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〈Original article〉

DeNitrification-DeComposition (DNDC) Improvement through Model Coupling and Sub-model Development Considering Agricultural Land Use and Future Climate Change

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Abstract - Climate change is the biggest concern of the 21st century. Greenhouse gas (GHG) emissions from various sectors are attracting attention as a cause of climate change. The DeNitrification-DeComposition (DNDC) model simulates GHG emissions from cropland. To study future GHG emissions using this simulation model, various factors that could change in future need to be considered. Because most problems are from the agricultural sector, DNDC would be unable to solve the factor-changing problem itself. Hence, it is necessary to link DNDC with separate models that simulate each element. Climate change is predicted to cause a variety of environmental disasters in the future, having a significant impact on the agricultural environment. In the process of human adaptation to environmental change, the distribution and management methods of farmland will also change greatly. In this study, we introduce some drawbacks of DNDC in considering future changes, and present other existing models that can rectify the same. We further propose some combinations with models and development sub-models.

Key words : DNDC model, model coupling, greenhouse gases emission

INTRODUCTION

Climate change is one of the most receiving attention issues in 21th century. The Intergovernmental Panel on Climate Change (IPCC) has stated that climate change is a phenomenon and its impacts on global warming are apparently occurring. A large proportion affecting change in climate is attributed to human activities which are continuing to increase greenhouse gas (GHG) emission (IPCC 2013). Agricultural soils are important source for GHG (CO_2, CH_4, and N_2O) emission and the emission can be directly or indirectly affected by agricultural practices (Giltrap *et al*. 2010). Relationship between agricultural practices and GHG emission can make feedback and more serious global warming problem.

There are various biogeochemical models to simulate GHG emission in unban, forest, cropland, sea and river. Denitrification-Decomposition (DNDC) model is a well-known for simulating GHG emission from cropland. DNDC was originally developed to simulate N_2O emission (Li *et al*. 1992) and has been expanded by many research groups for estimating carbon (C) and nitrogen (N) dynamics in agricultural ecosystem over 20 years (Gilhespy *et al*. 2014). As a process-based model, DNDC is capable to estimate the GHG emission from the soils (Giltrap *et al*. 2008). However, recent version of DNDC has a limit to predicting future GHG emissions. Xu *et al*. (2011) simulated farmland GHGs emission over the next 50 years. The research discussed that for more accurate simulation of future GHGs emission, it is necessary to simulate future changes in farmland distribution, impacts of climate change, and changes in future

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farming practices. When simulating a long-term future, it is imperative to simulate a large number of data that have been filled in through survey data at the present time. Since climate change will affect all other environmental changes, changes and adaptation of the agricultural environment to climate change must be considered. With the climate change, crop distribution and crop management technologies should be changed for new environment (Wang *et al.* 2014). Climate change can also bring huge disasters affecting agricultural area (Schipper and Pelling 2006). For simulating such complicate changes, new sub-model through model coupling can be developed. This research reviews about DNDC and suggests some possible model couplings for improving DNDC to simulate future GHG emissions with future climate event.

HISTORY OF DNDC

1. Appearance and development

DNDC was introduced in 1992 as a model to predict N_2O emissions from agriculture (Li *et al.* 1992). The first version of DNDC has three sub-models which arethermal-hydraulic, denitrification, decomposition, and predicts emission of N_2O, NH_3, CO_2 from agricultural soils. After the first DNDC, the model has been developed and modified to higher version to suit specific research purposes and circumstances. Moreover, the interaction between original and modified DNDC version help to create new version in response to temporal and spatial environment condition. This interaction is one of the strong aspects of DNDC to make it improve constantly. After Wetland-DNDC developed (Zhang *et al.* 2002), For example, DNDC version 8.5 incorporates 'anaerobic balloon' modified with Nernst and Michalis-Menten equation which is first applied in Wetland-DNDC (Li *et al.* 2004). DNDC version 9.5 is the latest version developed in 2013. Fig. 1 shows how DNDC changed during the period.

2. Various modified versions

1) DNDC versions for various types of ecosystem

Even DNDC developed for agricultural land; there are different modified versions for simulating C and N in eco system. PnET-N-DNDC, describing biogeochemical cycling of C- and N-trace gas fluxes, is the first modified version to simulate NO and N_2O emission from forest ecosystems. The model includes a module called 'Anaerobic balloon' during the development process, and the role of 'Anaerobic balloon' is to calculate the ratio of aerobic and anaerobic conditions in the soil (Li *et al.* 2000). PnET-N-DNDC is the root of other modified DNDC version for various ecosystems. Wetland-DNDC, Forest-DNDC and Forest-DNDC-Tropica are also modified from PnET-N-DNDC.

2) DNDC versions specialized in specific areas

Many research groups around world developed their own version of the DNDC for the specific purposes such as utilizing their specific database in relation to different environmental conditions. GRAMP (Global Research Alliance Modeling Platform), a group to develop and manage DNDC, introduces DNDC versions to Unite Kingdom (UK-DNDC), New Zealand (NZ-DNDC), Belgium (BE-DNDC), Europe (DNDC-Europe), Canada (CAN-DNDC) (Gilhespy *et al.* 2014). For example, NZ-DNDC is a modified version of DNDC that includes a number of alterations to reflect the conditions of soil types and crop characteristics found in New Zealand. NZ-DNDC was further modified to simulate the entire interaction among plant, soil, atmosphere, and management in an intensive grazed grassland system (Saggar *et al.* 2007). While, DNDC-CSW is focused on accurate estimation of spring wheat growth and N uptake in Canadian agroecosystem (Kröbel *et al.* 2011).

On the other hand, rice paddy is one of the largest sources of methane (CH_4). Methane generation usually depends on methanogenesis produced by degradation of organic matter under anaerobic condition (Seiler *et al.* 1983). Research of Shirato (2005) concluded that DNDC has high reliability in submerged soil because anaerobic balloon in DNDC could separate anaerobic and aerobic fraction well. Especially, DNDC-rice is more specialized model to calculate CH_4 production in rice paddy soil. Fumoto *et al.* (2008) revised DNDC-rice and evaluated the revised DNDC-rice with the original model to more accurately simulate GHG emission and rice growth. Most different components of DNDC-rice model includes 1) crop growth sub-model coupled with MACROS and 2) calculation of soil redox condition regarding the status of Mn^{2+}, Fe^{2+}, H_2S, and H_2. Even recent version developed after DNDC-rice, those components are

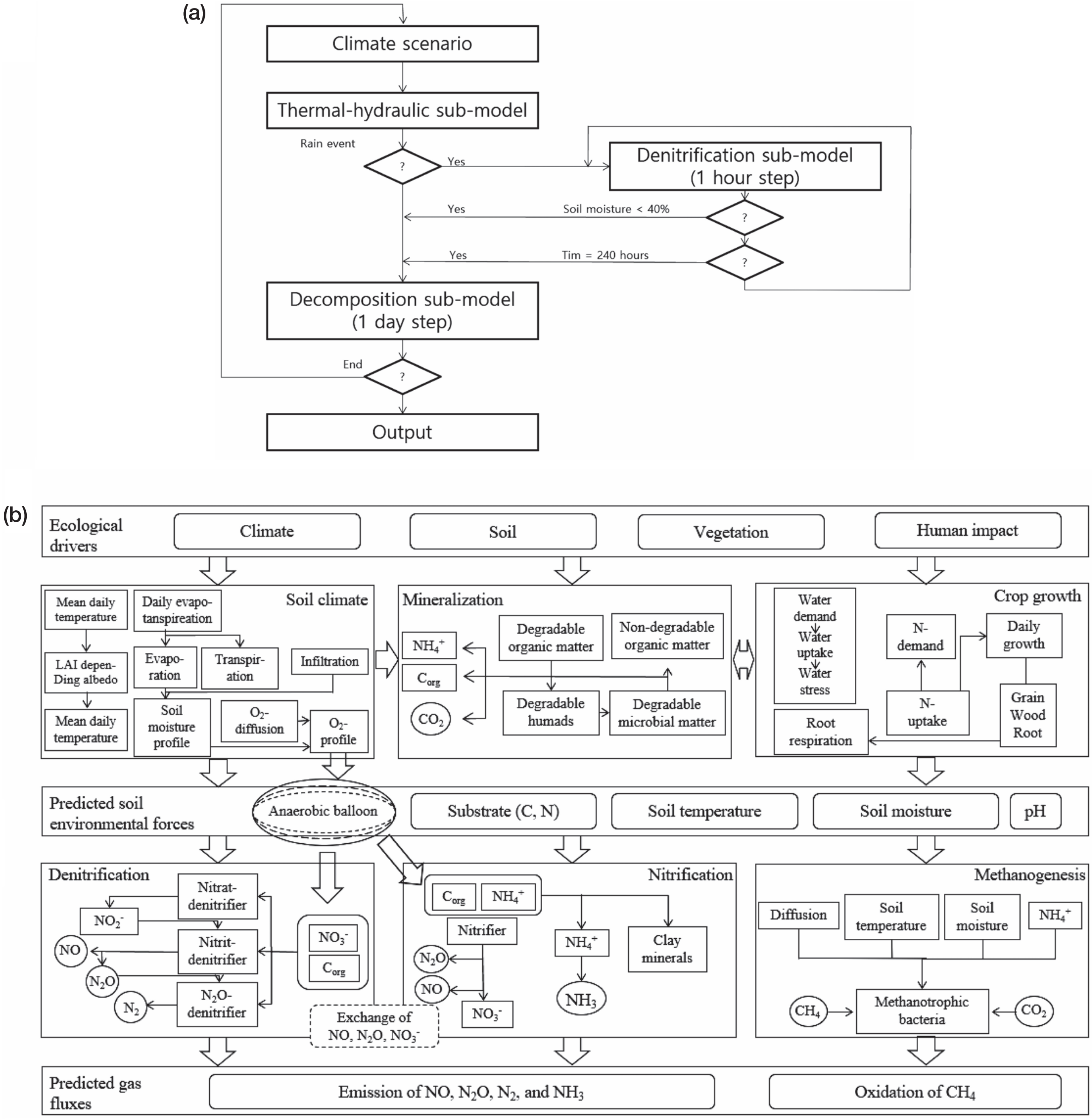

Fig. 1. The structure of DNDC. (a) is an earlier version of DNDC (figure from Li *et al*. 1992) and (b) is the latest version (figure from Li *et al*. 2000).

excluded in further developed version of DNDC.

3) DNDC versions with GIS connection module

Most of researches on estimating climate change and its impact on global warming potential (GWP) has been considered with graphical determination using geophysical information system (GIS). Utilizing GIS requires regional or national scale database as an input data for spatial distribution of DNDC result. Current DNDC model has no connection with GIS program but there are many trials to connect DNDC to GIS program. Butterbach-Bahl *et al*. (2009) modeled NO emission in EU15 states using DNDC. Input files for DNDC is prepared with six data sources as form of GIS data and the result converted to GIS map. EFEM-DNDC, a GIS-coupled economic-ecosystem model, is a coupling of the Economic Farm, Emission Model (EFEM) and DNDC model. The model allows for a realistic simulation of disaggregated soil, production system, and regional GHG emissions from agricultural systems at regional scale (Neufeldt *et al*. 2006). DNDC-MFT is a tool to assist DNDC program and help to gathering EXCEL files of DNDC input data automatically from GIS map in Canada (Smith *et al*. 2010). Most of the combinations of DNDC and GIS are focused on regional approach with own GIS databases. Furthermore, Huber *et al*. (2002) developed more general purposed version, DNDC-GIS which includes modules to use data expressed in ArcMap as DNDC input data and convert the result of modeling to ArcMap data.

SUB-MODELS

1. Denitrification and nitrification

In the original DNDC model, denitrification sub-model starts after rainfall event when relative soil moisture reached at or below 40%. Growth and death rates of denitrifier are main components to calculate denitrification for each step. Initial concentration of NO_3^- can adopte from decomposition sub-model. Nitrification sub-model in the DNDC is small part of decomposition sub-model (Li *et al*. 1992). Next DNDC version incorporates some concepts from PnET-N-DNDC (Li *et al*. 2000). The nitrification sub-model was separated from the decomposition sub-model and became its own sub-model. Activation rates of denitrification and nitrification are determined by the calculating result from ‘Anaerobic balloon’. ‘Anaerobic balloon’ defines volume ratio of anaerobic microsites in the soil in response to soil redox potential with Nernst equation. Denitrification starts in anaerobic sites and the ratio of anaerobic sites in the soil is calculated by ‘Anaerobic balloon’ and nitrification activates in aerobic sites which is considered as remain area except anaerobic sites. Before developing of Wetland-DNDC, anaerobic sites are assumed as sites only for reduction. In the real world, even the site is anaerobic, slight level of oxidation can be happened. The concept of Wetland-DNDC combines Michaelis-Menten equation in ‘Anaerobic balloon’ to estimate reduction in aerobic microsites (Li *et al*. 2004).

2. Decomposition

Decomposition sub-model includes decomposition and other oxidation reactions such as nitrification which are the dominant microbial processes when soil is in an aerobic state. Assimilation of inorganic carbon (C) and nitrogen (N) into microbial biomass also occurs simultaneously with decomposition of residues, microbial biomass and humads (materials partially stabilized by humification and adsorption) (McGill *et al*. 1981). Organic C, soluble C, ammonium, and nitrate through decomposition and assimilation are produced and may accumulate. The rates of these substrates depend on the balance between the rates of mineralization, assimilation, and loss (plant uptake, sorption, or volatilization). Decomposition sub-model includes mathematical equations which simulate C pool decomposition rate, biomass production and CO_2 evolution during residue decomposition, ammonium adsorption, transformation of ammonia to ammonium, ammonia volatilization, nitrification rate, and N_2O emission during nitrification (Li *et al*. 1992). For expanding DNDC to simulation of plant growth in response to water and N stress, plant growth sub-model was developed to updated DNDC model (Li *et al*. 1994) and modified nitrification sub-model was detached from decomposition sub-model (Li *et al*. 2000) (Fig. 1).

3. Fermentation

Methane is an end product of the biological reduction of carbon dioxide (CO_2) or organic C under anaerobic soil condition. Methane fluxes were strongly controlled by soil available C (i.e. dissolved organic carbon, DOC) content. The reduction of available C to CH_4 is mediated by anaerobic microbes (e.g. methanogens) that are only active when soil redox potential (soil Eh) is low enough (Sass *et al*. 1991; Wassmann *et al*. 1993). Methane production increased exponentially with decreasing Eh ranged from -150 to -200 mV. And also, CH_4 production increased with increasing temperature (Masscheleyn *et al*. 1993; Wang *et al*. 1993; Kludze and DeLaune 1995). With the scientific observations, DNDC involves fermentation sub-model to calculate CH_4

production rate as a function of DOC content and temperature as the predicted soil Eh reaches −150 mV or lower. Meanwhile, CH_4 is oxidized by aerobic methanotrophs in the soil. DNDC calculates CH_4 oxidation rate as a function of soil CH_4 concentration and Eh. Methane produced at low soil Eh could diffuse into high Eh microsites such the topsoil or the soil around roots, and hence be oxidized rapidly under higher Eh conditions. Fermentation sub-model employed in DNDC simulates CO_2 and CH_4 emission between soil layers on the basis of CO_2 and DOC concentration, soil Eh, temperature, and porosity in the soil (Li 2000). DNDC model added a concept called "anaerobic balloon" to simulate C and N behaviors using Michaelis-Menten and Nernst equations which indicate microbial growth and soil oxidation-reduction status, respectively (Li *et al.* 2004). Moreover, DNDC advanced fermentation sub-model in recent version considering soil Eh, pH, and microbial activities on more accurately modelling CH_4 production (Li *et al.* 2012a).

4. Plant growth

The original DNDC model estimated plant growth using an empirical plant growth data and its interaction with soil biogeochemical processes (Li 1992). Zhang *et al.* (2002) developed plant growth sub-model named 'Crop-DNDC' and they considered: 1) the dynamics of crop growth and its response to climatic conditions and farming practices, 2) interaction of crop growth with soil biogeochemical processes, and 3) the overall behavior of the model in simulating crop yield and trace gas emissions responding to climate condition and management practices. In the plant growth sub-model, the major variables include pheonlogical development, leaf area index (LAI), biomass and N content of crop organs. The sub-model also calculates C assimilation through photosynthesis in response to water and N demand. The actual N uptake also depends on the availability of mineral N in soil. Phenological stages and stress factors (water and N) determines C allocation and N demand for estimating yields of grain, leaf, stem, and root. Recent version of DNDC (V. 9.5) can simulate 62 plant species with default values of plant characteristics which can be modified by the actual data.

5. Soil climate

Thermal-hydraulic model is one of sub-models in DNDC for simulating soil climate. The sub-model calculates soil heat flux and moisture flow in the soil profiles. Horizontal and vertical heat fluxes and water flows are determined by the gradients of soil water potential and soil temperature, which are based on rainfall and irrigation event and air temperature, respectively. Water flow out of the bottom of the modelled profile is driven by gravity drainage. Heat flux into or out of the bottom layer is determined by the gradient between the bottom layer temperature and the annual mean air temperature imposed. DNDC characterizes soil physical properties by 12 soil textures. Soil water content and type of soil (mineral or organic) determines soil thermal conductivity. And also, it includes strong functions of soil water tension and unsaturated hydraulic conductivity. In DNDC, soil climate sub-model is main drive to influencing other sub-models (Li *et al.* 1992; Li *et al.* 2006).

FUTURE MODELING WITH CLIMATE CHANGE SCENARIO

1. Necessary of model couplings

Simulating GHG emission from short term or long term periods is important for evaluating global warming potential (GWP) and its impact on future climate change. Two biogeophysical models, CH4MOD and $\text{CH4MOD}_{\text{wetland}}$, developed by Li *et al.* (2012b) simulated regional CH_4 emission during 1950 to 2100 conducted for a rice paddy and natural wetlands in Northeast China. In order to predict the impact of climate change on CH_4 emission in the future, they assumed new scenarios referred as "Representative Concentration Pathways (RCPs)" for the fifth IPCC assessment report (AR5) (Moss *et al.* 2008). Abdalla *et al.* (2011) modeled CO_2 gas flux in Irish agriculture during 2061 and 2090 using DNDC model. Two climate scenarios are designed with high and low temperature sensitivity. Currently, many research groups pay more attention to future climate change using modelling approach. Because climate change will give us huge impact on social and environmental problems. Li *et al.* (2012a) suggests new sub-model to predict economic analysis in coupling with current DNDC model. For DNDC improvement, developing new sub-models and make connection with other models are necessary. Conceptual image for future scenario is described in Fig. 2. Detail proposals to realize Fig. 2 will be discussed in next chapter.

2. Land use change

Climate change affects crop yield and will require suitable cropland and appropriate agricultural management practice (Olesen and Bindi 2002). Most of farmers may alternate cropping system or use the land to other purpose due to unexpected impact of climate change. Many researchers expect that cropland in future will be response to climate change although current cropping system has been adapted in the area. Thus, our review pointed out appropriate crop cultivation area and considered social aspects using scenario analysis. According to the results of Ramirez-Villegas *et al*. (2011), alternate crop suitability was determined in relation to rainfall event and temperature throughout Ecocrop model simulation, and the model evaluated optimum conditions, marginal conditions or not suitable conditions for each crops. On the other hand, if social aspect is not considered, the area of suitable crop cultivation will be followed by land use change. However, there is limitation for proper crop cultivation. For example, urbanization reduces crop production and forest area is not suitable for crop growing. Veldkamp and Lambin (2001) researched that what is necessary for land use and land cover change model. The first stage of the model focused on only biophysical attribute except socio-economic drivers. InVEST is one of the models to consider social aspects and the model suggests the best land use for human well-being (Tallis and Polasky 2009). For DNDC model, we suggested a land cover changes sub-model to be coupled and linking to plant growth sub-model. Even the best scenario is not always applied; DNDC can predict better result as detailed input parameter is applicable for scenario analysis. The biggest problem to couple land cover model into DNDC model is the case of expending cropland. If cropland is available for crop cultivation, change in soil properties of possible cropland (include the site which not to be crop land yet) can be simulated by DNDC. The structure change to considering cropland expending is described in Fig. 3.

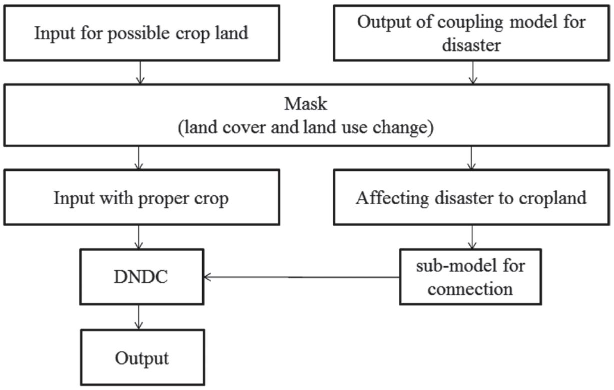

Fig. 2. Suggested model coupling for land cover change, land use change and future disasters.

3. Change in farming management practice

Agricultural activities such as tillage, fertilization, and ir-

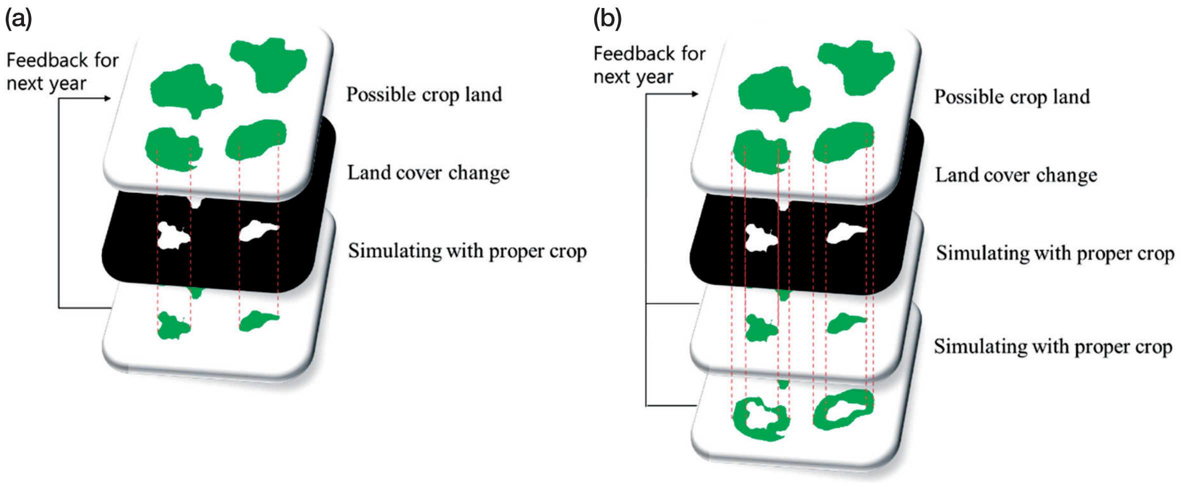

Fig. 3. Incorporating land cover change to DNDC. (a) is the scenario when crop land is not expending to the site with another purpose. (b) is the scenario where crop land can expend to the site with another purpose.

rigation have differentiated the effect on changing environmental condition between natural ecosystem and agroecosystem. For simulation of future climate change using DNDC model, we modified input parameters of farming management practices with the survey data in South Korea. The model result predicted that the different input parameters led to strong effect on GHGs emission (Wang *et al*. 2008). Wang *et al*. (2008) run DNDC with different quantity of fertilizer, manure and residue. These various source and rate of nutrient showed statistical effects on the quantities of soil organic matter content, which is the main source of CO_2 and CH_4 emission. Application of nutrients into cropland led to increase GHG emission, as compared to inherent soil. Previous research on simulating the effects of long-term discontinuous and continuous fertilization on crop yields and soil organic carbon (SOC) dynamics using the DNDC model indicated that generally the model showed good performance in simulating crop yields and SOC contents (Zhang *et al*. 2017). However, they suggested that the model results required further analysis and model improvement because the model cannot simulate the buffering process of crop yields in the first years without fertilizer in each test cycle. Though DNDC model focuses on soil biogeochemical reactions such decomposition and denitrification, the most important factor performing crop yield is to adjust crop parameters. Therefore, for predicting future crop production and GHG emission using the DNDC, detailed input parameters of farming management practice and crop characteristic should be considered to maximize model performance. Moreover, the DNDC needs to improve for estimating unexpected impact on crop production and climate change throughout model coupling with a model that can simulate best management for future condition.

4. Disasters

1) Pest occurrence

Climate change can evoke various disasters. Pest occurrence is one of the phenomenons caused by climate change ant it damages to sustainability of crop production. As well known, crop damage by climate change is usually higher than by other biological damages such as disease and weed (Rosenzweig *et al*. 2001). Aggarwal *et al*. (2006) pointed out that most of crop growth models including DNDC model do not consider pest damage to plant growth. InfoCrop, a model of crop growth in simulating pest impact on crop yield, has been utilized (Aggarwal *et al*. 2006). In recent research on improving crop growth model, there are many efforts to incorporate pest management model to crop growth model. Pinnschmidt *et al*. (1995) modified a model in incorporation of pest management to crop growth model for evaluating pest damage in various ways, empirical, regression and simple model. However, incorporating pest management to crop growth sub-model is insufficient for future climate change scenario. Modeling pest damage is based on pest type and population in the certain area or region. Changes in population and distribution of pest should be estimated toward future scenario analysis (Thomson *et al*. 2010). Climex is a model for distribution and population growth of specific species with environmental changes that are based on phenological species parameter and climate. The Climex model is used for estimating impact of climate change on plant, pathogen, and pest distribution (Sutherst *et al*. 2000; Shawa and Osborneb 2011; Shabani *et al*. 2012). Mexent is another simple model for easily simulating species distribution with logistic regression (Phillips and Dudik 2008). We considered that if the DNDC model linked to the Climex model, more applicable model will provide reliable data of crop production in response to pest species and population when new sub-model improved through linking the DNDC with the Climex model. In the case of Mexent, species of pest and sub-model for pest growth is necessary to simulate intersection between cropland and pest habitat Connection with Climex can be considered more convenient but pest growth also need to be considered in regarding with plant growth. After we find pest distribution and impact of the pest with model connection, with plant growth sub-model can give more detail result.

2) Flood

The DNDC model can simulate water dynamics (e.g. run-off, leaching, and evapotranspiration) which are conducted with rainfall and irrigation events. Run-off and flooded soil generally caused by heavy rainfall event influences sustainability of crop production and environmental loading. Vidal and Wade (2008) modeled precipitation and flooding risk with climate change and the results concluded that climate change increased amount of precipitation and flooding risk.

Flooding cannot be modeled with precipitation of target site. Precipitation around target site, catchment and topography are necessary. There are many researches to model the flooding and run off around catchment after climate change. Dankers and Feyen (2008) simulated flooding risk in Europe with LISFLOOD model. Lane *et al*. (2007) evaluated not only model risk of flooding but also model sediment delivery and channel change. The model can help to estimate flooding damage and land cover change. Nevertheless, the DNDC can simulate the damage of high water contents, it cannot estimate the effect of heavy rain and physical damage of flooding. For coupling the DNDC with mentioned flooding models, a sub-model for simulating flooding damage must be imperative to develop. Most of water flooding model's output is created from the data on seasonal and risk of flood. For daily simulation of DNDC, therefore, models may have to be precisely obtained from daily result.

5. Connection with GIS program

As mentioned above (see 2.2.3.) GIS connection is necessary for large-scale modeling and many modified versions of DNDC make a tool to connect DNDC and GIS program. Especially, suggested models coupling for future scenario analysis are focusing on the factors that happen out of the cropland and give the impact to the cropland. For such a modeling, geographic position should be considered. DNDC is not yet connected with GIS program but it is essential to conducting model with GIS connection.

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