Chapter 5
Patterns of CO_2 Emission from a Drained Peatland in Kampar Peninsula, Riau Province, Indonesia

Satyanto Krido Saptomo, Budi Indra Setiawan, Yudi Chadirin, Kazutoshi Osawa, Toshihide Nagano, Kosuke Mizuno, Dian Novarina, Susilo Sudarman, and Aulia Aruan

Abstract It was crucial to acquire soil CO_2 flux data from a bare peatland site in Kampar Peninsula, Riau Province, Indonesia so as to evaluate the carbon budget of the site in which water is managed, drained, and utilized for acacia plantation. CO_2 flux was continuously measured from July 2012 to February 2013 using an automatic soil CO_2 flux measurement system. In this study, the factors affecting carbon emission were analyzed and tested for indirect CO_2 flux estimation, and the results showed that CO_2 flux varied with weather, water, and soil-related variables, and where there was rainfall, soil temperature and soil moisture both played an important role. CO_2 flux was modeled using an artificial neural network (ANN) approach with inputs of soil moisture, temperature, and electrical conductivity (EC) as proxy variables. Based on the measurements, the total carbon dioxide (CO_2) emission during the measurement period from July 2012 to June 2013 was 52.25 t ha^{-1}. Total CO_2 emission in 2012 was estimated as 54.86 t ha^{-1} using the ANN model.

S. K. Saptomo (✉) · B. I. Setiawan · Y. Chadirin
Department of Civil and Environmental Engineering, IPB University, Bogor, Indonesia
e-mail: saptomo@apps.ipb.ac.id

K. Osawa
Utsunomiya University, Utsunomiya, Tochigi, Japan

T. Nagano
Takasaki University of Health and Welfare, Takasaki, Gunma, Japan

K. Mizuno
School of Environmental Science, University of Indonesia, Jakarta, Indonesia

Center for Southeast Asian Studies, Kyoto University, Kyoto, Japan

D. Novarina
Asia Pacific Resources International Limited, Jakarta Pusat, Indonesia

S. Sudarman
PT Riau Andalan Pulp and Paper, Pelalawan, Riau, Indonesia

A. Aruan
Alastair Fraser Forestry Foundation, Jakarta, Indonesia

Furthermore, the results generated by the model showed that levels of CO_2 flux declined as the temperature decreased, and soil moisture increased toward soil water saturation.

Keywords MRV · Peatland · Water management · Artificial neural network

5.1 Introduction

The development of peatland often involves permanent or temporary conversion from its natural condition into bare land. Bare peat will experience exposure to natural processes in the atmosphere and on the surface, which will affect wetting and drying and, later, will lead to peat decomposition, which releases CO_2. Peat is organic soil that is composed of partially decayed vegetation and contains very little mineral content. Slow decomposition caused by anaerobic conditions is a necessary condition for its development (Belyea and Clymo 2001).

Plant remains are deposited onto the upper peat layer above the mean water table, and they experience aerobic decomposition while the remaining organic matter is buried in the saturated layer below the water table with minimal decomposition—hence, water-table depth is key to the decomposition and accumulation of peat. The lowering of the water table will remove anaerobic constraints on decomposition and stimulate the loss of peat carbon to the atmosphere (Freeman et al. 2001). A lower water table will also increase the potential for forest fires and stimulate the loss of peat carbon through combustion (Page et al. 2011; Turetsky et al. 2011).

CO_2 emission from peatland has been suspected as one of the major greenhouse gases that contribute to global warming and climate change. It is thought that this emission is dependent on the water table (Jauhiainen et al. 2008; Couwenberg et al. 2010; Jauhiainen et al. 2012; Nagano et al. 2012) and, consequently, drainage of peatland due to development and utilization will alter the emission levels of CO_2. Hooijer et al. (2006) suggest that the annual amount of CO_2 emission over peatland with a depth of 1 m of groundwater level is, on average, around 91 t ha^{-1}. However, this figure does not take into account the diurnal variation of CO_2 flux emission over the peatland, its interaction with other environmental parameters, or peat bulk density.

Net CO_2 emission can be measured using a flux tower, which requires investment in tower construction and sophisticated instruments. An indirect method using carbon budget analysis can be conducted to estimate whether the land is the source or sink of carbon emission. This requires information about carbon stored in all parts of trees and emission levels from the land. Therefore, soil emission should be continuously measured so as to acquire a CO_2 emission diurnal data series throughout the period.

This study set up a monitoring station in an area that had been developed for forest plantation operations in Kampar Peninsula. As such, the land had been drained using canals following eco-hydro management, a water management scheme implemented on site. The water table is lowered by dropping the water level in the

canals that were designed and built for water management purposes. The water table is designated between 40 cm and 90 cm below the soil surface.

This study aims to quantify CO$_2$ emission from bare peat within the industrial forest area using continuous measurement; to determine environmental factors that affect carbon dioxide flux and develop an ANN model to estimate carbon dioxide flux with inputs of environmental factors. The measurement and analysis were conducted in the humid tropical area of Kampar Peninsula. The study focused on measuring and quantifying CO$_2$ flux from bare peat within the Monitoring, Reporting, and Verification (MRV) station. The quantity of CO$_2$ discussed in this paper is limited to CO$_2$ flux from bare peat (CO$_2$ efflux), and further use of the terms "CO$_2$ emission" and "CO$_2$ flux" will be limited to this.

5.2   Methodology

Observations were made at a specially designated MRV monitoring station on the Kampar peninsula. At this location, the land surface has been cleared, and it consists of an open area bordered by a fence to protect it from disturbances during the observation process. The water level in this concession area is maintained at an altitude of 40–90 cm below the surface. For this study, weather, soil, and CO$_2$ flux monitoring equipment was installed at the monitoring station.

The measurement of CO$_2$ flux from the soil was carried out using a closed chamber method (LICOR 8100 IRGA gas analyzer) that can measure CO$_2$ flux automatically based on a set time interval (Fig. 5.1). The dimension of the chamber was 20 cm in diameter and the time interval to close the chamber for data-reading was set to every 60 min (24 times per day). This was repeated three times, and the average CO$_2$ flux was considered to be the measurement result. At the same time, the soil temperature, electrical conductivity, and volumetric water content at a depth of 5–10 cm were measured with another sensor (5TE) and recorded by a data logger (EM50). The daily CO$_2$ emission was obtained by means of temporal integration
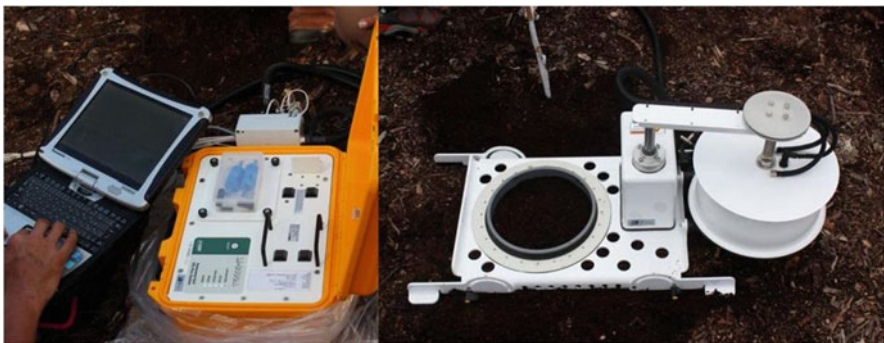

Fig. 5.1   Automatic soil CO$_2$ measurement system Li-8100: analyzer (left) and chamber (right)
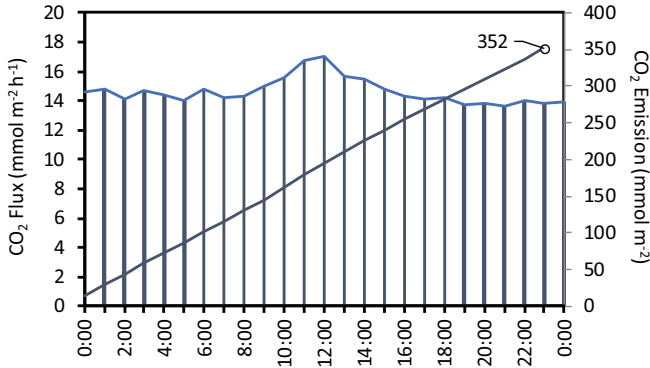
Fig. 5.2 Numerical integration to calculate daily CO_2 emission

over the CO_2 fluxes using the trapezoidal method. Then, the cumulative CO_2 emission was calculated by summing up the daily CO_2 emission for 365 days in order to obtain the total value for 1 year.

Measurement of CO_2 emission from the soil was carried out using a closed-circulation chamber methods. In this method, the soil is covered with a chamber for a designated time, and gases that come out of the soil will accumulate within the chamber. The measurement of CO_2 gas concentration was carried out by continuously flowing air from the chamber to the Infra-Red Gas Analyzer (IRGA) bench. Then, the analyzed air flowed back into the chamber. The measured change in CO_2 concentration data was then processed into CO_2 gas emitted from the ground. The whole process of measuring and processing data until the emission value was obtained was carried out automatically using the Li-8100 Automatic soil CO_2 measurement system (Fig. 5.1). The emission data obtained in this measurement was a mixture of various physical, biological, and chemical processes in the soil, resulting in CO_2 from the soil in the air per unit area.

The Li-8100 system includes a mechanical chamber and analyzer unit. The analyzer unit controls the mechanical CO_2 chamber movement and air flow using its internal pump from the chamber to the IRGA sensor, analyzes CO_2 concentration, calculates the CO_2 emission, and stores the data in a detachable memory card. The measurement was set to be conducted hourly with three replications, and the repetition data was calculated in order to get an hourly average CO_2 emission. At the end of the measurement, we produced an hourly data series for the measurement period.

The measured CO_2 concentrations during one observation event were calculated automatically by the Li-8100 system and converted into CO_2 flux with the unit of $\mu mol\ m^{-2}\ s^{-1}$. By multiplying the CO_2 flux by its molar mass divided by 10^{-6}, the CO_2 flux in units of $g\ m^{-2}\ s^{-1}$ was obtained, after which the total emission for 1 day (d) was calculated using an integration of the hourly (h) emission curve (Fig. 5.2). This integration was calculated numerically using the trapezoidal area method (Eq. 5.1) in which the daily value was the sum of the hourly values over 24 h.
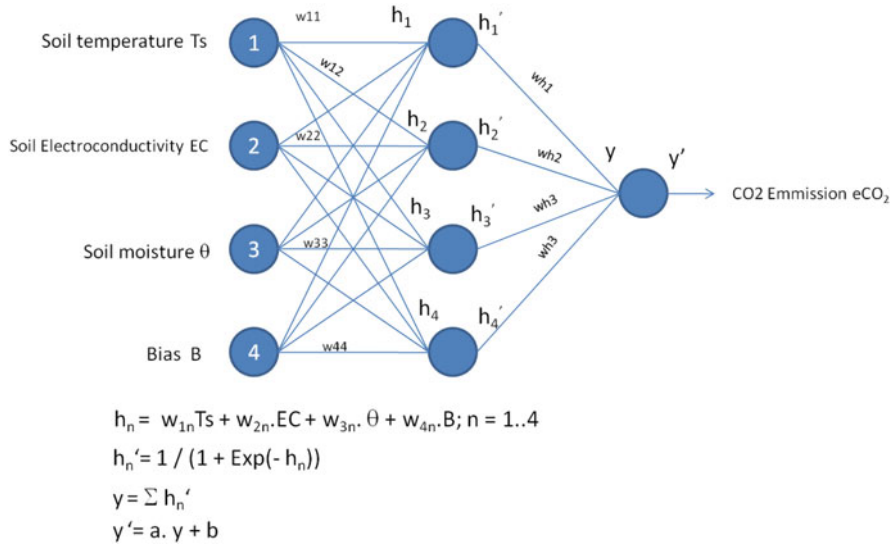
$h_n = w_{1n}Ts + w_{2n}.EC + w_{3n}.\theta + w_{4n}.B; n = 1..4$

$h_n' = 1 / (1 + Exp(- h_n))$

$y = \Sigma h_n'$

$y' = a. y + b$

Fig. 5.3 ANN model to calculate CO_2 flux

$$CO_{2\,d} = \sum\nolimits_{h=1}^{24} (0.5(CO_{2\,h-1} + CO_{2\,h}).3600) \tag{5.1}$$

Thus, the total CO_2 emission in 1 year can be calculated as follows.

$$CO_{2\,y} = \sum\nolimits_{d=1}^{365} CO_{2\,d} \tag{5.2}$$

Along with CO_2, weather and soil parameters were also measured. These measurements were part of the MRV activity conducted on the site. The measured variables were hourly rainfall, solar radiation, air temperature, air humidity, soil temperature, soil electrical conductivity, soil moisture, soil water potential, and the water table. These variables were essential to describe the environmental conditions that would influence the soilwater status and CO_2 emission from the soil. Occasional missing data of CO_2 emission was filled by the predicted value using the ANN model. Furthermore, the linear equation was used to estimate the accumulation of CO_2 emission within the missing periods.

As shown in Fig. 5.3, the ANN model consists of an input layer, a hidden layer and an output layer. The input layer had three variable inputs (soil temperature, electrical conductivity, and moisture), one bias input, and there was one variable output in the output layer, which was CO_2 flux. The model that was previously developed by Setiawan et al. (2013) in other sites had achieved considerable results with the coefficient of deterministic (R^2) being above 0.9. The related computer program (macro) was written in MS Excel, and the available Solver was used to find the optimized values of the weighted values. One reason to use these three variable inputs was knowing that there is a sensor available in the market that is capable of

measuring these variables simultaneously. Once these relationships have been well proven, it is then possible to calculate CO_2 flux at the same site from these three measured variables. For other sites, similar to this one, the model needs to be calibrated through the learning or optimization process.

5.3   Results and Discussion

5.3.1 CO_2 Dynamics

Raw data of soil emission measurement is shown in Fig. 5.4, which also shows soil temperature and soil moisture at the surface layer between 5 cm and 10 cm. Judging from the varying CO_2 flux data, it can be seen that the carbon emission is influenced by environmental parameters. Figure 5.5 shows the variation of rainfall, soil moisture, and daily CO_2 emission, on site. The red line is CO_2 flux data measured with the Li-8100 system, and the green line is estimated data to fill the gap of missing data with a linear model. It is clear that CO_2 emission also varies with weather conditions, i.e., rainfall, as well as water and soil-related variables.

Carbon emission was lowered during rainfall, which increased peat moisture and lowered temperature. The CO_2 itself is produced during biological activities that are affected by moisture and temperature, and it can also be caused by human activities such as clearing and drainage of land. Thus, as soil moisture and temperature affect microbiological activity, their variation will contribute to the differences in CO_2 emission in bare peatland.
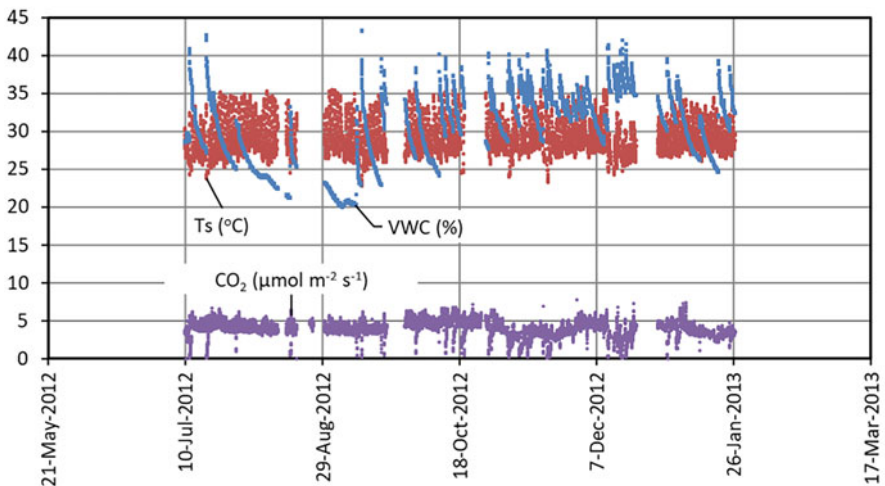

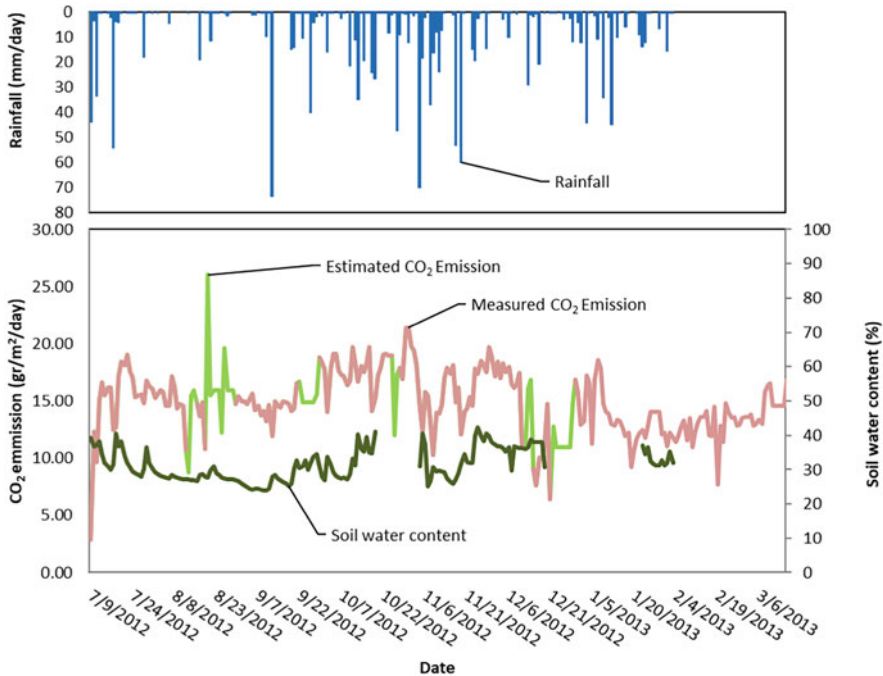**Fig. 5.4** Measured soil temperature (Ts), volumetric water content (VWC), and CO_2 flux

Fig. 5.5 Daily rainfall, soil volumetric water content, and CO_2 emission

5.3.2 *CO_2 Correlation with Environmental Parameters*

Soil CO_2 flux is the natural result of complex dynamic processes that involve organic decomposition, as well as respiration of roots and microbes (Šimůnek and Suarez 1993; Luo and Zhou 2006) in which moisture content, chemical content, and soil temperature play important roles. Berglund et al. (2010) evaluated the lysimeter method (Persson and Bergström 1991) to study the effect of temperature on CO_2 emission, which demonstrated the correlation of temperature to CO_2 by using a general model for peatland that had been drained for purposes similar to this study.

Figure 5.6 shows the individual correlations between CO_2 flux to air temperature (Ta), solar radiation (Rs), relative humidity (RH), soil temperature (Ts), soil electrical conductivity (EC), and soil volumetric water content (VWC). By looking to the low R^2, it is clear that CO_2 flux is poorly correlated with this individual variable. However, we can see that CO_2 flux tends to increase with the increase of Ta, Rs and Ts, and to decrease with the increase of RH, EC and VWC.

It is known that biological and chemical processes are dependent on temperature and energy. Water, on the other hand, has the opposite effect: Higher RH or VWC seemed to contribute to decreasing emission. It is known that CO_2 will result as oxidation occurs, i.e., the land is being drained. Conversely, oxidation will cease as the land becomes saturated with water, subsequently releasing CH_4. EC in the peat
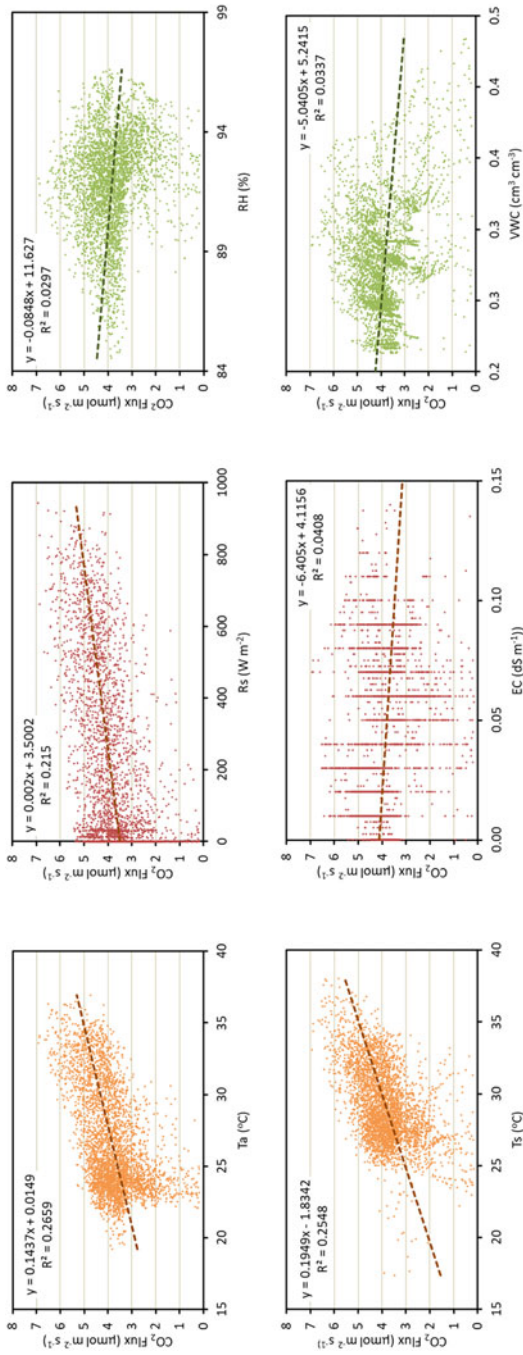
Fig. 5.6 Individual correlations between CO_2 flux with air temperature (Ta), solar radiation (Rs), relative humidity (RH), soil temperature (Ts), soil electrical conductivity (EC), and soil volumetric water content (VWC)
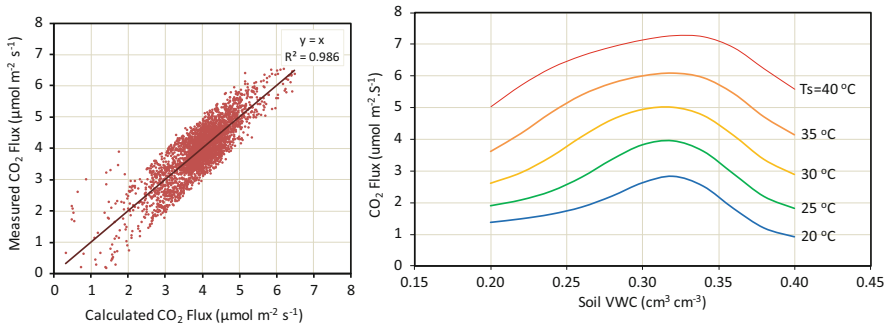
Fig. 5.7 Patterns of CO$_2$ flux under various soil Ts and VWC at EC $= 0.04$ mS cm^{-1}

can represent two parameters since the sensor actually detects conductivity, which may be due to an increase in chemical concentration or the conductive medium itself—water in the pores—and, thus, should be accounted for simultaneously with VWC. Heat and water strongly affect the emission, and two parameters that directly interact with biological processes in the soil are soil temperature and soil moisture. Therefore, these parameters can be a proxy in quantifying carbon emission.

Previously, Nagano et al. (2013) demonstrated the use of the groundwater table as a proxy parameter to estimate CO$_2$ emission using an empirical three-stage model (NAIS Peat Model). This is used to describe the effect of a lowering groundwater table on CO$_2$ release from peatlands. However, with highly porous material such as the peat in the study area and the water table at a depth of about 100 cm, capillary rise of water to the surface from groundwater is difficult to occur to wet the surface. Compared to the study area in Nagano et al. (2013), where the water table was less than 30 cm deep, it is reasonable to exclude the groundwater level from the model for the moment. In this case, CO$_2$ emission may not be affected by groundwater level, as it had probably been managed at a particular level in the area.

During a prolonged dry period, even though the water table was well managed at about 100 cm below the surface, the peat on the surface suffered from the very dry conditions. In a rainfall event, peat VWC immediately increased, and CO$_2$ flux dropped, as seen in the previous figures. These show that for the most direct estimation of CO$_2$, VWC can represent the water status of the peat better than water table if VWC measurement is available.

Figure 5.7 shows the flux estimated using the ANN model with inputs of Ts, VWC, and EC versus those measured by Li-8100 at the same time. ANN parameters and constant were optimized by using the measured data. The results of the CO$_2$ flux calculation using the ANN model show an R^2 value of 0.986, and the model is quite accurate when used for predictions of CO$_2$ flux by observing proxy parameters of soil temperature, moisture, and EC. The ANN CO$_2$ model seems to be able to represent the characteristic of flux as dependent on soil moisture, temperature, and EC, as seen in Fig. 5.7, which is the particular example at soil EC $= 0.04$ mS cm^{-1}.

CO$_2$ flux increases with the increase in temperature; soil humidity, however, has a different impact on the flux. In Fig. 5.7, at any level of temperature, the flux reaches its maximum at soil moisture of between 0.31 cm^3 cm^{-3} and 0.33 cm^3 cm^{-3}. The flux decreases as soil humidity falls to a drier level or increases toward saturation. It can be concluded that either dry conditions or a saturation effect lowers emission. Dry conditions, however, will lead to soil subsidence and increase the potential for a peat fire, so wet conditions are preferable.

5.3.3 Accumulation of CO$_2$ Emission

Figure 5.8 shows the daily accumulated CO$_2$ emission measured in Kampar Peninsula from July 2012 to March 2013. The daily emission accumulated is shown by a solid rising line to the end of the available data. Measurement failures during the periods caused missing data, which were then estimated by using linear interpolation between dates with available data.

The total CO$_2$ emission throughout the measurement period is shown by the ascending line in Fig. 5.8. If this line is extended to an entire 1-year period, using this simple approach, a 1-year accumulation of CO$_2$ can be estimated at 5225 g m^{-2} (52.25 t ha^{-1}). However, this approach ignores the effect of varying soil temperature, moisture, and EC, as presented in previous section and ANN CO$_2$ model.

The ANN model for CO$_2$ emission estimation can be used when direct measurement of CO$_2$ data is not available. This can be done with a careful calibration procedure that includes direct measurements of CO$_2$ flux, which provide sufficient data. In this case, calibration had been conducted at the MRV station in Estate Meranti, and the model can be used to predict the CO$_2$ emission from the bare peatland. Figure 5.9 shows the emission series by using the ANN model, which shows that, in 2012, the total emission can be estimated as 5488 g m^{-2} (54.86 t ha^{-1}).
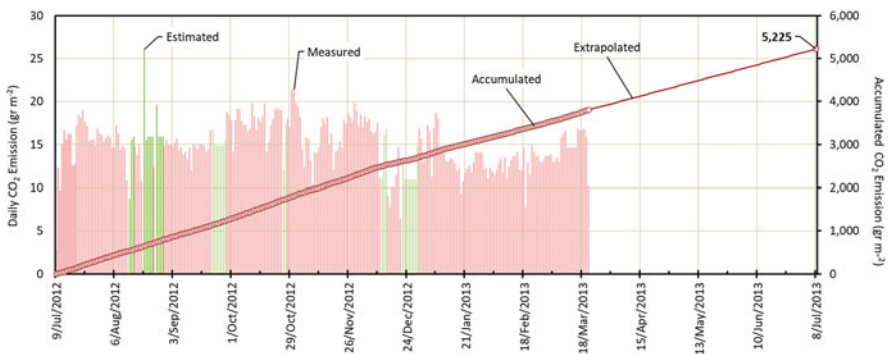

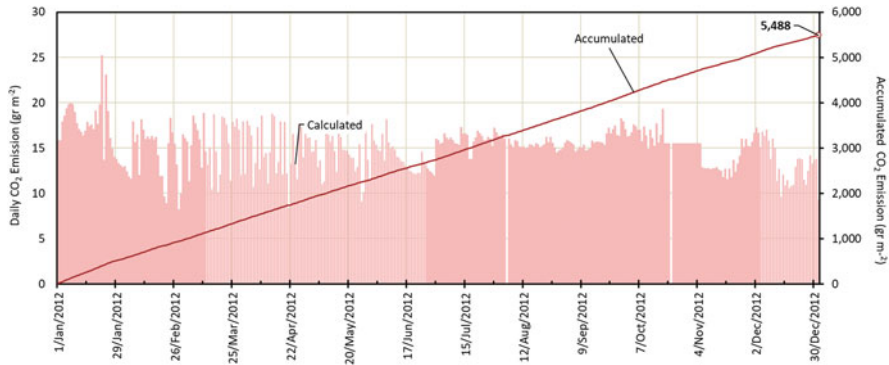**Fig. 5.8** CO$_2$ emission and accumulation

Fig. 5.9 CO_2 emission estimated using the ANN model for 2012

Long-term field data of CO_2 flux, including net ecosystem CO_2 exchange, ecosystem respiration, and soil CO_2 efflux to examine their variations for conditions of peat swamp forest in a tropical peat area in Central Kalimantan, Indonesia was presented by Hirano et al. (2016). Similar to Nagano et al. (2013), groundwater level is suggested as a practical measure to assess annual net ecosystem CO_2 exchange.

Among the results presented, the annual sum of soil CO_2 efflux or soil respiration for 2005 were 1347 g m^2 year^{-1}, 1225 g m^2 year^{-1} and 348 g m^2 year^{-1}, at the undrained, drained, and drained and burnt peat swamp forest. This is equal to 4939 g m^2 year^{-1}, 4492 g m^2 year^{-1} and 1276 g m^2 year^{-1} of CO_2, which is smaller than the estimation that has been made in this study. The data on the variation of the mean groundwater level presented at the site shows that the condition of the groundwater level presented by Hirano et al. (2016) is relatively shallower compared to the site in this study, which may lead to a lower CO_2 flux than that presented here. However, information on temperature, humidity and soil EC, and hourly measurement results are not available. Further studies on monitoring soil parameters, weather, measuring CO_2 emissions, and developing ANN models at these locations and other locations will be of interest in developing indirect CO_2 estimation methods.

5.4   Conclusion

Continuous measurement of CO_2 was conducted from July 2012 to February 2013, acquiring a CO_2 emission data series (except for missing data) during this period. Measurement showed that CO_2 flux emission varied with weather, water, and soil-related variables, especially rainfall, soil temperature, and humidity. Using linear estimation, the total estimated CO_2 emission during the measurement period from July 2012 to June 2013 is 52.25 t ha^{-1}. CO_2 emission can be estimated using the ANN approach developed in this study, with inputs of soil moisture, temperature,

and EC as proxy parameters; these can be applied for rapid estimation of CO_2 emission from bare peat where it was calibrated. Total CO_2 emission in the year 2012 is estimated as 54.86 t ha^{-1} using the ANN model, which also shows that CO_2 emission fell with the decrease in temperature and increase in soil humidity toward water saturation.

References

Belyea LR, Clymo RS (2001) Feedback control of the rate of peat formation. Proc Biol Sci 268(1473):1315–1321. https://doi.org/10.1098/rspb.2001.1665

Berglund Ö, Berglund K, Klemedtsson L (2010) A lysimeter study on the effect of temperature on CO_2 emission from cultivated peat soils. Geoderma 154(3–4):211–218. https://doi.org/10.1016/j.geoderma.2008.09.007

Couwenberg J, Dommain R, Joosten H (2010) Greenhouse gas fluxes from tropical peatlands in South-East Asia. Glob Change Biol 16(6):1715–1732. https://doi.org/10.1111/j.1365-2486.2009.02016.x

Freeman C, Ostle N, Kang H (2001) An enzymic 'latch' on a global carbon store. Nature 409:149. https://doi.org/10.1038/35051650

Hirano T, Sundari S, Yamada H (2016) CO_2 balance of tropical peat ecosystems. In: Osaki M, Tsuji N (eds) Tropical peatland ecosystems. Springer, Tokyo, pp 329–337. https://doi.org/10.1007/978-4-431-55681-7_21

Hooijer A, Silvius M, Wösten H et al (2006) PEAT-CO2: assessment of CO_2 emissions from drained peatlands in SE Asia. Delft Hydraulics report Q3943. Delft Hydraulics, Delft

Jauhiainen J, Limin S, Silvennoinen H et al (2008) Carbon dioxide and methane fluxes in drained tropical peat before and after hydrological restoration. Ecology 89(12):3503–3514. https://doi.org/10.1890/07-2038.1

Jauhiainen J, Hooijer A, Page SE (2012) Carbon dioxide emissions from an *acacia* plantation on peatland in Sumatra, Indonesia. Biogeosciences 9:617–630. https://doi.org/10.5194/bg-9-617-2012

Luo Y, Zhou X (2006) Soil respiration and the environment. Academic, Cambridge. https://doi.org/10.1016/B978-0-12-088782-8.X5000-1

Nagano T, Osawa K, Ishida T et al (2012) Field observation of the tropical peat soil respiration rate under various ground water levels. In: The 14th international peat congress, Stockholm, 3–8 June 2012

Nagano T, Osawa K, Ishida T et al (2013) Subsidence and soil CO_2 efflux in tropical peatland in southern Thailand under various water table and management conditions. Mires Peat 11:6

Page SE, Rieley JO, Banks CJ (2011) Global and regional importance of the tropical peatland carbon pool. Glob Change Biol 17(2):798–818. https://doi.org/10.1111/j.1365-2486.2010.02279.x

Persson L, Bergström L (1991) Drilling method for collection of undisturbed soil monoliths. Soil Sci Soc Am J 55(1):285–287. https://doi.org/10.2136/sssaj1991.03615995005500010050x

Setiawan BI, Saptomo SK, Bachtiar M et al (2013) Patterns of CO_2 flux in a bared tropical peatland. In: Suwardi, Nurcholis M, Agus F et al (eds) Proceeding of 11th international conference, the East and Southeast Asia federation of soil science societies. Land for sustaining food and energy security. Indonesian Society of Soil Science, Jakarta

Šimůnek J, Suarez DL (1993) Modeling of carbon dioxide transport and production in soil: 1. Model development. Water Resour Res 29(2):487–497. https://doi.org/10.1029/92WR02225

Turetsky MR, Donahue WF, Benscoter BW (2011) Experimental drying intensifies burning and carbon losses in a northern peatland. Nat Commun 2:art 514. https://doi.org/10.1038/ncomms1523