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Accumulation of carbon and nitrogen in vegetation and soils of deglaciated area in Ellesmere Island, high-Arctic Canada

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ABSTRACT

The amount of biomass, carbon (C), and nitrogen (N) in vegetation and soil were measured at two spatial scales in the high Arctic. At the scale of proglacial landscape, the amount of C and N in aboveground and belowground parts of vegetation, surface litter, and soil were significantly affected by the habitat (moraines vs hummocks), the relative age of the terrain after the deglaciation, and/or the vegetation. At another scale, we focused on mudboils as an agent of local disturbance in the vegetation and soil of the glacier foreland. The biomass and the amount of C and N in aboveground vegetation, surface litter, biological soil crust, and soil were generally increased with the stage of mudboils' inactivation. Biomass, C, and N in aboveground vegetation and surface litter were generally greater at moraine than at hummock, whereas those in biological soil crust and soil were greater at hummock. Principal component analysis identified two pathways, xeric and mesic ones on moraines and hummocks, respectively, of C and N accumulation both at the two spatial scales. These results suggested that the C and N accumulation was not linearly related to the time since deglaciation and that moisture condition, vegetation, and mudboil activity were locally important.

1. Introduction

Recently deglaciated terrain is a common landscape of high-Arctic ecosystems and has served as suitable sites for the study of vegetation succession and ecosystem development following deglaciation (Svoboda and Freedman, 1994). Previous studies have documented the primary succession of vegetation in such deglaciated terrain (Jones and Henry, 2003) and the accumulation of carbon (C) and nitrogen (N) in soil during the ecosystem development (Bekku et al., 2004; Nakatsubo et al., 2005). The number of studies on the accumulation of C and N at the ecosystem level (including both vegetation and soil) in deglaciated terrain of high-Arctic regions is still limited compared to studies on low-Arctic regions (e.g., Crocker and Major, 1955; Crocker and Dickson, 1957; Mellor, 1985), despite recent consensus regarding the importance of soil organic C pools in the northern permafrost region (Tarnocai et al., 2009).

The accumulation of C and N in aboveground biomass of plants in high-arctic regions is generally low (Oechel and Billings, 1992; Muc et al., 1994b), mainly due to harsh environmental conditions, such as extremely low temperature, low moisture, and a short growing season, that limit not only net primary productivity but also ground cover of plants (Chapin et al., 1992). Consequently, the mass of C and N accumulated in litter and soil is also generally low (Muc et al., 1994a) because of the poor development of vegetation, as well as low microbial activity and the relatively short period for soil development since deglaciation (Matthews, 1992). Further studies are needed to address the accumulation of C and N in both aboveground vegetation and soil and the effects of terrain age, microenvironmental conditions, such as moisture availability, and vegetation on C and N mass during the primary succession at glacier forelands of high-Arctic regions.

Patterned ground is a common feature in high arctic landscapes and is produced by freeze-thaw processes in the presence of permafrost (French, 1979; FitzPatrick, 1997). Of a variety of periglacial geomorphological features classified as patterned ground, mudboils (a type of sorted or nonsorted circle) are among the major ones in the Canadian Arctic (Zoltai and Tarnocai, 1981). They are 1–5 m in diameter, ubiquitous on till and on diamictic residual soils

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on flat to very gently sloping situations, and develop due to physical mass movement of soil driven by soil frost processes (cryoturbation), resulting in poorly vegetated circles surrounded by dense vegetation. The presence of such mudboils is indicative of localized disturbances caused by repeated eruptions of soil (mud) by the high pore pressures developing in subsoil layers during freeze-thaw cycles, which impede biological colonization and establishment on mudboils (FitzPatrick, 1997). This results in small-scale gradients of plant succession from the center of individual mudboils to the rim to the outer vegetation and along the time since the inactivation of a mudboil. Previous studies have demonstrated successional changes of plants on mudboils at such small scales (e.g., Anderson and Bliss, 1998; Makoto and Klaminder, 2012). The successive colonization and establishment of plants on inactivated mudboils suggests the concomitant accumulation of carbon (C) and nitrogen (N) in soil, but only a few studies have examined the amounts and changes of the amounts of C and N in mudboils in the Arctic (Bockheim, 2007; Wilson and Humphreys, 2010; Kelley et al., 2012).

The proglacial field of the southern front of Arklio Glacier in Ellesmere Island, Canada is one of the study sites extensively studied for the vegetation and soil microbes in a deglaciated chronosequence. Previous studies have examined the establishment and succession of vegetation there (Okitsu et al., 2004; Mori et al., 2006, 2008, 2013; Osono et al., 2006; Ueno et al., 2009; Mimura et al., 2013) and of soil microbes (Yoshitake et al., 2006; Osono et al., 2012, 2014). The purposes of the present study were to quantify the biomass, and the amount of C and N in aboveground and belowground parts of vegetation, surface litter, biological soil crust, and soil in the proglacial field at two spatial scales. At the scale of proglacial landscape, aboveground and belowground parts of vegetation, surface litter, and soil were sampled, and the effects of the relative age of terrain, moisture condition, and vegetation on the C and N accumulation was examined. At another scale, we focused on mudboils as an agent of local disturbance in the vegetation and soil of the glacier foreland. By careful observations in the field, we found that some mudboils became inactive (i.e., no eruption of fresh mud at the center), resulting in colonization of such stabilized mudboils by biological soil crust and vascular plants. This led to the primary succession of vegetation and soil development on the inactivated mudboils at the scale of less than one meter. Aboveground vegetation, surface litter, biological soil crust, and soil on mudboils were sampled, and the effect of the stage of inactivation, moisture condition, and relative age of terrain since deglaciation on the C and N accumulation was examined. Based on these measurements, we performed principal component analysis to characterize the pathways of C and N accumulation during the primary succession at the scale of proglacial area and at mudboils.

2. Materials and methods

2.1. Study area

The study area is located within the proglacial field of the southern front of Arklio Glacier in the Kreiger Mountains near Oobloyah Bay, Ellesmere Island, Nunavut, Canada. The details of the study area are described in Osono et al. (2014). The area is rich in well-preserved moraines (Fig. 1A). Arklio Glacier has five glacial moraines, denoted Moraines with Relative ages I to V from the closest to the farthest relative to the present glacier snout, with different development periods since the Last Glacial (Hasegawa et al., 2004). The order of establishment of these moraines is apparent based on the distance from the present glacier snout. Hasegawa et al. (2004) estimated the age of the terrain of Moraines I, II, III, IV, and V to be 250–400, 2400–3300, 8000, 12000–15000, and 25000–35000 years, respectively. Hasegawa et al. (2004) also estimated the relative age of the outwash plain between Moraines IV and V to correspond to Relative age II. In the present study, we refer to the five developmental stages of the deglaciated moraines as Moraine I (M-I), II (M-II), III (M-III), IV (M-IV), and V (M-V) (Fig. S1 of the supplementary material).

The moraines are covered with boulders and rocks, xeric vegetation, biological soil crust, and/or mud boil in varying proportions, depending on the relative age of the moraines. Between the moraines were found not only the outwash plain mentioned above and but also depressions with greener mesic vegetation that was easily distinguishable from xeric vegetation on the moraines (Fig. 1B). The mesic vegetation developed on wetter soils fostered by permafrost or glacier runoff. The development of earth hummocks is generally noticeable in these mesic habitats on the outwash plain and depressions. In the present study, we distinguished four relative ages for hummocky habitats and denote these as Hummock I (H-I), II (H-II), III (H-III), and IV (H-IV). The numbers for relative age of hummocks corresponded to those of moraines. No typical hummocks were found in terrain of Relative age V.

The study area is also rich in periglacial features developed in unconsolidated deposits, such as solifluction lobes and mudboils (FitzPatrick, 1997). Mudboils are very common on flat to very gently sloping situations. They generally occur at two habitats in the study area: xeric habitat on moraine ridges and mesic hummock habitat on river terraces and outwash plains (Fig. S2). We selected one xeric and one adjacent mesic habitat in each of Relative ages III and V since the deglaciation and established four study plots (each 5 × 5 m in area) for the survey of mudboils in July 2004 (denoted as ‘mudboil plots’, Table S1). The mudboils within the plots were surrounded by depressions (15.7–28.4 cm in mean depth) filled with vascular plants (mainly *Cassiope tetragona*, *Dryas integlifolia*, and/or *Salix arctica*) and mosses (*Racomitrium lanugnosum* and/or *Hylocomium splendens*) (Table S1).

2.2. Sample collection in proglacial area

In July 2003, additional study plots (2 × 2 m) were established along a line transect from near the glacier snout to the farthest moraines, and samples were collected from these plots. These plots were denoted as ‘proglacial plots’ to distinguish these from ‘mudboil plots’. A total of 21 proglacial plots were laid out along the transect (approximately 4 km long) at approximately 180- to 200-m intervals. These 21 plots included 17 on moraine (three each in M-I, M-II, M-III, and M-V and five in M-IV) and four on hummocks (two each in H-II and H-III). Additionally, eight proglacial plots were established in July 2004 on mesic habitats where earth hummock was developed: three in H-I, one each in H-II and H-III, and three in H-IV. This made a total of 29 proglacial plots, including three plots each for moraines of M-I, M-II, M-III, and M-V and H-I, H-II, H-III, and H-IV and five plots for M-IV.

In each ploglacial plot, the coverage of vascular plants was visually estimated by at least two observers with respect to the total plot area, from 0% to 100%, at 5% intervals. The occurrence of vascular plants was recorded within the plot (Table S2). A grid (10 × 10 cm) was arbitrarily placed on the vegetation cover, one grid per plot. Aboveground parts of vascular plants were harvested within the grid, and litter of vascular plants was collected from the surface of soil within the grid (denoted as surface litter). A soil block was sampled by digging soil in the grid (to include belowground parts of vascular plants) until the hole reached permafrost or gravel so that no more excavation was possible. Moss and biological soil crust on the soil surface were included in the soil sample.

At M-I plots, the colonization of vascular plants was very scarce