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Review

Impact of land use change on greenhouse gases emissions in peatland: a review

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Abstract. Peatland is a significant storage of carbon and nitrogen on the earth's surface. This paper reviews the impacts of changes in water table level and mineral nitrogen associated with human activities on greenhouse gases emissions in tropical peatland and northern boreal and temperate peatland, and evaluates the optimal water table level to minimize greenhouse gases emissions. CH_4 emission increased significantly with the rise of ground water table level above -20 cm, and larger in northern peatland with plant mediated CH_4 emission than tropical peatland with plant mediated oxygen supply. However, forest disturbance by fire in tropical peatland increased CH_4 flux to the similar level in northern peatlands (8.3 mg C m^{-2} h^{-1}) due to stagnant surface water associated with the peat subsidence. On the other hand, CO_2 and N_2O emissions were significantly lager in tropical peatland than in northern peatland especially due to nitrogen fertilization. CO_2 and N_2O emissions increased with falling ground water table level below -40 to -80 cm (19 Mg C ha^{-1} y^{-1} for CO_2 and 700 kg N ha^{-1} y^{-1} for N_2O). Total global warming potential was significantly low in the ground water table level from -20 and -40 cm.

Keywords: carbon dioxide, ground water table, methane, nitrogen fertilizer, nitrous oxide, peatland

INTRODUCTION

Peatland is generated in wetland due to lower microbial decomposition than plant production. It has been developed at the organic matter accumulation rate of 100 to 200 kg C ha^{-1} y^{-1} for past 10 000 years, and the area is 4.4 million km^2, 4 million km^2 in northern boreal and temperate region and 0.4 million km^2 in tropical region (Yu *et al.*, 2010). Although the area occupies only 3% of terrestrial area, it contains 612 Gt C (562 Gt C in northern boreal and temperate peatland, 50 Gt C in tropical peatland), accounting for 25% of total soil carbon. However, peatland is different among regions. Northern boreal and temperate peatland is usually covered by small vegetation, sphagnum (bog) and carex and shrub (fen). On the other hand, tropical peatland is covered by trees (peat swamp forest). Northern boreal and temperate peat profile is composed of fine fibric vegetation materials, it makes fine pore system. On the other hand, tropical peat profile contains woody materials, it makes macropore system. Therefore, natural tropical peatland has high water permeability (Melling, 2016).

As peatland is composed of organic matter, peat decomposition produces a significant amount of greenhouse gases (GHGs); carbon dioxide (CO_2) aerobically, methane (CH_4) anaerobically and nitrous oxide (N_2O) both aerobically and anaerobically. Global warming potential (GWP) of CH_4 and N_2O is 28 and 265 times larger than CO_2, respectively, over a 100-year period, and those GWP values do not include climate-carbon feedbacks (IPCC, 2014), and N_2O is an important ozone-depleting substance emitted into the atmosphere (UNEP, 2013). Land use change due to disturbance of peatland by fire and clearance of vegetation and the development of peatland for agricultural land use by drainage, plowing and fertilization influence GHGs emissions (Page and Baird, 2016; van der Werf *et al.*, 2009). Falling ground water level increases CO_2 (Couwenberg *et al.*, 2010; Ishikura *et al.*, 2017, 2018), but decreases CH_4 emission (Couwenberg *et al.*, 2010; Ishikura *et al.*, 2018). CO_2 emission increases with the increase of temperature (Lloyd and Taylor, 1994). On the other hand, CH_4 emission is controlled by redox potential in soil (Takai, 1970). Therefore, CH_4 emission is influenced by the ground water level of peatland, the water permeability of peat soil. Lower

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permeable peat with finer pore system may produce higher CH_4 emission. Concerning N_2O emission, it increases with increase of organic matter decomposition and nitrogen fertilization application (Mu *et al.*, 2009). Although it is not clearly mentioned the relationship between N_2O emission and ground water table level, nitrogen mineralization with falling ground water level may increase N_2O emission. However, nitrogen fertilizer application inhibits microbial organic matter decomposition, although it stimulates plant root respiration (Zhou *et al.*, 2014).

These mentioned above suggest that CH_4, and N_2O emissions together with CO_2 emissions can be controlled by the ground water table level. The aim of this paper is to discuss about optimal ground water table level minimizing CO_2, N_2O and CH_4 emissions by reviewing the published papers.

Wetland is a major source of CH_4. Natural wetland emits 217 Tg CH_4 y^{-1}, accounting for 63% of total natural CH_4 emission, and rice paddy field emits 36 Tg CH_4 y^{-1} accounting for 11% of total anthropogenic CH_4 emission (IPCC, 2013). CH_4 is produced in reductive subsoil, transported to top soil by molecular diffusion or ebullition as gas bubbles, and emitted from the surface of the soil or the plant leaves through aerenchyma from the roots (Schütz *et al.*, 1989), but 90% of the CH_4 produced in soil is oxidized during the transportation in the rhizosphere, either by oxygen released from plant roots or by other electron acceptors such as Fe(III) and SO_4^{2-} (Kolb and Horn, 2012) . Ground water table level is major controlling factor of CH_4 emission (Couwenberg *et al.*, 2010; Ishikura *et al.*, 2018). CH_4 emission increases significantly when ground water table level rise above -20 cm, however, CH_4 emission was lower in tropical peatland than in northern boreal and temperate peatland (Couwenberg *et al.*, 2010) (Fig. 1). This is probably due to rapid fluctuation of ground water table level associated with better water permeability in tropical peatland (Takahashi, 1999). CH_4 is produced in anaerobic condition by methanogenic bacteria using acetate and $CO_2 + H_2$ after the sequential utilization of a series of electron acceptors of oxygen, NO_3^-, Mn(IV), Fe(III), and SO_4^{2-} (Takai, 1970). Therefore, peat soil with lower permeability, lower fertility and lower contamination of mineral soil produces CH_4 more easily due to less contain of electron acceptors. Recent global model uses 0.2 to 0.25 for the CH_4/CO_2 mole ratio in boreal natural peatland and 0.0052 in tropical natural peatland (Spahni *et al.*, 2011). This is because of strong oxidizing power in natural tropical peatland induced by the plant mediate oxygen supply through aerial roots (Adji *et al.*, 2014) and fast water flow in well water permeable peat layer (Kelly *et al.*, 2014). Peat fire or clear tree cutting increases CH_4 emission in tropical peatland due to the disappearance of plant mediate oxygen supply and the rise of ground water table level with peat subsidence, while drainage decreases CH_4 emission due to the fall of ground water table level (Adji *et al.*, 2014; Jauhiainen *et al.*, 2008) (Fig. 2). Maximum CH_4 flux was 8.3 mg C m^{-2} h^{-1} in burnt area. This is significantly large value within tropical peatland other than rice paddy fields (2.6-11 (Hadi *et al.*, 2005) and up to 26 mg C m^{-2} h^{-1} (Furukawa *et al.*, 2005)) and is similar to the maximum of CH_4 emission in boreal and temperate peatland (Couwenberg *et al.*, 2010).

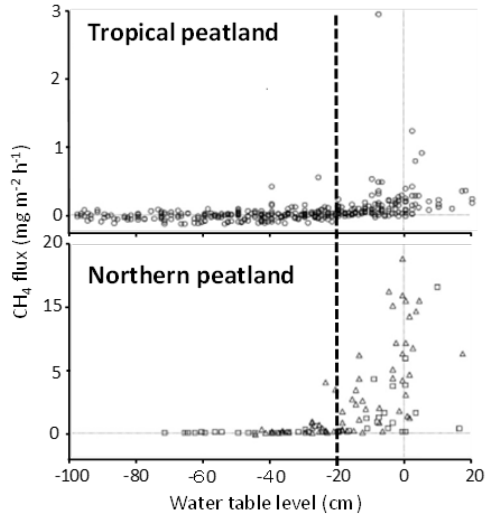

Fig. 1. Relationship between CH_4 flux and ground water table level. Dashed line shows -20 cm of ground water table level at which CH_4 flux clearly increased (modified from Couwenberg *et al.*, 2010).

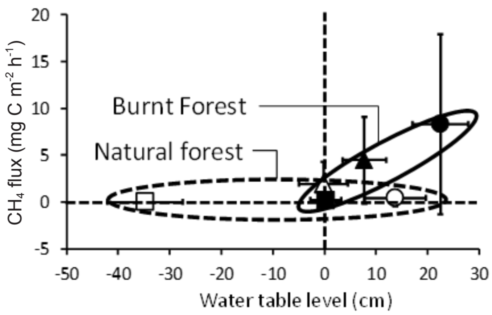

Fig. 2. Relationship between CH_4 flux and ground water table level in a tropical peatland (modified from Adji *et al.*, 2014).

CH_4 flux from tree stem in natural tropical peatland is reported, but the value was only 0.021 mg C m^{-2} h^{-1} (Pangala *et al.*, 2013). On the other hand, in northern boreal and temperate peatlands, pond vegetation accelerates CH_4 emission due to transportation through the aerenchyma. An observation in a thermokarst depression of 63.7 ha including pond, wet grassland, dry grassland near forest in Yakutia for four years from 2006 to 2009 showed that 96.3 ± 5.4% of total CH_4 emission was emitted from thermokarst pond (the area was 60.6 ± 19.2% of the total area) and plant mediated CH_4 emission from the pond vegetation accounted for 57.9 ± 23.2% of total CH_4 emission (Desyatkin *et al.*, 2014).

Natural wetland is not a source of N_2O, rather a sink of N_2O. This is because of slow N mineralization, low nitrification activity, and high denitrification activity in the anaerobic condition (Kolb and Horn, 2012). But, once peatland is drained and agriculturally used, the peatland emits N_2O significantly. Significantly large amount of N_2O emission more than 200 kg N ha^{-1} was recorded in NO_3-N accumulated upland fields in tropical peatland especially in wet season (Takakai *et al.*, 2006; Toma *et al.,* 2011) and 9 to 14 kg N ha^{-1} was found even in tundra peatland (Repo *et al.*, 2009). This is because of nitrogen application for crop production and incomplete denitrification with NO_3-N leaching (Kolb and Horn, 2012). N_2O emission from agricultural soil accounts for 34% of total anthropogenic N_2O emission of 6.9 Tg N y^{-1}, although N_2O emission from natural ecosystem is estimated to be 11.0 TgN y^{-1} (IPCC, 2013). Denitrification is the major N_2O production process in most soils, although N_2O is produced in nitrification process (Šimek *et al.,* 2002). Denitrification rate in soil is increased with the increases of NO_3^- content, available organic carbon content, temperature, soil moisture (Saggar *et al.*, 2013), and decrease of soil pH (Mukumbuta *et al.*, 2018). N_2O is produced as an intermittent product through the process of NO_3^- reduction to N_2 by nitrate respiration of denitrifers. Therefore, presence of NO_3^- and available organic carbon is indispensable for N_2O production in denitrification. N_2O is mainly produced in the range of water-filled pore space (WFPS) between 60 to 100%, because optimal WFPS for nitrification producing NO_3^- is around 60 while 100% of WFPS (water saturation) is optimal for denitirification (Linn and Doran, 1984). Peat soil has high amount of pore space, and drained and plowed agricultural peat soil may have ideal WFPS for nitrification and denitrification processes. Soil pH is also important for denitrification. The N_2O reductase is less active at low pH compared to other enzyme activities in denitrification process (McMillan *et al.*, 2016), which leads to increase of N_2O emission with increase of acidity in a Japanese Andosol (Mukumbuta *et al.*, 2018). Peat soil is acidic due to rich in organic acids, which can increase of N_2O emission especially in cropland.

Mu *et al.* (2014) shows that N_2O emission increased with the increase of CO_2 emission by peat decomposition using the 122 published data of N_2O and CO_2 emissions measured at forests, grasslands and croplands in northern and tropical peatlands. The emission data were obtained by closed chamber methods. However, some of peat decomposition (Rh, kg C ha^{-1} y^{-1}) was estimated from soil respiration (Rt, kg C ha^{-1} y^{-1}) including root respiration using an empirical equation, $Rh=10\exp(0.22+0.87\ln(Rt/10))$, proposed by Bond-Lamberty and Thomson (2010). It was shown that N_2O emission was significantly correlated with mineral N input (sum of application rate of nitrogen fertilizer and mineralized nitrogen estimated by dividing Rh by soil C/N ratio), ground water table level, and soil pH. However, data sets from tropical peatlands were only 12 from Malaysia and Indonesia. Therefore, newly published 30 data sets from tropical peatlands were added in this paper (Melling *et al.*, 2007; Takakai *et al.*, 2006; Toma *et al.*, 2011), total 152 data sets including 87 data from unfertilized northern peatland, 23 data from fertilized northern peatland, 26 data from unfertilized tropical peatland and 16 data from fertilized tropical peatland were obtained. In this paper, comparison between tropical peatland and northern boreal and temperate peatland was conducted in terms of the relations between N_2O and CO_2 emissions and the effect of fertilization on the emissions. Statistical analyses were performed with Excel Statistics version 5.0 (Esumi, Tokyo, Japan). The differences in the emissions between fertilization and unfertilization and between tropical peatland and northern boreal and temperate peatland were analyzed with a two-way analysis of variance (ANOVA) and Tukey test.

CO_2 emission was significantly higher in tropical peatland than northern boreal and temperate peatland, and increased with N fertilization significantly (3815 ± 2900 and 4822 ± 2313 kg C ha^{-1} y^{-1} in unfertilized and fertilized northern boreal and temperate peatland, respectively, and 7382 ± 3558 and 13001 ± 3027 kg C ha^{-1} y^{-1} in unfertilized and fertilized tropical peatland, respectively) (Fig. 3). N_2O emission increased with N fertilization significantly, especially in tropical peatland (4.93 ± 10.04 and 17.76 ± 21.15 kg N ha^{-1} y^{-1} in unfertilized and fertilized northern boreal and temperate peatland, respectively, and 8.08 ± 15.69 and 178.59 ± 218.28 kg N ha^{-1} y^{-1} in unfertilized and fertilized tropical peatland, respectively) (Fig. 4). Furthermore, in all peatlands, CO_2 and N_2O emissions increased with the fall of ground water table level, and much larger increase was found in nitrogen fertilized peatlands (Figs 5, 6). Increase of CO_2 emission with the fall of water table level was larger in tropical peatland than in northern boreal and temperate peatland, and maximum CO_2 emission of 19 Mg C ha^{-1} y^{-1} was found at -80 cm of water table level (Fig. 5). Increase of N_2O emission with the fall of water table level was distinct below -40 cm of water table level, and especially in tropical peatland, maximum N_2O emission of 700 kg N ha^{-1} y^{-1} was found in -60 to -70 cm of water table level (Fig. 6).

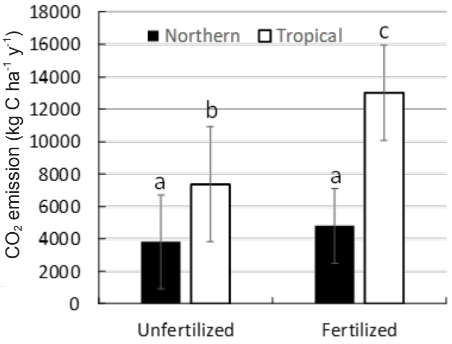

Fig. 3. Comparison of annual CO_2 emission with peat decomposition in terms of nitrogen fertilization and climate zone. Error bar reveals standard deviation. Different letters reveals significant difference among the treatments of both fertilization and climate zone (data compiled by Mu *et al.*, 2014 and combined with those from Melling *et al.*, 2007; Takakai *et al.*, 2006; and Toma *et al.*, 2011).

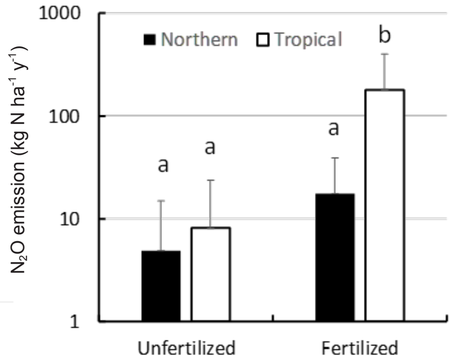

Fig. 4. Comparison of annual N_2O emission in terms of nitrogen fertilization and climate zone. Error bar reveals standard deviation. Different character reveals significant difference among the treatments of both fertilization and climate zone (data compiled by Mu *et al*., 2014 and combined with those from Melling *et al*., 2007; Takakai *et al*., 2006 and Toma *et al*., 2011).

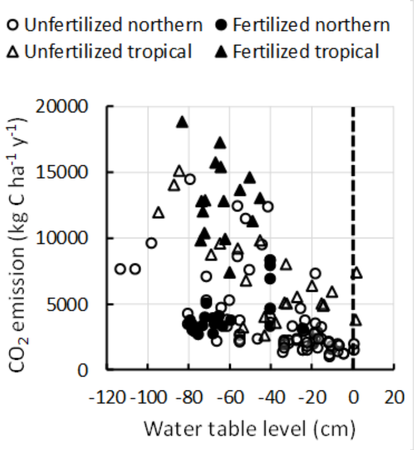

Fig. 5. Relationship between annual CO_2 emission and annual mean ground water table level in peatlands (data compiled by Mu *et al*., 2014 and combined with those from Melling *et al*., 2007; Takakai *et al*., 2006 and Toma *et al*., 2011).

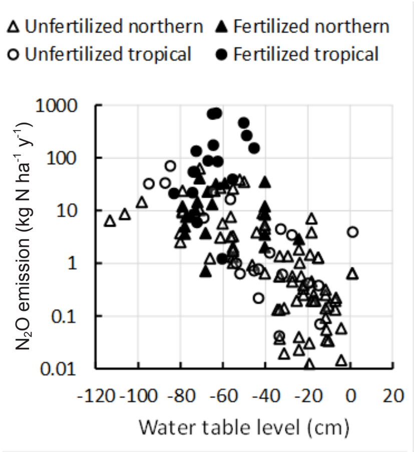

Fig. 6. Relationship between annual N_2O emission and annual mean ground water table level in peatlands (data compiled by Mu *et al*., 2014 and combined with those from Melling *et al*., 2007; Takakai *et al*., 2006 and Toma *et al*., 2011).

There was a significant relationship between mineral nitrogen input and N_2O emission (Fig. 7). This indicates that increase of peat decomposition with a fall of water table level and N fertilizer application increases N_2O emission.

In an upland field of tropical peatland where large N_2O emission was observed, there was a significant relationship between NO_3-N content in top soil and N_2O flux at more than 60%, of WFPS suggesting N_2O emission was caused by denitrification after mineralization and nitrification (Takakai *et al.*, 2006). Soil microbes which adapted to low pH of tropical peatland and obtained nitrate respiration ability, fungi (*Fusarium oxysporum* and *Neocosmospora vasinfecta*) (Yanai *et al.*, 2007) and bacteria (*Janthinobacterium*) (Hashidoko *et al.*, 2008), were identified.

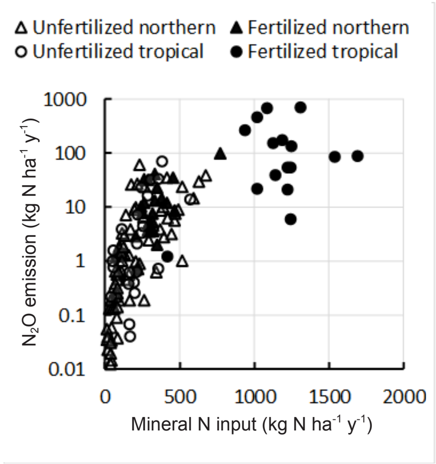

Fig. 7. Relationship between annual N_2O emission and annual mineral nitrogen input in peatlands (data compiled by Mu *et al*., 2014 and combined with those from Melling *et al*., 2007; Takakai *et al*., 2006 and Toma *et al*., 2011).

From the findings above, ground water table level is major controlling factor of CH_4 and N_2O emissions from peatlands. Ground water table level rising above -20 cm increases CH_4 emission. The increase of CH_4 emission is lager in northern boreal and temperate peatland than in tropical peatland due to higher water permeability in tropical peatland. However, loss of natural vegetation with aerial roots and peat subsidence by disturbance especially by fire in tropical peatland increases CH_4 emission significantly due to loss of plant mediated oxygen supply and decrease of redox potential under stagnant water on the soil surface. On the other hand, ground water level from -40 to -70 cm stimulates N_2O emission together with CO_2 emission. Nitrogen fertilizer application increases N_2O and CO_2 emissions significantly especially in tropical peatland. Overall emission data show the lowest emissions of CH_4 and N_2O are achieved in the range of -20 to -40 cm of ground water level. Figure 8 shows the mean and standard deviation of total GWP of CO_2, N_2O and CH_4 in three ranges of water table level, higher than -20 cm, from -20 to -40 cm and lower than -40 cm. The GWP (kg CO_2 ha^{-1} y^{-1})

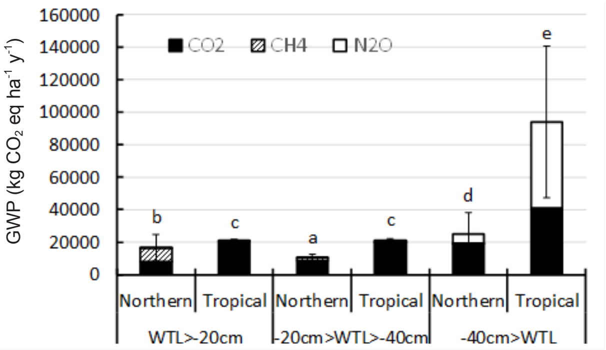

Fig. 8. Comparison of annual global warming potential (GWP) in terms of ground water table level (WTL) and climate zone. Error bar reveals standard deviation of total GWP. Different character reveals significant difference among the treatments of ground water table level and climate zone.

of each gas was obtained from the data of Fig. 1 for CH_4 and Fig. 5 for CO_2 and Fig. 6 for N_2O, using the factors reported by IPCC 2014, as GWP_{CO_2} = CO_2 emission (kg C ha^{-1} y^{-1})×44/12, GWP_{CH_4}=CH_4 emission (kg C ha^{-1} y^{-1}) ×16/12×28 and GWP_{N_2O}=N_2O emission (kg N ha^{-1} y^{-1}) ×44/28×265. Unit of CH_4 emission in Fig. 1 was converted to calculate GWP_{CH_4}. Northern boreal and temperate peatland showed the significantly lowest total GWP in the range of water table level from -20 to -40 cm, and tropical peatland showed that total GWP was significantly lower in the range of water table level from -20 to -40 cm than the water table level lower than -40 cm, and there was no significant difference of total GWP between the ranges of water table level higher than -20 cm and from -20 to -40 cm. However, total GWP was significantly higher in tropical peatland than in northern boreal and temperate peatland. In both tropical and northern boreal and temperate peatlands, contribution of CO_2 emission to total GWP was highest in the all ranges of water table level. CH_4 emission showed larger contribution in the higher range of water table level, and especially in northern boreal and temperate peatland, contribution of CH_4 emission was similar to that of CO_2 emission. On the other hand, contribution of N_2O emission was higher in the lower range of water table level, and especially in tropical peatland, contribution of N_2O emission was similar to that of CO_2 emission.

SUMMARY

Water table level from -20 cm to -40 cm was optimal to minimize CH_4, CO_2 and N_2O emissions in peatlands. Tropical peatland was lower in CH_4 emission than northern boreal and temperate peatland, however, stagnant surface water in subsided and fired tropical peatland induced high CH_4 flux. On the other hand, tropical peatland was higher in N_2O emission than northern boreal and temperate peatland. Falling ground water table level stimulated organic matter decomposition significantly, leading to increase of mineralized N resulting in increase of N_2O emission. Application of nitrogen fertilizer especially in tropical peatland increases N_2O emission significantly due to significant increase of organic matter decomposition.

Conflict of interest: The Authors do not declare conflict of interest.

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