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Report from the International Permafrost Association: Carbon Pools in Permafrost Regions

The IPA Carbon Pools in Permafrost Regions (CAPP) Project started in 2005, with endorsement of the Earth System Science Partnership (EESP) Global Carbon Project and the World Climate Research Programme (WCRP) Climate and Cryosphere Project CAPP is also a project of the IPY. The project was launched because there is considerable concern and increased awareness both within the international scientific community and the general public about the effects of global warming on the very large soil organic-matter pool in permafrost regions (Figure 1). A new estimate (Schuur *et al.,* 2008; Tarnocai *et al.,* 2009) indicates that the total below-ground carbon pool in permafrost regions (ca. 1672 PgC) is more than double the present atmospheric pool (ca. 730 PgC) and more than three times larger than the total global forest biomass (ca. 450 PgC). Permafrost degradation has already been observed in parts of the northern circumpolar region and a significant portion of permafrost is expected to thaw this century (ACIA, 2004). This could result in the release of greenhouse gases (both carbon dioxide and the much more potent methane) from soil organic-matter decomposition. This positive feedback within the Earth System has not yet been considered in climate model projections of future global warming. A unique aspect of permafrost degradation is that gradual thawing of the ground with depth over time will be accompanied by more dramatic events, such as ground subsidence due to melting of buried ice bodies and lateral erosion along the edges of thaw lakes and arctic coastlines (Figure 2), further accelerating the release of greenhouse gases.

CAPP is not a funding programme. Its aim is to develop a network of established and young scientists carrying out research on a wide range of topics related to carbon in permafrost in order to discuss the most recent findings and insights. A 1st CAPP-related workshop took place in Stockholm from 24-26 November 2005; new results will be discussed at the 2nd CAPP workshop to be held in Stockholm from 3-5 June 2009. CAPP will participate in the IPA contribution to the IPY Oslo Science Conference and organise a session at the 3rd European Conference on Permafrost in Svalbard, both in June 2010.

The overall aims of the IPA CAPP Project are to assess below-ground organic-matter quantity and quality along ecoclimatic and edaphic gradients in high-latitude and high-altitude regions characterised by the presence of permafrost. The longer term plan of IPA CAPP is to contribute and initiate new research activities at up to 10 to 12 high-latitude transects in the northern hemisphere representing the range of ecoclimatic and permafrost regions, complemented by transects in subantarctic and high alpine environments. Intensive study sites along transects will permit investigation of below-ground carbon allocation in the landscape, comparing quantity and quality between different permafrost settings. Within the more limited time frame of IPY 2007-09, an important objective for CAPP has been to contribute to the Northern Circumpolar Soil Carbon Database (NCSCD), maintained by Charles Tarnocai (Ottawa). In cooperation with the IPA Cryosol Working Group and the Global Carbon Project, a new update has now been completed (Tarnocai *et al.,* 2009). An *Atlas of Northern Circumpolar Soil* was also recently produced (European Commission, 2009). CAPP-related research is underway in Alaska, Canada, Scandinavia and Russia. Here, we present some recent results, including an update of the soil carbon database, assessments of different permafrost carbon pools from across the Circumpolar North and the role of thawing permafrost

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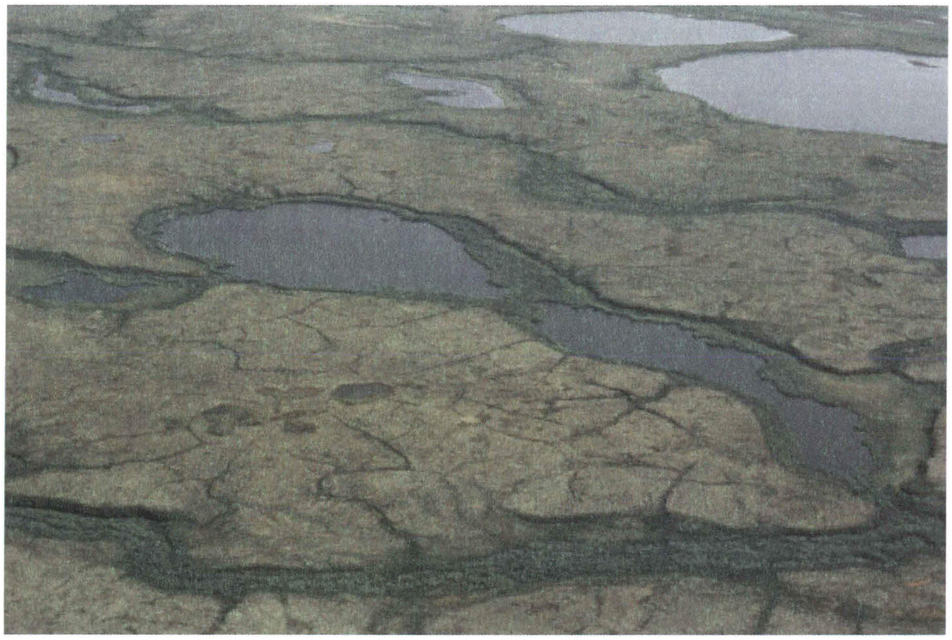

Figure 1 Peat plateau with thaw lakes. The peat plateau contains thick peat deposits that are perennially frozen (Copyright © P. Kuhry). This figure is available in colour online at www.interscience.wiley.com/journal/ppp.

in the Earth System. This overview is not intended to be comprehensive.

The NCSCD was developed in order to determine carbon pools in soils of the northern circumpolar permafrost region. The area of all soils in the northern permafrost region is approximately 18782 x 10^3 krrr', or about 16% of the global soil area. In the northern permafrost region, cryoturbated permafrost-affected

Figure 2 Peat erosion along the edges of thaw lakes, which accelerates the production of greenhouse gases (Copyright © P. Kuhry). This figure is available in colour online at www.interscience.wiley.com/journal/ppp.

mineral soils and organic soils (peatlands) have the highest mean soil organic carbon contents (32-70 kg Cm^{-2}). Tarnocai *et al.* (2009) report a new estimate of the carbon pools in soils of the northern permafrost region, including deeper layers and pools not accounted for in previous analyses. Carbon pools were estimated to be 191 Pg for the 0-30-cm depth, 496 Pg for the 0-100-cm depth and 1024 Pg for the 0-300-cm depth. The estimate for the first metre of soil alone is about double that reported for this region in previous analyses. Additional carbon pools in layers deeper than 300 cm were estimated to be 407 Pg in Yedoma and 241 Pg in deltaic deposits. In total, the northern permafrost region contains about 1672 Pg of organic carbon, of which approximately 1466 Pg, or 88%, occurs in perennially frozen soils and deposits. This 1672 Pg of organic carbon represents approximately 50% of the estimated global below-ground organic carbon pool.

Various components of the total soil carbon pool in permafrost regions have been the subject of recent research. These include permafrost peatlands, cryoturbated soils and Yedoma. Hugelius and Kuhry (2009) analysed soil organic-matter quantity and quality in relation to climate, vegetation and permafrost conditions in the Usa Basin (northeast European Russia), using multivariate statistical techniques. This area comprises a lowland gradient from taiga to tundra, and varies from seasonally frozen to continuous permafrost terrain, The average soil carbon storage is 38 kg Cm^{-2}, Most of the soil carbon (> 70%) is found in peatlands, even though they occupy only ca. 30% of the landscape. About 42% of the carbon stock in the Usa Basin is in permafrost terrain (including the active layer). Most of the permafrost terrain (ca. 90%) and perennially frozen (>95%) carbon stocks are found in bogs, where relatively dry surfaces promote permafrost aggradation (forming palsas and peat plateaus). The present palsas and peat plateaus first developed as non-permafrost fens starting as early as 9500 ^{14}C yr BP Permafrost only aggraded more recently, mostly after 3000 ^{14}C yr BP Permafrost bogs also have some of the most labile carbon. This is corroborated by an analysis of subarctic peat plateaus in Central Canada which showed that peat accumulated under long-term and stable permafrost conditions has experienced little decay since incorporation into permafrost (Sannel and Kuhry, 2009).

An analysis of carbon stores in permafrost-affected soils of Alaska and the North-American transect points to the importance of cryoturbation (Figure 3). The carbon stores in upland soils follow a latitudinal gradient, increasing from 16 kg Cm^{-2} in the High

Figure 3 Cryoturbated organics in deeper horizons of a tundra soil (Copyright © C. L. Ping). This figure is available in colour online at www.interscience.wiley.com/journal/ppp.

Arctic to 51 kg C^{-2} in the Low Arctic and then decreasing to 44 kg Cm^{-2} in the boreal forest. In both the High and Low Arctic 70-86% of the total carbon pool is cryoturbated or buried such that it is stored in the lower active layer and upper permafrost. However, in the Boreal (Subarctic) only about 37% of the stored carbon is found in the lower active layer and upper permafrost (Ping *et al.*, 2008). Most of the Arctic has been glaciated and thus most of the upland soils are of Holocene age and the cryoturbated and buried carbon generally dates from <9700 ^{14}C yr BP Bockheim (2007) suggested that cryoturbation might have been particularly active during the warmer Middle Holocene. However, the Alaskan Arctic Coastal Plain was not glaciated and carbon can be much older. Four coastal plain sites sampled from depths of 100-140 cm had radiocarbon ages ranging from 23 600 to 35 900 ^{14}C yr BP (Michaelson *et al., 2008).*

Figure 4 Duvanny Yar Exposure of Yedoma along the Kolyma River (Copyright © S. Zimov). This figure is available in colour online at www.interscience.wiley.com/journal/ppp.

The plains and valleys of northern Central Siberia are covered with late Pleistocene loess-like sediments with a network of massive ice wedges (Figure 4). The local name of this formation is Yedoma. Similar sediments can be found on Chukotka, Taymyr, North-West Yakutia, some arctic islands, Alaska and Yukon. The typical thickness of these sediments is 20-40 m, reaching up to 100 m. These deposits represent the former soils of the steppe-tundra ecosystem that dominated in these regions during the Pleistocene. Yedoma accumulated at relatively fast rates, implying that the organic matter in it experienced limited decay before incorporation into permafrost and, therefore, contains much labile carbon. The total carbon content in Yedoma is estimated at 400-500 PgC (Zimov *et al.,* 2006; Tarnocai *et al., 2009).* The high content of labile carbon in Yedoma makes it very sensitive to climate warming. During the Last Deglaciation the more southern portions of Yedoma thawed, resulting in large emissions of greenhouse gases to the atmosphere (Zimov *et al.,* 2006; Walter *et al.,* 2007). Khvorostyanov *et al.* (2008) modelled the heating due to decomposition which could further accelerate permafrost thawing and greenhouse gas release.

The ultimate strength of the feedback from permafrost carbon to climate change depends on both the pool size of organic carbon stored in permafrost and the rate of release to the atmosphere (Schuur *et al.,* 2008). Recent studies have focused on an upland thermokarst site near Denali National Park in Alaska, where researchers are studying changes in plant and soil processes as a function of time since thermokarst disturbance was initiated. They showed that increased permafrost thaw and ground surface subsidence increased net and gross primary productivity as plant growth was stimulated by thaw (Vogel *et al., 2009).* Plant species composition changed along with changes in plant growth rates, as graminoid-dominated moist, acidic tundra shifted to shrub-dominated tundra with increased thaw (Schuur *et al., 2007).* Increased uptake by plants initially offset increased ecosystem respiration such that this thermokarst was a net sink-of carbon 15 years after the initiation of thaw, even though decomposition of older carbon deep in the soil was taking place (Schuur *et al.,* 2009; Vogel *et al.,* 2009). Over more decades of thaw, plant growth rates remained high but increased old soil carbon losses eventually offset increased uptake and this thermokarst became a net source of carbon to the atmosphere

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(Vogel *et al.,* 2009). The documented emission rates suggested that 4.5-6.0 kg Cm^{-2}, or 9.5-13.0% of the soil organic-matter pool, could be lost on a century time-scale (Schuur *et al.,* 2009). If these rates were a typical response, annual net carbon emissions from widespread permafrost thaw could be similar in magnitude in the future to current biospheric emissions from land-use change.

Feedbacks from the soil organic layer in arctic regions to the climate system are not restricted to potential greenhouse gas releases. Rinke *et al. (2008)* incorporated a soil organic layer in an Arctic Regional Climate Model (RCM) and found that the distinct heat and hydraulic conductivity properties of the organic layer not only affected ground thermal regimes, but also near-surface temperatures and regional climate through changes in the surface energy balance (soil moisture, evaporation and latent heat fluxes).

Future plans for the CAPP project will be discussed at the upcoming 2nd CAPP workshop in Stockholm (June 3-5, 2009). Significant uncertainties remain with the circumpolar estimates of total carbon storage, particularly related to the Russian area and deeper carbon in cryoturbated soils and quaternary deposits (Yedoma and deltaic deposits). Relatively little is known about the lability of soil organic-matter stored in permafrost regions. Also of paramount importance is better understanding and quantification of the physical processes that will lead to carbon remobilisation such as talik formation and thermokarst erosion, The thawing permafrost carbon feedback needs to be included in model projections of future climate change.

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