Available online at www.sciencedirect.com
ScienceDirect
Polar Science 5 (2011) 391–397
http://ees.elsevier.com/polar/

Vegetation development and carbon storage on a glacier foreland in the High Arctic, Ny-Ålesund, Svalbard

Shinpei Yoshitake [a,*], Masaki Uchida [b], Toshiyuki Ohtsuka [c], Hiroshi Kanda [b], Hiroshi Koizumi [d], Takayuki Nakatsubo [e]

[a] Faculty of Science and Engineering, Waseda University, 2-2, Wakamatsucho, Shinjuku-ku, Tokyo 162-8480, Japan
[b] National Institute of Polar Research, 10-3, Midoricho, Tachikawa, Tokyo 190-8518, Japan
[c] River Basin Research Center, Gifu University, 1-1,Yanagido, Gifu 501-1193, Japan
[d] Faculty of Education and Integrated Arts and Sciences, Waseda University, 2-2, Wakamatsucho, Shinjuku-ku, Tokyo 162-8480, Japan
[e] Graduate School of Biosphere Science, Hiroshima University, 1-7-1, Kagamiyama, Higashi-Hiroshima 739-8521, Japan

Received 19 August 2010; revised 25 January 2011; accepted 7 March 2011
Available online 21 March 2011

Abstract

The distribution of organic carbon and its relationship to vegetation development were examined on a glacier foreland near Ny-Ålesund, Svalbard (79°N). In a 0.72-km^2 area, we established 43 study plots on three line transects along primary succession from recently deglaciated area to old well-vegetated area. At each plot, we measured the type and percent coverage of vegetation types. The organic carbon content of vegetation, organic soil, and mineral soil samples was determined based on their organic carbon concentration and bulk density. Cluster analysis based on vegetation coverage revealed five types of ground surfaces representing variations in the amounts and allocation patterns of organic carbon. In the later stages of succession, 7%–24% and 31%–40% of organic carbon was contained in the organic and deeper soil layers, respectively. Organic carbon storage in the later stages of succession ranged from 1.1 – 7.9 kg C m^{-2}. A larger amount of organic carbon, including ancient carbon in a raised beach deposit, was expected to be contained in much deeper soil layers. These results suggest that both vegetation development and geological history affect ecosystem carbon storage and that a non-negligible amount of organic carbon is distributed in this High Arctic glacier foreland.

Keywords: Carbon storage; High arctic glacier foreland; Succession; Svalbard; Vegetation

1. Introduction

Recent global model simulations indicate that climatic warming is more pronounced at high latitudes in the Northern Hemisphere (Anisimov et al., 2007). In addition, reports suggest that the carbon cycle in Arctic regions might be extremely sensitive to climate change (e.g., Oechel and Vourlitis, 1994). The organic carbon pool is an essential component of High Arctic biogeochemical cycles, and detailed knowledge of the quantity, characteristics, and spatial distribution of organic carbon is necessary to predict the response of northern high latitude terrestrial ecosystems to climate change.

Several studies have examined ecosystem carbon cycling and storage in the Alaskan Arctic (e.g., Michaelson et al., 1996; Potter, 2004; Shaver et al., 2006), but ecosystem carbon storage in the High Arctic has received

* Corresponding author. Fax: +81 3 3355 0316.
E-mail address: syoshitake@kurenai.waseda.jp (S. Yoshitake).

1873-9652/$ - see front matter
doi:10.1016/j.polar.2011.03.002

much less attention. It is difficult to evaluate biogeochemical carbon cycles in the High Arctic because of heterogeneous soil conditions, which are partly caused by cryogenic disturbances, especially cryoturbation; i.e., the mixing of soil horizons by freeze–thaw processes (Hodkinson et al., 2003). Moreover, successional processes following glacial retreat create heterogeneity in vegetation cover and in patterns and processes of soil carbon storage (e.g., Hodkinson et al., 2003; Jones and Henry, 2003). Several studies have examined the size of soil carbon pools in the High Arctic (e.g., Elberling et al., 2004) and in alpine regions (Grieve, 2000; Limin et al., 2002; Ohtsuka et al., 2008). However, quantitative assessments of carbon storage at landscape scales have not been conducted in High Arctic regions.

Since 1994, we have been investigating the ecosystem carbon cycle in a deglaciated area of Ny-Ålesund, Svalbard (Nakatsubo et al., 2005). One goal of the current research in this area is to clarify the patterns and processes of carbon cycling using a compartment model, to predict the impact of future climate change on ecosystem-scale processes. We have quantified soil organic carbon storage at a limited number of study plots as a basis for model development (e.g., Nakatsubo et al., 2005). However, it is necessary to establish the relationship between vegetation properties and organic carbon storage at landscape scales in order to expand the output of the model to a much larger area of this glacier foreland. Therefore, the aim of this study was to examine the horizontal and vertical distributions of soil and vegetative organic carbon in the region, as well as the temporal patterns of carbon storage and vegetation change related to successional processes.

2. Materials and methods

2.1. Study site

This study was conducted at the terminus of the Austre Brøggerbreen (East Brøgger) Glacier near Ny-Ålesund, northwestern Spitsbergen, Svalbard (79°N, 12°E; Fig. 1). The retreat rate of this glacier is about 10–20 m yr^{-1} (Nakatsubo et al., 2010; Svendsen et al., 2002). The annual mean air temperature and precipitation between 2001 and 2008 were −4.2 °C and 433 mm, respectively.

Previous reports have described the successional pattern of vegetation in this glacier foreland (Nakatsubo et al., 2005; Ohtsuka et al., 2006). The ground surface varies along a succession gradient from almost bare ground to well-developed vegetation cover. Only small isolated plants, such as *Saxifraga oppositifolia* L., and patches of biological soil crust (BSC; soil surface communities comprising cyanobacteria, algae, lichens, mosses, fungi, and bacteria) are found in the early successional stages. Later successional stages are dominated by a variety of plants, including mosses, such as *Sanionia uncinata* (Hedw.) Loeske, and vascular plants, such as *S. oppositifolia* and *Salix polaris* Wahlenb. A glacial outwash floodplain spatially divides the earlier and later stages of succession (Fig. 1). A recent study revealed that areas of later successional stage were developed on a raised beach deposit (Nakatsubo et al., 2008).

In the summer of 2003, three ca. 1.8-km line transects (A, B, and C; Fig. 1) were extended in parallel at 200-m intervals from a newly deglaciated area to an old well-vegetated area. Fifteen plots (2 × 2 m) were identified along each transect at intervals of 120 m (Fig. 1). Plots A1, B1, and C1 were located near the glacier edge, and plots A15, B15, and C15 were located near the sea. Plots B10 and C10 were excluded because the positions of these plots were on a river (Fig. 1). Consequently, 43 plots were established in the study area. In addition, to test the vertical distribution of organic carbon from surface to deeper mineral soil layers, one special plot (plot V; Fig. 1) was established on an exposed cliff face adjacent to the river, near plot B5.

2.2. Field measurements and sample collection

In the summers of 2003 and 2005, the coverage (% of ground area) of total vegetation, vascular plants, mosses, lichens, and BSC was measured in each plot. To calculate ground coverage, we used the actual surface coverage for measurements of surface vegetation such as mosses, and the projected canopy area for measurements of aerial vegetation such as vascular plants. As a result of overlaps between aerial and surface vegetation, some cumulative percentages exceed 100%.

Between one and five small quadrats (10 × 10 cm) were placed in each plot with reference to the relative coverage of each vegetation type within the plot. From each quadrat, we collected all above ground parts of plants, the organic soil layer, and the surface layer (0–1 cm) of mineral soil (volume, $v = 100$ cm^3). At the same time, the thickness of the organic soil layer was measured. Mineral soil samples ($v = 50$ cm^3) were also collected from the center of each quadrat at depths of 1–3.5 cm, 5–7.5 cm, 10–12.5 cm, 15–17.5 cm, and 20–22.5 cm (depths below the organic soil layer), using a stainless steel cylinder ($Ø = 5$ cm, $H = 2.5$ cm,). In some quadrats, subsurface samples were not collected because of the predominance of large gravel and a high water table. At plot V, mineral soil samples ($n = 3$) were collected at depths of 0–1 cm, 1–3.5 cm, 5–7.5 cm, 10–12.5 cm, 20–22.5 cm, 40–42.5 cm, 60–62.5 cm, 80–82.5 cm, and 100–102.5 cm (depths below the organic soil layer). All samples were collected in plastic bags and taken immediately to the nearby field laboratory in Ny-Ålesund.

2.3. Carbon content

All samples were weighed and air-dried at 10–15 °C for several days at the field laboratory, and were then taken to Japan for further analysis. Mineral soil samples were passed through a 2-mm-mesh sieve to remove gravel and coarse plant roots. Fine roots which passed through the sieve were removed with tweezers. All samples were freeze–dried, weighed, and then ground to pass through a 500-μm-mesh sieve. Inorganic carbon (carbonate) in the mineral soil samples was removed using phosphoric acid according to the method of Sollins et al. (1999). Organic carbon concentrations of all samples were measured with CN analyzers (Perkin–Elmer 2400 II, Perkin–Elmer Inc., Wellesley, MA, USA; Sumigraph NC-22, Sumika Chemical Analysis Service Ltd., Tokyo, Japan).

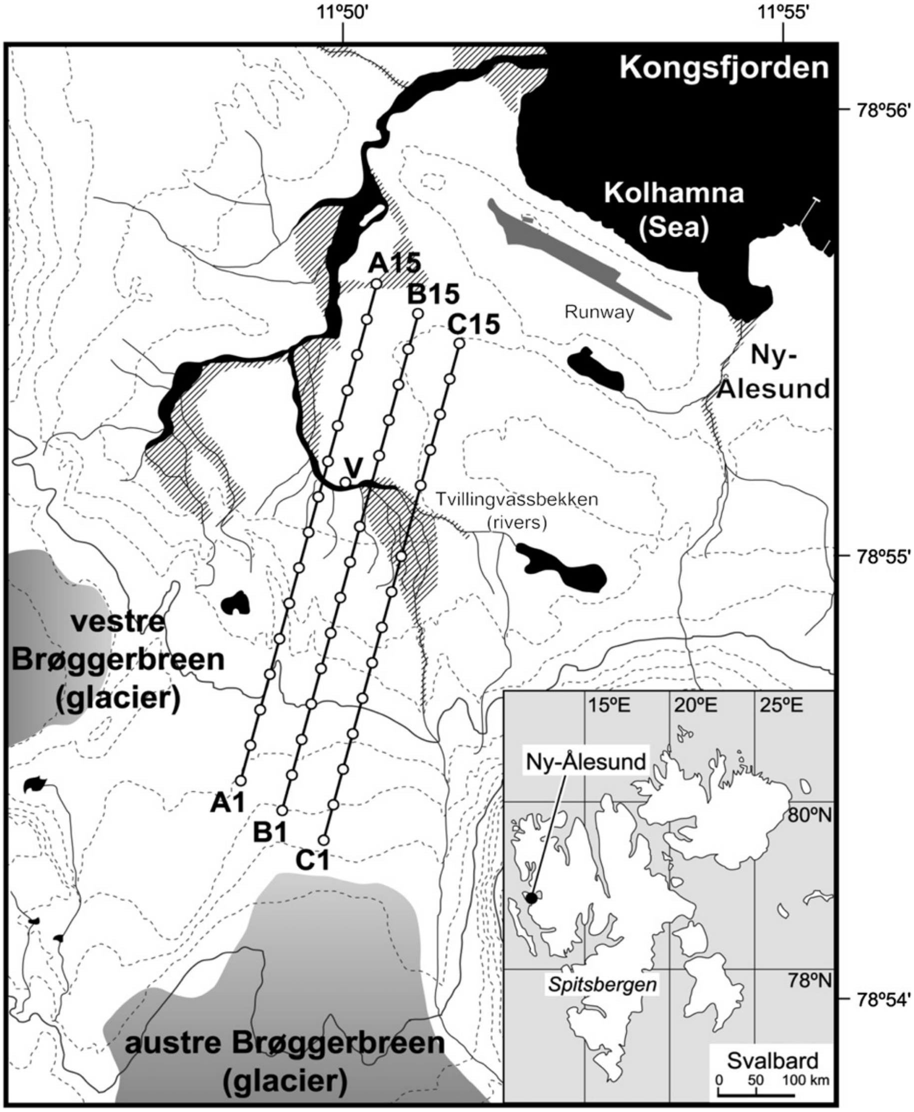

Fig. 1. Map of the study area. Forty-three study plots were established at 120-m intervals on three parallel (ca. 1.8-km) line transects along the primary successional trajectory from recently deglaciated areas toward the Kolhamna Sea. Plot V was located on a cliff face adjacent to the river to examine the vertical soil distribution of organic carbon. The location of the Austre Brøggerbreen (East Brøgger) Glacier reflects its position in 2008. Cross-hatched areas represent glacial outwash floodplains or marshes.

2.4. Data analysis

To analyze variations in vegetation among the study plots, we performed a hierarchical cluster analysis (Ward, 1963) of the coverage datasets from each plot using the Euclidean distance in the PAST software program (Hammer et al., 2001). Coverage data for the four vegetation types (vascular plants, mosses, lichens, and BSC), expressed as percentages, were first arcsine-square-root transformed.

The amount of organic carbon per unit area in each layer (kg C m^{-2} $layer^{-1}$) was calculated on the basis of the organic carbon concentration and the mass of material soil in each layer. The total amount of organic carbon per unit area (kg C m^{-2}) was calculated by integrating the area under the carbon content vs. soil depth curve, constructed using the organic carbon content values from all layers. For each plot, the amount of organic carbon per unit area was calculated as the average of the values of the quadrats in the plot.

3. Results and discussion

Total vegetation coverage tended to increase with increasing distance from the glacier edge, although it decreased in the floodplain (Fig. 2a). In addition, the

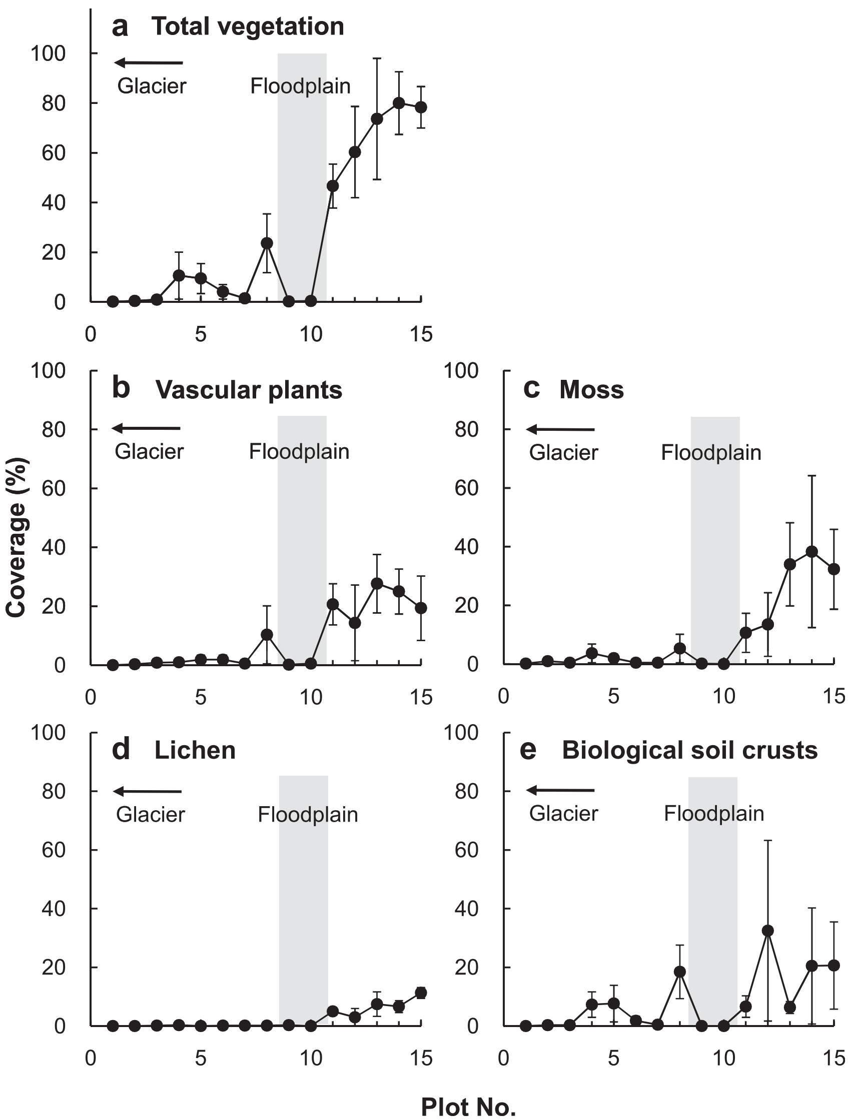

Fig. 2. Spatial changes in coverage (% of ground area) of (a) total vegetation, (b) vascular plants, (c) mosses, (d) lichens, and (e) biological soil crust (BSC) along the line transects (Fig. 1) from the glacier's edge (plot 1) to an older well-vegetated areas (plot 15). Values represent the mean ± SE of three line transects ($n = 3$), except for plot 10 ($n = 1$).

dominant vegetation cover changed from BSC in the early stages of succession (the area between the glacier edge and floodplain) to vascular plants and mosses in later successional stages (the area between the floodplain and the sea) (Fig. 2b,c,e). These successional changes in vegetation are similar to that reported previously for other High Arctic glacier forelands (Hodkinson et al., 2003).

Cluster analysis based on the datasets of vegetation type coverage revealed two primary clusters (Fig. 3): one contained almost all the plots representing early stages of succession (group 1); the other consisted of plots representing later stages of succession. The second primary cluster consisted of four secondary clusters (group 2–5); however, these bore no relationship to the distance of plots from the glacier edge (Fig. 3). Plot B14 (group 5) was segregated from the other the plots, probably because it was located on a hollow and was 90% covered by mosses (Table 1).

Total vegetation coverage in group 1 was significantly lower than that in groups 2–4 (one-way ANOVA and Scheffé's F-test, $P < 0.05$; Table 1). Group 2 represented plots dominated by BSC, as well as high total coverage values. Coverage of vascular plants in groups 3 and 4 was significantly higher than that in groups 1 and 2. In addition, coverage of mosses in group 4 was significantly higher than that in groups 1–3. Therefore, the study area can be characterized by five types of ground surfaces: almost bare ground with sparse vegetation at the early stage of succession (group 1), and well-developed vegetation dominated by BSC (group 2), vascular plants (group 3), vascular plants and mosses (group 4), or mosses (group 5) at later stages of succession.

The organic carbon content from surface to the 20-cm mineral soil depth varied among the five groups, with levels increasing in the following order: group 1 (bare ground) < group 2 (BSC) < group 4 (vascular plants and mosses) < group 5 (moss) < group 3 (vascular plants) (Fig. 4a). The very low organic carbon content in group 1 may be explained by the very early successional stage of plots in this group, located proximal to the retreating glacier margin and exposed by deglaciation, probably within the last 100 yr (Nakatsubo et al., 2010).

The allocation patterns of organic carbon also differed among the five groups (Fig. 4b). A considerable amount of organic carbon was contained in the organic soil layers of plots at later stages of succession (groups 2–5), especially in group 4 (vascular plants and mosses), in which the organic soil layer contained about 24% total organic carbon. The relatively high levels of organic carbon in the organic soil layer in group 2–5 plots reflect the successional development of this layer. The average thickness of the organic soil layer was lowest in group 1 (<0.1 cm) and

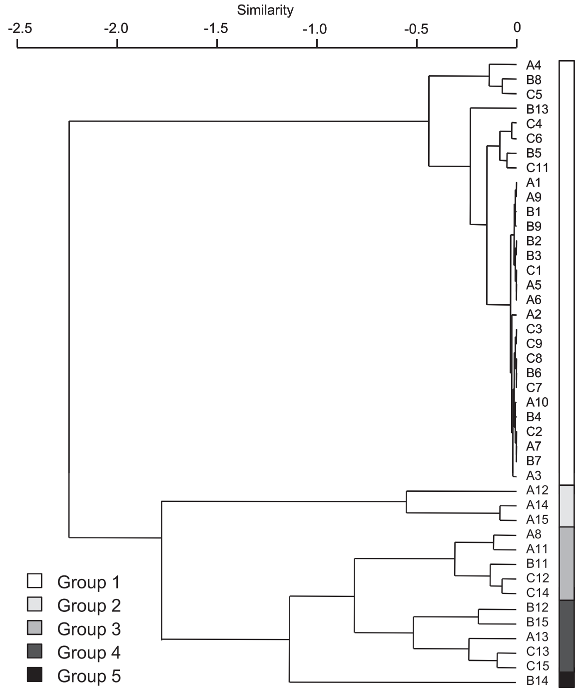

Fig. 3. Dendrogram showing the degree of similarity of vegetation cover among the 43 plots by hierarchical cluster analysis (Ward, 1963) based on coverage datasets of each vegetation type.

highest in groups 4 and 5 (about 2.6 and 3.1 cm, respectively). The decomposition rate of moss litter is generally low (Hobbie, 1996; Liu et al., 2000), which partly explains the thick organic soil layer in plots covered by mosses (group 4 and 5). These results indicate the effect of vegetation development during succession on ecosystem carbon storage in this High Arctic glacier foreland.

At later stages of succession (groups 2–5), more than 25% of total organic carbon was contained in the deeper layers of mineral soil (10–20 cm) (Fig. 4b). In addition, the vertical distribution of organic carbon content

Table 1
Average coverage of each vegetation type in the five groups identified by.

Group	n	Average coverage (% of ground area)				
		Vascular plants	Moss	Lichen	BSC	Total
1	29	1^a	1^a	1^a	3^a	6^a
2	3	11^a	7^{ab}	7^a	68^b	87^c
3	5	33^b	13^b	5^a	9^a	51^b
4	5	24^b	43^c	6^a	5^a	79^c
5	1	20	90	3	1	90

n = number of plots.
Lowercase letters represent groups with coverage values significantly different from those in other groups(Scheffé's F -test, $P < 0.05$).
As a result of overlaps between aerial vegetation such as vascular plants and surface vegetation such as mosses and lichen, some percentages may add to more than 100%.

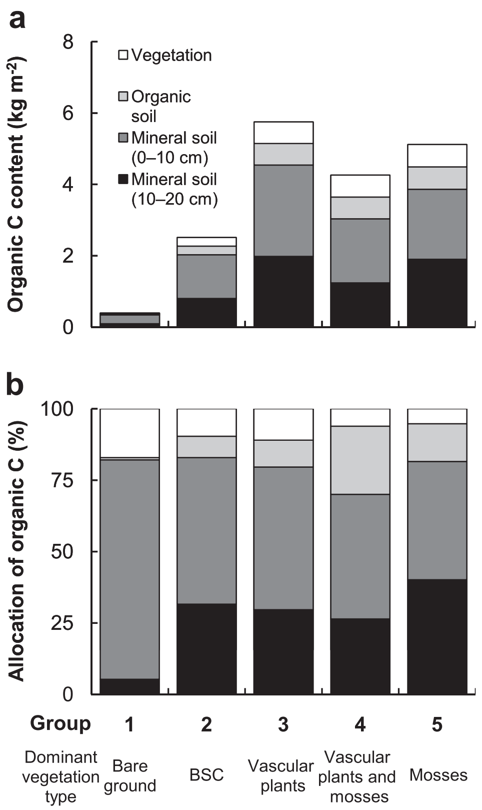

Fig. 4. (a) Organic carbon contents in vegetation, the organic soil layer, and mineral soil layers (0–10 and 10–20 cm) in each group; and (b) allocation pattern of organic carbon in each group of plots. Groups were identified by cluster analysis.

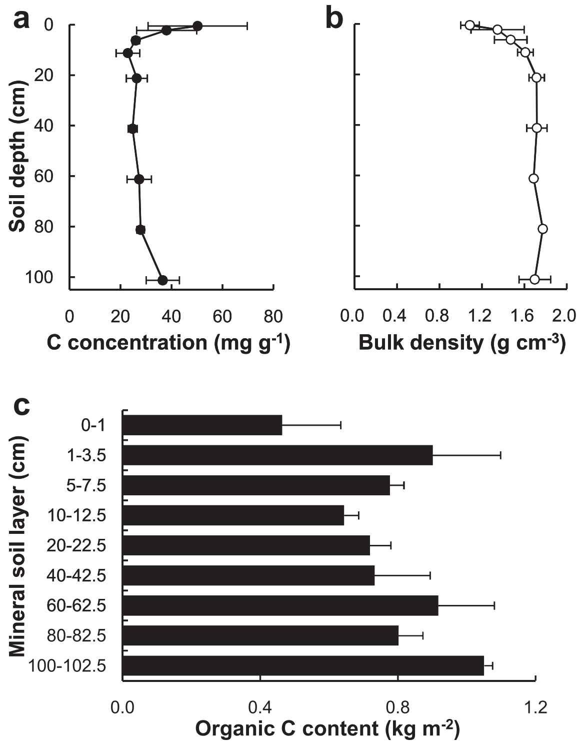

Fig. 5. Vertical distribution of (a) organic carbon concentration, (b) bulk density, and (c) organic carbon content in each layer of plot V. Values are means ± SE (n = 3).

measured in plot V indicates that the amount of organic carbon contained in deeper layers (20–100 cm) is comparable to or greater than that in shallower layers (Fig. 5). Nakatsubo et al. (2008) reported that part of this area had developed on a raised beach deposit and that deeper layers (depth below the organic soil layer > 10–20 cm) contain ancient beach deposit organic carbon dating to more than 20,000 yr BP (^{14}C dating of graphitized soil organic carbon). Another possible reason for high carbon contents in deeper layers is the transport of organic carbon from upper soil layers to the permafrost boundary by cryoturbation (Ping et al., 1997), or by cryochemical precipitation in which dissolved organic carbon from upper layers precipitates at the permafrost boundary under the influence of low temperatures (Gundelwein et al., 2007). Although the location of the permafrost boundary at our study plots was not determined, the thickness of the active layer in soils near the study site was estimated as 0.9–1.1 m (Roth and Boike, 2001). Therefore, the transport of organic carbon from upper soil layers to the permafrost boundary is expected to affect the organic carbon contents of deeper layers in this study area.

The average organic carbon content in plots at later stages of succession (the area between the floodplain and the sea) was about 4.3 kg C m^{-2} (range: 1.1–7.9 kg C m^{-2}). Although this value is less than values observed in Alaskan Arctic areas (up to 20 kg C m^{-2} in the upper 20 cm; Chapin et al., 1980) and alpine areas (up to 13 kg C m^{-2}; Grieve, 2000; Ohtsuka et al., 2008), it is comparable to values observed in Greenland (7.0 kg C m^{-2} in the upper 20 cm; Elberling et al., 2004). In addition, deeper mineral soil layers (>20 cm) may contain much more organic carbon in the form of raised beach deposits (cf. Fig. 5).

This study revealed that both vegetation development and geological characteristics of soils affect ecosystem carbon storage in this High Arctic glacier foreland. A non-negligible amount of organic carbon, including ancient organic carbon, is distributed within soil profiles, especially in areas representing later stages of succession.

Acknowledgments

We thank Dr. A. Kishimoto and Dr. Y. Shirato of the National Institute for Agro-Environmental Sciences for their help in measuring the carbon concentrations of the samples. This study was partly supported by a Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science. Thanks are also extended to anonymous reviewers for their respectful comments.

References

Anisimov, O.A., Vaughan, D.G., Callaghan, T.V., Furgal, D., Marchant, H., Prowse, T.D., Vilhjálmsson, H., Walsh, J.E., 2007. Polar regions (Arctic and Antarctic). In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 653–685.

Chapin III, F.S., Miller, P.C., Billings, W.D., Coyne, P.I., 1980. Carbon and nutrient budgets and their control in coastal tundra. In: Brown, J., Miller, P.C., Tieszen, L.L., Bunnnell, F.L. (Eds.), An Arctic Ecosystem: The Coastal Tundra at Barrow, Alaska. Dowden, Hutchison and Ross, Stroudsburg, pp. 458–486.

Elberling, B., Jakobsen, B.H., Berg, P., Søndergaard, J., Sigsgaard, C., 2004. Influence of vegetation, temperature, and water content on soil carbon distribution and mineralization in four High Arctic soils. Arct. Antarct. Alp. Res. 36, 528–538.

Grieve, I.C., 2000. Effects of human disturbance and cryoturbation on soil iron and organic matter distributions and on carbon storage at high elevations in the Cairngorm Mountains, Scotland. Geoderma 95, 1–14.

Gundelwein, A., Müller-Lupp, T., Sommerkorn, M., Haupt, E.T.K., Pfeiffer, E.M., Wiechmann, H., 2007. Carbon in tundra soils in the Lake Labaz region of arctic Siberia. Eur. J. Soil Sci. 58, 1164–1174.

Hammer, Ø, Harper, D.A.T., Ryan, P.D., 2001. PAST: paleontological statistics software package for education and data analysis. Paleontol. Electron 4, 9.

Hobbie, S.E., 1996. Temperature and plant species control over litter decomposition in Alaskan tundra. Ecol. Monogr. 66, 503–522.

Hodkinson, I.D., Coulson, S.J., Webb, N.R., 2003. Community assembly along proglacial chronosequences in the High Arctic: vegetation and soil development in north-west Svalbard. J. Ecol. 91, 651–663.

Jones, G.A., Henry, G.H.R., 2003. Primary plant succession on recently deglaciated terrain in the Canadian High Arctic. J. Biogeogr 30, 277–296.

Limin, D., Gang, W., Jingzhu, Z., Hongmei, K., Guofan, S., Hongbing, D., 2002. Carbon cycling of alpine tundra ecosystems on Changbai Mountain and its comparison with arctic tundra. Sci. China (Ser. D) 45, 903–910.

Liu, W., Fox, J.E.D., Zu, X., 2000. Leaf litter decomposition of canopy trees, bamboo and moss in a mountain moist evergreen broad-leaved forest on Ailao Mountain, Yunnan, south-west China. Ecol. Res. 15, 435–447.

Michaelson, G.J., Ping, C.L., Kimble, J.M., 1996. Carbon storage and distribution in tundra soils of Arctic Alaska, USA. Arct. Alp. Res. 28, 414–424.

Nakatsubo, T., Bekku, Y.S., Uchida, M., Muraoka, H., Kume, A., Ohtsuka, T., Masuzawa, T., Kanda, H., Koizumi, H., 2005. Ecosystem development and carbon cycle on a glacier foreland in the High Arctic, Ny-Ålesund, Svalbard. J. Plant Res. 118, 173–179.

Nakatsubo, T., Yoshitake, S., Uchida, M., Uchida, M., Shibata, Y., Koizumi, H., 2008. Organic carbon and microbial biomass in a raised beach deposit under terrestrial vegetation in the High Arctic, Ny-Ålesund, Svalbard. Polar Res. 27, 23–27.

Nakatsubo, T., Fujiyoshi, M., Yoshitake, S., Koizumi, H., Uchida, M., 2010. Colonization of the polar willow *Salix polaris* on the early stage of succession after glacier retreat in the High Arctic, Ny-Ålesund, Svalbard. Polar Res. 29, 385–390.

Oechel, W.C., Vourlitis, G.L., 1994. The effects of climatic change on land–atmosphere feedbacks in arctic tundra regions. Trends Ecol. Evol. 9, 324–329.

Ohtsuka, T., Adachi, M., Uchida, M., Nakatsubo, T., 2006. Relationships between vegetation types and soil properties along a topographical gradient on the northern coast of the Brøgger Peninsula, Svalbard. Polar Biosci. 19, 63–72.

Ohtsuka, T., Hirota, M., Zhang, X., Shimono, A., Senga, Y., Du, M., Yonemura, S., Kawashima, S., Tang, Y., 2008. Soil organic carbon pools in alpine to nival zones along an altitudinal gradient (4400–5300 m) on the Tibetan Plateau. Polar Sci. 2, 277–285.

Ping, C.L., Michaelson, G.J., Kimble, J.M., 1997. Carbon storage along a latitudinal transect in Alaska. Nutr. Cycl. Agroecosyst 49, 235–242.

Potter, C., 2004. Predicting climate change effects on vegetation, soil thermal dynamics, and carbon cycling in ecosystems of interior Alaska. Ecol. Model. 175, 1–24.

Roth, K., Boike, J., 2001. Quantifying the thermal dynamics of a permafrost site near Ny-Alesund, Svalbard. Water Resour. Res. 37, 2901–2914.

Shaver, G.R., Giblin, A.E., Nadelhoffer, K.J., Thieler, K.K., Downs, M.R., Laundre, J.A., Rastetter, E.B., 2006. Carbon turnover in Alaskan tundra soils: effects of organic matter quality, temperature, moisture and fertilizer. J. Ecol. 94, 740–753.

Sollins, P., Glassman, C., Paul, E.A., Swanston, C., Lajtha, K., Heil, J.W., Elliott, E.T., 1999. Soil carbon and nitrogen. In: Robertson, G.P., Coleman, D.C., Bledsoe, C.S., Sollins, P. (Eds.), Standard Soil Methods for Long-Term Ecological Research. Oxford University Press, New York, pp. 89–105.

Svendsen, H., Beszczynska-Møller, A., Hagen, J.O., Lefauconnier, B., Tverberg, V., Gerland, S., Ørbæk, J.B., Bischof, K., Papucci, C., Zajaczkowski, M., Azzolini, R., Bruland, O., Wiencke, C., Winther, J.G., Dallmann, W., 2002. The physical environment of Kongsfjorden–Krossfjorden, an Arctic fjord system in Svalbard. Polar Res. 21, 133–166.

Ward, J.H., 1963. Hierarchical grouping to optimize an objective function. J. Am. Stat. Assoc. 58, 236–244.