current changes in tropical forest ecology and the sensitivity of these forests to future climatic change.

In contrast to the Southeast Asian tropical peatlands, these Amazonian peatland sites do not appear to be currently directly affected by anthropogenic actions. Nevertheless, climate change, deforestation, large-scale land-use projects (such as river damming, road construction and development of oil palm plantations) and extensive gas and oil exploration (Malhi et al., 2008) represent an indirect threat to the peatlands insofar as they contribute to drying of the regional climate. Consequently, there is an urgent need to investigate further, and conserve, these little-known Amazonian ecosystems.

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Peatland exchanges of CO_2 and CH_4: The importance of presence or absence of permafrost

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The presence of permafrost is shown to have dramatic impacts on land-atmosphere exchanges of key greenhouse gases.

Permafrost and the carbon cycle

Permafrost, soil that stays frozen for two or more years in a row, is a hot topic that has attracted a lot of attention in both the scientific and popular literature in recent years. Permafrost underlies 25% of the land areas in the Northern Hemisphere including substantial areas with peatlands. With a warming climate that is particularly pronounced at high northern latitudes, where most permafrost is present, many questions have been raised regarding what may happen to peatlands and their functioning when permafrost thaws. In areas with infrastructure, such as towns in northern Siberia, or oil and gas pipelines through areas underlain by permafrost, the thawing represents a serious and possibly very expensive issue. Thawing permafrost may, however, have global implications through changes in natural ecosystem greenhouse-gas emissions.

Figure 1: The Zackenberg valley in NE Greenland, an area underlain by continuous permafrost. The automatic chambers were used for the studies of methane emission dynamics during freeze-in (Mastepanov et al., 2008). Local inhabitants, the muskoxen, are present in the background. Photo by C. Sigsgaard, from Christensen et al., 2009, reprinted with permission.

Permafrost areas in the circumpolar North are estimated to hold more than 1600 Pg of organic carbon (C) including almost 300 Pg in the form of peat (McGuire et al., 2009; Tarnocai et al., 2009) most of which has accumulated since the last glacial maximum. In terms of atmospheric exchange of carbon, in the form of CO_2 and CH_4, the potential for additional releases are probably greater from these areas than anywhere else in the world. While the potential release from the huge stocks of carbon is significant, the actual data and year-round monitoring of atmospheric exchanges remain rare, and continuous flux measurements of CO_2 are limited to a handful of sites. Continuous monitoring of CH_4 fluxes is even rarer; the number of operational sites is less than five. Our empirically based understanding of what permafrost does to the dynamics and interannual variability in atmospheric (and dissolved run-off) fluxes of organic carbon is therefore still very poor. The longer-term dynamics on decadal to centennial timescales are even less well understood.

Carbon dynamics

Basic features of how ecosystems are functioning with and without permafrost have recently been discovered. At a central Alaskan site, Schuur et al. (2009) demonstrated that permafrost thawing is accompanied by respiration of previously frozen, ancient organic carbon. In Siberian thaw lakes, methane has been observed forming from recently thawed Pleistocene organic deposits (Walter et al., 2007).

The interannual and across-site variability of CO_2 exchange in continuous permafrost ecosystems are driven primarily by growing-season dynamics and moisture conditions. Several studies have shown that growing-season rates of CO_2 uptake by these ecosystems is closely re-

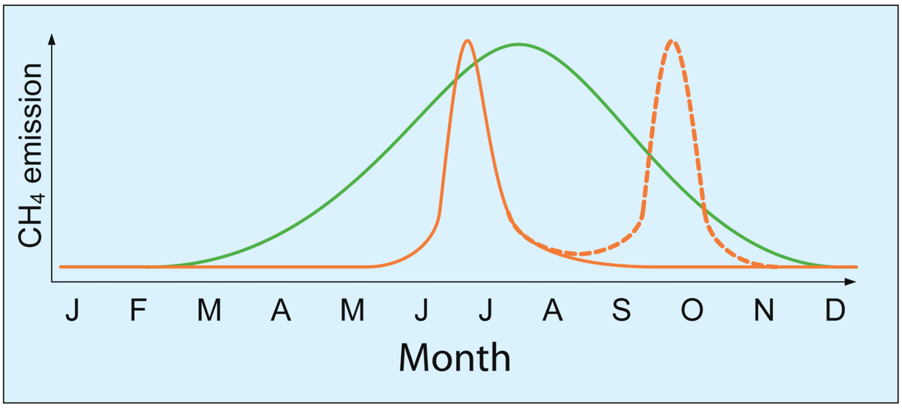

*Figure 2: Schematic illustration of the seasonal dynamics of methane emissions from peatlands as observed in Zackenberg (**orange**) and subarctic Sweden (**green**), respectively. These very different seasonal patterns reflect differences in both the length of the peatlands growing season (solid lines) and the special emission patterns associated with the freeze-in burst observed in a continuous permafrost environment (**dashed line**) (based on data from Jackowicz-Korczyński et al. in press and Mastepanov et al., 2008). Figure from Christensen et al., 2009, reprinted with permission.*

lated to the timing of snow melt, with earlier snowmelt resulting in greater uptake of atmospheric CO_2 (Aurela et al., 2004; Groendahl et al., 2006). The annual C budget is not only controlled by growing-season exchange, but also to a large extent by the losses during the shoulder (snow melt/soil thaw and plant senescence/soil freeze) and winter seasons (Johansson et al., 2006). These more complex impacts on the annual budgets become more important outside permafrost regions, where warmer shoulder-season conditions prevail.

In northern Sweden we have documented changes in permafrost dynamics and effects on ecosystems and feedbacks on climate in terms of methane emissions (Christensen et al., 2004; Johansson et al., 2006) and in relation to catchment scale greenhouse gas exchanges (Christensen et al., 2007). Here, the thawing permafrost generally leads to wetter hydrological conditions and subsequently greater emissions at the landscape scale. The seasonal and interannual pattern at this subarctic site is predictable and the emissions are stable from year to year (Jackowicz-Korczyński et al., in press). In contrast, we observed some surprising autumn emission dynamics at our high-arctic measurement site in NE Greenland (Fig. 1). These findings (Mastepanov et al., 2008) show a second seasonal peak of emissions during the freeze-in (Fig. 2). This distinct feature has previously not been observed, most likely because earlier flux studies in continuous permafrost regions have not extended into the frozen season. After further investigation in collaboration with atmospheric scientists, we have reached the preliminary conclusion that it may be a general feature of permafrost areas. This phenomenon helps to explain the observed seasonal dynamics in atmospheric methane concentrations during the autumn (Mastepanov et al., 2008).

The mechanism behind the freeze-in emissions in continuous permafrost areas is hypothesized as a release of methane from the subsurface pool accumulated over the growing season (Fig. 3). The methane is present mainly in gaseous form in entrapped gas bubbles below the water table level. The volume of the gas phase in the peat beneath the water table can be significant (from 0 to 19%; Tokida et al., 2005), while the volumetric percentage of methane in this gas can be more than 50% (Tokida et al., 2005). When the soil starts to freeze from the surface down, a gas-proof layer forms and propagates downwards. The permafrost works as a gas-proof bottom preventing the gas from migrating deeper down. Because the ice has lower density than water, the freezing process causes an increase in the volume of the frozen zone, raising the pressure in the unfrozen layer. This process results in squeezing of the methane-rich gas to the atmosphere. An additional hypothesized necessary condition for the late-season methane burst to occur is the presence of some channels for the pressurized gas to escape to the atmosphere. We suggest it may be residual vascular plant tissues, or cracks in the frozen upper soil layer.

Records of changes in permafrost

Longer records of peatland permafrost are available from the geographical margins of the permafrost zone. For example, in Abisko, northern Sweden, permafrost has been monitored for decades. Here, the surface active layer has become thicker over the last three decades. In nine peatlands along a 100 km-long transect the trend is similar and in some peatlands the permafrost has even disappeared completely (Åkerman and Johansson, 2008). This trend is also reflected in larger scale modeling of permafrost (palsa) peatlands in northern Scandinavia (Fronzek et al., 2006) and from observations in North America (Vallee and Payette, 2007; Turetsky et al., 2007). This prevalent trend towards transformation of permafrost landscapes calls for an understanding of ecosystem fluxes both where the permafrost is still present and where it has disappeared.

Modern process studies, monitoring and measurement of fluxes in these ecosystems need to be complemented by paleorecords of longer-term permafrost aggradation and degradation cycles

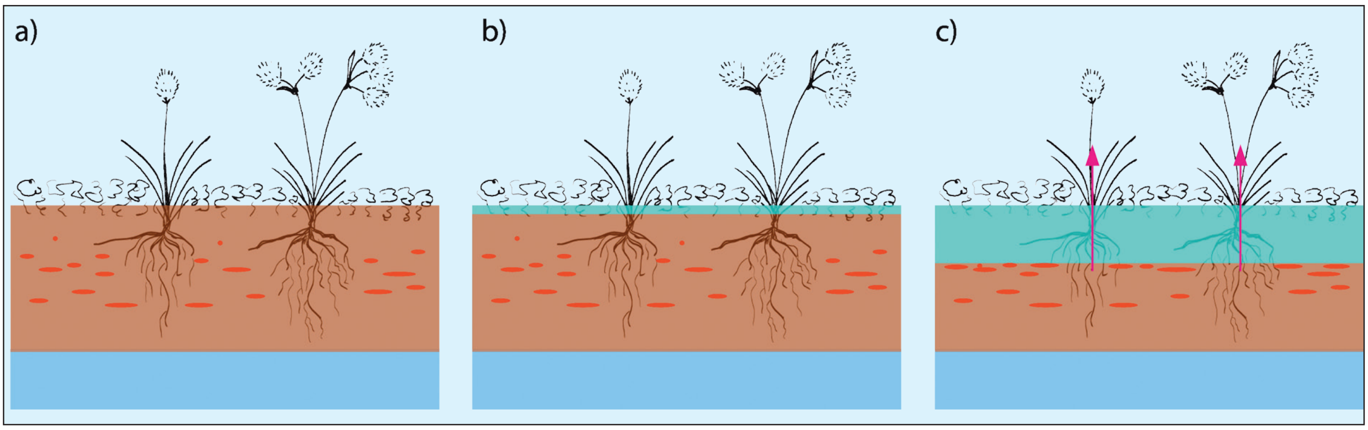

*Figure 3: An illustrated hypothesis for how the freeze-in burst of methane emission in continuous permafrost environments is released. **a**) Soil (brown), which sits on top of the permafrost (blue), is unfrozen during the growing season. As the ground freezes primarily from the surface down (**b**) the pressure builds up in the unfrozen zone and the accumulated gas (red) in the soil gets pressed out (**c**) through physical cracks and pores remaining in place from old vascular plants. Figure from Christensen et al., 2009, reprinted with permission.*

(e.g., Kokfelt et al., submitted), to fully understand permafrost dynamics and the relationship with atmospheric methane concentrations over longer timescales. It is clear from paleorecords that peatland permafrost has expanded and contracted over the Holocene at different times in different places (e.g., Vardy et al., 2005; Oksanen, 2006). Although the impacts of Holocene peatland expansion on atmospheric methane are now being explored (Smith et al., 2004; Korhola et al., 2010; Beilman et al., this issue), the implications of Holocene permafrost variability on past global methane concentrations have not yet been assessed. The sparse data on contemporary methane emissions show that peatlands with and without permafrost differ significantly in their functioning. More continuous measurements are required to document ongoing changes. Modern process models of carbon dynamics linked to paleoreconstructions of permafrost could produce critical insights into long-term role and functioning of northern peatlands in the global carbon cycle.

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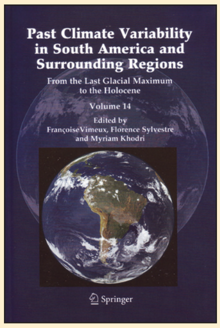

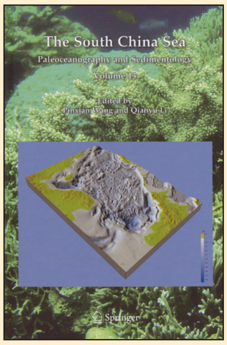

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