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The impact of high tephra loading on late-Holocene carbon accumulation and vegetation succession in peatland communities

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ABSTRACT

Peatlands are major terrestrial stores of carbon (C) of importance to the global climate system. Recent studies have made progress in understanding the climatic controls on the C cycle; however, important interactions between volcanic deposition and peatland C stores remain to be addressed. This study uses a 3000-year peatland record from northern Japan to examine the interactions between carbon accumulation, vegetation community succession and volcanic ash deposition. Plant macrofossil and testate amoebae records are presented alongside records of total organic carbon, nitrogen and phosphorous. Age–depth models are developed using a Bayesian approach, with seven AMS radiocarbon dates and two identified historical tephras from Baitoushan (AD 969 (981 cal. BP)), and Hokkaido-Komagatake (AD 1640 (310 cal. BP)) volcanoes. Results show that moderate to high tephra loading can shift peatland plant communities from *Sphagnum* to monocotyledon domination. This vegetation change is associated with increased peat humification and reduced carbon accumulation. Where tephra deposition and reworking has occurred, the apparent rate of carbon accumulation can be halved while high tephra loading of the mire surface is sustained. *Sphagnum* species vary in their tolerance to tephra deposition. After each ash fall *Sphagnum magellanicum* disappeared from the plant macrofossil record, whereas *Sphagnum papillosum* showed apparent continuity of development through the 1856 (94 cal. BP) Ko-c1 tephra. High rates of carbon accumulation (peaking at >100 g m^{-2} yr^{-1}), 2–3 times faster than the average for northern peatlands, were recorded in the *Sphagnum* communities that established after the cessation of tephra deposition and reworking from the AD 969 Baitoushan ash fall (B-Tm tephra). This peak in C accumulation was coincident with a radical shift in mire nutrient cycling most probably caused by the interaction of *S. magellanicum* with leachates from the underlying tephras. The phase of high C accumulation continued for over 300 years, offsetting the initial negative impact of the B-Tm tephra on peatland C accumulation. These results suggest that management for ash-tolerant *Sphagnum* species could be a highly effective strategy for minimising volcanic disruption to peatland carbon accumulation. The study also shows that consideration of volcanic impacts on peatlands is essential for development of more realistic terrestrial carbon balance models in volcanically active regions.

1. Introduction

Peatlands are an important component of the global carbon (C) cycle since they presently accumulate 100 Tg of carbon annually (Dean and Gorham, 1998) and they are estimated to store 547,000 Tg C (547 Gt) (Yu et al., 2010). The rate of carbon accumulation in peatlands is dependent upon the balance between primary production and peat decomposition (Charman, 2002). Changes in this balance are of importance for modelling of future climates and to understand the likely sensitivity of peatland systems to regional environmental and climatic change. Whilst we are beginning to understand the broad-scale climatic controls that govern feedbacks between carbon accumulation and climate change (e.g. Yu et al., 2010; Charman et al., 2012), there is still considerable uncertainty over key regional controls such as the impact of volcanism on peatland communities and C stores.

Extensive tracts of boreal peatland occur throughout the Pacific Rim region from northern Japan and eastern Russia (e.g. Hokkaido, Kamchatka and eastern Siberia) to the Pacific seaboard of North America. These C-rich peatlands lie in close proximity to chains of

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active volcanoes that intermittently deposit widespread, heavy ash falls (Machida, 2002). For example, the AD 969 ± 20 eruption of Baitoushan, on the border of North Korea and China, deposited tephras throughout northern Japan with visible ash fall 1000 km from the eruption centre (Horn and Schmincke, 2000). Some larger eruptions from the Pacific Rim spread tephras well beyond the region. The largest Holocene volcanic eruptions of western continental North America have distributed ash across much of the continent (Pyne-Donnell et al., 2012), with the greatest of these eruptions from Mt. Mazama (7627 ± 150 GISP2 years BP), depositing >4 cm of ash (compacted depth) 1100 km from the eruption centre (Hoblitt et al., 1987). In the late-Holocene Alaskan tephras such as Aniakchak II and the White River Ash eastern lobe distributed tephras widely across North America (Pyne-Donnell et al., 2012). Such impacts on peatlands are also found widely, for example, in Northern Europe – originating from Iceland (e.g. Charman et al., 1995), throughout much of South America (e.g. Kilian et al., 2006) and in the forested peatlands of Southeast Asia (e.g. Jago and Boyd, 2005). Modern observations suggest that depositions of tephra in peatlands may be sufficient to alter mire functioning, nutrient status and vegetation communities (e.g. Wolejko and Ito, 1986) through enhanced nutrient delivery, smothering of vegetation and the deposition of plant toxins. These impacts have the potential to affect the carbon balance of peatlands because they alter both primary production and litter decomposition rates.

Commonly the addition of major nutrients (Nitrogen (N), Phosphorous (P) and Potassium (K)) to ombrotrophic peatlands is observed to shift plant communities from species producing more recalcitrant litter, such as *Sphagnum*, to more labile litter such as that produced by vascular plants, reducing the capacity for peatland carbon accumulation (e.g. Malmer et al., 2003). Very similar short-term impacts following tephra deposition have been noted by Hotes et al. (2006, 2010) in Japan and Payne and Blackford (2008) in Alaska. These tephra-induced shifts in plant communities (see Section 1.2 for more detail) are also accompanied by changes in testate amoebae communities and wider microbial activity that may be important for peat decomposition (Payne et al., 2010; Payne, 2012) and C storage. However, long-term (multi-centennial-scale) changes in peatland plant communities and C stores impacted by high volcanic deposition have received little attention.

1.1. Aims of this study

The aim of this paper is to examine the impact of high tephra loading on multi-centennial-scale mire succession and C accumulation, using an example from Hokkaido, Japan. The study will test the hypothesis that heavy tephra deposition (>5 cm thickness) reduces peatland carbon accumulation over multi-centennial timescales.

1.2. Effects of volcanism on peatlands

The likely impacts of distal volcanic activity on peatlands have been reviewed by Payne and Blackford (2008). Here we briefly update that review to provide the necessary context for the present study.

1.2.1. Ecological studies

Few studies have made direct observations of the impact of natural tephra deposition on mire plant communities and to overcome this lack of data several field experiments have been performed. Hotes et al. (2004, 2010) used a combination of natural tephra from Tarumai volcano, Hokkaido (Ta-a) and ground glass to simulate deposition of ash with three distinct ranges of grain sizes from medium silt-sized particles (glass – median size 9 μm), through coarse sand (Ta-a tephra – median size 855 μm) to coarse sand/fine gravel (ground glass – median size 2400 μm) with three application depths of 1, 3 and 6 cm. Hotes et al. (2004, 2010) found that thicker, finer-grained tephra layers had greater effects on vegetation and that leaching of fine-grained glass shards caused sustained changes in peat pore waters and increases in pH, electrical conductivity and concentrations of sodium, potassium and silicon dioxide. In contrast, oxygen saturation decreased. They found that some plant species disappeared from treatment plots and that mosses were more severely affected than vascular plants but most species survived and where *Sphagnum* carpets were smothered they were able to re-establish by growing through the natural tephra and ground glass treatments. Hotes et al. (2010) also concluded that whilst mire communities could display a degree of resilience to tephra deposition, some plots subject to tephra deposition developed to an alternative state with a high cover of the dwarf shrub *Myrica gale*. The mechanism behind the emergence of these alternative equilibria in community composition remains to be clarified. Payne and Blackford (2005) also treated mire vegetation plots using tephra, with the addition of acid applications, to simulate the Hekla-4 eruption. Their application rate was much smaller than that applied by Hotes et al. (2010) and at this dose they found that impacts on vegetation were only associated with the acid applications.

While experimental studies may be very useful in studying tephra impacts on peatlands, they are limited by the short duration of observations relative to the rate of vegetation succession and the life span of the plant species involved (Walker, 1970; Pickett et al., 2009) and, as noted by Payne and Blackford (2008), there is some uncertainty over the degree of realism that tephra/ground glass-loading experiments represent. Similarly, the realism of the acid application in the experiments by Payne and Blackford (2005) has also been discussed in relation to the quantity of acid applied (Payne et al., 2013).

1.2.2. Palaeoecological studies of plant communities

Palaeoecological studies provide a means of tracking long-term vegetation change because peatlands preserve a detailed record of their past biodiversity (Barber, 1993). Previous plant and macrofossil studies have reported variable mire vegetation responses to tephra loading in ombrotrophic and blanket bogs from Alaska, Europe and Hokkaido (Edwards et al., 2004; Hotes et al., 2001, 2006; Payne and Blackford, 2008). In these sites macrofossil records showed both increases and decreases of individual macrofossil types following tephra deposition; however, Hotes et al. (2006) noted that there was no clear response pattern to tephra deposition and even in cases where tephras ranging in thickness between 0.5 cm and >25 cm fell on *Sphagnum*-dominated vegetation '*no fundamental shifts to new plant communities were found*' (p. 561). In cores from Alaska Payne and Blackford (2008) found that some macrofossil records showed little response to tephra loading, while in others the vegetation appeared to shift from *Sphagnum* dominance towards monocotyledon-rich communities immediately following tephra deposition, especially where tephra loading was relatively high.

Palynological studies of tephra impacts on vegetation have also recorded a variety of vegetation changes during volcanic events. For example, Charman et al. (1995) found that, of three tephras present at Kildonan, only one was associated with a major vegetation change, as indicated by a marked decline in Cyperacaeae pollen representation. Similarly, in Iceland Edwards et al. (2004) found that, whilst shifts in pollen assemblages from two small peatland basins occurred across phases of tephra deposition, they may not