed into other forms such as oxidation (CH_4 converts into CO_2) and reduction (N_2O converts into N_2). Therefore, the amount of CH_4 released from rice fields into the atmosphere is a balance of two opposing processes, the reduction to produce CH_4 and the oxidation of CH_4 (Wassmann et al., 2000). N_2O gas is produced from the aerobic oxidation of ammonium (NH_4^+) to nitrite (NO_2^-) and nitrate (NO_3^-), and then anaerobic oxidation of NO_3^- to NO_2^- and finally to NO, N_2O, and N_2 gases in the soil. These reactions depend on the amount of water in the soil and the content of mineral N, degradable organic C, and temperature.

1.2. Monitoring and calculating greenhouse gas emissions from crop cultivation

N_2O is an intermediate product of nitrification and denitrification, very volatile in the anaerobic environment of flooded rice soil, and easily reduced to N_2. As a result, although many studies on N_2O emissions from rice cultivation have been carried out in the last two decades, monitoring these emissions is still not as widely conducted as CH_4. Efforts to calculate N_2O emissions through simulation models are also underway. However, they are difficult to be precise because the formation and release of N_2O from rice soils are influenced by natural and artificial factors (Majumdar, 2009).

In recent years, Vietnam has researched GHG emissions from agricultural cultivation, focusing on rice cultivation in various agroecological regions with different farming methods. However, most of the performed studies are small-scale, isolated, and mainly research on CH_4 emissions. For upland crops, especially some critical crops with large cultivated areas (such as maize, cassava, sugarcane, coffee, rubber, tea, or coffee), the research on emissions during the cultivation of these crops is not much yet and mainly focuses on applying the IPCC method to inventory GHG.

1.3. Modeling and spatial analysing to calculate greenhouse gas emissions from crop cultivation

Using modeling is one of the popular approaches widely applied to estimate and forecast GHG emissions from agricultural and forestry activities (Yan et al., 2003; Li & cs., 2004). Quantification of GHG emissions from regional and global agricultural production is essential in the context of large-scale climate change (Li et al., 1997). GHG emission calculation models in agriculture are built with input data mainly on meteorology, hydrology, land, and farming.

Among the biogeochemical models, the DNDC model is considered the most widely applied model in the world. The model has been tested and applied to calculate GHG emissions in agricultural farming systems in various countries such as the USA, Italy, Germany, most commonly in China and UK (Li, 2000). The DNDC model has a structure that simulates relatively fully the biophysical-chemical processes in soil and other environmental factors (temperature, precipitation, etc.) affecting the formation and release of GHGs from the soil into the atmosphere. Furthermore, the inputs are more detailed and completed than other models. Thus, DNDC has proven its reliability in GHG calculations and is considered one of the most comprehensive tools to calculate and forecast GHG emissions from agricultural and forestry activities, etc., especially for regional GHG inventories and studies.

In Vietnam, the application of the DNDC model to estimate CH_4, N_2O emissions from agroecosystems is gradually gaining attention. However, most studies are limited to a certain number of sites with a particular climate, soil, and crop condition.

1.4. Current status of farming methods to reduce greenhouse gas emissions in the Red River Delta

The main activities in rice cultivation in the Red River Delta include tillage; sowing rice seeds (pharmaceutical planting or yard plating), weeding; pest control; harvest; threshing and drying, packing, storing, and preserving. The Red River Delta region is considered to have a high level of rice intensification compared to the national average in terms of both productivity and investment. Some farming methods to reduce GHG emissions are applied in the Red River Delta, such as alternating wet and dry irrigation (AWD), system of rice intensification (SRI), GHG emission reduction through the application of three reductions, three increases (3G3T), emission reduction through composting, use of biochar, use of early ripening (short-duration) varieties, minimal farming, emission reduction through the transformation of production structure.

With other annual crops, polyculture systems, which combine many crops, husbandry with planting, short-term crops such as black beans, groundnuts, maize, cassava, ginger, galangal, medicinal plants, are intercropped between rows of perennial trees. Typical integrated agricultural systems such as VAC (garden, pond, barn) and mixed garden are prevalent. Produce according to organic agriculture or VietGap to provide safe products and contribute to environmental protection, reducing GHG emissions by limiting or entirely not using synthetic chemicals for plants and animals. Notably, organic agriculture pays special attention to restoring the fertility and structure of the soil by using only organic fertilizers and biological pesticides.

1.5. Overview of the Red River Delta

The Red River Delta, a large region located downstream of the Red River in North Vietnam, includes ten provinces and cities. The whole region has an area of 15,082 km², accounting for 4.5% of the country's area, a population of 21,295,400 people (22.3% of the country's population), with the capital Hanoi being a significant economic, political, cultural, scientific, and technical center of the region and the whole country (General Statistics Office, 2019).

The Red River Delta is one of the two central rice-producing regions of Vietnam. The area of food crops ranks second in the country (1242.9 thousand hectares). Rice is the main food crop in the Red River Delta, with the cultivated area accounting for 94.07% of the area of grain crops in the region.

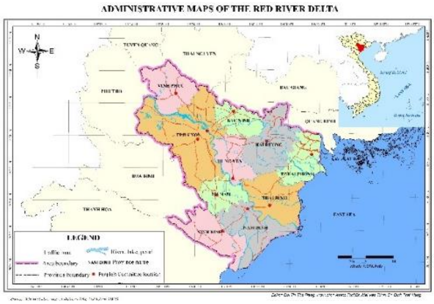

Figure 1.14: Geographical location of the Red River Delta region map

For annual upland crops, the Red River Delta has main crops such as corn, sweet potato, potato, cassava, sugarcane, vegetables and beans (cabbage, kohlrabi, carrots, watermelon, onions, etc.), fiber plants (jute and sedge), plants containing essential oils (soybeans, peanuts, and sesame), tobacco, pipe tobacco, flowers, ornamental plants, and some other annual upland crops.

Chapter 2. METHODOLOGY OF THE RESEARCH

2.1. Research framework

The research steps were followed according to the diagram in figure 2.1 below.

2.2. Methodology of the research

2.2.1. Data collection

- Spatial data: current land use map of the Red River Delta in 2015; soil map of the Red River Delta in 2016; scale 1:250,000.
- Soil data: soil types, soil layer thickness, mechanical composition, physiological and biochemical properties of the soil, etc.
- Plant data: seeds, physiological and biochemical characteristics; seasonal calendar; farming techniques; types and characteristics of fertilizers, etc.

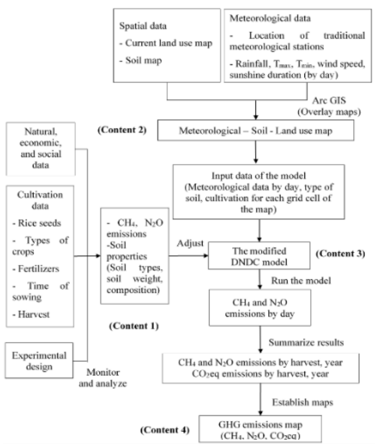

Figure 2.1. Research framework

- Meteorological data: Data for the years from 2010 to 2020 at 28 traditional meteorological stations in the network of national monitoring of Viet Nam Meteorological and Hydrological Administration. These stations ensure measurements on a unified basis, serve for basic investigation. Collected data includes station coordinates, day's highest air temperature, day's lowest air temperature, total daily sunshine hours, wind direction and speed, daily rainfall, and humidity.

2.2.2. Gas sampling and analysis

Rice: Rice was transplanted at a density of 30-35 clusters/m^2. The farming model was entirely according to the local people's custom, in which the water was submerged 10 cm on the field until the rice was ripe, then the water was drained (spring crop was withdrawn from 20/05/2018 to 30/05/2018; seasonal crop from 01/10/2018 to 19/10/2018; depending on each experimental site). After harvesting, the straw was collected and brought home, and the stubble was plowed. In spring crop: tillage from 05/02/2018 to 18/02/2018; transplanting from 08/02/2018 to 20/02/2018; harvest from 02/06/2018 to 11/06/2018. In crop: tillage from 24/06/2018 to 25/06/2018; transplanting from 30/06/2018 to 02/07/2018; harvest from 17/10/2018 to 27/10/2018.

Fertilizer was applied three times/crop (basal fertilizing and two times for applying additional fertilizer). Basal fertilizing used 100% phosphate fertilizer, 30% nitrogenous fertilizer, and 30% potash fertilizer. The first applying additional fertilizer at branching stage used 40% nitrogenous fertilizer. At panicle initiation, the second applying additional fertilizer used 30% nitrogenous fertilizer and the remaining 70% potash fertilizer.

Maize: Experiments were conducted to measure N_2O emissions in the winter crop of 2018 on fluviols of the Red River, Hanoi city. The experimental plot area was 20m^2 (5m x 4m), and each formula was repeated three times. LVN17 was rice seed used. Plant density was six trees/m^2.

Fertilizer included urea nitrogen fertilizer (46% N), superphosphate fertilizer (16% P_2O_5), potassium chloride fertilizer (60% K_2O). Fertilizer dosage was 500 kg of microbial organic fertilizer + 164 kg of N, 112 kg of P_2O_5, and 90 kg of K_2O. Regarding the fertilization method, all manure, microbial organic fertilizer, and phosphate fertilizer were basally fertilized. When applying additional fertilizer, 30% nitrogenous fertilizer and 30% potash fertilizer were used first, and then 50% nitrogenous fertilizer and 50% potash fertilizer. Finally, all remaining fertilizers were used for the third time.

Gas sampling

Gas samples were obtained by using a sealed chamber method according to Lindau's design. The steps were followed in the Manual of GHG emissions monitoring from wet rice cultivation (Mai Van Trinh, 2016).

Analysis of gas samples

Gas samples were analyzed by gas chromatography. CH_4 gas was determined by a flame ionization detector (FID) at 300°C, and N_2O was determined by an electron capture detector (ECD) at 350°C.

Regarding the GHG emission calculation method, the intensity of CH_4 or N_2O emissions (mg/m^2/hour) was calculated using the equation of Smith and Conen (2004).

2.2.3. Field experiment and soil analysis

Soil samples were taken in the survey field at the cultivation layer before the experimental layout. Soil sampling was carried out following the Vietnam standards: Soil mechanical composition by Pipette (TCVN 8567:2010); soil pH by using a pH meter (TCVN 5979-2007); Total OC by Walkley - Black (TCVN 9294:2012); Total N following the Kjeldahl procedure (TCVN 7373:2004); Total P following colorimetric method (TCVN 8940:2011); Total K following atomic absorption spectroscopy method (TCVN 8660:2011); CH_3COONH_4 by using ammonium acetate extraction method; available K_2O (TCVN8662:2011); available P_2O_5 by Olsen (TCVN8661:2011).

2.2.4. Modeling

The DNDC model was used to calculate GHG emissions in rice cultivation and some other annual crops.

The input data of the model included meteorology (temperature, precipitation, wind speed, solar radiation, humidity); cultivation (seeds, time of sowing, harvesting, fertilizers, watering, crop management, weeds, etc.); soil (soil type, pH, weight, water conductivity, clay content, OC content, etc.)

The output data of the model involved CH_4, N_2O emissions per unit of cultivated area, and other indicators related to OC, Eh, etc.

2.2.5. Spatial analysis

The spatial GHG calculation method combining the DNDC and GIS (ArcGIS 10.1) models was used.

ArcGIS 10.1 was applied in two ways:

- Create a map of the combination of meteorology - soil - land use for spatial emission research;
- Present emissions of CH_4, N_2O, and CO_2eq by space.

2.2.6. Statistical analysis

Data and results of conducting experiment and applying the DNDC model were processed and synthesized by Microsoft Excel. Greenhouse gases were converted to CO_2eq with a factor of 28 for CH_4 and 265 for N_2O according to IPCC 2014.

Chapter 3. RESEARCH RESULTS ON GREENHOUSE GAS EMISSIONS FROM ANNUAL RICE AND UPLAND CROP CULTIVATION IN THE RED RIVER DELTA

3.1. Physical and chemical properties of soils at experimental sites

Besides good and average levels at some sites, organic and total N contents were rich at most research sites. Regarding the organic content, because fluvisols outside the dyke are regularly accreted, the organic C was determined to be low of less than 1%; in contrast, due to fluvisols in low-lying areas being poorly drained, poorly mineralized, the organic C content was higher than 2.2%. Fluvisols having OC ranged from 0.9-2.61%; solonetz soils ranged from 0.4 - 2.29%; thionic soils were 3.3%, and gray soils were 1.23%. Thus, the organic content in thionic soils was much higher than the remaining three soil types. Additionally, most of the total N fluctuated in the range of 0.12 - 2.7%.

At most of the study sites, phosphorus and available potassium were rich, especially available phosphorus was very rich. The soils' cation exchange capacity (CEC) was at a medium to high, ranging from 12.6 to 26.7 cmol/kg. Mainly, thionic soils with total phosphorus were in the middle and poor level.

In terms of acidity, solonetz soil, fluvisols, and gray soil had minor acidic reactions; thionic soils had acidic reactions. pH_{KCl} fluctuated as follows: fluvisols (4.8 - 5.56); solonetz soils (5.04 – 5.9); gray soil (5.51); and thionic soil (3.88).

The mechanical composition was classified according to 3 levels (clay, silt, sand). Fluvisols mainly had silt particles, clay from 21.4 to 31.4%, silt from 54.2 to 57.2 %, and sand from 14.4 to 21.4%. Soils varied from sandy to silt, clay, depending on the topographical conditions, the distribution distance of the soils from the river, and the distribution upstream, midstream, or downstream of the river.

3.2. CH_4 and N_2O emissions from rice and maize soils

3.2.1. CH_4 emissions from rice soils

The research results show that CH_4 emissions by seasonal crop at the experimental sites ranged from 74.4 to 698.51 kg/ha/crop. This is unified with the results of many previous studies such as Pandey et al. (2014), Mai Van Trinh et al. (2017), and Tariq et al. (2017).

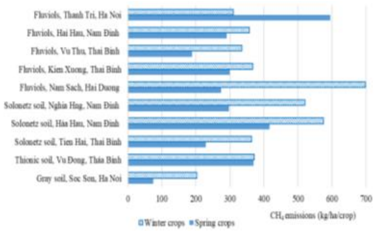

Figure 3.1: CH_4 emissions from rice soils at the measurement sites in spring and winter crops

CH_4 emissions by seasonal crop tended to be larger than spring crop emissions at the sites. One of the reasons is that the spring crop temperature is low, the carbon decomposition is weak. In contrast, the crop temperature is very high, the process of carbon decomposition is intense and producing a lot of methane gas.

Evolution of CH_4 emissions from rice soils

After analyzing the evolution of CH_4 emissions at the different sites, the emission rates varied by seasonal crops. Specifically, the average emissions rates of CH_4 in the spring/winter-spring crop (Figure 3.2) ranged from 3.12 to 14.67 mg CH_4/m^2/hour. CH_4 emissions in spring/winter-spring crops started slowly and were low in the early stages, gradually increased in later growth stages, and peaked at tillering, internode development, and decreased in later stages to harvest. The research results show that the early spring/winter-spring crop was cold, so the emissions were slow, low, and increased later, but the emission rate also decreased soon. The studies of Pandey et al. (2014), Tariq et al. (2017), and Mai Van Trinh et al. (2016) also claimed a sharp decrease in the final stage of CH_4 emission measurement.

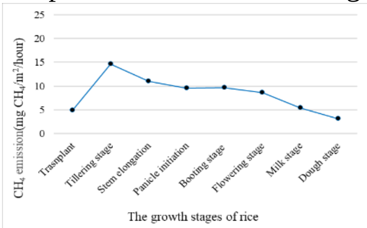

Figure 3.2: Evolution of average CH_4 emissions from rice soils in spring crop

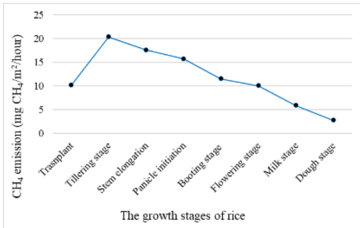

Figure 3.3: Evolution of average CH_4 emissions from rice soils in seasonal crop

In the seasonal/ summer-autumn crops (Figure 3.3), the average emission rate was from 2.74 to 20.36 mg CH_4/m^2/hour. Emissions tended to increase right after transplanting because of the high temperature from the beginning. The maximum emission rate was reached during the tillering stage, which is a period of flood soils, enough time for bacteria to quickly decompose organic matter to produce a lot of CH_4. At this stage, the rice plants grew and developed strongly with high biomass productivity; the increase in temperature in early summer led to high evaporation at the leaf surface; a high flow of CH_4 gas was through the stem and released into the air; then gradually decreased to the end of the crop.

3.2.2. N_2O emissions from rice soils

N_2O emissions by crop ranging from 0.3 kg/ha/crop to 1.8 kg/ha/crop are shown in Figure 3.4.

Most of the N_2O emissions in the spring crop were higher than in the seasonal crop. The reason is that the spring crop in the North of Vietnam has a low temperature leading to a low growth rate of rice, and low nitrogen uptake. However, local people applied more fertilizer at the beginning of the crop and less at the end. This caused excess nitrogen in the early stages, easy to metabolize and emit N_2O.

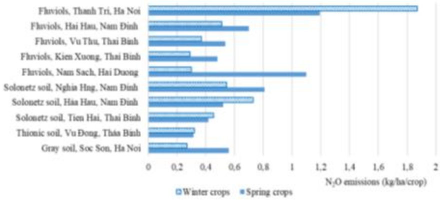

Figure 3.4: N_2O emissions from rice soils at measurement sites in spring and winter crops

The results are consistent with the research results of many previous authors such as Pandey et al. (2019), Mai Van Trinh et al. (2017), and Tariq et al. (2017).

Evolution of N_2O emissions from rice soils

In the spring/winter-spring crop (Figure 3.5), the N_2O emission rate was high at the stage of nitrogen fertilizer application. The rapid emission after the application was witnessed, the maximum emission rate was reached on the 3rd day, and then decreased gradually. The reasons were a decrease in the amount of free nitrogen, an increase in the amount of nitrogen absorbed by plants, and a decrease in the free nitrogen for N_2O transformation and formation. The emission rate fluctuated in the range of 0.11 - 0.3 g N_2O/m^2/hour.

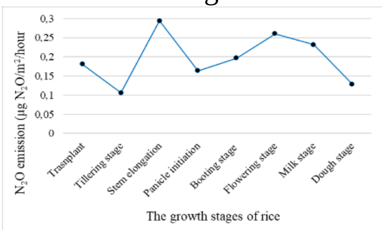

Figure 3.5: Evolution of average N_2O emissions from rice soils in the spring crop

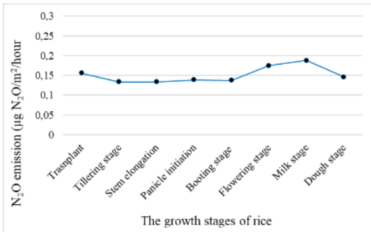

Figure 3.6: Evolution of average N_2O emissions from rice soils in the seasonal crop

In the summer/summer-autumn crop (Figure 3.6), N_2O emissions were similar to those in the spring/winter-spring crop, and the emission rates were also often associated with nitrogen fertilizers. N_2O emission rates fluctuated in the range of 0.13 - 0.19 µg N_2O/m^2/hour. However, if the seasonal observations were made, the N_2O emission rate in the crop season would be lower than in the spring/winter-spring crop. There were many similarities with the climatic characteristics of the region.

The rate of N_2O emission in rice soils at experimental sites fluctuated in the measurements, in which emissions were relatively consistent with the trend. In the rooting period, for instance, the emission and the nitrogen fertilizer were high; in contrast, the rice plants were still small, the nutritional requirements were low, and the roots were still weak. This led to a large amount of excess nitrogen and be ready for nitrogen metabolism and N_2O emissions. The internode development period coincided with the top dressing, so the soil's nitrogen content in the soils was also high, the nitrogen metabolism was strong, and the N_2O emission was high. It can be seen that the emission rate at each measurement site in both crops was different and had a relationship with the amount of nitrogen applied to the rice, climatic conditions, and soil environment.

3.2.3. Evolution of CH_4 and N_2O emissions from four types of rice soils

Evolution of CH_4 emissions from four types of rice soils

CH_4 emissions in the whole spring crop were highest measured in the thionic soils (Thai Binh province) and the lowest in the gray soils (Hanoi city) (Figure 3.7).

In the spring crop, analysis results show that in fluvisols and solonetz soils, when the rice took root and turned green stage, the CH_4 emission rate increased continuously, and reached the highest at the tillering period (from 17-22 mg CH_4/m^2/hour), then gradually decreased towards the end of the crop. In gray soils, the emissions increased gradually and reached the highest at the internode development (6 mg CH_4/m^2/hour). Particularly, in the thionic soils, CH_4 emissions increased continuously until the flowering stage and reached the highest level of the crop at the time of flowering and pollination (32 mg CH_4/m^2/hour).

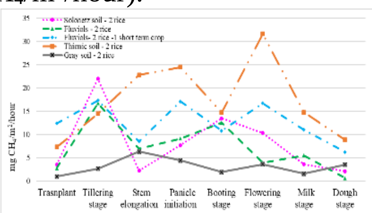

Figure 3.7: Evolution of CH_4 emissions from four types of rice soils in the spring crop

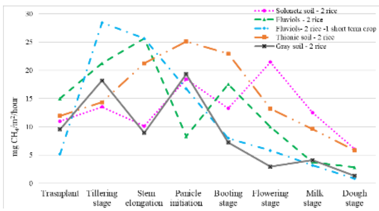

Figure 3.8: Evolution of CH_4 emissions from four types of rice soils in the seasonal crop

In the seasonal crop, a common trend of increasing emissions immediately after transplanting and reaching maximum emission rates during tillering to flower differentiation (Figure 3.8) was demonstrated at all experimental sites on the soil types. This stage was the flooded soil stage, enough time for bacteria to decompose organic matter to grow strongly, producing much methane.

Evolution of N_2O emissions from four types of rice soils

In the spring crop, the evolution of N_2O emissions on soils was significantly different according to the stages of growth and fertilization. In fluvisols, the emissions increased gradually to the internode development stage, then decreased slightly, and increased to the highest at the stage of color exposure, pollination, and flowering (reaching 0.326 and 0.4 μg/m²/hour). After pollination and flowering, NO_2 emissions decreased steadily until the end of the crop.

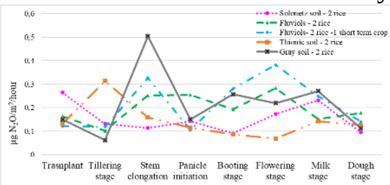

Figure 3.9: Evolution of N_2O emissions from four types of rice soils in the spring crop

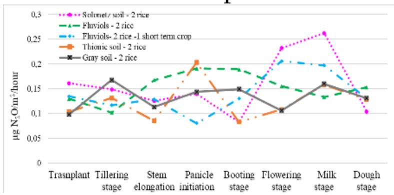

Figure 3.10: Evolution of N_2O emissions from four types of rice soils in the seasonal crop

In general, in seasonal crop on soil types, the high level of emissions reached at the stage of flower differentiation until milky compression. The amount of emissions ranged as follows: on fluvisols with 2 rice (0.102-0.191 μg/m²/hour); fluvisols with 2 rice - 1 color (0.08-0.206 μg/m²/hour); solonetz soils (0.08-0.262 μg/m²/hour); thionic soils (0.082-0.203μg/m²/hour); gray soil (0.098-0.1598 μg/m²/hour).

3.2.4. N_2O emissions from maize on fluvisols of the Red River

The analysis results of N_2O emission after fertilizing on fluvisols at the study sites (Figure 3.11) show that the N_2O emission rate was highest on the 3rd day after fertilizing. After that, the N_2O emission decreased rapidly and was very low from day seven. Furthermore, there was a relationship between N_2O emissions and the fertilizer method, amount, and time range.

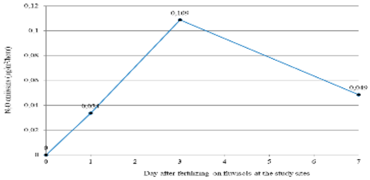

Figure 3.11: Evolution of N_2O emission from fluvisols for maize cultivation after fertdilizing

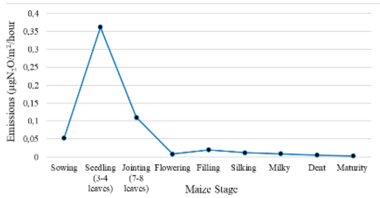

Figure 3.12: Evolution of N_2O emission from fluvisols for maize cultivation in winter crop

N_2O emissions in maize cultivation

The process of emitting N_2O into the atmosphere occurred before nitrogen in the form of nitrate was reduced to molecular N, which depended on environmental factors such as soil pH, soil moisture, redox potential, mineral N, organic C, and temperature. Figure 3.12 shows that the high N_2O emission rate was concentrated in the periods of high nitrogen fertilization, such as the first top dressing period (when the maize had 3-4 leaves) and the second top dressing period (when the maize had 7 - 8 leaves). At the later stages of the second top dressing or the period of solid growth of maize, the biomass was extensive with a large amount of nitrogen absorbed by the plant, and the nitrogen residue in the soils was still very low, so the metabolism and emissions were not significant. Therefore, the emission rate of the later stages was lower and almost zero-emission in the milky compression stage compared to the previous stages.

The total emissions of the whole crop were calculated as the cumulative sum of emissions over the entire period of the maize crop. The total emission of maize on fluvisols of the Red River was 1,251 kg/ha/crop. The amount of N_2O emitted per kg of nitrogen fertilizer was calculated, resulting in the emission coefficient on fluvisols of the Red River was 0.0076.

3.3. Sensitivity assessment, calibration, and verification of DNDC model for calculation of greenhouse gas emissions

3.2.1. Sensitivity of parameters for CH_4 emissions

The temperature was a parameter that greatly affected the level of CH_4 emissions. When the temperature fluctuated by 25%, 50%, and 75% of the initial value, the CH_4 emissions increased or decreased sharply, ranging from 75-530%. This is consistent with Li et al. (1992) research because the microbial activity involved in the production of methane increased significantly with increasing and decreasing temperature. Changes in precipitation did not have much effect on CH_4 emissions. This result is conformable with the published studies of Sass et al. (1990), Yagi et al. (1996), Adhya et al. (2000), Lu et al. (2000).

Density and clay rate were the following sensitive factors. Some parameters that did not affect CH_4 emissions were the wilting point in moisture soils and salinity index. These results were similar to those reported in research by Li et al. (2000, 2004), Wassmann et al. (2000), Yagi et al. (1996). Among rice cultivation methods, nitrogen (urea) and manure were the two primary farming practices that significantly impacted seasonal CH_4 emissions.

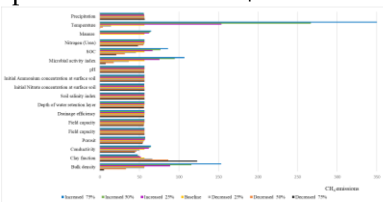

Figure 3.13: Sensitivity of the parameters for CH_4 emissions

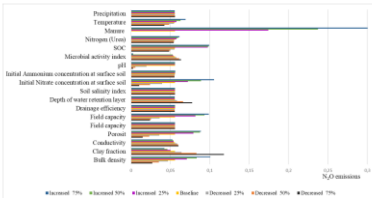

Figure 3.14: Sensitivity of the parameters for N_2O emissions

3.3.2. Sensitivity of the parameters for N_2O emissions

N_2O emissions were not much influenced by meteorological factors and precipitation while temperature oscillated by 25%, 50%, and 75% of initial values, N_2O emissions, respectively, increased by 3.59%, 12.92%, 24.52%, and decreased 2.02%, 13.12%, 24.01%. The reason is that microorganisms involved in the nitrification process decreased when the temperature decreased and increased significantly. This result is consistent with the studies of Li & cs. (1992).

In addition, N_2O emissions were impacted significantly by the clay rate and the microbial activity index. A lower influence on N_2O emissions from rice soils was experienced by parameters (drainage capacity, water movement speed, initial ammonium content in the topsoil) at the study sites. The wilting point in moisture soil and salinity index were unaffected factors.

Regarding fertilizers, nitrogen levels were positively linearly correlated with N_2O emissions. The oscillation of the amount of N fertilizer applied to the soil by 25%, 50%, and 75% of the initial values made N_2O emissions increased or decreased by 2.29% and 10.72%, respectively. When the manure was changed from 0 to 1-2 ton/ha, the N_2O emissions increased sharply.

The trends in this research are similar to those of Li et al. (1994, 1996), Brouwman et al. (2002).

3.3.3. Calibration of DNDC model for emission calculation

The model coefficients were adjusted according to the measurement results at the experimental sites. After that, the CH_4 and N_2O emissions calculated by the DNDC model were compared with the measured data in the field.

Based on the CH_4 and N_2O emission values measured in the field and calculated through the model by showing the point distribution, the GHG emissions values were distributed close to the 1:1 line. A good correlation between the actual and simulated values was presented with R^2 in spring and summer crops reaching 0.86 and 0.79, NSI reaching 0.82 and 0.77 (for CH_4); R^2 in spring and winter crop reaching 0.62 and 0.69, NSI reaching 0.69 and 0.76 (for N_2O), respectively.

3.3.4. A set of parameters after DNDC model calibration

According to the model calibration results, parameters were set to calculate GHG emissions in the Red River Delta.

3.3.5. DNDC model verification

The results of model verification show: (i) comparing CH_4 emissions observed and modeled in the spring crop, NSI = 0.79 and R^2 = 0.95; in the seasonal crop: NSI = 0.88 and R^2 = 0.95; (ii) comparing observed and modeled N_2O emissions in spring crop, NSI = 0.79 and R^2 = 0.81; in the seasonal crop: NSI = 0.73 and R^2 = 0.87. Thus, a good correlation between the field measured values, and the calculated values by the model were demonstrated. The model had a relatively high correlation (shown by the R^2 and NSI asymptotically up to 1).

3.4. A built set of input data for the model

Meteorological data: Data were collected from 28 meteorological stations in the Red River Delta in the period 2010-2020. The input meteorological factors of the model were daily observation data. The coordinates of meteorological stations in the region are shown in Figure 3.19.

Figure 3.19: Location map of meteorological stations

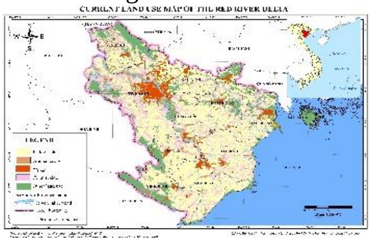

Figure 3.20: Current land use map of the Red River Delta

Current land use map in the Red River Delta

Filtering and building thematic maps were conducted; thereby, a current land use map was built with the main groups being soil for rice and other annual crops cultivation, urban areas, rural areas, and others. The result is shown in Figure 3.20.

Soil map in the Red River Delta

From the collected soil map, filtering and establishing the thematic map were carried out; thereby, a new soil map for the Red River Delta was formed with the main soil types being fluvisols, gray soil, solonetz soil, thionic soil, sand soil, sloping, peat soil, erosion, chalk soil (Figure 3.21).

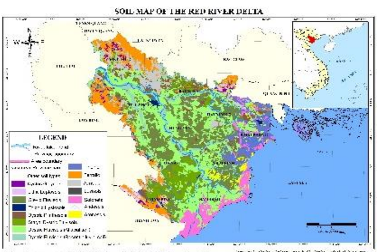

Figure 3.21: Soil map of the Red River Delta

Figure 3.22: Complex map of meteorology - soil - land use in the Red River Delta region

Complex map of meteorology - soil - land use in the Red River Delta region

From the coordinate data of meteorological stations, the current land use map, and the distribution map of the soil types, a complex map of meteorology - soil - land use (Figure 3.22) was built by using the overlay analysis method.

3.5. Greenhouse gas emissions from rice soils by space

3.5.1. Greenhouse gas emissions by soil types

Rice

The amount of CH_4 emissions in gray soils was the lowest (average 250.57 kg/ha/year), while this in thionic soils was the highest (average 802.74 kg/ha/year). The emissions ranged from 72.20 to 859.16 kg/ha/year.

Similarly, the amount of N_2O emissions was the lowest (average 0.667 kg/ha/year) in gray soils, and the highest (average 1,389 kg/ha/year) in solonetz soils. The emissions ranged from 0.306 -2,247 kg/ha/year.

A correlation between the content of the soil substances and emissions was shown when the soil analysis results were compared. Gray soil had lower organic and total nitrogen content than other soils, which led to lower emissions than other soils. Besides, thionic soil had high organic matter content, so CH_4 emission was the highest among soil types.

Annual upland crops

Thionic soils had the lowest N_2O emissions (average 0.723 kg N_2O/ha/year); in contrast, fluvisols witnessed the highest N_2O emissions (average 1,957 kg/ha/year). The values ranged from 0.716 - 2,728 kg N_2O/ha/year.

3.5.2. Global warming potential

Based on the calculation method of IPCC (2014), the global warming potential was calculated by converting all gases to CO_2 equivalent (CO_2eq). It is shown that the area at Tam Dao station had the lowest emissions (average 4,586.33 kg CO_2eq/ha/year); the area at Nam

Dinh station experienced the highest emission (average 22,842.21 kg CO_2eq/ha/year).

3.5.3. Map of greenhouse gas emissions from annual rice and upland crops cultivation in the Red River Delta region

Distribution map of CH_4, N_2O emissions

Based on the results of the DNDC model for each unit in the complex map of meteorological - land - land use, thematic maps showing the distribution of CH_4 emissions from rice soil (Figure 3.23), N_2O emissions distribution from rice soil (Figure 3.24), and N_2O emissions distribution from the annual upland crops soil (Figure 3.25) were established.

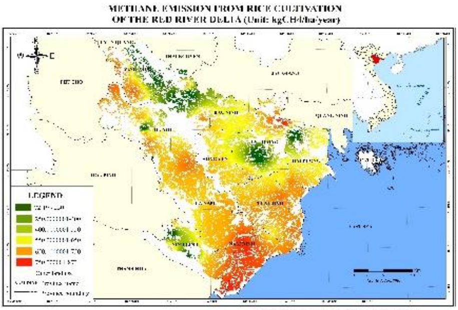

Figure 3.23: CH_4 emissions map from rice soil in the Red River Delta

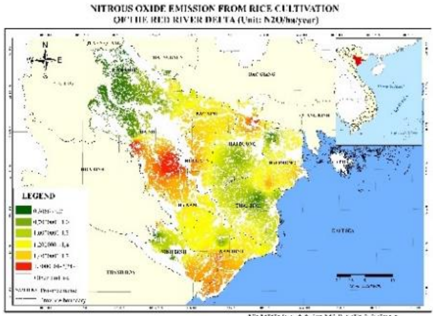

Figure 3.24: N_2O emissions map from rice soil in the Red River Delta

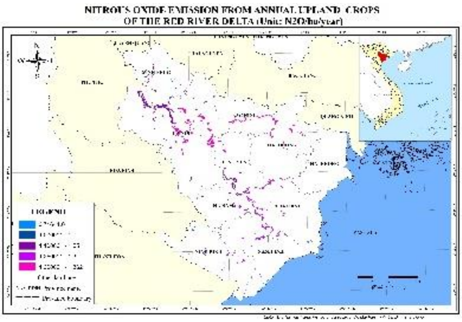

Figure 3.25: N_2O emissions map from annual upland crop soil in the Red River Delta

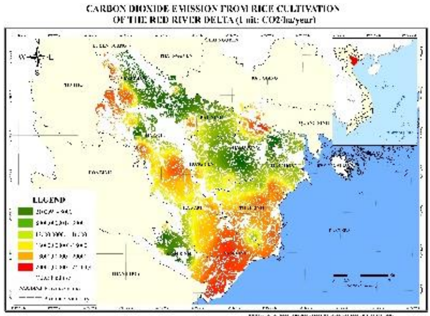

Figure 3.26: Map of total GHG emissions converted from rice soil in the Red River Delta region

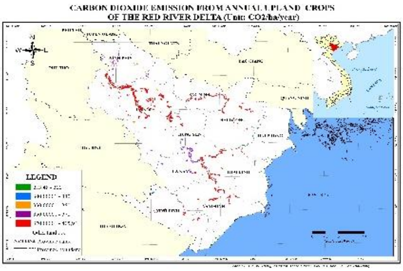

Figure 3.27: Map of total GHG emissions converted from annual upland crop soil in the Red River Delta region

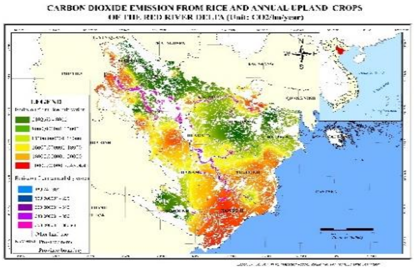

Figure 3.28: Map of total GHG emissions converted from annual rice and upland crops soil in the Red River Delta region

CONCLUSIONS AND RECOMMENDATIONS

1. Conclusion

1. The advantages and disadvantages of the research to calculate GHG emissions in agriculture and, in particular, crop cultivation were analyzed and evaluated, thereby developing a method to calculate GHG emissions from annual rice and upland crop cultivation activities for the whole Red River Delta from monitoring, modeling, spatial analysis, and emission distribution mapping with different climate and soil conditions;

2. A method to calculate the amount emissions of CH_4, N_2O, CO_2eq from annual rice and upland crops in the Red River Delta according to different climatic and soil conditions in time and space was developed;

3. GHG emissions from rice and maize cultivation (representing annual upland crops) were monitored, analyzed, and calculated at experimental sites in the Red River Delta;

4. The operating mechanism, sensitivity analysis of the parameters, calibration, and verification of the DNDC model for GHG emission calculation were studied and performed. The DNDC model results have great sensitivity to some parameters and inputs but no response to some parameters. And then, after adjusting the model for four types of soil, a set of parameters was built. A good correlation between actual and simulated values was shown;

5. From the data set of meteorological stations in and around the Red River Delta, the current land use map, the topographic and soil map, a complex map of Meteorology - Soil - Land Use was built for the Red River Delta region. Each unit of this map contains complete information about climate, soil, and crops, as input data for modeling GHG emissions from crop production;

6. From the spatial analysis and collected input data, GHG emissions were researched and calculated for the cultivation field of the Red River Delta (annual rice and upland crops) using the DNDC model. The model's outputs were used to build thematic maps on the distribution of GHG emissions (CH_4, N_2O, GWP) for each unit of the complex map of climate, soil, and crops.

2. Recommendations

1. Within the framework of the doctoral thesis, GHG emissions were only considered for cultivation areas of annual rice and upland crops in the Red River Delta with different climate and soil conditions. When running the DNDC model, recommend further studies on the influence of farming techniques in tilling the soil, fertilizing, etc., to calculate GHG emissions for the area to have an entirely scientific basis for assessing and proposing solutions to reduce GHG emissions.

2. The process of calibrating and verifying the DNDC model, the research implemented for cultivated rice in the condition of frequent flooding. Therefore, the following studies should pay attention when applying the set of parameters after calibration. It is possible to expand the study further to complete this set of parameters, which will be very useful for the GHG inventory in agricultural production in each ecoregion and country.

3. For annual upland crops, the thesis was only conducted for maize. Recommend the following studies performed with more experiments and more extensive scale for other annual crops.