Dissolved organic carbon and physicochemical variables of peat water in tropical peat swamp forests

S Sundari

1Botany Division, Research Center for Biology, Indonesian Institute of Sciences (LIPI), Jl. Raya Jakarta Bogor KM. 46 Cibinong Science Center, Cibinong 16911

E-mail: siti046@lipi.go.id

Abstract. Degradation of peatlands in Indonesia has been caused by fires, drainage, and deforestation of peat swamp forests. Fires release carbon dioxide (CO\textsubscript{2}) intensively but occasionally, whereas drainage enhances CO\textsubscript{2} emission from the soil and dissolves organic carbon (DOC) leaching through peat water flow. DOC was affected not only by peat degradation but also by the physicochemical variables of peat water. A study on DOC and physicochemical variables of peat water to investigate the effects of drainage and fires has been conducted in three tropical peat swamp forests of Central Kalimantan. They were a relatively intact peat swamp forest with little drainage (UF), a drained peat swamp forest (DF), and a drained, burnt peat swamp forest (DB). The DOC concentration was analyzed using a total organic carbon (TOC) analyzer, while physicochemical variables, including electrical conductivity (EC), pH, and inorganic nitrogen were measured using EC meter, pH meter, and ion analyzer, respectively. Research results showed that the highest DOC concentration was measured in DF, whereas the lowest DOC concentration was in DB. DOC was resulted from peat decomposition due to low pH, low C/N, and high EC conditions. These results indicate that DOC leaching through peat water flow may occur by drainage rather than fires.

1. Introduction
Tropical peat has been formed under swamp forests over millennia [1, 2]. However, peatland ecosystems have been devastated by logging, land development, and management since the 1970s [3]. This huge carbon pool is presently being disturbed on a large scale, and consequently, it has become vulnerable [4]. Peat degradation occurs most rapidly and extensively in Indonesia, where 47% of tropical peatlands are located [5]. Therefore, peat is degraded by fires, drainage, and deforestation of swamp forests [6-11].

Peat burning releases CO\textsubscript{2} intensively but occasionally, whereas drainage raises CO\textsubscript{2} emissions steadily through accelerated aerobic peat, and deforestation simply halts CO\textsubscript{2} uptake by trees. Therefore, under such anthropogenic pressure, tropical peatlands present the threat of switch from a role as a global carbon sink to a role as a huge carbon source to the atmosphere. Indonesia’s peatlands drained for agriculture and plantation productions (some of which have become abandoned and mismanaged areas) release about 2,000 Mt of CO\textsubscript{2} every year. Fires have been still largely used for land clearing and vegetation cropping, and repeatedly cause large CO\textsubscript{2} emissions almost every year [8].

Peat soils are a major source of dissolved organic carbon (DOC) to surface waters composed of an accumulation of dead plant materials [12, 13]. They are usually carbon (C) and nitrogen (N) rich, including inorganic nitrogen (NO\textsubscript{2}-N, NO\textsubscript{3}-N, NH\textsubscript{4}+-N) that affects C/N contents in the peat [12].
DOC is an important component of the carbon cycle within peat soils, and peat soil is a vital store of terrestrial carbon [14]. The DOC is significant in peatland carbon cycles because it represents a part of the C released from decomposing peat and plant tissue, and this is a part of the overall C cycle, CO₂ and methane (CH₄) [15]. DOC is defined as the organic matter that can pass through a filter (filters generally range in size of 0.25 μm). The DOC is the main form in which organic carbon is transported downwards into the subsoil, where it can be mineralized, stabilized, or further leached to the groundwater.

The DOC is an important part of ecosystem-scale carbon balances and in the transport of dissolved substances and trace metals [16, 17]. Besides, DOC plays many important ecological and geological roles both within peatlands and in downstream ecosystems, affecting acidity (pH), nutrient availability, metal mobility, which affect electrical conductivity (EC) and light penetration in aquatic habitats [18]. pH or power of hydrogen is an acidity level used for stating peat water acidity or basicity level. The pH of peat water shows the dissolved hydrogen ions contents. Meanwhile, the EC of peat water indicates the amount of metal mobility in the peat water.

Two primary sources of DOC to headwater streams are leached DOC from plants in throughfall and DOC derived from the decompositions of organic matter and plants within the soil [19]. Of these, DOC concentrations are typically highest in water within organic-rich upper layers of the soil profile and decline with depth [20, 21]. There are two major sets of drivers that control the production and transport of DOC. The first is the functions of biological and physical processes that release DOC and the retention processes such as microbial utilization and sorption. The second is hydrologic pathways in which water moves and retention times. The DOC pathway through forest stands results from DOC input through precipitation and throughfall, leaching through the forest floor and mineral soil, and is eventually exported from the forest ecosystems through groundwater discharge [15]. The DOC export is controlled by site hydrology [22, 23] and is generally greater from peatlands to downstream ecosystems [22]. Thus, any disturbance altering factors affecting DOC production or hydrology could potentially change the quantity and chemistry of exported DOC. Many peatlands are drained for forestry, agriculture, or peat extraction [24]. This process involves the construction of ditches, thereby increasing both peatland discharge and DOC export [25].

Besides, DOC impacts water quality in terms of color, taste, safety, and aesthetic value, as well as altering the acidity base and metal complexation characteristics of soil water and stream water. Together with the carbon losses, considerable nutrient export may occur as well, potentially increasing impacts on aquatic diversity downstream [26]. Peat degradation may affect the DOC leaching through peat water flow and physicochemical variables of peat water, including electrical conductivity, pH, inorganic nitrogen, etc. To date, knowledge based on field data has not yet been accumulated well. This research was conducted to investigate the effects of drainage and fires on the dissolved organic carbon and physicochemical variables of peat water in a relatively intact peat swamp forest in Sebangau, a drained peat swamp forest and a drained, burnt peat swamp forest in Kalampangan, Central Kalimantan.

2. Materials and methods

2.1. Study sites

Dissolved organic carbon (DOC) and physicochemical variables were measured in three tropical peat swamp forests in the upper catchment of the Sebangau River, near Palangkaraya, the capital city of Central Kalimantan Province, Indonesia. In Central Kalimantan, a large peatland area was deforested and drained during the late 1990s mainly to develop farmlands according to a national project, Mega Rice Project (MRP). However, the MRP was revoked in 1999. Consequently, vast devastated peatlands were left [3]. One site was a relatively intact peat swamp forest with little drainage (UF) in the Setia Alam area. The others were a drained peat swamp forest (DF) and a drained, burnt peat swamp forest (DB) in the Kalampangan area.

The UF site had been logged selectively until the late 1990s. It was designated as a National Park in 2006. Although no large canal was excavated in this area, a network of small canals that had been built for illegal logging remained, influencing the forest hydrology [27]. Dominant tree species
included *Tetramerista glabra*, *Calopyllum* sp., *Shorea* sp., *Combretocarpus rotundatus*, *Palaquium* sp., *Buchanania sessilifolia*, *Syzygium* sp., *Dactylocladus stenostachys*, *Dyera costulata*, *Ilex cymosa*, *Tristaniopsis obovate* and *Dyospyros* sp. [28]. Rich shrubbery, including young trees of the dominant species, grew in the understory. The soil surface was covered with thick tree debris, mainly comprising leaf litter. Few herbaceous plants existed on the soil surface [29]. The peat depth was 2–3 m.

The DF site and DB site were remaining forests in Block C of the MRP. The forests had also been selectively logged until the end of the 1990s. Dominant tree species were *Combretocarpus rotundatus*, *Cratoxylum arborescens*, *Palaquium* sp., *Shorea* sp., and *Dyera costulata*. A large canal (25 m wide × 3.5–4.5 m deep) excavated in 1996 and 1997 has been functioned to facilitate drainage of the forest [27]. In June–August 2005, the canal was blocked at several points by small dams to facilitate the hydrological restoration of the devastated ex-MRP area [30]. The DB site had experienced repeated fires and was characterized by vegetation regrowth dominated by fern. The peat depth at this site was around 3-4 m. The sites are shown in Figure 1.

![Figure 1](image-url)

**Figure 1.** Study sites: a relatively intact peat swamp forest with little drainage (UF), a drained peat swamp forest (DF), and a drained, burnt peat swamp forest (DB) in Central Kalimantan [31, 32].

2.2. Dissolved organic carbon
There were three wells at each site (UF, DF, and DB sites). The three wells in the UF site were named by UF1, UF2, and UF 2. In the meantime, the three wells in the DF site were named by DF1, DF2, DF3. The three wells in the DB site were named by DB1, DB2, and DB3. Peat water was collected from each well at the three sites and kept in 50 mL plastics bottles. This method was suitable for groundwater sampling in the peatland [33]. The samples of peat water at each site were stored in a freezer below -18°C. They were thawed at room temperature and filtered through glass microfiber filters with a diameter of 25 mm (Whatman GF/F), in which organic materials were removed using a muffle furnace (1 hour at 285°C) before DOC concentrations analysis. Filtered samples were analyzed using a total organic carbon analyzer (TOC-VCPh, SHIMADZU) to determine DOC concentrations. The DOC analysis using a TOC analyzer for each sample was conducted by three times repetitions.

2.3. Physicochemical variables
The peat water samples from each well in each site were measured directly in the field for electrical conductivity (EC) and pH using EC meter (HORIBA B-173) and compact pH meter (HORIBA B-212), respectively [33]. Then, the samples were stored in the freezer. They were thawed at room temperature and filtered through glass microfiber filters with a diameter of 25 mm (Whatman GF/F),
in which organic materials were removed using a muffle furnace (1 hour at 285°C). Filtrated samples were analyzed using ion analyzer (IA-300, TOA DKK) to determine ion concentrations. Nitrite-nitrogen (NO2-N), ammonium-nitrogen (NH4-N), and nitrate-nitrogen (NO3-N) were calculated after the ion analysis. The summation of them was calculated as dissolved inorganic nitrogen (DIN). Besides, C/N was calculated by dividing DOC with inorganic nitrogen (NO2-N, NO3-N, NH4-N). The physicochemical variables measurements for each sample were conducted by three times repetitions.

3. Results and discussions

3.1. Dissolved organic carbon

The highest DOC was measured in a drained peat swamp forest in the Kalampangan area, followed by a relatively intact peat swamp forest with little drainage in the Setia Alam area and a drained, burnt peat swamp forest in Kalampangan. The DOC concentrations are shown in Table 1.

| Sites                                      | Relatively intact peat swamp forest with little drainage (UF) | Drained peat swamp forest (DF) | Drained, burnt peat swamp forest (DB) |
|--------------------------------------------|-------------------------------------------------------------|--------------------------------|----------------------------------------|
| [DOC] mgL⁻¹ ± SE                           | 37.46 ± 37                                                  | 65.38 ± 24                     | 24.54 ± 45                             |

The DF and DB sites had been drained in the late 1990s for Mega Rice Project, and the DB site was burnt more than three times after drainage, in 1997, 2002, 2009, and 2015. Mostly in the El Nino year, when the dry season was much longer than the rainy season, fires occurred in this area, burning the soil and vegetation, also affected the peat water. Fires drastically change the biological and physical properties of the land surfaces, affecting many biological and hydrological processes [34], whereas drainage to lower groundwater level (GWL) potentially enhances peat decomposition steadily [35, 36].

In the DB site, DOC concentration was the lowest among the sites because of the reduction of organic matter decomposition in burned soil and DOC dilution. The reduction of soil organic matter would decrease the production of DOC, and much water on relatively flat peat in the DB site would increase the dilution of DOC. The fires significantly decreased the DOC concentration about one month after the fire in the spruce forest because the production of black carbon (charcoal) from the burned soil would affect the DOC dynamics on the land surface. It is likely that the black carbon from the burned soil adsorbed DOC had contributed to the decrease of the DOC concentration in the leached water from the soil layer [37]. DOC remained low at the burnt drained peat swamp forest, although the fires occurred a long time before. It was suggested that the effect of several fires decreased the DOC concentrations.

However, in the DF site, DOC concentration was the highest among the sites because the groundwater level lowered by drainage could directly enhance the production of DOC by increasing the aerobic zone. The DOC was produced during the decomposition of organic matter in soil. It could also be used as a substrate for microbial activity, which involves the further production of DOC resulted in higher DOC production [38]. DOC concentration in the pore water of drainage peatland in southern Quebec increased because of elevated DOC production. It was associated with higher plant productivity and larger water table fluctuations after drainage [39]. Drainage of peat bogs in eastern Quebec and New Brunswick increased runoff, and DOC export led to increased DOC concentration in peat pore water. The DOC concentrations often become highest in periods under warm, dry conditions, when DOC has time to accumulate [40].

DOC concentration in the UF site was lower than in the DF site, but it was higher than in the DB site. The UF site condition remained better than the DF site and DB site. Although no large canal was excavated in this area, a network of the small canal that had been built for illegal logging remained, influencing the forest hydrology [27]. The vegetation and soil are still preserved in the UF site. The
number of big trees with tall stands was also found in this site, so peat decomposition was less than in the DF site. As the DOC production was affected by peat decomposition and resulted in DOC concentration, therefore DOC concentration in the UF site was lower than that in the DF site.

3.2. Physicochemical variables
Physicochemical variables of peat water included electrical conductivity, pH, inorganic nitrogen (NO₂⁻-N, NO₃⁻-N, NH₄⁺-N), dissolved organic nitrogen (DIN), and C/N which was measured at each site. Correlation matrix of DOC, EC, pH, nitrate ion (NO₃⁻), and C/N is shown in Table 2.

| Variables | DOC | EC | pH | NO₃⁻ |
|-----------|-----|----|----|-------|
| EC        | 0.23|     |    |       |
| pH        | -0.11| -0.17|    |       |
| NO₃⁻      | 0.11| 0.41⁺| 0.02|       |
| C/N       | -0.01| 0.06| -0.07| -0.17ᵇ |

⁺: p<0.01
ᵇ:  p<0.05

![Figure 2. Relationship between DOC and EC, DOC and C/N.](image1)

![Figure 3. Relationship between DOC and pH, EC and NO₃⁻.](image2)
DOC had a positive correlation with EC and nitrate ion (NO$_3^-$), but it had a negative correlation with pH and C/N. EC had a negative correlation with pH, but it had a positive correlation with NO$_3^-$ and C/N. Although pH had a negative correlation with C/N, it had a positive correlation with C/N. NO$_3^-$ also had a negative correlation with C/N. The C/N was determined by dividing DOC concentration with inorganic nitrogen (NO$_2^-$-N, NO$_3^-$-N, NH$_4^+$-N). It indicated that DOC increased with the increase of EC. However, it increased with the decrease of C/N and pH. All the correlations could be supported by the relationship between DOC and EC, DOC and C/N, DOC, and pH, which are shown in Figures 2 and 3.

The highest DOC concentration was measured in the DF site because the decomposition extent was higher than other sites. EC was related to the nitrification process by aerobic bacteria producing NO$_3^-$. From the correlation and relationship above, the DOC production was resulted during the decomposition of organic matter in peat soil and leached through peat water flow in the condition of low pH, low C/N, and high C/N.

4. Conclusion

DOC concentration was higher in the drained peat swamp forest in the Kalampangan area than in other sites. However, DOC concentration was lower in the drained, burnt site peat swamp forest in the Kalampangan area than in other sites. The DOC was produced by peat decomposition because of low pH, low C/N, and high EC conditions. These results suggested that the DOC leaching might occur by drainage rather than fires.

Acknowledgment

This work was supported by the National Project of the Indonesian Institute of Sciences (LIPI). The author thanks Kitso Kusin and CIMTROP staff, the University of Palangka Raya for fieldwork, and also all the people who have helped for fieldwork and laboratory analysis.

5. References

[1] Dommain R, Couwenberg J and Joosten H 2011 Development and carbon sequestration of tropical peat domes in south-east Asia: links to post-glacial sea-level changes and Holocene climate variability Quaternary Sci. Rev. 30: 999-1010
[2] Page S E, Rieley J O, Shotyk O W and Weiss D 1999 Interdependence of peat and vegetation in a tropical peat swamp forest Philos. T. Roy. Soc. B 354:1885-1897
[3] Rieley J and Muhamad N Z 2002 Impact of inappropriate land use change on the peat swamps of Central Kalimantan Peatland Inter. 1:24-27
[4] Canadell J G, Pataki D E, Gifford R, Houghton R A, Luo Y, Raupach M R, Smith P and Steffen W 2007 Saturation of the terrestrial carbon sink. Terrestrial ecosystems in a changing world edited by Canadell, J G, Pataki D E and Pitelka, L F (Berlin Heidelberg: Springer-Verlag) pp 59-78
[5] Page S E, Rieley J O and Banks C J 2011 Global and regional importance of the tropical peatland carbon pool Global Change Biol. 17: 798-818
[6] Couwenberg J Dommain R and Joosten H 2009 Greenhouse gas fluxes from tropical peatlands in south-east Asia Global Change Biol. 16: 1715-1732
[7] Herougualc'h K and Verchot L V 2011 Stocks and fluxes of carbon associated with land use change in Southeast Asian tropical peatlands: A review Global Biogeochem. Cy. 25, GB2001, doi: 10.1029/2009GB003718
[8] Hooijer A, Page S, Canadell J G, Silvus M, Kwadijl J, Wosten H and Jauhiainen J 2010 Current and future CO$_2$ emissions from drained peatlands in Southeast Asia Biogeosci. 7, 1505-1514
[9] Murdiyarso D, Hergoualc'h K and Verchot L V 2010 Opportunities for reducing greenhouse gas emissions in tropical peatlands P. Natl. Acad. Sci. USA 107: 19655-19660
[10] Page S E, Siegert F, Rieley J O, Boehm H D V, Jaya A and Limin S 2002 The amount of carbon released from peat and forest fires in Indonesia during 1997 Nature 420: 61-65
[11] Van der Werf G R, Dempewolf J, Trigg S N, Randerson J T, Kasibhatla P S, Gigliog L, Murdiyarso D, Peters W, Morton D C, Collatz G J, Dolman A J and Defries R S 2008
Climate regulation of fire emissions and deforestation in equatorial Asia. *P. Natl. Acad. Sci. USA*, **105**: 20350-20355

[12] Urban N R, Baily S E and Eisenreich S J 1989 Export of dissolved organic carbon and acidity from peatlands *Water Resources Research* **25**: 861-862

[13] Aitkenhead J A, Hope, D and Billet M F 1999 The relationship between dissolved organic carbon in stream water and soil organic pools at different spatial scale *Hydrological Proc.* **13**: 1289-1302

[14] Gorham E 1991 Northern peatlands: role in the carbon cycle and probable responses to climate warming *Ecological App*. **1**: 182-195

[15] Moore T R and Dalva M 2001 Some control on the release of dissolved organic carbon by plant tissue and soils *Soil Sci.* **166**: 38-47

[16] McDowell W H 1985 Kinetics and mechanisms of dissolved organic carbon retention in headwater stream *Biogeochem*. **1**: 329-352

[17] Worral F, Parker A and Johnson A C 1997 A study of adsorption kinetics of isoproturon on soil and subsoil: the role of dissolved organic carbon *Chemosphere* **34**: 87-97

[18] Steinberg P D and Rillig M C 2003 Differential decomposition of arbuscular mycorrhizal fungal hyphae and glomalin *Soil Biol. and Biochem.* **35**: 191-194

[19] Thurman E M 1985 *Organic Geochemistry of Natural Waters* (Dordrecht: Kluwer Academic Publishers Group) p 497

[20] Boyer E W, Hornberger G M, Bencala K E and McKnight D M 2000 Effects of asynchronous snowmelt on flushing of dissolved organic carbon a mixing model approach *Hydrological Proc.* **14**: 3291-3308

[21] Worral F, Burt T P, Jaeban R Y, Wartubon J and Schedden R 2002 Release of dissolved organic carbon from upland peat *Hydrological Proc*. **16**: 3487-3505

[22] Hinton M J, Schiff S L and English M C 1997 The significance of storm for the concentration and export of dissolved organic carbon from two Precambrian Shield catchments *Biogeochem*. **36**: 67-88

[23] Pastor S, Sholin J, Bridgham S D, Updegraff K, Harth C, Weishampel P and Dewey B 2003 Global warming and the export of dissolved organic carbon from boreal peatlands *Oikos* **100**: 380-386

[24] Joosten H and Clarke D 2002 *Wise use of mires and peatlands—background and principles including a frame work for decision-making*. Ed. Heathwaite A L and Göttlich Kh, (Saarijarvi: International Mire Conservation Group and International Peat Society) pp 25-36

[25] Van Seters T E and Price J S 2002 Towards a conceptual model of hydrological change on an abandoned cutover bog, Quebec *Hydrological Proc*. **16**: 1965-1981

[26] Waldron S, Flowers H, Arlaud C, Bryant C and McFarlane S 2008 The significance of organic carbon and nutrient export from peatland-dominated landscapes subject to disturbance *Biogeoosciences Discuss*., **5**: 1139-1174

[27] Page S, Hoscilo A, Wosten H, Jauhiainen J, Silvius M, Rieley J, Ritzema H, Tansey K, Graham L, Vasander H and Limin S 2009 Restoration Ecology of Lowland Tropical Peatlands in Southeast Asia: Current Knowledge and Future Research Directions *Ecosystems* **12**: 888-905

[28] Tuah S J, Jamal Y M and Limin S 2003 Nutritional characteristics in leaves of plants native to tropical peat swamps and heath forests of Central Kalimantan, Indonesia *Tropics* **12**: 221-245

[29] Jauhiainen J, Takahashi H, Heikkinen J E P, Martilainen P J and Vasander H 2005 Carbon fluxes from a tropical peat swamp forest floor *Global Change Biol*. **11**: 1788-1797

[30] Jauhiainen J, Limin S, Silvennoinen H and Vasander H 2008 Carbon dioxide and methane fluxes in drained tropical peat before and after hydrological restoration *Ecology* **89**: 3503-3514

[31] Hirano T, Segah H, Kusin K, Limin S, Takahashi H and Osaki M 2012 Effects of disturbances on the carbon balance of tropical peat swamp forests *Global Change Biol*. **18**: 3410-3422

[32] Sundari S, Hirano T, Yamada T, Kusin K and Limin S 2012 Effect of groundwater level on soil respiration in tropical peat swamp forests *Journal of Agri. Meteorol*. **68**(2): 121-134
[33] Sundari S 2012 Soil respiration and dissolved organic carbon efflux in tropical peatlands. [Dissertation] (Sapporo: Hokkaido University) pp 24-44

[34] Bayley S E and Schindler D E 1991 The role of fire in determining stream water chemistry in northern coniferous forests. *Ecosystem experiments Scope 45* ed HA Mooney, E Medina, DW Schindler, E Dschulze and BH Walker (Chichester: John Wiley and Sons) pp 141-165

[35] Furukawa Y, Inubushi K, Ali M, Itang A M and Tsuruta H 2005 Effect of changing groundwater levels caused by land-use changes on greenhouse gas fluxes from tropical peatlands *Natur. Cycl. Agroecosys.* 71: 73-91

[36] Melling L, Hatano R and Goh K J 2005 Soil CO₂ flux from three ecosystems in tropical peatland of Sarawak, Malaysia *Tellus* 57B: 1-11

[37] Shibata H, Petrone C K, Hinzman L D and Boone R D 2003 Effect of fire on dissolved organic carbon and inorganic solutes in spruce forest in the permafrost range of interior Alaska *Soil Sci. Plant Nutr.* 49: 25-29

[38] Bengtson P and Bengtsson G 2007 Rapid turnover of DOC in temperate forests accounts for increased CO₂ production at elevated temperatures *Ecol. Lett.* 10: 783-790

[39] Strack M, Kellner E and Waddington J M 2008 Spatiotemporal variability in peatland biogeochemistry *Global Biogeochem. Cy.* 19, GB1003, doi: 10.1029/2004GB002330

[40] Glatzel S, Kalbitz K, Dalva M and Moore T 2003 Dissolved organic matter properties and their relationship to carbon dioxide efflux from restored peat bogs *Geoderma* 113: 397-411