ISBN 978-93-84422-85-1
11th International Conference on Chemical, Agricultural, Biological and Environmental Sciences (CABES-2018)
April 17-18, 2018 Kyoto (Japan)

Simulating CO_2 Emissions from Tropical Forest Soils by Denitrification-Nitrification Decomposition (DNDC) Model

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Abstract: *Model is useful in the estimation of greenhouse gas emissions and improving our understanding of their variations in response to environmental variables. This study tries to simulate CO_2 emissions from forest soil respiration using a process-based biogeochemical DNDC model. The studied forest was a secondary dry dipterocarp forest in Ratchaburi, western Thailand. In this forest ecosystem, the annual soil respiration was 4.1 $kgCO_2/m^2/yr$. Soil respiration highly varied on the seasonal timescale, being higher during the wet and lower than the annual average during the dry season. DNDC model was able to reproduce soil respiration reasonably well (within 5% of annual estimate). It can capture the temporal variations throughout the year. However, when DNDC was input with some site-specific parameters, the difference between observed and modeled values became larger. This discrepancy was discussed with respect to the unique characteristics of this forest when compared to the natural-grown tropical forests.*

Keywords: *Soil respiration, secondary dry dipterocarp forest, DNDC model.*

1. Introduction

Greenhouse gas emissions have become the important issues due to their impacts on global warming and climate change. Since the beginning of industrial revolution, the atmospheric concentration greenhouse gases, mainly CO_2, CH_4 and N_2O, have been increasing significantly [1]. As a consequence, the average global temperature has increased by 0.85ºC since that time [1]. Atmospheric CO_2 is expected to increase further in the coming decades due to emissions from fossil consumption and land use change. Therefore, further warming is also expected. Accompanying with warming is its effects on ecosystem and human well-being.

Forest ecosystems are important as good and services providers to human and other ecosystems. Forest is also the most important sink of atmospheric CO_2. Any changes of forest well beings, therefore, will affect various components of earth system *en route* from primary producers to consumers of various levels, and from site-specific scale of physics and biogeochemical changes to global-scale changes. One of the current concerns foreseen to affect good and services of the forest ecosystem is the impacts of climate change [2]. This can have the effects on forest ecosystem in various ways, for example, species extinction (plant and wildlife), changes of growth and productivity of forest, changes of forest type and distribution, and forest fire [3]. Studies in the past have indicated that there will be likely changes in forest type and distribution in Thailand following changes in rainfall amount and distribution driven by global warming [4]-[6].

The entry point to examine whether forest ecosystem is adversely or beneficially impacted by short and long term climate variability/change is the measurements of carbon exchange between forest and the atmosphere. Regarding this, one could measure the carbon exchange above canopy or at forest soil surface. Above canopy measurements give the overall picture of the whole ecosystem carbon dynamics. However, such measurements

https://doi.org/10.17758/IICBE1.C0418131

are involved with high cost, specific instrumentation and protocols, and large forest areas are required. On the other hand, studying CO_2 emission from forest soil surface can be carried out with relatively low cost, while some research questions relating to the impacts and response of forest to environmental changes can also be addressed.

In the current study, the interest is the emissions of CO_2 from soil respiration. CO_2 flux through this process is one of the largest in global carbon cycle. Generally, the carbon cycle in the forest initiates when carbon is fixed via photosynthesis. Some of the fixed organic carbon compounds are used to grow tissues. Some are broken down to supply the plants with energy. During this process, carbon is released to the atmosphere from ecosystem respiration (Re), disturbance and herbivory. In forest ecosystems, CO_2 is produced from aboveground (Ra) and belowground (Rs) activity by respiration process which can be represented as; Re = Ra + Rs, where, (Ra) is the combined CO_2 emission from leaf respiration (RL), and live woody respiration (Rw) and (Rs) is defined as the production of CO_2 by soil organisms (Rm) and the plant parts in soil (Rb). Therefore, the CO_2 flux rate measured at the ecosystem respiration (Re) is the sum of plant respiration (autotrophic respiration) and microbial respiration from litter and soil organic matter decomposition (heterotrophic respiration); Re = (RL + Rw) + (Rb + Rm).

In dry dipterocarp forest in western Thailand, Rs contributes about 80% of Re [7]. Soil respiration is therefore the crucial component of forest CO_2 exchange with the atmosphere. It is important in determining forest sink or source capacity, and will react actively to climate change and variability. Understanding ecosystem respiration, thus, is one of the key areas to advance our knowledge of carbon cycle and to evaluate the impacts of climate change to forest ecosystem.

Modeling is an effective tool in the estimation of greenhouse gas emissions and improving understanding of their variations in response to environmental variables. It also allows for the evaluation of the effectiveness of mitigation measures which are relevant to decision making. Due to the high temporal and spatial variations in GHG emission, it is impractical to estimate emissions by relying on only observation. Simulation models are effective supplementary tools which extend quantitative calculations beyond limited observations in time and space. Moreover, models can provide insight into mechanisms and basic processes governing the emissions, scenario analysis and decision supports for policymakers.

Comprehensive modeling techniques of the greenhouse gas emissions from the agro-forest ecosystems have been widely developed since 1970s [8]. The development of process oriented, biogeochemical models has provided a tool for researchers to pursue the aim of soil respiration and its component simulations. Most of these models are capable of simulating both plant and soil respiration processes based on plant type-specific physiological and phenology parameters. Soil respiratory processes, including both root autotrophic and microbial heterotrophic respiration, have been explicitly incorporated into the framework of these models [8]. Forest-DNDC is one of the models that has been developed for C biogeochemical cycling studies [9]-[10]. As a process-based model, Forest-DNDC simulates forest production, soil C sequestration and trace gas (CO_2, NO, N_2O, and CH_4) emissions from upland or wetland forest ecosystems. Accordingly, the objective of the current study is to simulate CO_2 emissions from forest soil respiration using DNDC model, thereby improving our understanding of how soil respiration responds to climate variability, and serving as the basis for climate change impacts evaluation on carbon dynamics of Thai forest ecosystems.

2. Materials and Methods

2.1 Soil Respiration Dataset and Measurements

Datasets on soil respiration with necessary input parameters was obtained from the previous field measurement as reported by Hanpatanakit et al. [7]. Soil respiration was continuously measured by a closed-automated chamber for four years during February 2008 – December, 2011. The measuring system was consisted of a set of automatic flux chamber and a central control and data storage unit (Liang et al., 2004). The chamber had two parts; the cover and base. The cover was made of acrylic of 0.3 m width × 0.3 m length × 0.3

m height and the base was made of stainless steel with dimension of 0.3 m width × 0.3 m length × 0.15 m height. The base was permanently inserted into the soil where gas sampling was conducted. To monitor the net CO_2 exchange through soil respiration and to prevent any possible carbon uptake by the vegetation, an opaque lid was installed over the unvegetated enclosed areas. The chambers were closed and opened by a pneumatic system which was controlled by a program on the data logger (CR10x, Campbell Scientific, Logan, UT, USA) and a two-way solenoid valve. At any given time, CR10x commanded the two-way solenoid valve to close the chamber lid, and another one way solenoid valve was set open. Then, an air sample inside the chamber was pumped (1.0 L min-1) into the measurement unit where the CO_2 concentration was determined by infrared gas analyzer (Licor-820, Licor Corporation, Lincoln, Nebraska, USA). The data generated were stored in the data logger and downloaded manually. After the analysis of CO_2 concentration, the air sample was channeled back to the chamber through a one-way solenoid valve. One sampling cycle took about 7 min. In the present study, root respiration and microbial respiration were measured hourly. There were three replications for each of root and soil respiration measurement. During the course of measurements, CO_2 in ambient air was also measured hourly. The system was calibrated with standard CO_2 gas regularly (monthly). In addition to these measurements, soil and air temperatures and soil water content were continuously measured inside and outside in trench plots. Soil temperature was measured at a depth of 0.05 m with two averaging soil thermocouple probes (TCAC, Campbell Scientific, Inc. Logan, Utah, USA). Soil water content was measured at 0.05 m depth with two water content reflectometers (CS615, Campbell Scientific, Inc., Logan, Utah, USA).Water filled pore space (%WFPS) was calculated from the volumetric water content measured by CS-615 as indicated in equation 1. SWC is the volumetric soil water content, BD is the bulk density(1.42 g/cm3) and PD is the particle density (2.68 g/cm3); %WFPS = [(SWC/BD)/(1-(BD/PD))]

2.2 Simulating Soil respiration by DNDC model

DNDC model with the user manual can be free-downloaded from the model website (www.dndc.sr.unh.edu). Forest-DNDC was developed by integrating an upland forest model, PnET-N-DNDC [11]-[12], with a hydrology-driven model, Wetlands-DNDC [13]. The input information required for the model simulation include parameters such as the daily maximum and minimum air temperature, precipitation, humus layer type, litter layer and mineral soil pH, stone content, texture, organic matter content, forest age and type. The structure of DNDC model is given in Fig. 2. Forest-DNDC has been shown to simulate several different types of carbon fluxes, including photosynthesis, growth and maintenance respiration of the canopy, woody parts and roots, and soil microbial respiration at a daily time step (Li et al., 1992, 2000). Forest-DNDC has been widely utilized for carbon sequestration and trace gas studies in different forest types, such as pine, oak, spruce, beech, spruce and eucalyptus [14]-[15]. Forest-DNDC provides default values for a number of soil hydraulic or forest physiological parameters, which are subject to modification or redefining by the users. Daily weather data are required to drive Forest-DNDC for simulations. The daily air temperature and precipitation data are available together with soil respiration dataset. These have been also continuously recorded at dry dipterocarp forest site in Ratchburi.

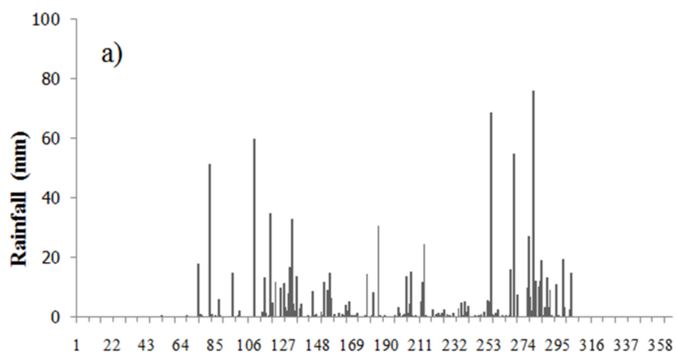
3. Results and Discussion

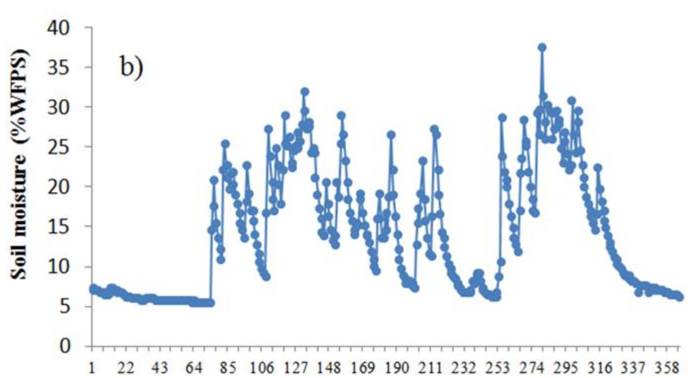
3.1 Observed Meteorological Parameters

In this study, rainfall, soil moisture and soil temperature were recorded (Fig. 1). Maximum and minimum temperatures were observed in April and January, respectively. Monthly mean air temperature varied between 21 to 33 °C in the dry season and 24 to 31 °C in the wet season. A general pattern of rainfall at the site is as followed; dry period between November-April when monthly precipitation was usually below 100 mm and the rest of the time is a wet season with monthly precipitation exceeding 100 mm. During the dry period, most trees shaded their leaves and at the end of the season no leave usually remains on the tree. Within the wet season a rain break when precipitation amount decreases to below 100 mm usually occurs during July-August every year. The total precipitation amounts 1022 mm/y in 2011. The pattern of soil water content (SWC) in general changed in corresponding to the precipitation. During the dry months (November-April) SWC decreased to below 5-7 %WFPS, while during the rest of the year it stayed above 10 %WFPS.

3.2 Soil CO_2 Observation Results

Variations in soil respiration were observed both within a day and longer timescales. It was found that in general within a day soil respiration (Rs) ranged between 150-450 mg $CO_2/m^2/h$, and450-1000 mg $CO_2/m^2/h$ for dry and wet seasons, respectively (Fig. 2). The average soil respiration rate for this year was 473±217 $CO_2/m^2/h$, equivalent to 4.1 $kgCO_2/m^2/yr$. About 80% of annual soil respiration occurred during the wet season, indicating the soil moisture is an important controlling factor as found in other studies [16-18]. Regression analysis indicates that both soil temperature and soil moisture affect soil respiration. Positive exponential correlations between soil temperature and Rs were found for the soil temperature ranges of 20-27˚C (Fig. 3). Beyond this temperature range a negative relationship was found, indicating the temperature 20-27˚C is optimal for soil respiration in this ecosystem. For soil moisture, soil respiration increase up to about 20-25 %WFPS and then decreased when the soil moisture increased beyond this range (Fig. 4). It was found that during the dry months soil respiration remained relatively constant. Once rain comes and soil moisture increases, soil respiration becomes active. This well-known effect is a result of the stimulation of biological activity in the soil [18]. The substrate availability is also important to microbial activity. In this dry dipterocarp forest, litter fall occurs starting at the wet season and finishes by the end of February-March [19]. There is therefore about one or two months that this forest is mostly without leaves and forest floor is directly exposed to sunlight, driving up soil temperature. However, litter decomposition starts only when soil moisture increases to certain levels. Hanpattanakit and Chidthaisong [19] studied the litter decomposition in this forest and found that rapid decline in leaf residual weights were noticed from the beginning of wet season. This agrees with the increase in microbial biomass during the same period. The means microbial biomass during wet season was about four times higher than in dry season ($p< 0.05$).





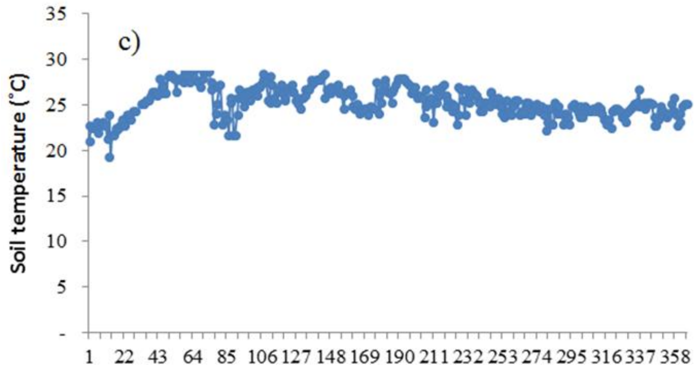


Fig. 1: Meteorological conditions Affecting Soil respiration at DFR site; a) Rainfall, b) Soil moisture and c) Soil temperature

3.3 DNDC Simulation Results

Forest-DNDC simulates forest production, soil C sequestration and trace gas (CO_2, NO, N_2O, and CH_4) emissions from upland or wetland forest ecosystems [20]. In this study, simulation was carried out and reported only for the soil CO_2 emission through soil respiration, as currently only these are available to check the model performance. To do so, however, all input parameters required for simulating forest production are needed. The key input information required for model simulation include the daily maximum and minimum air temperature, precipitation, humus layer type, litter layer and mineral soil pH, stone content, texture, organic matter content, forest age and type. Some of these input parameters were obtained from in situ measurements at the sites. However, many of these values were not available, especially for the forest parameters such as coefficients for photosynthesis and wood maintenance respiration as a fraction of gross photosynthesis. Forest-DNDC provides default values for a number of soil hydraulic or forest physiological parameters, which are subject to modification or redefining by the users. In this study, the forest type “rain forest” was adopted, with modified physiology and phenology parameters based on observed data or literature reviews. In the case there was no input parameter available, the model default values (rain forest) were used. This may cause the inconsistencies between the observed and simulated values and thus some key parameters need to be collected when possible.

The spin-up run, which is a repetitive simulation using the same inputs and parameters over many years was first performed to determine when a steady state in the C pools is reached. Initial C inputs for spin-up runs were based on the model default of rain forest and measured soil properties at the site. In the spinning up run, model simulation starts with relatively high photosynthesis, soil respiration and net ecosystem exchange. This trend continues for about 5-7 years, and then steadily increases. The small changes in these parameters, indicating the steady state, were found after a model run after 80 years. In this study, thus the initial parameters at 80 years were used.

In general, model could reproduce the timing and other temporal variations of soil moisture reasonably well (Fig. 5). The agreement between observed and modeled soil moisture is statistically significant at $p<0.01$. Since soil respiration is mainly controlled by soil moisture as mentioned above, the ability to reproduce this environmental driver is an important requirement for modeling soil respiration in this ecosystem. It is concluded here that the input parameters that affect soil moisture (climate, soil characteristics and properties) are reliable.

Fig. 6 plots the observed and modeled soil respiration. DNDC-rainforest can capture the temporal variations of soil respiration at the DFR site quite well (correlation coefficient (r) = 0.55). As mentioned above, the total soil respiration measured at the site was 4.1 $kgCO_2/m^2$/ yr. The simulation by DNDC model yielded the result of 3.9 $kgCO_2/m^2$/y, or about 5% lower. It is noted, however, that model starts with relatively higher soil emissions during the dry period (day 1-79). Model also gives higher CO_2 emission peaks between days 79-131, while lower than the observed values during day 131-284. During the last stage of day 248-313, there is a good agreement in terms of magnitude and timing of CO_2 emissions.

From the measurement results and simulations mentioned above, it can be said that generally DNDC can capture the temporal variations of soil respiration in this forest ecosystem reasonably well. This in part can be explained by the ability of model to simulate well the temporal variations of soil moisture (Fig. 5). The mismatch between observation and simulation was on the magnitude of soil respiration. Although model could estimate soil respiration well when model default parameters of rainforest were used, but when the input parameters were adjusted for the site-specific parameter, large difference in soil respiration was resulted. Since the difference of input was only on forest parameters, these findings could be interpreted as follows.

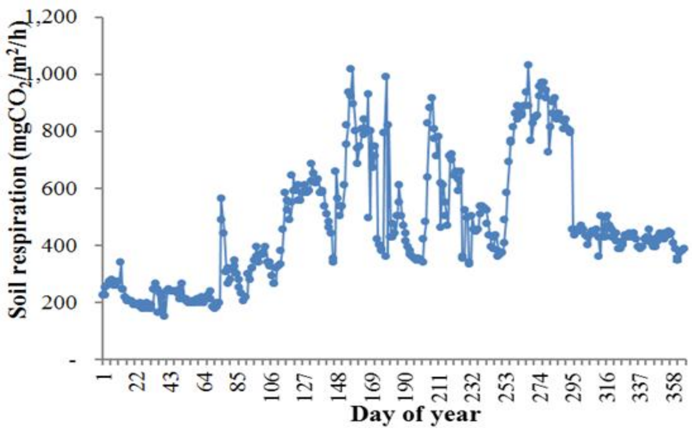


Fig. 2: Observed Soil Respiration at DRF site

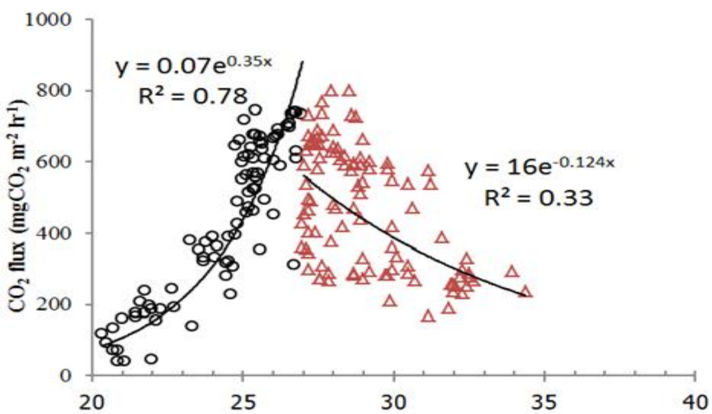


Fig. 3: Relationship between Soil Respiration and Soil Temperature

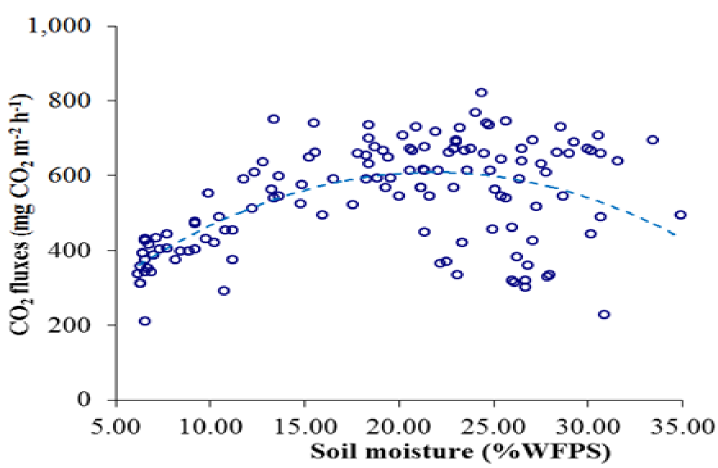


Fig. 4: Relationship between Soil Respiration and Soil Moisture

Forest-DNDC model is designed for natural grown forest with respects to soil, climate and forest type-related parameters. Thus, a theological growth dynamics of forest is followed in the model, based on the interactions among environmental drivers and soil fertility conditions. However, the forest in this study is a secondary forest that has been disturbed continuously for many years. Since there is no record available for how old the forest is, it is therefore difficult to simulate its growth, biomass and soil respiration. This forest is deciduous forest with distinct leave biomass between wet and dry season, and different from a general rainforest as indicated in the model default. Thus, many key parameters such as initial biomass, photosynthesis coefficients and forest dynamics (such as budding, maturity and senescence) may be different. This DFR forest has been allowed to regrow since around 2005 (6 years prior to soil respiration measurements started). While the above ground biomass has been repeatedly removed by villagers (for charcoal production), its roots remain intact. Thus the ratios of aboveground to belowground biomass are more than 1 [7], which is not common for tropical forest ecosystem. Simulation for such specific case by using a general forest DNDC model may not suitable. Specific information for all input parameters is therefore needed. Thus the dynamics of soil respiration was well captured by model, due to the ability of forest-DNDC model to soil moisture as soil moisture is the key parameters controlling the temporal variations of soil respirations. However, from the results it seems that the magnitude of soil respiration is controlled mainly by plant activities, as the forest-plant input parameters significantly affect to the annual emission of CO_2 from soils. To improve simulation results, to estimate soil respiration in other forest or in the future, and to investigate the response of forest soil respiration, relevant information of forest parameters are needed.

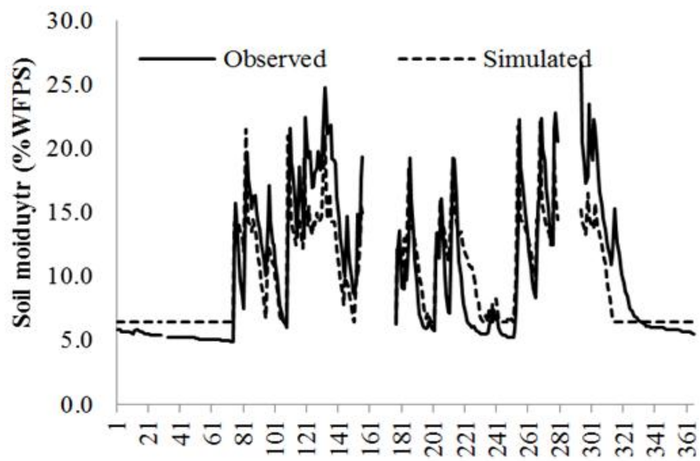


Fig. 5: Results of Soil Moisture Simulation by DNDC

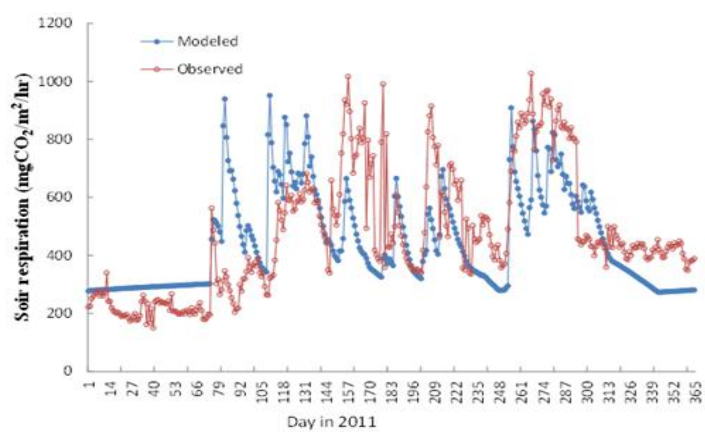


Fig. 6: Simulation results of Soil respiration

4. Conclusion

This study tries to simulate soil respiration in a secondary dry dipterocarp forest in Ratchaburi, western Thailand by a biogeochemical-process based DNDC model. The simulation was verified against the measurement of soil respiration at the same site. In this forest ecosystem, the annual soil respiration was 4.1 $kgCO_2/m^2/y$. Soil respiration highly varied on the seasonal timescale, being higher during the wet and lower during the dry season. This indicates that climate and plant growth parameters have the profound effects on soil respirations. DNDC can simulate soil respiration at the site very well. This reproducibility is the important first step since soil moisture is the key factor controlling soil respiration at the site. When running the model using the default input parameters of rain forest available from the model database, DNDC model was able to reproduce soil respiration reasonable well (within 5% of annual estimate). It also captures very well the temporal variations of soil respiration throughout the year. However, when DNDC was inputs with some site-specific parameters, the difference between observed and model soil respiration became significantly large. This discrepancy was discussed and may arise from the unique characteristics of this forest (secondary-disturbance forest with distinct biomass dynamics and amount, and etc.) when compared to the natural-grown tropical forests. It is suggested that model evaluation in mode details and collection of forest input parameters are needed to improve model performance.

5. Acknowledgements

This study is supported by grant from S&T Postgraduate Education and Research Development Office (PERDO).

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