Available online at:
http://journal.unila.ac.id/index.php/tropicalsoil
DOI: 10.5400/jts.2014.19.2.91

Estimation of the Potential Carbon Emission from Acrotelmic and Catotelmic Peats

Siti Nurzakiah[1], Supiandi Sabiham[2], Budi Nugroho[2] and Dedi Nursyamsi[1]

[1]*Indonesian Swampland Agriculture Research Institute. Jl. Kebun Karet. Loktabat Utara. Banjarbaru*
e-mail: zakiah_balittra@yahoo.co.id
[2]*Departement of Soil Science and Land Resources, Bogor Agricutural University.*
Jl. Meranti, Kampus IPB Darmaga. Bogor

Received 21 March 2014 / accepted 30 April 2014

ABSTRACT

Agricultural development on peatland in Indonesia has been constrained by the presence of environment issues in relation to the release of greenhouse gases (GHGs) particularly carbon dioxide (CO_2) and methane (CH_4) to the atmosphere. This study was aimed to predict the potential carbon emission based on carbon stocks in acrotelmic and catotelmic peats with the reference of groundwater level of peatland. The results showed that groundwater levels have played an important role in carbon release, which has close relationship with water regime of the upper layer of peats that influenced by oxidative and reductive conditions of the land. From the layer that having groundwater level fluctuations during the period from rainy to dry season (acrotelmic peat), the emissions were mostly dominated by CO_2 release, while from permanent reductive-layer (catotelmic peat) was not detected. The decrease of groundwater level from -49.6 to -109 cm has clearly influenced carbon emission. From each decreasing 1.0 cm groundwater level, CO_2 emission measured during the period of February - October 2013 was calculated to yield about 0.37 Mg ha^{-1} yr^{-1}.

Keywords: Acrotelmic and catotelmic peat, carbon emission, groundwater level

INTRODUCTION

The ability of acrotelmic and catotelmic peats in storing carbon is strongly influenced by the groundwater level. The depth of the groundwater level is important in determining the intensity of the decomposition process of peat decomposition. In the tidal peat swamp, water levels fluctuate due to tides or rainfalls that cause the peat to undergo a process of drying and moistening affecting the soil water content and level of carbon emissions. Several studies have revealed that there was a positive correlation between the depth of groundwater level and CO_2 emissions (Agus *et al.* 2011a; Berglund and Berglund 2011: Couwenberg *et al.* 2009; Dinsmore *et al.* 2009; Hirano *et al.* 2009; Jauhiainen *et al.* 2005). Drying and moistening processes also affected stability of organic acid produced from peat decomposition, characterized by the carbon loss of CO_2 dan CH_4 emissions (Sabiham 2010).

Carbon emissions can be identified through two approaches, namely the direct and indirect measurement of the concentrations of carbon gases. Direct measurement of the carbon gas concentration is carried out by the micro-meteorological method (Eddy covariance) and by closed chamber (Grøndahl 2006). Both methods differ in the scales of measurement and targeted objectives. Micro-meteorological method uses a tower to continuously characterize CO_2 flux at the ground level (hectare scale) and is highly dependent on wind speed during the measurement period. This method provides information on net flux and is often used to study the balance of the ecosystem. The closed chamber method provides estimates of GHG flux at the observation plot level of less than1m^2 (small scale) and is used to study aprocess-the process that occurs inside soil including microbial activities and has been applied to more detailed studies of various treatments such as fertilization and provision of ameliorant materials. This method can be conducted by means of GHG sampling, and it is then analyzed by Chromatography Gas (CG) or by conducting direct measurementof GHG flux using Infrared Gas Analyzer (IRGA).

Indirect measurement of carbon gas concentration can be conducted by ash content approach (Gronlund *et al.* 2008), carbon stocks (Agus 2009) and subsidence (Hooijer *et al.*2006).

The approach based on subsidence has been used as a reference recently. Hooijer *et al*. (2010) reported that each 1cm decrease in ground water level will emit CO_2 of 0.91 Mg ha^{-1} yr^{-1}. This approach results in a less precise calculation. Data obtained are from several research results that allow the presence of uncertainty in measurement. The uncertainty in measurement includes the thickness and maturity of peat, bulk density, carbon content and decrease in the ground water level. This is because the Indonesian peatland has a variability in thickness and maturity as well as different origin of peat-forming materials. It is, therefore, necessary to study the other carbon emission prediction methods or to improve the existing emission prediction methods adapted to the environmental condition in order to obtain carbon emission data which are closer to the conditions in the field. The purpose of this study was to predict the potential for carbon emissions based on carbon stocks in acrotelmic and catotelmic peats with the reference of groundwater level of peatland.

MATERIALS AND METHODS

Study Sites

The study was conducted by a survey method. The location of the study area was determined by using the purposive sampling method. The study in Jabiren Village, Jabiren Raya District, Central Kalimantan in the coordinates of 02°51'48.6" S and 114°17'00.2" E. The thickness of peat was between 5 - 7 meters with clay substratum, degree of maturity hemic and sapric peats. This study was on the secondary channel that connects the primary channel of PLG (Peat Land Development) and Jabiren River that empties directly into Kahayan River. Land use was in the form of intercropping between rubber and pineapple. Soil and greenhouse gases (CO_2 dan CH_4) sampling were conducted based on the perpendicular transect of the drainage channel (Figure 1).

Sampling and field measurements

Soil Sampling and Determination of Carbon Stock

Measurement of carbon stocks was conducted in July 2013. The drilling was performed until it reached a depth of 300 cm with a consideration that the height of the groundwater level was the lowest during the dry season in 2012 of -150 cm so that the peat with a depth of 0 - 150 cm was categorized as acrotelmic peat whereas the peat with the depth of 150 - 300 cm was categorized as catotelmic peat (permanently reductive). In each point of observation were performed six times of soil sampling with a peat auger (Eijkelkamp model) in the points adjacent to each other. The sixth points

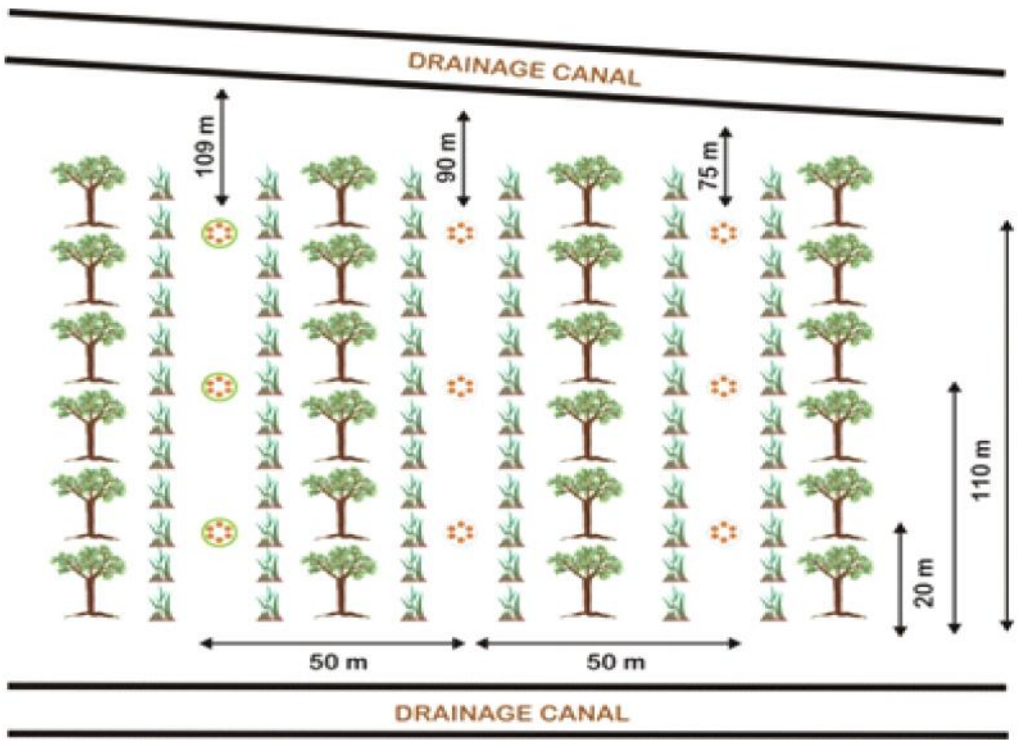

Figure 1. Location of soil and carbon gases sampling in the coordinates of 02°51'48.6" S and 114°17'00.2" E in peat land planted with rubber and pineapple in intercropping system, = Rubber tree; = Pineapple; = Point of Soil sampling; = Point of Carbon Gas Sampling.

of the soil sampling with details of three points for the determination of carbon stocks and the other three points for the analysis of pH (H_2O, 1: 2.5) as well as the fiber content so that each point of observations experienced with three replications.

Parameters observed to determine the carbon stock were bulk density (g cm^{-3} or kg dm^{-3}, gravimetric method), carbon content (% weight, loss on ignition method), and peat thickness (directly observed in the field by using a drill peat). Several other parameters were also observed as it could assist in interpreting the data, that were wide peatlands and peat maturity (Agus 2009). Content of soil organic material (OM) was calculated based on percentage of soil dry weight, which is:

$$OM (wt\%) = (CB-BA)/LB \times 100\%$$

Where :

BA = weight of ash soils (determined by loss on ignition method in the furnace at a temperature 550 °C for 6 hours).

CB = weight of dried soil (determined by gravimetric method in the oven at a temperature 105 °C for 2 x 24 hours or until of contants weight).

LB = CB * water content corection Carbon stock in the soil is C weight in a unit volume of soil, using the formula:

$$C\text{-stock} = C\text{-org (vol\%)} \times A \times L$$

Where :

C-org (vol%) = weight per volume of soil carbon (g cm^{-3} or Mg m^{-3}).

C-org (% vol) : C-org (% weight) × BD-ash

C-org (%weight) : OM/1.724

L = area of peatland (m^2)

A = peat thickness (m).

Greenhouse Gas (CO_2 dan CH_4) Sampling and Measurement of CO_2 dan CH_4 fluxes

The sampling of greenhouse gases (CO_2 dan CH_4) was conducted in the morning (from 6 am to 8 am) from February to October that represented the soil conditions of wet (rainy season), moderately (transition) and dry (dry season) so that the data of carbon emissions in a year were obtained. Gas chamber is block-shaped made of polycarbonate material (length 50 cm; width 15 cm; height 30 cm). The top chamber is equipped with a hole covered with a septum for gas sampling and the hole for the thermometer. Gas sample was taken using a syringe with the size of 10 ml. The time inter valused for gas sample collection was the 3rd, 6th, 9th, 12th, 15th, 18th, 21st, and 24th minute. The sample was then analyzed using micro GC type 4900. The concentration of CO_2 and CH_4 gases from the gas samples analyzed will be simultaneously released. The measurement of CO_2 dan CH_4 fluxes was carried out using the method of closed chamber technique adopted from the International Atomic Energy Agency (IAEA 1992). The calculation of fluxes at each observation point was performed using the following equation:

$$E = \frac{Bm}{Vm} x \frac{¢\, Csp}{¢\, t} x \frac{V}{A} x \frac{273.2}{T + 273.2}$$

Where:

= CO_2/CH_4 emissions (mg m^{-2} $minute^{-1}$)

V = chamber volume (m^3)

A = width of chamber base (m^2)

T = average temperature inside the chamber (°C)

dCsp/dt = change rate of concentrations of CH_4 and CO_2 gases (ppm $minute^{-1}$)

Bm = molecule weight of CH_4 dan CO_2gases in a standard condition

Vm = gas volume at the *stp* condition (*standard temperature and pressure*) *i.e.* 22.41 liters at 23°K

Groundwater Level Observations

The measurement of groundwater level was carried out once a week (from January to December 2013) on 48 pieces piezometers in a five-hectare land. Pizeometer was made of PVC q 1.5 inch and length of 2 m.

Data Analysis

The data processing was carried out using MS Excel program by Systat Software Inc. The results of the actual measurements of CO_2 and CH_4 fluxes were linked with the fluctuations of groundwater level to obtain the potential predictive value of carbon emissions.

RESULTS AND DISCUSSIONS

Ground water level plays an important role in the process of accumulation and decomposition of peat which will affect the amount of carbon emissions. The data of groundwater level of the year were used as the basis for determining the zone of acrotelmic and catotelmic peats. From the observation results it was known that acrotelmic peat zone was at the depth of 0 to -109 cm while catotelmic peat zone was at the depth of > -109 cm (Figure 2).

Acrotelmic zone is a peat layer where plant roots grow and is often in a state of oxidative-reductive condition although at one time it can be saturated. This zones are influenced by groundwater level fluctuations in which the layer depth boundary is the lowest groundwater level in dry season. Catotelmic zone is a layer of peat containing no oxygen (Ivanov 1981). Under the ideal condition, the hydraulic conductivity of acrotelmic peat is much higher than that of catotelmic peat. Unlike acrotelmic peat, catotelmic peat remains permanently saturated because the rate of water movement is almost non-existent. Acrotelmic peat surface will decrease significantly its capacity of storing water when there is an activity in the construction of drainage channels, and this is due to peat degradation as a result of oxidation and compression accompanied by the occurrence of subsidence.

High water-holding capacity is one of the nature and importances of the peat. The maximum ability of peat to store water is very large ranging from 200 to 1000% on the weight basis or 50 to 90% on the volume basis (Andriesse 1988). Highwater-holding capacity of peat can be interpreted gravimetrically by the water content. High water content occurs because the structure of peat is coarse (fibrous), very loose and porous so that it can hold large amounts of water. In addition, peat has low bulk density and bearing capacity as a result of high buoyancy capacity and pore volume.

High water content value is influenced by the high groundwater level, origin of peat-forming materials and degree of peat decomposition. In acrotelmic zone, fibric peat can store more water than Hemik and Saprik peats, but in catotelmic zone, its ability varies according to the distance to the ground water level. At the location of this research, the dominant maturity levels are hemik saprik marked with by the average bulk density (BD) ranging from 0.11 to 0.18 g cm^{-3}, average water content ranging from 510 to 886%, and average organic C ranging from 37.9 to 54.8%. The decomposition rate affects peat porosity, and the porosity is controlled by layout of particle size or peat fibers. Figure 3 shows the variations of BD, water content and C-organic and soil samples at one observation point. Bulk density increased with the increasing depth of soil while the water content and C-Organic decreased with the increasing soil depth (Figure 3a). The reduced capacity of the peat land to store water was due to its peat particle size which became finer and more solid (Figure 3b). This could be due to the presence of mineral matter mixed in the peat so that the water content was lower and the measured value of BD was higher ranging from 0.16 to 0.28 g cm^{-3} followed by a decline in the value of the C-Organic or an increase in ash content. The high ash content was caused by the enrichment of minerals over flowing the river due to the tides and accumulated in the peat layer. According to Chaudhari *et al.* (2013) BD was strongly influenced by the intensity of compaction, origin of peat-forming material, degree of decomposition and presence of mineral materials at the time of sampling.

In catotelmic peat, it can be seen that there was a great increase in the ash content with the increase of BD while in acrotelmic peat, the increase of BD was not always followed by the increase of ash content (Figure 4). This further clarified the presence of mineral matter in peat layer, especially at a depth of 150 – 300 cm as indicated by the values of ash content ranging from 16.55 to 36.43% and BD ranging from 0.147 to 0.216 g cm^{-3}. The presence of mineral materials can also be seen at a depth of 109 - 150 cm, although the amount was not as much as in the layer under neath because there area lot of peat materials with BD ranging from

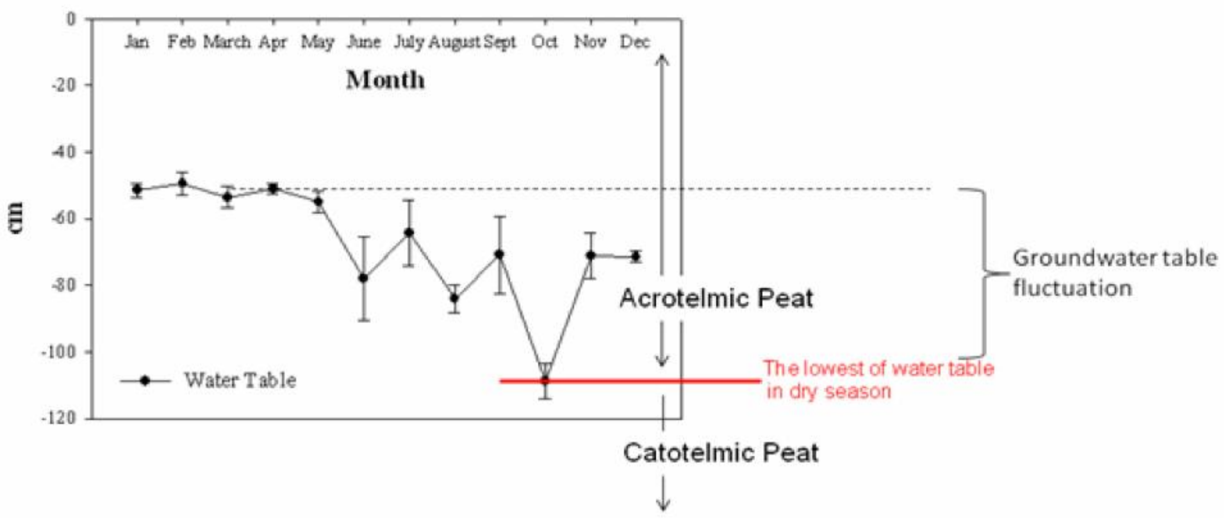

Figure 2. Limit zones of acrotelmic and catotelmic peats based on groundwater level measured in 2013.

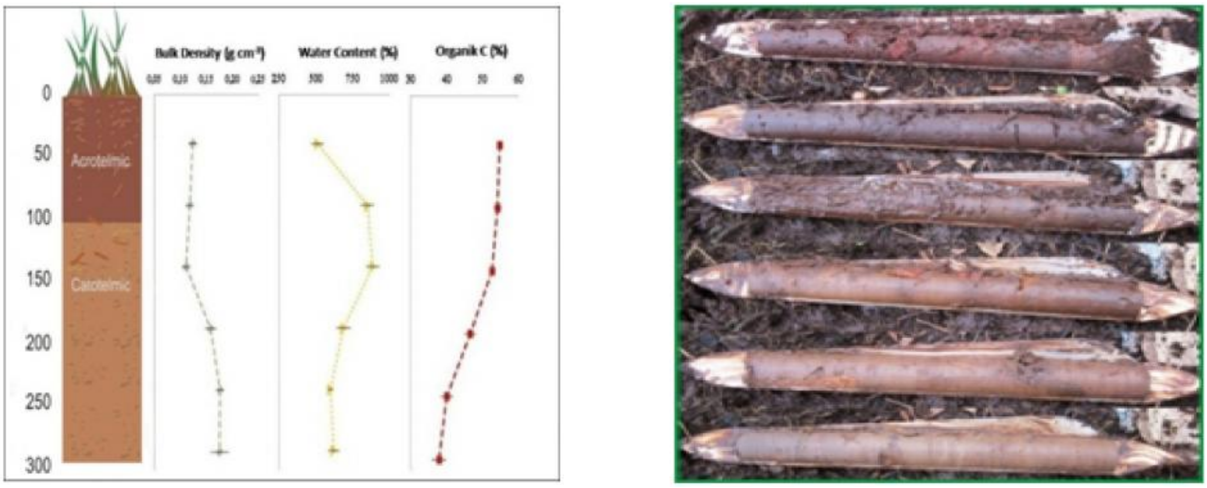

Figure 3. (a) Variation of bulk density, water content and C-Organic in acrotelmic and catotelmic peats, (b) soil samples at one observation point (in order from the top to the bottom: 50 cm, 100 cm, 150 cm, 200 cm, 250 cm, 300 cm.

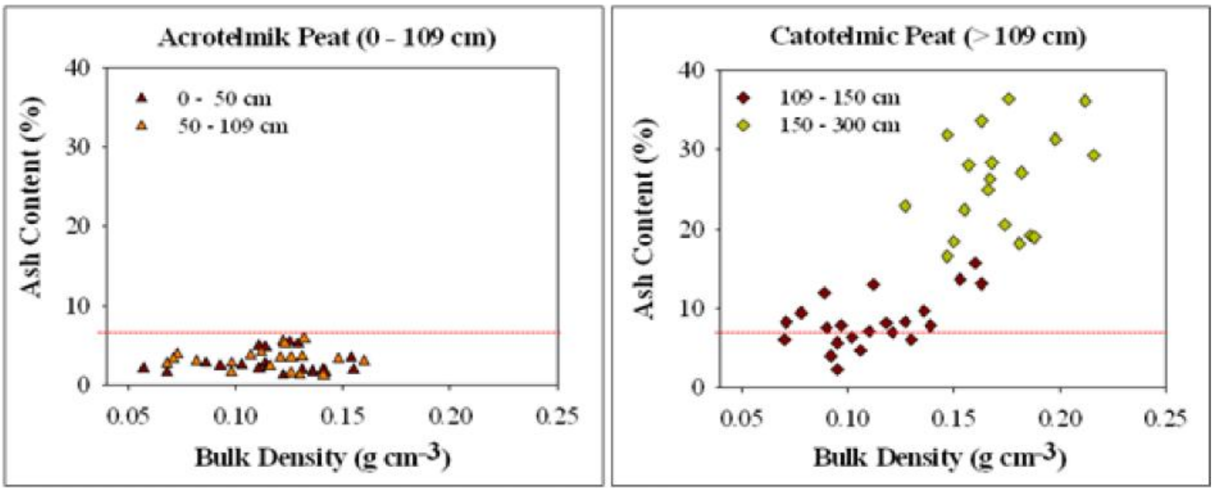

Figure 4. Distribution of value of ash content in some bulk density values.

0.070 to 0163 g cm^{-3} and ash content ranging from 2.26 to15.74%. Unlike the catotelmic peat, acrotelmic peat contained lower amounts of ash content ranging from 1.12 to 5.83% with BD ranging from 0.068 to 0.155 g cm^{-3}. Variations in the values of BD were caused by differences in the degree of maturity (hemic and Sapric) and by the consolidation which could increase BD characterized by the peat particle size which was finer and solid. In this zone, all layers were peat materials due to the presence of plant fiber, especially at a depth of 0 – 50 cm. The BD value was influenced by the moisture content. The decrease in BD would increase the peat water content (Figure 5). Acrotelmic peat at the depth of 0 - 50 cm has a lower water content than that at the depth of 50-109 centimeters. This was caused by the consolidation effect which could lead to a reduction in the buoyancy of the peat surface, thus resulting in lower water-holding capacity. In contrast, at a depth of 50 - 100 cm, the moist condition of peat increased water content. Different conditions occured in catotelmic peat with a depth of 150-300 cm in which high BD had a lower water content than that on the beneath layer that was from 507.55 to 714.77%. This was due to the presence of mineral matter in peat that had lower water holding capacity. The water content in agrotelmik peat was varied in narrow ranges of BD values while in catotelmic peat, the water content had wide ranges of BD values i.e.from 0.070 to 0.216 g cm^{-3}.

Bulk density and percentage of carbon/ash content are the parameters that greatly influence the amount of carbon stocks in peat (Hooijer *et al.* 2006). The research results showed that carbon stocks in acrotemic peat was of 658.68 ± 22.99 Mg C ha^{-1} (Figure 6) or each 1cm depth of acrotelmic peat, the carbon stocks reached 6.59 Mg C ha^{-1}.

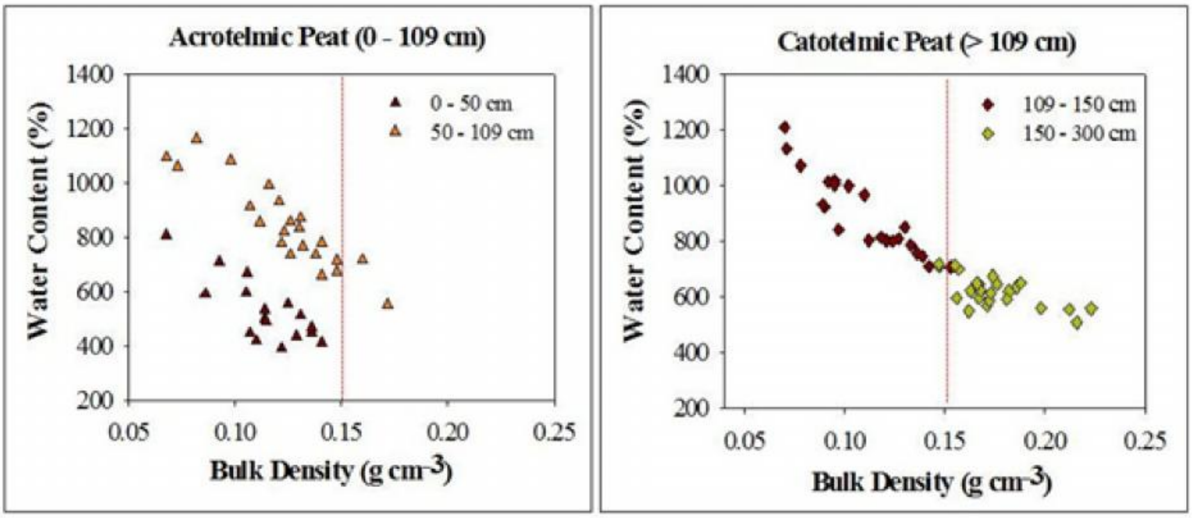

Figure 5. Distribution of water content in several bulk density values.

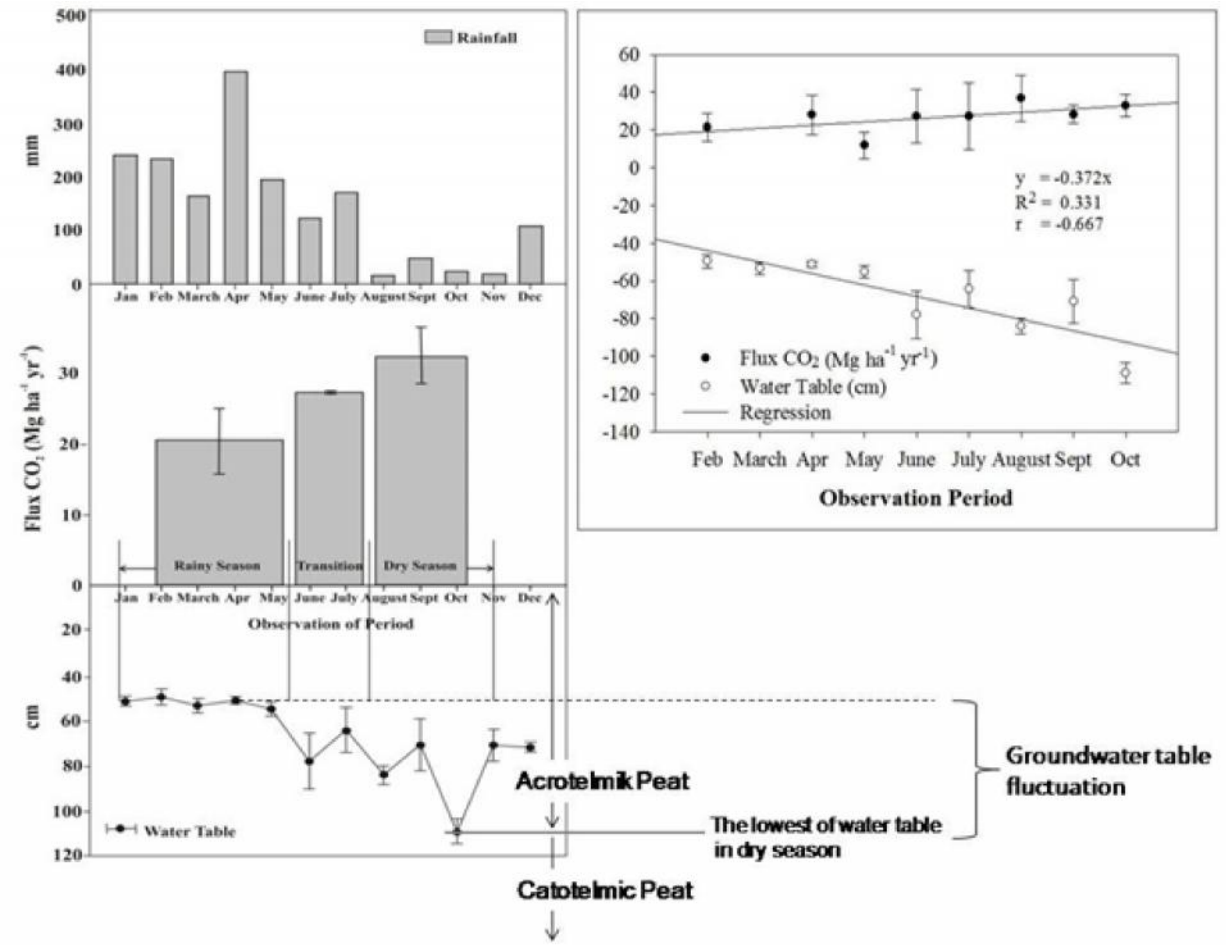

Figure 6. Flux $CO_{2,}$ fluctuations in groundwater level and rainfall based on the results of measurements for one year (2013).

Based on the results of a number of studies, they showed that there was a positive correlation between the depth of the peat and the amount of carbon stocks so that carbon stocks can be predicted by using peat depth data. Nurzakiah *et al.* (2013) reported that in Tegal Arum Village, South Kalimantan peats dominated by fibric maturity degree with the depth of 36 - 338 cm had carbon stocks varying from161.8 to 1142.2 Mg C ha^{-1} so that the shallow peats in the area had carbon stocks of 3.45 Mg C ha^{-1} cm^{-1}. This figure was lower than the figure mentioned by Page *et al.* (2002) *i.e.* approximately 6.00 Mg C ha^{-1} cm^{-1} and the same amount was obtained in this research in which the

Table 1. Soil properties at the study site.

Parameters	Acrotelmic Peat (0-109 cm)	Catotelmic Peat (109-300 cm)
pH	3.48 ± 0.023	3.81 ± 0.031
Water content (% weight)	679.04 ± 20.886	698.14 ± 15.624
Ash content (% weight)	5.17 ± 0.796	22.90 ± 1.153
Fiber content (% vol)	22.24 ± 0.472	24.89 ± 0.658
Organic C (% weight)	54.51 ± 0.458	44.32 ± 0.663
Bulk density (g cm^{-3})	0.12 ± 0.004	0.15 ± 0.004
Carbon stock (Mg ha^{-1})	658.68 ± 22.999	1335.68 ± 30.670

maturity degree of the peats were dominated by hemic and Sapric. Different maturity degree of peat will result in different amounts of carbon stocks. The differences in the amounts of carbon stocks will affect the potential of carbon emissions.

Table 1 also shows that the peat zones of acrotelmic and catotelmic affected the values of the observation parameters. The soil pH of acrotelmic peat was lower than that of catotelmic peat. This relates to the origin of peat-forming materials dominated by woody plants (lignin). In the acrotelmic condition, lignin degradation will produce a compound with the C-carboxylate bond. The carboxylate group plays a role in the process of soil acidification. The higher the content of this group, the lower the pH of the soil. The proton (H^+ion) released by the root system as a result of active absorption of cation nutrients by plant roots contributes to the soil acidification process (Poss *et al.* 1995). The capacity of peat to store water and high or low bulk density are influenced by the maturity degree of peat and the presence or absence of inorganic materials deposited on the layer of peat soil and groundwater level fluctuation. These conditions will affect the level of carbon emissions in peatlands. The emission of greenhouse gases is strongly related to the decomposition rate (Lafleur *et al*. 2005; Laiho 2006; Kuzyakov 2006).

The acrotelmic zone will primarily emit carbon dioxide (CO_2) generated through aerobic decomposition process while catotelmic zone will emit methane (CH_4) through the an aerobic decomposition process. However, the formation of methane gas is not only resulted from the anaerobic condition but should also be supported by the value of the redox potential (Eh) < -200 mV (Mer and Roger 2001). This Eh value is difficult to obtain in the Indonesian peats with deficient nutrients (despite their rich organic matters). Low nutrient availability may reduce the rate of respiration. Nutrient distribution between labile and non-labile fractions is very important because both can regulate the availability of nutrients to the decomposing organisms (Chimner and Ewel 2005). Due to nutrient lacks in peats, it is difficult to reduce the value of potential redox so that the release of carbon in the form of CO_2 is greater than that in the form of CH4. During the observation period, CH_4 was not detected by the micro GC type CP 4900 so that emissions measured were obtained only from CO_2. Therefore, the prediction of the carbon emission potential is only performed on acrotelmic peat. From the results of the CO_2 flux measurements, it can be seen that the average value of emissions was 26.5 Mg ha^{-1} yr^{-1}. Figure 6 shows the CO_2 flux and groundwater level fluctuations and regressions of the two parameters as well as rainfall fluctuations during the research period.

CO_2 flux is higher in the dry season and different in the rainy season. The water content in the dry season is less than that in the wet season, and this can increase the depth of the acrotelmic peat zone. With the increase of acrotelmic zone, decomposition process occurs so rapidly that more CO_2 is produced. This condition usually lead to greater CO2 emissions in most peatlands (Elberling *et al*. 2011). In addition, higher soil water content will inhibit the diffusion of CO_2 and microbial activities. Hirano *et al.* (2007) reported that the results of measurements of the CO_2 emissions from tropical peat vary greatly depending on time and place, when the land begins its conversion (degree of humification), variations of locations (differences in micro climates such as soil temperature and air temperature), nutrient status and time variations in the measurements (change of season) so that seasons greatly affect the results of measurements of CO_2 emissions in a region. From the regression results of CO_2 flux and groundwater level fluctuation, the potential emissions generated per 1cm decrease in groundwater level can be predicted with the assumptions that CO_2 emissions only occur from the layer of 0 – 109 cm, not from the deeper layer, that all CO_2 emissions measured come from heterotrophic respiration, and CH_4 emissions are ignored/insignificant. Thus, for the CO_2 flux between

11.87 to 36.75 Mg ha^{-1} yr^{-1} and groundwater level between -49.6 to -109 cm, CO_2 emissions occured at 0.37 Mg ha^{-1} yr^{-1} of each 1 cm decrease in groundwater level.

The lost carbon from peatlands does not only from CO_2 emissions but also from DOC (dissolved organic carbon) (Aitkenhead and McDowell 2000) whose amount is greater than the amount of the actual CO_2 emissions. In some cases, the DOC flux may also contribute to the energy balance in the river and the transfer of nutrients from the terrestrial to aquatic ecosystems. Dissolved organic carbon (DOC) contained in the river water mainly comes from soil carbon so that when the level of carbon in the soil is high, it will release DOC into the river in large amounts.

CONCLUSIONS

The amounts of carbon stocks influenced the potential carbon emissions. The potential of carbon emissions was closely related to acrotelmic peat layer. Carbon stocks in acrotemic peat was in the range of 635 - 681 Mg C ha^{-1}. In every 1 cm decreased in groundwater level from -49.6 to -109 cm, CO_2 emissions increased by 0.37 Mg $ha^{-1}yr^{-1}$. The accuracy of prediction on the potential for carbon emissions with a reference to groundwater level is greatly determined by the intensity of the observations of groundwater level and measurements of CO_2 and CH_4 fluxes so that intensive and more observation points are required.

ACKNOWLEDGEMENTS

Author thanks to Swampland Agriculture Research Institute which funded partly of this research through the research activity of Environmentally Friendly Technology for Wetlands Management and to Dr. Ir. Haris Syahbuddin, DEA and Dr. Ir. Budi Kartiwa, DEA who granted us their permission to access the data on the groundwater level throughout the study.

REFERENCES

Agus F. 2009. Cadangan, emisi, dan konservasi karbon pada lahan gambut. Prosiding Seminar Dies Natalis Universitas Brawijaya ke 46. Malang. 31 Januari 2009 (in Indonesian).

Agus F. Maswar, MA Firmansyah, Jubaedah and S Nurzakiah. 2011a. Spatial Variation of Water Table Depth and CO_2 Emission from a Peat Soil in Indonesia. Final draft report of project "Reducing Emissions from All Land Uses (REALU II), Project. Indonesian Soil Research Institute, submitted to World Agroforestry Centre (ICRAF).

Agus F, K Hairiah and A Mulyani . 2011b. Pengukuran Cadangan Karbon Tanah Gambut. Petunjuk Praktis. World Agroforestry Centre-ICRAF, SEA Regional Office dan Balai Besar Penelitian dan Pengembangan Sumberdaya Lahan Pertanian (BBSDLP), Bogor, Indonesia. 58 p (in Indonesian).

Andriesse JP. 1988. Nature and Management of Tropical Peat Soils. Soil Resources, Management and Conservation Cervice. FAO Land and Water Development Division. FAO, Rome. 165p.

Aitkenhead JA and WH McDowell. 2000. Soil C:N ratio as a predictor of annual riverine DOC flux at local and global scales. *Global Biogeochem Cy* 14: 127-138.

Berglund Ö and K Berglund. 2011. Influence of water table level and soil properties on emissions of greenhouse gases from cultivated peat soil. *Soil Biol Biochem* 43: 923-931.

Chaudhari PR, DV Ahire, VD Ahire, M Chkravarty and S Maity. 2013. Soil bulk density as related to soil texture, organic matter content and available total nutrients of Coimbatore Soil. *Inter Sci Res Public* 3: 1-8.

Chimner RA and KC Ewel. 2005. A tropical freshwater wetland: II. Production, decomposition, and peat formation. *Wetlands Ecol and Manage* 13:671-684.

Couwenberg J, R Dommain and H Joosten. 2009. Greenhouse gas fluxes from tropical peatlands in south-east Asia. *Global Change Biol,* doi: 10.1111/j.1365-2486.2009.02016.x

Dinsmore KJ, UM Skiba, MF Billet and RM Rees. 2009. Effect of water table on greenhouse gas emission form peatland mesocosm. *Plant Soil* 318: 229-242.

Grøndahl L. 2006. Carbon dioxide exchange in the High Arctic – examples from terrestrial ecosystems. [Dissertation]. Dept. of Arctic Environmental, NERI and Institute of Geography, University of Copenhagen. National Environmental Research Institute, Roskilde, Denmark. 210 pp.

Gronlund A, H Atle, H Anders and PR Daniel. 2008. Carbon loss estimates from cultivated peat soils in Norway: a comparison of three methods. *Nutr Cycl Agroecosyst* 81: 157-167.

Elberling B, L. Askaer, CJ. Jørgensen, HP Joensen, M Kühl, RN Glud and FR Lauritsen. 2011. Linking soil O_2, CO_2, and CH_4 concentrations in a wetland soil: implications for CO_2 and CH_4 fluxes. *Environ Sci Technol* 45: 3393-3399. doi.org/10.1021/es103540k.

Hirano T, H Segah, T Harada, S Limin, T June, R Hirata and M Osaki. 2007. Carbon dioxide balance of a tropical peat swamp forest in Kalimantan, Indonesia. *Global Change Biol* 13: 412- 425.

Hirano T, J Jauhiainen, T Inoue and H Takahashi. 2009. Controls on the carbon balance of tropical peatlands. *Ecosystems* 12: 873-887.

Hooijer A, M Silvius, H Wösten and S Page. 2006. PEAT CO_2, Assessment of CO_2 Emission from drained peatlands in SE Asia. Wetland International and Delft Hydraulics report Q3943.

Hooijer A, S Page, JG Canadell, M Silvius, J Kwadijk, H Wosten and J Jauhiainen. 2010. Current and future CO_2 emissions from drained peatlands inSoutheast Asia. *Biogeosciences* 7: 1505-1514. doi : 10.5194/bg-7-1505-2010.

IAEA [International Atomic Energy Agency]. 1992. Manual on Measurement of Methane and Nitrous Oxide Emission from Agricultural Vienna: IAEA.

Ivanov KE. 1981. *Water movement in Mirelands*. [English translation by Thompson A and HAP Ingram]. Academic Press. London. 276 p.

Jauhiainen J, H Takahashi, JEF Heikkinen, PJ Martikainen and H Vasander. 2005. Carbon fluxes from a tropical peat swamp forest floor. *Global Change Biol* 11**:** 1788-1797.

Kuzyakov Y. 2006. Sources of CO2 efflux from soil and review of partitioning methods. *Soil Biol Biochem* 38: 425-448.

Laiho R. 2006. Decomposition in peatlands: Reconciling seemingly contrasting results on the impacts of lowered water levels. *Soil Biol Biochem* 38: 2011-2024.

Lafleur PM, Moore TR, Roulet NT, Frolking S. 2005. Ecosystem respiration in a cool temperate bog depends on peat temperature but not water table. Ecosystems 8: 619- 629.

Mer J and P Roger. 2001. Production, oxidation, emission and consumption of methane by soils: A review. *Europ Soil Biol* 37: 25-50.

Nurzakiah S, F Agus and H Syahbuddin. 2013. Ameliorant application on variation of carbon stock and ash content on peatland South Kalimantan. *J Trop Soils* 18: 11-16. DOI: 10.5400/jts.

Page SE, F Siegert, O Rieley, HDV Boehm, A Jaya and SH Limin. 2002. The amount of carbon released from peat and forest fire in Indonesia during 1997. *Nature* 420: 61-65.

Poss R, CJ Smith, FX Dunin and JF Angus. 1995. Rate of soil acidification under wheat in a semi-arid environment. *Plant Soil* 177: 85-100.

Sabiham S. 2010. Properties of Indonesian peat in relation to the chemistry of carbon Emission. *Proceedings* of International Workshop on Evaluation and Sustainable Management of Soil Carbon Sequestration in AsianCountries. Bogor, Indonesia Sept. 28-29.