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学 位 論 文 題 名

Soil respiration and dissolved organic carbon efflux in tropical peatlands

（熱帯泥炭池における土壌呼吸と溶存炭素流出）

学位論文内容の要旨

Tropical peatlands store soil carbon up to 15-19% of global peat carbon. That huge carbon pool is presently being disturbed on a large scale by land development and management, and has consequently become vulnerable. Peat degradation occurs most rapidly and massively in Indonesia's peatlands because of fires, drainage and deforestation of swamp forests. Fire releases carbon dioxide (CO_2) intensively but occasionally, and drastically changes the biological and physical properties of the land surface, affecting many biological and hydrological processes. Drainage to lower groundwater level (GWL) potentially increases CO_2 release from soil through the enhancement of aerobic peat decomposition, and deforestation simply halts CO_2 uptake by trees. Under such circumstances, tropical peatlands would release a huge amount of carbon from soil ecosystems through soil CO_2 efflux or soil respiration (RS), which is a major carbon source to the atmosphere, and dissolved organic carbon (DOC) outflow by groundwater discharge. The DOC flux is important on a watershed scale through river flow. The main objective of the study is to investigate the effects of disturbances by drainage and fires on carbon loss from soil ecosystems in tropical peatlands by CO_2 emissions to the atmosphere and by DOC leaching along with groundwater flux. To achieve the objective, RS and DOC flux were measured for more than one year in undrained and drained peat swamp forests (UF and DF sites) in Central Kalimantan, Indonesia. In addition, DOC flux was measured in a burnt drained area (DB site). Using such field data, RS and DOC flux in tropical peatland ecosystems were assessed, and the effects of disturbances on them were investigated.

The RS was measured continuously for more than one year between 2004 and 2006 using automated chamber systems, with consideration of microtopography, at the UF and DF sites. The system consisted of six chambers, a programmable data logger, an infrared CO_2 analyzer, an air pump and some electric parts to switch airflow between the analyzer and chambers. Soil temperature and GWL were measured using thermocouple thermometers and water level loggers, respectively, at both sites. Precipitation was measured on the tower at the DF site using a tipping-bucket rain gauge. The annual sum of precipitation was 2620 mm y^{-1} in 2005, which was almost equivalent to the mean of 2540 mm y^{-1} obtained over nine years, whereas the seasonal pattern of precipitation differed in 2005 from the mean pattern. In 2005, GWL peaked in late February and continued to decrease through late September, when it increased rapidly with the onset of the rainy season at both sites. At the UF site, the minimum and maximum GWLs were -0.63 m and 0.27 m, respectively, in 2005. At the DF site, they were -1.24 m and -0.11 m, respectively, in 2005. Daily mean soil temperature varied between 24°C and 28°C. In analyses, daily mean RS dataset for 2005 was specifically used at both sites. At the UF site, seasonal variation in daily mean RS showed a distinct seasonal variation with large decrease under flooded conditions and limited variation with sharp decrease when GWL was higher than about 0.05 m. However, RS at the DF site remained almost constant throughout the year. The RS was controlled mainly by local hydrology. In the UF site, RS decreased sharply under flooded conditions because of anoxia. In contrast, in the DF site, with its lower GWL, RS showed a quadratic relationship with GWL and gradually increased as GWL decreased when GWL was lower than about -0.8 m, which was caused chiefly by the enhancement of peat decomposition. These relationships indicate that lowering GWL by drainage increased RS, whereas annual RS was larger in the UF site (1347 gC m^{-2} y^{-1}) than in the DF site (1225 gC m^{-2} y^{-1}) in 2005. These facts do not support the inference that RS is increased by

drainage, although peat decomposition is expected to be larger at the DF site. The difference in annual RS in 2005 was probably attributable to higher forest productivity in the UF site. Using the relationships, daily RS was estimated continuously from GWL until the end of 2011 for both sites.

The DOC flux through groundwater was evaluated at the UF, DF and DB sites. It was determined by multiplying DOC concentration by groundwater flux. Groundwater was sampled every two weeks and DOC concentration was analyzed using a total organic carbon (TOC) analyzer. The groundwater flux was estimated using a single tank model from evapotranspiration and precipitation, which were measured at each site. Evapotranspiration was measured using the eddy covariance technique. Then, specific yield and run-off coefficient at each site were given as adjustment parameters. The specific yields were determined using relationships between precipitation and GWL. In order to evaluate the accuracy of the model, GWL was measured continuously using water level loggers at each site from July 2010 to January 2012, and the period of June and August was defined as the dry season in 2011. The GWL ranged from -0.53 to 0.18 m, from -1.13 to -0.30 m, and from -0.50 to 0.12 m, respectively, at the UF, DF and DB sites. The lowest GWL was measured at the DF site. The DOC concentration ranged from 6.41 to 54.03 mg L^{-1}, from 13.42 to 78.61 mg L^{-1}, and from 10.83 to 38.48 mg L^{-1}, respectively, at the UF, DF and DB sites. The highest DOC concentration was measured at the DF site. The DOC concentration was higher in the dry season than in the wet season at each site. The highest value was similar to a boreal peatlands. The seasonal variation was probably caused by enhanced peat decomposition during the dry season. The RMSEs of estimated GWL by the tank model were 0.14, 0.11 and 0.10 m, respectively, for the UF, DF and DB sites. The daily groundwater flux ranged from 0.59 to 3.19 mm d^{-1}, from -1.43 to 10.37 mm d^{-1} and from 0.40 to 2.52 mm d^{-1}, respectively, at the UF, DF and DB sites. The highest value was obtained at the DF site, suggesting a drainage effect. Cumulative DOC flux in 2010 for six months at the UF, DF and DB sites were estimated at 14.45, 52.01 and 6.51 gC m^{-2}, respectively. Annual DOC flux in 2011 at the UF, DF and DB sites were 32.87, 93.82 and 14.03 gC m^{-2} y^{-1}, respectively. These results suggest that the effect of drainage was larger than that of fires on the export of DOC through groundwater flow.

Carbon loss from soil ecosystems in tropical peatlands was assessed by the summation of RS and DOC flux. In order to estimate it in the UF and DF sites from July 2010 to December 2011, RS was calculated from GWL using an empirical model, which was made using field data in 2004 and 2005. Cumulative RS in 2010 for six months at the UF and DF sites were estimated at 599 and 640 gC m^{-2}, respectively. Annual RS in 2011 at the UF and DF sites were 1427 and 1256 gC m^{-2} y^{-1}, respectively. As a result, total carbon losses from soil ecosystems in the UF and DF sites were summed up to 613 and 692 gC m^{-2}, respectively, for six months in 2010, and 1460 and 1350 gC m^{-2} y^{-1}, respectively, in 2011. Comparison between RS and DOC flux showed that the contribution of RS to the total carbon loss from soil ecosystems was much higher than that of DOC flux. Total carbon loss from soil ecosystems was larger at the DF site than at the UF site in 2010, although it was larger at the UF site in 2011. The discrepancy in carbon loss from soil ecosystems between 2010 and 2011 was due to interannual variation in GWL that affected RS. In 2010, a La Nina year, GWL was very high for a long period. The RS decreased under anoxic conditions created by water saturation at the UF site, whereas RS in surface soil and litter decomposition enhanced under moist conditions at the DF site. In contrast, in 2011, GWL decreased sharply during the dry season. The RS was greater at the UF site when GWL decreased after flooding, it occurred when GWL dropped just below the surface. However, RS decreased in surface soil and litter at the DF site mainly because of desiccation.

学位論文審査の要旨

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本論文は図 18，表 6，引用文献 115 を含む 60 頁の英文論文であり，参考論文 1 編が添えられている。

東南アジアを中心に分布する熱帯泥炭には，地球上の泥炭に含まれる土壌炭素の 15～19%が存在しており，巨大な量の炭素を蓄えている。しかし現在では，農業開発などによる大規模撹乱のため，泥炭の脆弱性が高まっている。排水は地下水位（GWL）を低下させ，泥炭の好気的分解を促進し，土壌からの CO_2 放出を増加させる。また，地下水の流動にともない，溶存態炭素（DOC）の流出も生じる。本研究の目的は，熱帯泥炭土壌からの炭素損出を定量化するとともに，排水などの環境撹乱が炭素損出に与える影響を明らかにすることである。そのため，インドネシア中部カリマンタン州の熱帯泥炭地の撹乱程度が異なる 3 つの生態系（未排水の泥炭林（UF），排水された泥炭林（DF），排水後に火災によって焼失した泥炭林跡地（DB））において，1 年以上にわたり土壌呼吸速度（RS）と DOC フラックス（流出量）を測定した。

UF サイトと DF サイトで 2005 年を中心に自動開閉チャンバーを用いて RS を連続測定した。2005 年の GWL の範囲は，UF サイトと DF サイトでそれぞれ-0.63～0.27，-1.24～-0.11 m であった。UF サイトでは RS に明瞭な季節変化が認められ，GWL が 0.05 m 以上の湛水条件で RS が大きく低下した。このような RS の低下は，土壌中の酸素が不足し，泥炭の好気分解が抑制されたことによると考えられる。一方，湛水条件にならなかった DF サイトでは，RS の季節変化は小さかったが，GWL と RS の間の関係は凹型の 2 次曲線で近似でき，GWL が-0.8 m 以下になると RS が上昇する傾向がみられた。これらの結果は，GWL の低下が泥炭の分解を促進することを示しているが，RS の 2005 年の年間値は UF サイトで 1347，DF サイトで 1225 gC m^{-2} y^{-1}

となり，GWL が高い未排水の泥炭林の方で大きくなった。この理由は，森林の光合成に強く関連した根呼吸の違いによると考えられる。

水の流動にともなう DOC フラックスは，2010 年 7 月～2011 年 12 月に DB を含む 3 サイトで観測された。DOC フラックスは水の DOC 濃度に地上水あるいは地下水の流量を乗じて計算した。各サイトで 2 週間おきに地下水を採取し，TOC 分析計で DOC 濃度を測定した。また，雨季には地上水の DOC 濃度も測定した。水の流量は，降水量，蒸発散量，GWL および土壌の比産出量から，タンクモデルを用いて推定した。UF，DF，DB サイトの GWL は，それぞれ-0.53～0.18，-1.13～-0.30，-0.50～0.12 m であり，DF サイトで最も低かった。地下水の DOC 濃度は，3 サイトでそれぞれ 6.4～54.0，13.4～78.6，10.83～38.5 mg L^{-1} であり，DF サイドで高かった。また，3 サイトともに DOC 濃度は乾季で高かったが，これは乾季に泥炭の好気分解が促進されたためだと考えられる。地下水流量は，3 サイトでそれぞれ 0.59～3.19，-1.43～10.4，0.40～2.52 mm d^{-1} であり，排水路の影響を受けた DF サイトで大きかった。2010 年 7 月～12 月および 2011 年の累積 DOC フラックスは，UF サイトで 14.5，32.9，DF サイトで 52.0，93.8，DB サイトで 6.5，14.0 gC m^{-1} となり，排水された泥炭林（DF サイト）で最大となった。

DOC フラックスの観測期間に合わせて，UF サイトと DF サイトの RS を GWL から推定した。DOC フラックスに RS を加えた炭素損失量は，2010 年 7 月～12 月と 2011 年で，UF サイトで 613，1460，DF サイトで 692，1350 gC m^{-2} となった。土壌からの炭素損失に占める割合は，RS の方が DOC フラックスよりもかなり大きかった。両サイトの値を比較すると，2010 年後半は DF サイトで大きかったが，2011 年では UF サイトの値の方が大きかった。この違いは，2010 年の気候に関係している。この年にはラニーニャ現象が発生し，降水量が多く GWL が高かった。その結果，UF サイトの RS が大きく低下し，炭素損出量も減少した。

地球温暖化の観点から，熱帯泥炭地の炭素収支の定量化と，炭素循環に与える環境撹乱の影響を明らかにすることが重要になっている。本論文は，熱帯泥炭土壌の炭素動態を明らかにするために不可欠な土壌呼吸量と溶存炭素流出量を実測により定量化し，それらの比較により環境撹乱の影響を評価した。本論文で得られた知見，特に溶存炭素に関する内容の学術的な価値は非常に高いといえる。よって審査委員一同は，Siti Sundari が博士（農学）の学位を受けるに十分な資格を有していると認めた。