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学 位 論 文 題 名

Methane budget of Taiga-Alas ecosystem in continuous permafrost region (Central Yakutia, Russia)

（連続永久凍土地帯（ロシア中央ヤクチャ）の
タイガ-アラス生態系におけるメタン収支）

学位論文内容の要旨

Introduction: Central Yakutia is located in potentially risky region to global warming. Taking into account that the present climate change is already underway, this region can be a huge source of CH_4. In Central Yakutia, there are 16,000 mature thermokarst depressions called "Alas". Since these thermokarst depressions are closed ecosystems without runoff from the depression, accumulation of great amount of organic matter proceeds inside the depression. Due to the high accumulation of organic matter inside the depression, flooding with the expansion of pond area can lead to the high emission of CH_4. The goal of this study is to estimate CH_4 budget in Taiga-Alas ecosystem, taking into account main sources and sinks of CH_4 in forests, grasslands and ponds composing the Taiga-Alas ecosystem.

Study sites: Four thermokarst depressions in typically different stages of thermokarst formation were chosen in the east bank of the Lena River, approximately 50 km east from Yakutsk city (62°54′N, 130°33′E). The stage I was characterized by the small polygonal subsidence of deforested areas. The stage II was characterized by a well-depressed area with a hillocky bottom, slopes and a periodical small pond. The stage III was characterized by a deeper depression fully filled with water supplied from the melted ice complex and run-off water from the surrounding forests. The stage IV was characterized by a mature and stable thermokarst depression with a pond, and steppe vegetation inside. At the dry and wet grasslands, ponds of the thermokarst depressions and surrounding forests, CH_4 fluxes from soil and via aerenchyma of aquatic vegetation, CH_4 ebullition in pond, CH_4 production in pond sediment, and CH_4 content trapped in ice wedge were measured. CH_4 fluxes from soil and via aerenchyma of aquatic vegetation were measured by closed chamber method. CH_4 ebullition was measured by using floating gas traps during summer and winter periods at three locations from the edge to the center of pond. CH_4 production in pond sediment was measured by *in situ* incubation. During the observation period of 2006-2009, climatic conditions of studied area were warmer than long term average value, but changed from wetter to drier.

CH_4 emission from different stages of thermokarst in Central Yakutia: Cumulative CH_4 flux of Taiga-Alas ecosystem showed significant difference between land covers (forest, grassland and pond) and years (from 2006 to 2009). Forests surrounding three different thermokarsts showed net CH_4 uptake from the atmosphere in all observation years. Dry grasslands took up CH_4 in all observation years other than 2008, but the values were not significantly different among the sites (from -0.17 ± 0.10 to 0.26 ± 0.28 kg C ha^{-1}

period^{-1}). Wet grasslands always emitted CH_4 which ranged from 0.11 to 397 kg C ha^{-1} period^{-1}. The highest CH_4 emission in each year was recorded from the oldest stage IV. Ponds also always emitted CH_4. Averaged CH_4 emission in three studied ponds was lowest in 2007, which was 46.4 kg C ha^{-1}, while it was 140, 193 and 240 kg C ha^{-1} in 2006, 2008 and 2009, respectively. The emission of CH_4 via aerenchyma of aquatic vegetation had significant quota, which accounted for 79.3% to 95.1% of whole ecosystem CH_4 emission in wet grasslands, and 32.1 to 88.4% in ponds.

CH_4 ebullition from the thermokarst ponds: CH_4 ebullition from the surface of pond during summer was estimated as 4.92, 4.01 and 1.84 kg C ha^{-1} from the edge, middle and center of pond, respectively. Averaged CH_4 ebullition in winter time was 5.11 kg C ha^{-1} in the edge and middle of pond, respectively, and 0.43 kg C ha^{-1} in the center of pond. Annual CH_4 ebullition was estimated to be 10.3, 9.1 and 9.9 kg C ha^{-1} from edge, middle and center of ponds, respectively. Consequently, CH_4 ebullition accounted for 3.3 to 5.6% of total CH_4 emission from pond.

CH_4 production and consumption in thermokarst pond: Cumulative production of CH_4 in sediments measured by *in-situ* incubation ranged from 39.5 kg C ha^{-1} at the middle of pond to 2,369 kg C at the center of pond. At the edge of pond, it was estimated as 629 kg C ha^{-1}. At the same time, dissolved CH_4 content in the pond was very small (0.22 to 0.25 kg C ha^{-1}), although dissolved total C content in the pond was very high (1,699 to 2,017 kg C ha^{-1}). Therefore, CH_4 should be oxidized in the pond, and total oxidation of CH_4 was estimated to be 54 to 97% of CH_4 produced in bottom sediments.

CH_4 content in permafrost: CH_4 storage in permafrost with an ice-wedge complex, which was estimated from volumetric content of ice and CH_4 concentration in ice and frozen soil in permafrost, was 2.6 kg C ha^{-1}. It was significantly small compared to the CH_4 emission from thermokarst pond. Therefore, current microbial CH_4 production in thermokarst pond can be a main source of considerably high CH_4 emission in this region.

CH_4 budget in thermokarst depression of Central Yakutia: Based on the precise measurements of the CH_4 fluxes and CH_4 production in thermokarst depression, annual CH_4 budget in the depression of the stage IV (63.7 ha) was estimated. Land covers (dry and wet grassland and pond area) changed due to flooding. Pond area increased from 20.4 ha in 2006 to 43.3, 46.5 and 44.4 ha in 2007, 2008 and 2009, respectively. Within those pond areas in respective years, 10.2, 26.0, 23.2 and 17.7 ha were occupied by aquatic vegetation. Including CH_4 emission from dry and wet grasslands, pond and pond vegetation, annual total CH_4 emission from the total area of the depression was 3.1, 5.2, 21.7 and 50.1 Mg C area^{-1}. Such difference of annual CH_4 emission was caused by the flooding in grasslands with easily decomposable organic C stored in the soils. Annual CH_4 emission from the pond surface accounted for 14.8% of the CH_4 production in the pond in 2006 and 11.8% in 2007, then increased to 37.6 and 100% in 2008 and 2009, respectively.

Upscaled CH_4 budget for Central Yakutia: Using three years (2006-2008) available GIS land cover data based on satellite images (ALOS) in the area of 71.2 km^2 including the studied thermokarst depressions and four year average of cumulative CH_4 fluxes in each land cover, averaged CH_4 budget in the area was estimated. In this area, forest occupied 46.4 km^2, and the sum of grasslands and ponds in thermokarst depressions accounted for 15.7% of the total area. However, during the three years, the areas of ponds and grasslands changed due to flooding. Pond area increased by almost 8 times, from 0.4 km^2 in 2006 to 3.5 km^2 in 2008. Such increase in pond area led to decrease of grasslands area. Area of aquatic vegetation increased from 0.04 km^2 in 2006 to 0.8 km^2 in 2008, respectively. CH_4 uptake by forest in this area was estimated as 2.6, 1.3 and 3.7 Mg C area^{-1} in 2006, 2007 and 2008, respectively. CH_4 emission from grasslands was estimated to be 1.8 Mg C area^{-1} in 2006 and 8.2 Mg C area^{-1} in 2007, but significantly increased to 106.1 Mg C area^{-1} in 2008, due to increase of effect of flooding. CH_4 emission from pond increased gradually from 6.0

to 10.7 and 67.4 Mg C area^{-1} from 2006 to 2008. CH_4 emission from the area covered by aquatic plants despite of their smallest area of in the area also was high, and amounted 10.4 and 56.9 Mg C area^{-1} in 2007 and 2008, respectively.

Conclusion: Most important factor controlling amount of CH_4 emission from thermokarst depression was fluctuation of pond size inside the depression. Thermokarst pond was affected by the climatic conditions and showed significant fluctuation of the area. Continuous flooding of grasslands inside the depression increased CH_4 emission considerably. Release of CH_4 trapped in the permafrost was not significant compared to the high CH_4 emission from thermokarst depressions. Current CH_4 emission from the thermokarst depressions has been derived mainly from microbial CH_4 production especially in pond sediment. Since Central Yakutia is located in potentially risky region under the global warming, the CH_4 emission can increase significantly with the increase of warm period and flooding, which can also accelerate the thermokarst processes.

学位論文審査の要旨

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本論文は９章からなり図51、表28、引用文献185を含む145ページの英文論文であり、他に参考論文２編が添えられている。

中央ヤクーチャは、タイガ林の中に永久凍土が融解し陥没して生成した１万6000個の円形のサーモカルスト「アラス」により特徴付けられる。アラスは、外部への流出がない閉鎖生態系で、多量の有機物が蓄積した沼地を草地が取り巻いており、沼の面積の拡大はCH_4放出を増加させると見られている。一方タイガ林はCH_4吸収源であるとされている。本論文の目的は、タイガ-アラス生態系のCH_4収支を、生態系を構成する森林、草地、沼といった主要なCH_4ソースとシンクを考慮して見積もることである。

ヤクーツク市(62°54′N, 130°33′E)から東に約50km離れたレナ川東岸で発達程度の異なる４つのサーモカルストを対象に、森林、草地、沼地の土壌、沼水および水生植物を通じてのCH_4フラックス、沼における気泡によるCH_4放出、沼床堆積物のCH_4生成量、地下氷中の封入CH_4含量を測定した。土壌からあるいは水生植物を通じてのCH_4フラックスは、クローズドチャンバー法で測定した。気泡によるCH_4放出は、池の辺縁部から中央部にかけ３つの異なる地点で、浮かべたガス採取装置を用いて夏期、冬期に測定した。沼床堆積物のCH_4生成量は、現場での培養により求めた。観測期間の2006-2009年は、平年より気温が高く、降水量から見て湿潤から乾燥へと変化していた。

タイガ-アラス生態系のCH_4放出量は、森林、草地、沼で異なり年次変化が見られた。森林は、すべての年で大気からのCH_4吸収を示した。森林近傍の乾燥した草地でも吸収傾向を示したが、沼に近い湿潤な草地では常にCH_4放出が見られ、大きな発達したアラスほど放出量は大きかった。沼でも常にCH_4放出が見られ、放出量は年々増加した。このことは、沼の草地への拡大が沼中の易分解性有機物の増加をもたらしたためであると考えられた。植物体を通じてのCH_4放出は湿潤草地では全放出量

の 79.3～95.1%、沼では 32.1～88.4%を占め、主要な CH_4 の放出経路であった。

沼表面からの気泡による CH_4 放出量は、冬期、夏期間ともに沼の辺縁部で高く、年間では、全体の CH_4 放出量の 3.3～5.6%を占めた。

沼床堆積物の CH_4 生成量は沼中央で最も大きかった。沼からの CH_4 放出量は生成量より小さく、溶存 CH_4 も少なかったことから沼床で生成された CH_4 は沼内のどこかで酸化されていると考えられた。酸化された CH_4 は沼床で生成された CH_4 の 54～97%と見積もられた。

永久凍土に封入された CH_4 量はサーモカルスト沼からの CH_4 放出量と比べて有意に小さかった。よって、この地域における高い CH_4 放出量の主要因は、現在のサーモカルスト沼における生物学的 CH_4 生成であると考えられた。

測定した CH_4 フラックスと生成速度を用いて、良く発達したアラス(63.7 ha)の年間 CH_4 収支を算出した。沼地の拡大に対する降雨の増大の影響は 1 年遅れで現れ、冠水により草地面積は減少した。2006 年から 2009 年にかけて降雨量は 326mm から 197mm へ低下していったが、沼の面積は 20.4 ha から 46.5 ha に拡大した。沼の面積の約半分が水生植物により占められていた。この間、アラス全域からの年間 CH_4 放出量は 3.1 から 50.1 Mg C $area^{-1}$ へ増加し、そのうち沼からの放出が 14.8%から 100%に増加した。

2006 年から 2008 年の衛星画像(ALOS)を用いて広域(71.2 km^2)の森林、草地、沼地の面積を算出し、CH_4 収支を算出した。森林による CH_4 吸収量は、2.6 から 3.7 Mg C $area^{-1}$ であったが、沼の拡大によりその CH_4 放出量は 6.0 から 67.4 Mg C $area^{-1}$ に増加し、草地での CH_4 放出量はその湿潤化により 1.8 から 106.1 Mg C $area^{-1}$ に増加した。中央ヤクーチャは地球温暖化の影響を受けやすい地域にあるため、将来の気温上昇と沼面面積増加が CH_4 放出量を増加させ、それがさらに沼面面積の増加を加速させる可能性がある。

以上のように、本研究は、中央ヤクーチャに特有なタイガ-アラス生態系が、沼の拡大により大きな CH_4 の放出源となることを明らかにしたものであり、今後の地球温暖化の予測とその対策のための研究に貢献するものである。よって審査員一同は、Alexey Romanovich Desyatkin が博士(農学)の学位を受けるに十分な資格を有するものと認めた。