

Frost-Boil Ecosystems: Complex Interactions between Landforms, Soils, Vegetation and Climate

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ABSTRACT

Frost boils in northern Alaska vary from large, 2–3-m diameter, barren non-sorted circles to completely vegetated hummocks. Summer warmth increases southwards from the coast. Average thaw-layer thickness shows the opposite trend. Frost heave shows no trend along the climate gradient but is affected by soil texture. Heave is greatest on frost boils with fine-grained sediments. Biomass increases from 183 g m⁻² at the coast to 813 g m⁻² in the Arctic Foothills. An aggrading permafrost table is evident in most of the frost-boil soil profiles, indicating that, over time, accumulation of plant biomass leads to reduced thaw-layer thickness. A conceptual model suggests how vegetation affects the morphology of patterned ground forms. In the coldest parts of the High Arctic well-developed frost boils do not form and there is little vegetation on frost boils or the inter-boil areas. In the warmest parts of the Low Arctic, vegetation is usually sufficient to stabilize the frost boil soils. Frost boils play an important role in Arctic ecosystems functions, including the flux of trace gases to the atmosphere, flux of water and nutrients to streams, and the recycling of important nutrients to wildlife populations. Copyright © 2004 John Wiley & Sons, Ltd.

INTRODUCTION

This paper presents observations of frost boils in northern Alaska. It presents a hypothesis of how vegetation affects small-scale patterned-ground features across the complete Arctic climate gradient. Although not directly part of the Circumpolar-Active-Layer-Monitoring (CALM) project, frost boils influence the thaw layer and are relevant to CALM.

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Frost Boil Terminology

Frost boils are small, 0.5 to 3 m diameter, patches of barren or sparsely vegetated soil formed by frost action (Everdingen, 2002) (Figure 1). They are caused by differential frost heave in permafrost regions and occur in regular patterns over much of the Arctic. Although the term *frost boil* (= mud boil in the Canadian literature) has been widely used, the term is problematic for several reasons. First, evidence of active frost churning ('boiling') is often absent from the central portion of frost boils. Like many patterned

Received 15 April 2003
Revised 28 February 2004
Accepted 10 March 2004



Figure 1 Frost boils on Howe Island, Sagavanirktok River delta, northern Alaska. The frost boils are 1–2 m in diameter.

ground forms, frost boils are formed by several interacting mechanisms including but not limited to differential frost heave, frost cracking, mass displacement, and sorting processes. Washburn (1980) used the term *non-sorted circle* to describe the form without reference to a specific genetic cause. Other terms, including *frost medallion* and *frost scar*, have also been proposed to avoid implying a specific genesis. None is fully applicable to the features studied here because a variety of forms grade into each other as one moves along the climate gradient. Non-sorted circles grade into large turf-covered hummocks in the southern part of the Arctic, into non-sorted polygons, nets and small earth hummocks in the High Arctic, and into sorted patterns where there are coarse materials. Because no single term fully describes this range of variation, we retain the term ‘frost boil’ to apply to the range of small frost-heave features studied in this paper.

METHODS

Locations and Summer Warmth Indices

Seven 10 × 10-m grids were constructed in zonal habitats along a Low Arctic climate gradient in Alaska

(Figure 2). All sites except for Howe Island are easily accessible from the Dalton Highway. Extensive snow, and ground-temperature data are available from most sites (Romanovsky and Osterkamp, 1995; Romanovsky and Osterkamp, 1997). One study site, Happy Valley, is located within a CALM grid, and the West Dock site is adjacent to another (Brown *et al.*, 2000). Air temperature data were collected at each location at standard height using Campbell data loggers. The summer warmth index (SWI) (the sum of the monthly mean temperatures above freezing (°C mo)) is an integrated value for the total amount of summer warmth available for plant growth. This index has been used to describe the northern limits of arctic plant-species distributions (Young, 1971). It is highly correlated with thawing degree-days (TDD), which is the sum of the daily mean temperatures greater than 0°C. SWI is used for broad regional comparisons because it can be easily derived from monthly mean summaries. Howe Island and West Dock are in Bioclimate Subzone C; Deadhorse, Franklin Bluffs, and Sagwon MNT are in Subzone D; and Sagwon MAT and Happy Valley are in Subzone E. The summer warmth indices at these sites were 9.3, 14, 19.27, 28.2, 28.2, and 30.2°C mo, respectively.

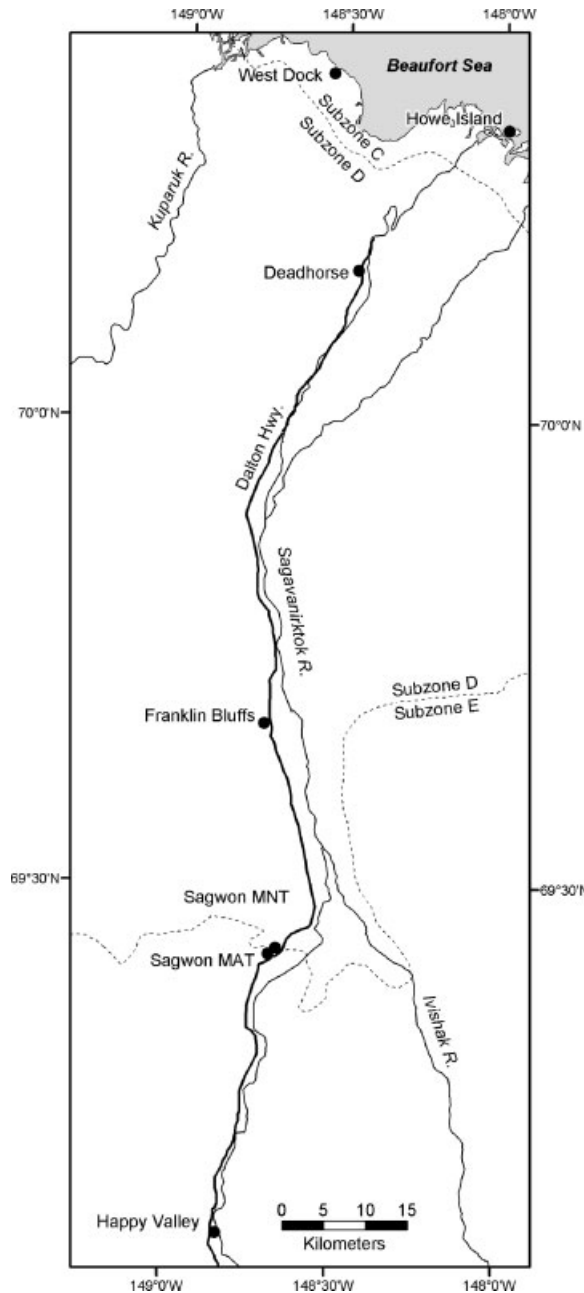


Figure 2 Locations of study grids along the Dalton Highway, northern Alaska. The approximate boundaries between bioclimate subzones C and D and between D and E are shown.

Vegetation

Aerial photographs were taken of each grid from a helicopter at approximately 50-m altitude. The vegetation was mapped on aerial photographs supplemented

with plant-community and micro-site data collected from 441 points in each grid. Detailed studies of plant community composition were made using the Braun-Blanquet relevé approach (Westhoff and van der Maarel, 1978). Vegetation was sampled in the grids and in nearby replicate plots. Biomass, leaf-area index, and the normalized difference vegetation index (NDVI) data were collected at each site along two 50-m transects located adjacent to the grids. Biomass data were collected from six 20 × 50-cm plots located at 5, 25 and 45 m along the 50-m transects. The samples were sorted in the field into plant functional types (shrubs, graminoids, forbs, mosses, lichens), and then later separated into woody, foliar, live and dead components. Leaf Area Index (LAI) was measured using a LI-COR LAI-2000 Plant Canopy Analyzer at 2-m intervals along the 50-m transects. The details of the biomass and LAI sampling methods are described in Walker *et al.* (2003).

NDVI is a unitless remotely-sensed index of vegetation green biomass that can be measured from earth-orbiting satellites, aircraft, or with field instruments (Goward *et al.*, 1985; Rouse *et al.*, 1973). NDVI was used in this study to complement the biomass data, to give an index of the density of vegetation along the bioclimate gradient, and to contrast the abundance of vegetation on frost boils and inter-boil areas. The index is given by:

$$\text{NDVI} = (\text{NIR} - \text{R}) / (\text{NIR} + \text{R}), \quad (1)$$

where NIR is the spectral reflectance in the near-infrared band (0.725–1.1 μm), dominated by light scatter from the plant canopy, and R is reflectance in the red (0.58–0.68 μm), chlorophyll-absorbing portion of the spectrum (Markon, 1999). The index has been used extensively in tundra vegetation of northern Alaska as an indicator of biomass and other ecosystem properties such as CO₂ flux (Hope *et al.*, 1995; Hope *et al.*, 1993; Jia *et al.*, 2002; Jia *et al.*, 2004; Shippert *et al.*, 1995). The values can vary theoretically from 0 (no green vegetation) to 1.0 (very high cover of green vegetation).

Regional-scale NDVI was measured using AVHRR satellite-based time-series data for 1995–1999 (US Geological Survey (USGS) Alaska Data Center). These data were based on 14-day composite periods to match the processing of global data sets. We used the portion of the data between 1 April and 31 October, which brackets the snow-free period. Here we report maximum NDVI (MaxNDVI). We used 1:60 000-scale color-infrared (CIR) aerial photographs (acquisition dates, 1978 and 1982) to delineate areas of homogeneous vegetation in the vicinity of the grids. This was a portion of the same data set used by



Figure 3 Heave instrument, Deadhorse, AK. (a) The horizontal bar is bolted to the vertical support members, which are deeply anchored in permafrost. (b) The thin vertical rods ride up and down with frost heave and settlement. Each bar is attached to a small foot that is buried just below the soil surface. Readings are periodically taken from each vertical rod.

Jia *et al.* (2002) for the analysis of intra-seasonal patterns of NDVI in relation to the climate record. Polygons were drawn around these areas on mylar transparent overlays. The aerial photographs and polygons were then digitized and geo-registered to the AVHRR imagery using ARC/INFO software. Details of the registration procedures are in Jia *et al.* (2002). MaxNDVI for each polygon was calculated from the set of annual maximum NDVI values for all pixels within the polygon. The integrated NDVI is the sum of all the biweekly NDVI values during the green period.

Plot-scale NDVI was measured to compare the density of vegetation on and between frost boils in subzones D and E. NDVI data were collected from frost boils and inter-boil areas using a hand-held PS-II portable field spectrometer made by Analytical Spectral Devices, Inc. The spectrometer measures reflectance in 256 channels. We grouped the data into the same red and near-infrared portions of the spectrum as those used for the AVHRR-derived NDVI values. Study plots were subjectively chosen as representative of typical frost boils and inter-frost-boil areas at each site. Data were collected from three frost-boil plots and three inter-boil plots at the Happy Valley, Sagwon MNT and Franklin Bluffs on 30 June 2002. Three replicate measurements were made on each plot.

Thaw Depth and Frost Heave

Thaw depths were measured on each of the 10×10 -m grids during 14–16 August 2002. Measurements were made at 0.5-m intervals (441 points in each grid) using

a metal probe. Frost heave was monitored using the device shown in Figure 3. Each instrument measured heave at 10 points along a short transect traversing a representative frost boil and the adjacent inter-boil area. One heave instrument was located adjacent to each 10×10 -m grid. At Happy Valley and Sagwon MAT, heave was measured on two types of frost boils: (a) large well-vegetated hummocks and (b) small barren inter-tussock frost boils. Maximum heave was recorded in mid-May of 2002 at all sites except Howe Island, where data were collected in May 2003. Base heave was recorded when the soils had thawed to their maximum thaw-layer thickness in late August.

Soils

Soil pits were excavated using shovels and a gas-powered jackhammer to a depth of 1 m. One pit was dug at each site adjacent to the 10×10 -m grid, such that the pit traversed a frost boil and inter-frost-boil area. Soil morphological properties were described according to the Soil Survey Manual (Soil Survey Staff, 1993). Soil samples from the genetic horizons were shipped to either the Palmer Research Center Laboratory or the National Soil Survey Laboratory (NSSL) for analysis. Soil pH values reported here were from the top mineral horizon using the saturated paste method with distilled water. Particle size was determined using the hydrometer method. Soil moisture was calculated on a volumetric basis (Gardner, 1986). Data reported are the average of three replicates from each soil.

RESULTS

Frost-Boil Morphology and Vegetation

The vegetation maps of the grids are shown in Plate 1. The percentage cover of barren frost boils (hachured gray areas in Plate 1) declined southward from 25% at Howe Island to 1% at Sagwon MAT and Happy Valley. The total of all vegetated and non-vegetated frost-boil habitat types declined from 25% at Howe Island to 5% at Sagwon MAT and 13% at Happy Valley. The inter-boil areas and the vegetated frost-boil habitat types had a corresponding increase in area. The West Dock site is not shown in Plate 1 because the vegetation was a continuous mat of moist tundra with no frost boils. This site had a thin organic mat that lay directly on a coarse sandy gravel alluvial material that was relatively unaffected by frost heave.

The morphology of the frost boils and species composition of the accompanying vegetation changed considerably along the temperature gradient (Table 1). At the northernmost site on Howe Island in Subzone C, the frost boils had only a few widely scattered grasses (*Puccinellia angustata*) and forbs (*Braya purpurascens*) on large otherwise barren 1 to 2-m patches of soil (see Figure 1 and Plate 1). Such large barren frost boils are uncommon along the Beaufort coast of northern Alaska and more similar to the frost boils that occur in the central portions of Subzone C, such as Banks, Victoria, and other islands of the Canadian Archipelago. Crustose lichens were dominant in dry microsites surrounding the frost boils (see Table 1 for species). A continuous cover of vegetation consisting of prostrate shrubs, forbs, and mosses occurred in the relatively moist micro-sites in troughs of ice-wedge polygons.

Within Subzone D, there was a gradual southward diminishment of the cover of bare soil on the frost boils (Table 1 and Plate 1). The relatively barren portions of the frost boils had a distinctive plant association composed of scattered herbaceous plants, small mosses and liverworts, and soil lichens (see Table 1 for species). Many of the common species are calciphiles, such as the vascular plants *Saxifraga oppositifolia*, *Dryas integrifolia*, *Cardamine hyperborea*, *Senecio atropurpureus*, and *Tofieldia coccinea*, the small mosses *Catascopium nigratum*, *Ditrichum flexicaule*, and *Distichium capillaceum*, and soil lichens *Cladonia pocillum* and *Lecanora epibryon*. More stable portions of the frost boils had a plant association consisting of prostrate dwarf-shrubs, many herbaceous plants, a thin layer of mosses less than 3 cm thick, and many lichens. Inter-boil areas in Subzone D consisted of plant communities of the

association *Dryado integrifoliae-Caricetum bigelowii* (Walker *et al.*, 1994) that also occurred on non-acidic mesic uplands and hill slopes. Moss carpets in the inter-boil areas thickened toward the south and formed mats in excess of 10 cm near the Subzone E boundary. Areas with somewhat wetter soils had rings of tussock cottongrass (*Eriophorum vaginatum*) around the margin of the frost boils.

In tussock-tundra areas of Subzone E at Sagwon MAT and Happy Valley, the frost boils had two distinctive forms. The first were small, 20–30-cm diameter barren patches that were widely scattered and occurred in depressions between cottongrass tussocks (note small hachured gray areas in the maps of Sagwon MAT and Happy Valley, Plate 1). These were often wet sites with few vascular plants and a thin layer of cryptogamic plant species, mostly liverworts (see Table 1 for species). Also in Subzone E, large well-vegetated raised hummocks occurred on stabilized frost boils (hachured orange areas in maps of Plate 1; see Figure 10). These features were 1–1.5 m in diameter and about 30–50 cm high. The hummocks had vegetation that was somewhat drier than the surrounding tussock tundra with complete vegetative cover consisting of sedges, acidiphilic dwarf shrubs, mosses, and abundant lichens. The inter-boil areas consisted of the tussock tundra plant association *Sphagno-Eriophoretum vaginati* (Walker *et al.*, 1994).

Biomass, LAI, and NDVI increased toward the south in response to the warmer summer temperatures (Table 2). A five-fold increase in total biomass occurred along the gradient (183 g m⁻² at Howe Island and 932 g m⁻² at Sagwon MAT, Table 2). A large increase in shrub biomass occurred at the Subzone D-E boundary, with generally less than 100 g m⁻² of shrubs north of the boundary and more the 250 g m⁻² south of the boundary. LAI of the plant material above the moss layer also showed a major increase from values less than 0.9 south of the boundary to about 1.5 south of the boundary.

MaxNDVI increased from 0.259 at Howe Island to 0.534 at Sagwon MAT and 0.527 at Happy Valley, and the integrated NDVI increased from 1.42 at Howe Island to 4.23 at Sagwon MAT. The NDVI values were not measured directly on the grids but were measured from large homogeneous areas of tundra in the immediate vicinity of the grids, and indicate that the greenness of large landscapes in the vicinity of the grids increased toward the south.

There were no data to directly compare the biomass on frost boils vs. inter-boil areas. The biomass data cited above were from randomly selected sites, and were thus average landscape biomass values.

Table 1 Frost-boil morphology and typical plant species growing on frost boils in subzones C, D and E, northern Alaska.

Subzone	Frost-boil morphology	Frost boils	Inter-boils
C (Howe Island)	Large barren circles, 1–2 m diameter, 20 circles per 100 m ²	Very scattered grasses and forbs (including <i>Puccinellia angustata</i> , <i>Braya purpurascens</i>)	Dry microsites: Mostly crustose lichens (including <i>Fulgensia bracteata</i> , <i>Lecanora epibryon</i> , <i>Mycobilimbia lobulata</i> , <i>Polyblastia sendtneri</i>). Moist microsites: Continuous cover of vegetation consisting of prostrate shrubs (<i>Dryas integrifolia</i> , <i>Salix arctica</i> , <i>Salix ovalifolia</i>), forbs (including <i>Artemisia borealis</i> , <i>Cerastium beeringianum</i> , <i>Chrysanthemum integrifolium</i> , <i>Cochlearia officinalis</i> , <i>Draba alpina</i> , <i>Melandrium apetalum</i> , <i>Minuartia arctica</i> , <i>Pedicularis neoalaskanum</i> , <i>Polygonum viviparum</i> , <i>Saxifraga oppositifolia</i>), and mosses (including <i>Amblystegium serpens</i> , <i>Ctenidium procerrimum</i> , <i>Ditrichum flexicaule</i> , <i>Distichium capillaceum</i> , <i>Tortula ruralis</i> , <i>Tomentypnum nitens</i>).
D (Deadhorse, Franklin Bluffs, Sagwon MNT)	Partially vegetated circles, with some areas of barren soil, 1–1.5 m diameter, 15–20 circles/100 m ²	Mosaic consisting of: Active barren patches: scattered basiphilous herbaceous plants (including <i>Antennaria friesiana</i> , <i>Cardamine hyperborea</i> , <i>Carex capillaceum</i> , <i>C. membranacea</i> , <i>Eriophorum angustifolium/triste</i> , <i>Juncus biglumis</i> , <i>Minuartia rossii</i> , <i>Polygonum viviparum</i> , <i>Saxifraga oppositifolia</i> , <i>Senecio atropurpureus</i> , <i>Tofieldia coccinea</i>), small mosses and liverworts (including <i>Aneura pinguis</i> , <i>Bryum wrightii</i> , <i>Catascopium nigratum</i> , <i>Didymodon icmadophylos</i> , <i>Distichium capillaceum</i> , <i>Encalypta rhapsocarpa</i> , <i>Tortella tortuosa</i>), and soil lichens (<i>Cladonia pocillum</i> , <i>Collema</i> sp., <i>Lecanora epibryon</i> , <i>Mycolimbica lobulata</i> , <i>Polyblastia sendtneri</i> , <i>Rinodina roscida</i> , <i>Solorina bispora</i>). More stable patches: plant association consisting of prostrate dwarf shrubs (<i>Dryas integrifolia</i> , <i>Salix reticulata</i>), many herbaceous plants (including <i>Astragalus umbellatus</i> , <i>Cardamine hyperborea</i> , <i>Carex membranacea</i> , <i>C. scirpoidea</i> , <i>Eriophorum triste</i> , <i>Lupinus arcticus</i> (toward the south), <i>Minuartia rossii</i> , <i>Pedicularis capitata</i> , <i>P. lanata</i> , <i>Polygonum viviparum</i> , <i>Rhododendron lapponicum</i> (toward the south), <i>Senecio atropurpureus</i> , <i>Tofieldia coccinea</i>), a thin layer of mosses less than 3 cm thick (including <i>Distichium capillaceum</i> , <i>Ditrichum flexicaule</i> , <i>Rhytidium rugosum</i> , <i>Sanionia uncinatus</i> , <i>Tomentypnum nitens</i>), and many lichens (including <i>Cetraria islandica</i> , <i>Cladonia pocillum</i> , <i>Dactylina arctica</i> , <i>Flavocetraria cucullata</i> , <i>F. nivalis</i> , <i>Thamnolia</i> spp.)	Association <i>Dryado integrifoliae-Caricetum bigelowii</i> (M.D. Walker <i>et al.</i> , 1994). The dominant plants are sedges (including <i>Carex bigelowii</i> , <i>C. membranacea</i> , <i>Eriophorum triste</i>), dwarf shrubs (<i>Cassiope tetragona</i> , <i>Dryas integrifolia</i> , <i>Salix arctica</i> , <i>Rhododendron lapponicum</i> (toward the south), <i>S. richardsonii</i> , <i>S. reticulata</i>), and mosses (including <i>Aulacomnium turgidum</i> , <i>Catascopium nigratum</i> , <i>Distichium capillaceum</i> , <i>Ditrichum flexicaule</i> , <i>Hylocomium splendens</i> , <i>Tomentypnum nitens</i>) and a few lichens (including <i>Cetraria islandica</i> , <i>Dactylina arctica</i> , <i>Flavocetraria cucullata</i> , <i>F. nivalis</i> , <i>Peltigera aphthosa</i> , <i>P. canina</i> , <i>Thamnolia</i> spp.)
E (Sagwon MAT, Happy Valley)	Two types: a. Scattered small barren patches 20–30 cm diameter located between	a. Few vascular plants (<i>Juncus biglumis</i> , <i>Luzula arctica</i>) and a thin layer of cryptogamic plant species, mostly liverworts (including <i>Anthelia juratzkana</i> , <i>Cephalozia bicuspidata</i> , <i>Cryptocolea imbricata</i> , <i>Diplophyllum</i> sp., <i>Jungermannia</i> sp.,	a. Association <i>Sphagno-Eriophoretum vaginati</i> (M.D. Walker <i>et al.</i> , 1994). This association consists of tussock cottongrass (<i>Eriophorum vaginatum</i>), dwarf shrubs (including <i>Betula nana</i> , <i>Empetrum</i>

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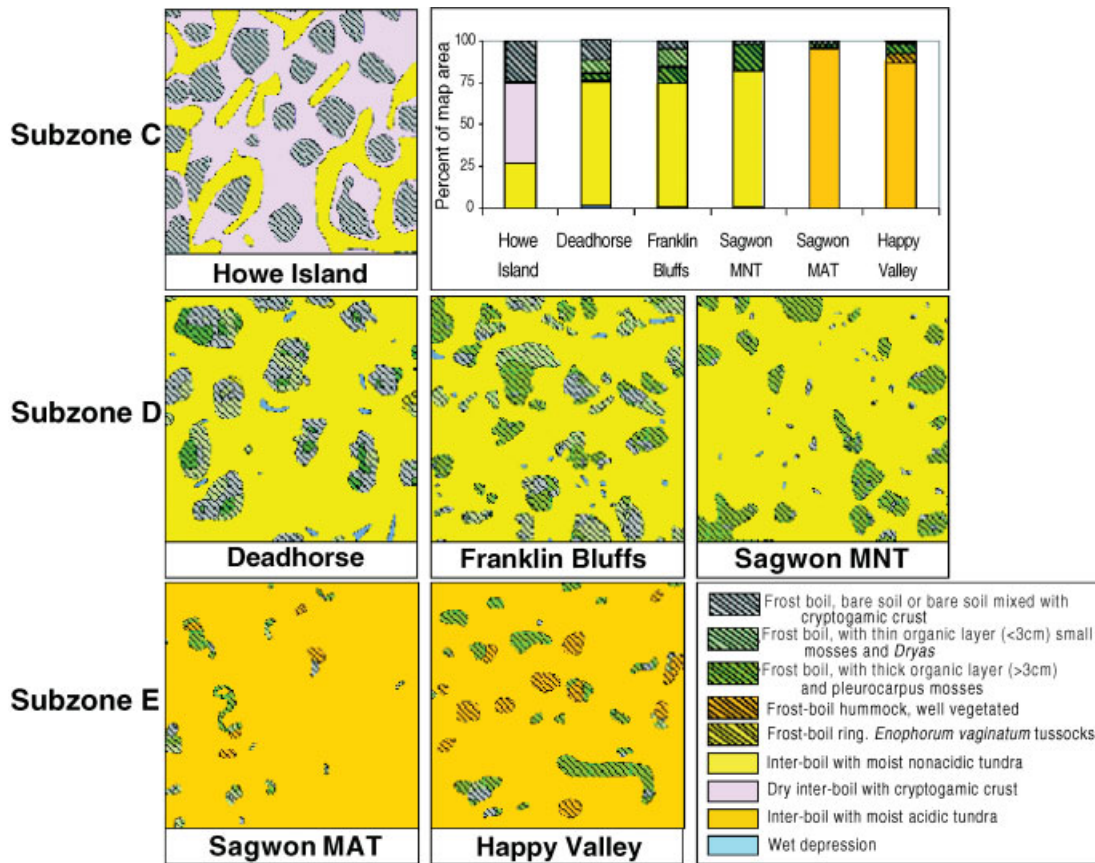


Plate 1 Vegetation/habitat types associated with frost boils on 10 × 10-m grids at six sites along the bioclimate gradient near the Dalton Highway. Note the trend of less bare soil with warmer summer temperatures (toward the right and down). Also note the frost-boil hummocks in Subzone E.

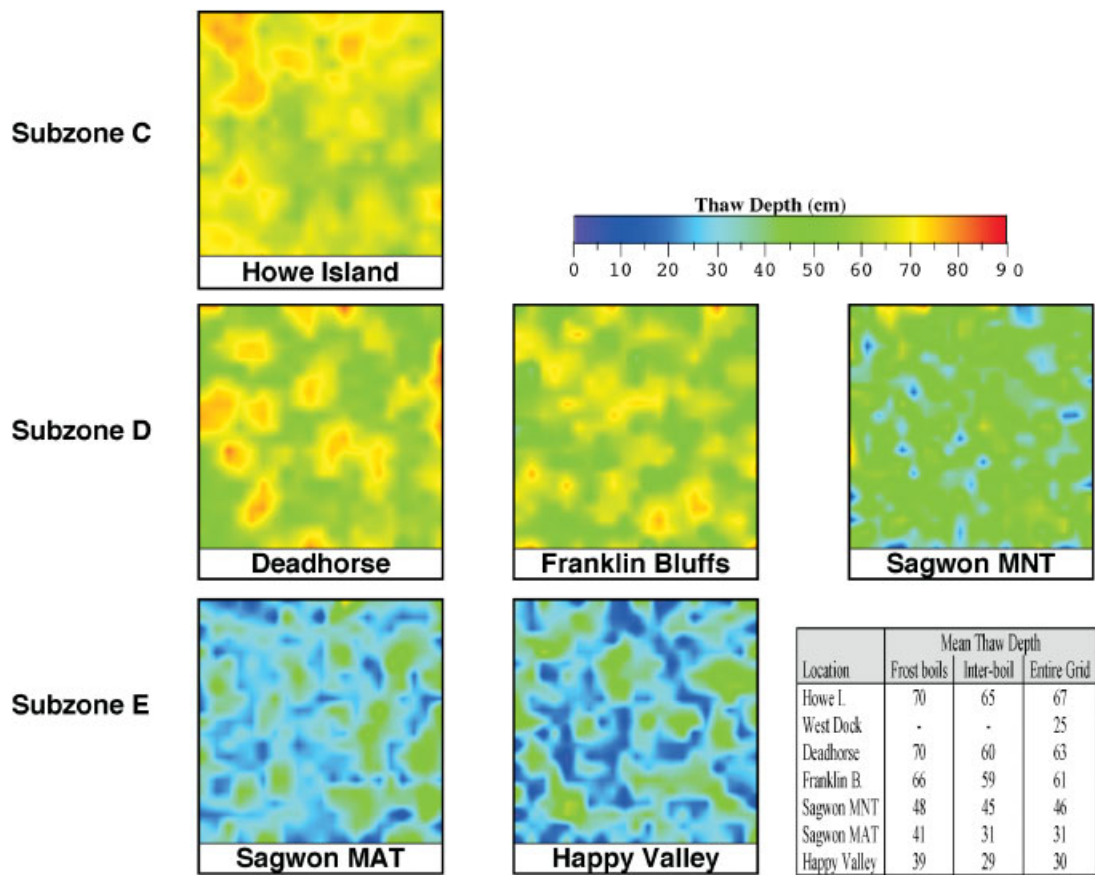


Plate 2 Maps of thaw layers in the 10 × 10-m grids, northern Alaska, August 2002. West Dock is not shown because there were no frost boils at that site.

Table 1 Continued.

Subzone	Frost-boil morphology	Frost boils	Inter-boils
	cottongrass tussocks, 5–10 patches/100 m ²	<i>Lophozia</i> spp., <i>Sphenolobus minutus</i>), mosses (including <i>Dicranella subulata</i> , <i>Hylocomium splendens</i> , <i>Pohlia crudoides</i>), and few lichens (including <i>Arthrorhaphis</i> sp., <i>Cetraria cucullata</i> , <i>Cladonia fimbriata</i> , <i>C. coccifera</i> , <i>C. chlorophaea</i> , <i>Dactylina ramulosa</i> , <i>Peltigera aphthosa</i> , <i>P. rufescens</i>).	<i>nigrum</i> , <i>Ledum decumbens</i> , <i>Rubus chamaemorus</i> , <i>Salix pulchra</i> , <i>Vaccinium vitis-idaea</i> , <i>V. uliginosum</i>), mosses (including <i>Sphagnum</i> spp., <i>Aulacomnium turgidum</i> , <i>Dicranum</i> spp., <i>Hylocomium splendens</i> , <i>Polytrichum strictum</i>), and scattered lichens (including <i>Cetraria islandica</i> , <i>Cladina arbuscula</i> , <i>C. mitis</i> , <i>C. rangiferina</i> , <i>Cladonia amaurocraea</i> , <i>Flavocetraria</i> spp., <i>Peltigera</i> spp.)
	b. Large hummocks, 20–30 cm high and 1–1.5 m diameter, 5–10 hummocks/100 m ²	b. Vegetation somewhat drier than the surrounding tussock tundra with complete vegetative cover consisting of sedges (mainly <i>Carex bigelowii</i>), grasses (<i>Arctagrostis latifolia</i>), acidiphilous dwarf shrubs (<i>Betula nana</i> , <i>Ledum decumbens</i> , <i>Vaccinium vitis-idaea</i>), mosses (including <i>Aulacomnium turgidum</i> , <i>Dicranum elongatum</i> , <i>Hylocomium splendens</i> , <i>Racomitrium lanuginosum</i> , <i>Pleurozium schreberi</i>), and abundant lichens (including <i>Cetraria</i> spp., <i>Cladina mitis</i> , <i>C. stygia</i> , <i>Cladonia chlorophaea</i> , <i>Dactylina arctica</i> , <i>Nephroma arcticum</i> , <i>Peltigera</i> spp.)	b. Same as inter-boil areas of a.

However, ground-level measurements of NDVI and LAI were collected from frost boils and inter-boil areas at three sites, Happy Valley, Sagwon MNT, and Franklin Bluffs (Figure 4). These data provide some impression of the green biomass on frost boils compared to inter-boil areas across the Subzone D/E boundary (see Figure 2). Across all three locations, the average ground-level NDVI on the frost boils was 0.41, and the average LAI was 0.19, whereas the inter-boil areas had an average NDVI of 0.54 and an LAI of

0.88. The NDVI was much higher at the Happy Valley Subzone E site, particularly on the frost boils because of the much denser cover of plants on the Subzone E frost boils.

Thaw Depth and Frost Heave

The least thaw was recorded in Subzone C, at the coastal West Dock site (25 cm) (see Table insert in Plate 2). However, this site had no frost boils. Sites with frost boils showed a trend of thinner thaw layers inland from the coast. The deepest thaw occurred at Howe Island, where the average thaw was 70 cm within the frost boils, and 65 cm in the inter-boil areas. The least thaw occurred at Happy Valley, 39 cm in the frost boils and 29 cm between frost boils.

Thaw-depth maps give a better indication of frost boil locations than vegetation maps. For example, at Happy Valley and the Sagwon MAT sites, the map of the thaw depths (Plate 2) shows the presence of a thaw pattern similar to that in areas with abundant frost boils, whereas the vegetation maps show little surface indication of frost boils because most are completely covered with vegetation. This is not to suggest that all areas have a subsurface pattern of frost boils. Frost boils are generally associated with fine- and medium-textured soils, and are uncommon in coarse-textured sandy and gravelly soils. For example, the West Dock site had near-surface gravels and no surface expression of frost boils, and thaw likewise did not vary much.

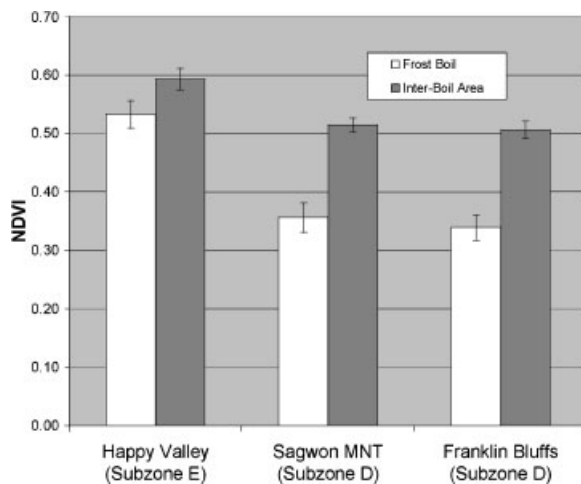


Figure 4 NDVI (mean and standard error) measured on frost boils and inter-boil area at three sites, 25 Jul 2002, northern Alaska.

Table 2 Summary of bioclimate, NDVI, thaw depth, biomass, and soil information for the study sites. Vegetation types are SDNT (sandy dry nonacidic tundra), SMNT (sandy MNT), MNT (moist nonacidic tundra), and MAT (moist acidic tundra). Soil pH, soil water, and texture are from the top mineral horizon in inter-boil soils. Thaw depth is the mean of 441 points in each of the grids.

Site	Sub zone	Veg type	SWI (°C mo)	Max NDVI	Integrated NDVI	Biomass (g/m ²)				LAI	Thaw depth (cm)	Soil pH	O hor. (cm)	Soil H ₂ O (% vol)	Sand (%)	Silt (%)	Clay (%)
						Total	Lichen	Moss	Shrub								
Howe Island	C	SDNT	9.3	0.259	1.42	183	14	59	109	1	0.01	67	1	36	61	24	16
West Dock	C	SMNT	14.0	0.280	1.71	389	21	104	59	204	0.61	25	6	46	60	24	16
Deadhorse	D	MNT	19.0	0.342	2.15	412	6	86	84	221	0.89	63	10	28	32	47	21
Franklin Bluffs	D	MNT	27.0	0.462	3.14	544	24	237	120	157	0.81	61	11	29	5	68	27
Sagwon MNT	D	MNT	28.2	0.477	3.56	658	46	483	58	70	0.49	46	8	32	10	65	25
Sagwon MAT	E	MAT	28.2	0.534	4.23	932	59	515	268	84	1.5	31	16	32	33	45	22
Happy Valley	E	MAT	30.2	0.527	4.19	813	68	262	272	208	1.48	30	10	36	9	63	28

Frost heave varied from less than 1 cm at the West Dock site to 20 cm on frost boils at Deadhorse (Figure 5). Heave on the frost boils with silt-loam to loamy soils was 9–20 cm versus only 4 cm in the sandy loam soil at Howe Island. Heave in the inter-boil areas varied from 3 cm at Howe Island to 5 cm at the Sagwon MNT site. The soil at West Dock had only slight heave. Differential heave (the difference between the heave on the frost boil and inter-boil areas) was greatest at Deadhorse and Franklin Bluffs (17 cm). The least differential heave occurred at West Dock (0 cm) and Howe Island (1 cm), sites with relatively sandy soils.

The low amount of heave in the frost boils on Howe Island occurred on the site with the most clearly expressed frost boils (Figure 1). Why such a small amount of heave has such a large effect on the vegetation is not clear. One possible explanation is that the barren frost boils in colder environments have higher salt concentrations (Michaelson, unpublished data). The barren frost boils typical of coastal areas are apparently pumping salt to the surface because of relatively high evaporation. Salt has been shown to be particularly toxic to *Dryas*, the dominant plant in Subzone C zonal sites (Simmons *et al.*, 1981), and may have similar effects on other typical tundra species. The two species of vascular plants found growing in the barren frost boils at Howe Island, *Puccinellia angustata* and *Braya purpurascens*, are both salt-tolerant species commonly found in dry disturbed saline coastal habitats at Prudhoe Bay.

There was no relationship between air temperature and soil heave. The large difference in heave between the frost boils and the inter-boil areas appears to result from a combination of factors. The thicker thaw layer of the frost boils probably allows more ice lensing to develop, resulting in more heave. However, the

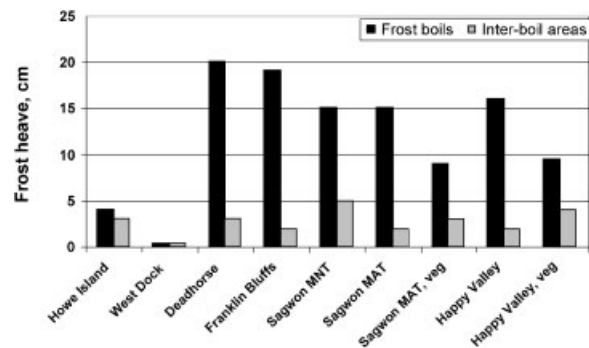


Figure 5 Maximum heave on frost boils and inter-boil areas, northern Alaska, 2001–2002, except for Howe Island, which was measured in 2002–2003.

difference in the amount of heave between the frost-boil and inter-boil areas cannot be explained completely by differences in thaw-layer thickness alone. Cryosuction probably pulls water from the inter-boil areas to increase the amount of heave within the frost boil, as explained in the differential-frost-heave model (Peterson and Krantz, 2003).

Soils

Soil pH, organic horizon thickness, soil moisture, and texture are shown in Table 2. Soil pH was high at the northern end of the gradient in subzones C and D (7.9–7.5), and low at the southern end of the gradient in Subzone E (5.0–5.1). Organic soil horizons were 1–6 cm in Subzone C, 8–11 cm in Subzone D and 10–16 cm in Subzone E. Volumetric soil moisture varied between 28 and 46%, but showed no major trend across the transect. Soil textures were sandy loams at Howe Island and West Dock, silt loams at Franklin Bluffs and Sagwon MNT, and loams at Deadhorse, Sagwon MAT, and Happy Valley. Other observations

important to our conceptual model of frost-boil formation are summarized here.

1. Most frost-boil soils exhibit a platy structure that crumbles to a granular structure. This is the result of ice-lenses and veins that form during the winter (Fowler and Krantz, 1994; Gilpin, 1980) (Figure 6).
2. The lowest part of several soil profiles exhibited a zone termed the *intermediate layer* (Shur, 1988). The cryogenic structure of this zone consists of a continuous matrix of ice containing blocks of soil aggregates (Figure 7).
3. Soil properties vary considerably across frost boils (Figure 8). Nutrient concentrations and water content decline and the bulk density increases from the margin toward the center in response to more active, less vegetated soils near the center of the frost boils. As one moves from the coast inland, the soils on frost boils become more vegetated. Within Subzone E, the frost boils are completely vegetated, and form hummocks that have well developed organic soil horizons (Figure 9).

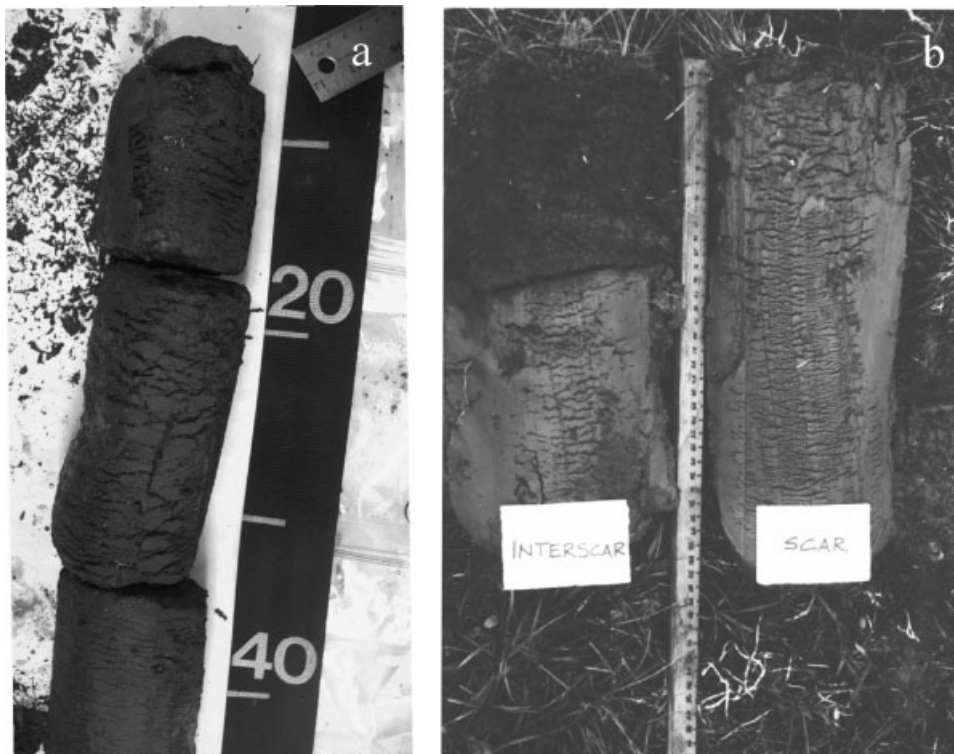


Figure 6 Ice lenses in frost-boil soils. (a) Soil core taken from a frost boil in winter 2002 at the Franklin Bluffs site. Dark-colored veins are ice lenses 1–3 mm thick. The lenses are thicker at the top of the core and thin toward the bottom. (b) Soils taken in summer from an inter-frost-boil area (left) and a frost boil (right). The platy structure of the soil is the result of ice lenses that were present during the winter. Note the dark 20-cm thick organic layer above the mineral portion of the inter-frost-boil soil.

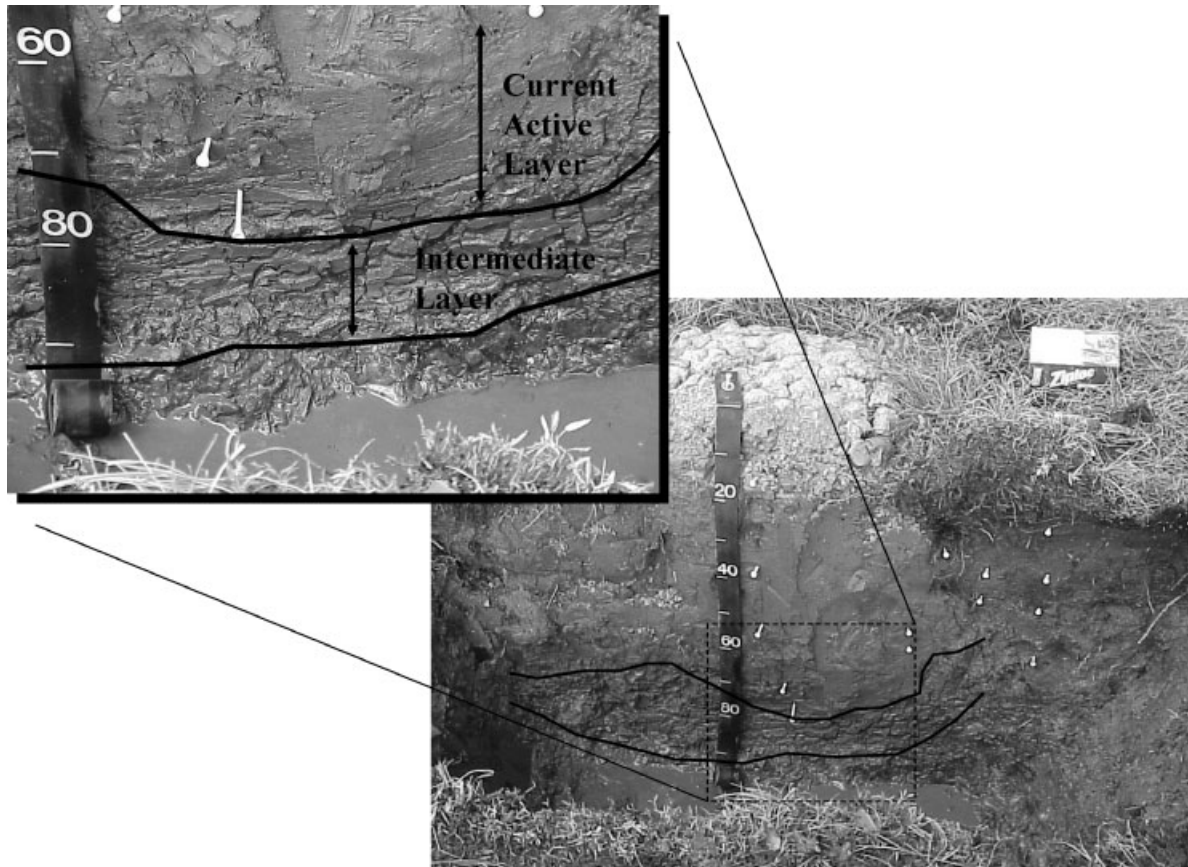


Figure 7 Soil pit traversing a frost boil and inter-boil area, showing the structure of the soil at the top of the permafrost table. Soil below the active layer was exposed with a jackhammer. Note the reticulate pattern of horizontal ice lenses and vertical veins in the ice-rich intermediate layer. The darker color of the intermediate layer is caused by high organic matter content.

DISCUSSION

The Relationship of Vegetation to Patterned-Ground Morphology

One of the most intriguing aspects of frost boils is their regular pattern (Figure 1). Models of self-organization of frost boils have been presented for sorted forms (Kessler *et al.*, 2001; Kessler and Werner, 2003), and non-sorted forms (Peterson and Krantz, 2003; Peterson *et al.*, 2003). The Peterson and Krantz differential-frost-heave (DFH) model is appropriate for fine-grained sediments in northern Alaska. The model is based on differential frost-heave processes and predicts order of magnitude heave and spacing of frost boils and can account for the circular motion of soils within frost boils. It is an inception model that describes initiation of frost boils in homogeneous soils.

The most thorough analysis of the relationship between ecosystems and frost boils to date is that of

Nadezhda Matveyeva (Chernov and Matveyeva, 1997; Matveyeva, 1998). She described the trends of horizontal and vertical structure of the vegetation in frost boil systems, and developed a concept of succession associated with frost boils occurring on the Taimyr Peninsula. Similar relationships with respect to bioclimate zonation have been verified in North America (Gould *et al.*, 2003). The major elements of Matveyeva's zonal scheme are summarized in Figure 10. The names of Matveyeva's subzones have been modified to show relationships to the circumpolar arctic vegetation map (CAVM Team, 2003).

In Subzone A, the coldest regions of the extreme High Arctic (in the sense of Polunin (1951)), nearly barren, small non-sorted polygons approximately 20 cm in diameter form due to desiccation and/or seasonal frost cracking (Figure 10). Small mosses and lichens fill some of the cracks.

In Subzone B, some of the cracks widen, possibly due to preferential thermal cracking at these sites,

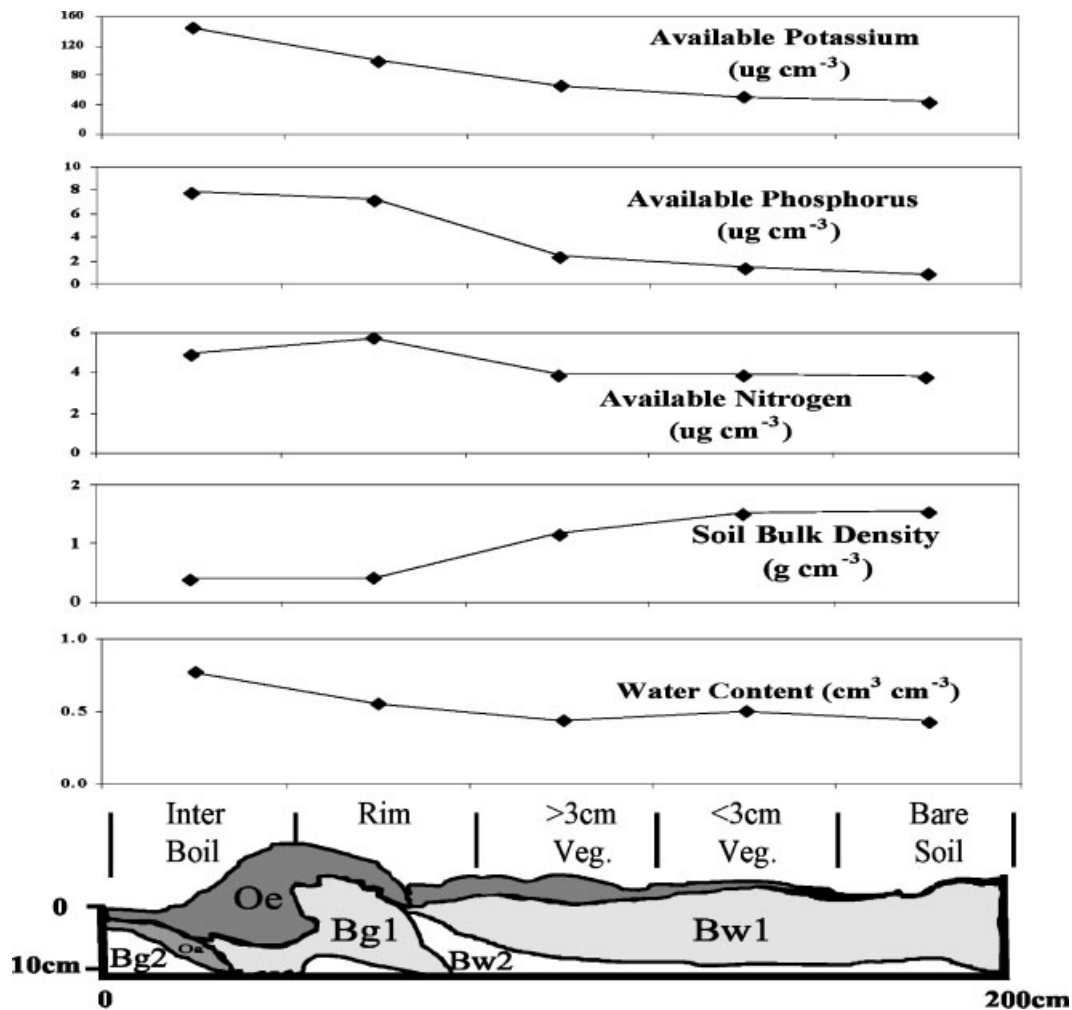


Figure 8 Spatial variation in soil properties across a frost boil. Data are from a frost boil at the Deadhorse site.

forming well-developed hummocks with a diameter of about 1–2 m. Distinct troughs between the hummocks are filled with a mix of herbaceous and cryptogam plants. The tops of the hummocks are sparsely vegetated and have desiccation features and smaller hummocks.

The best-developed frost-boils occur in the 'typical tundra' of Matveyeva, which is the southern portion of the Middle Arctic and the northern portion of the Low Arctic of Polunin, more or less equivalent to subzones C and D in Figure 10. Landscapes with frost boils in this region are called *spotted tundra* in the Russian literature (Alexandrova, 1980). In Subzone C, frost boils are predominantly barren. The diameter of the barren frost boils is 1–3 m. Inter-boil areas are well vegetated, but generally have thin moss carpets.

In Subzone D, the vegetation on the frost boils is more active, forming distinct zonation on the frost boils with areas of bare soil and some areas with thin cryptogam and vascular-plant cover. Areas between the frost boils are very well vegetated with thicker moss carpets.

In Subzone E, the frost boils are often completely covered with vegetation. The moss layer and organic soil horizons are thinner than in the inter-boil area. Thick vegetation mats often completely mask the frost boils, and sometimes the vegetation forms hummocks or mounds 1–2 m in diameter on old inactive frost boils. Soils in portions of the mounds can be re-exposed through heaving or other disturbance, but these areas are quickly re-vegetated. Matveyeva considers the series in Figure 10 to also be a succession

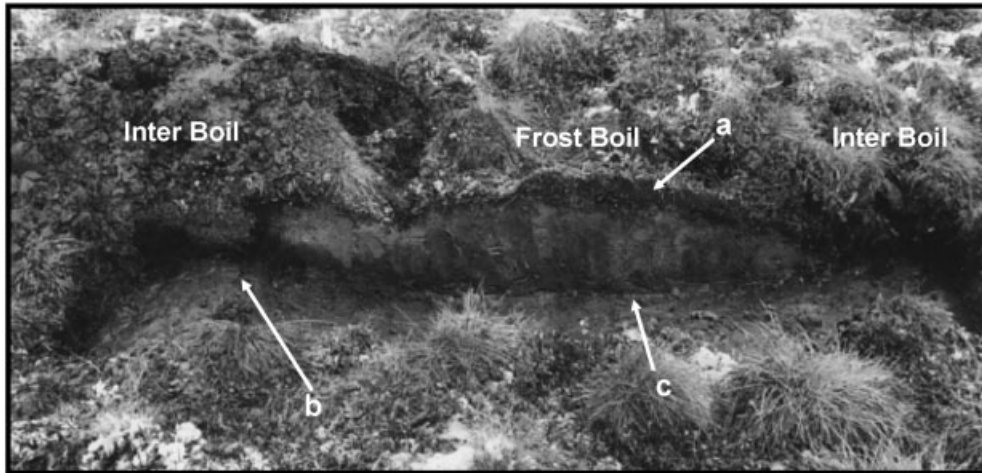


Figure 9 Soil trench across a vegetated frost boil hummock at the Sagwon MAT site (Subzone E). The trench extends to the base of the thaw layer. Note: (a) the well vegetated frost-boil surface and 8-cm thick dark-colored A/O soil horizon, indicating a long stable period; (b) the rise in the permafrost table, the shallow active layer (20 cm), and the lack of a mineral horizon in the inter-boil areas; and (c) and relatively thick active layer (40 cm) and saucer-shaped depression in the permafrost beneath the frost boil.

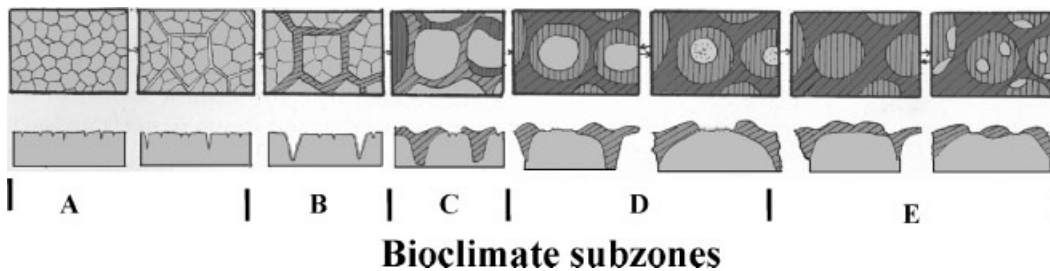


Figure 10 Patterned-ground forms along the Arctic bioclimate gradient. (Adapted from Chernov and Matveyeva (1997, Fig. 16.51) Modified to show the trends with respect to bioclimate subzones of the Arctic vegetation map (CAVM Team, 2003).

sequence, so frost boils typical of colder subzones can occur in warmer subzones because of local disturbance factors or non-zonal site conditions. A more complete description of the zonal trends of patterned ground morphology and vegetation can be found in Chernov and Matveyeva (1997).

Effects of Heave and Vegetation on Frost-Boil Soils

Frost boils are normally associated with fine and medium textured soils in ice-rich permafrost regions. The silty and loamy soils of northern Alaska are ideal for frost-boil formation. In such soils, the center portion of a frost boil is elevated in winter with the growth of ice lenses (Figure 11). In summer, viscous relaxation occurs and the frost boil settles back toward its previous position. The soils, however, do not settle completely back each year, and over time, net upward particle trajectories occur in the center of the frost boil (Peterson *et al.*, 2003). At the surface of the frost boil,

particle trajectories are outward from the center due to soil creep, and then downward around the margins of the frost boil. Well-developed organic soil horizons develop in the undisturbed inter-boil areas. Particles and dissolved organic material are carried downward at the margins of the frost boil by soil movement and leaching. Organics accumulates in the thawed bowl at the base of the frost boil. Toward the center of the frost boil, particle trajectories are upward, and some organic material from the base of the thaw layer is carried upward, where it is acted on by biological activity to release nitrogen and minerals for plant uptake, and CO_2 to the atmosphere (Figure 11). The vertical motion of material within the frost boil is apparently a slow process, requiring one or more centuries for one cycle (Peterson *et al.*, 2003). No radiocarbon dates are currently available from our frost boils, but dates from Canadian mud boils suggested average movement rates of less than 1 mm y^{-1} for subducted organic matter on three frost boils of the

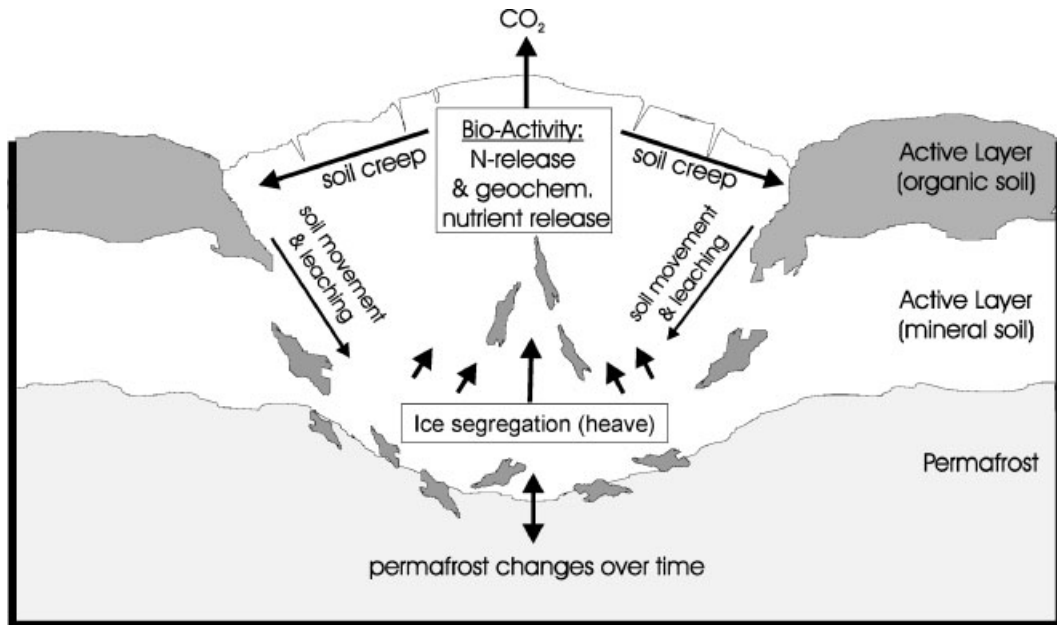


Figure 11 Conceptual diagram of biogeochemical cycling within frost boils. See text for explanation.

Boothia Peninsula (Dyke and Zoltai, 1980). These very slow rates indicated that the frost boils had been in place for several millennia.

The intermediate zone (see Figure 7) reflects periodic and directed changes in the thaw-layer thickness (Shur, 1988). The permafrost table is aggrading partly because loess and organic matter continue to accumulate on the soil surface and partly because the thickness of the thaw layer is decreasing as the site becomes more vegetated (Ping *et al.*, 2002). Soil heat flux is reduced due to the insulation effect of the vegetation layer (Ping *et al.*, 2002) (see Figure 6b). Studies in northern Yakutia have shown that the vegetation mat also affects the intermediate layer. Shur (1988) found that the intermediate layer was less developed near the shore of the Arctic Ocean than in areas 100–200 km inland where the vegetation is more active. Our comparisons of the intermediate layer in Arctic Alaska show similar large differences in ice content and cryogenic structure.

A Conceptual Model of Frost-Boil Formation Along a Climate Gradient

Based on our observations from Alaska, some reconnaissance studies in Canada, and information from the literature, we have formed a general hypothesis regarding climate-frost-boil interactions. A simple conceptual model of the frost-boil system on zonal sites is shown in Figure 12. The system consists of two spatial

elements, frost boil and inter-boil area. Each element consists of three *components*, the ice lenses, which are responsible for heave, the soils and the biogeochemical cycles within them, and the vegetation. The large bold arrows in Figure 12 indicate interactions between the frost boil and the inter-boil area, namely via gravity (the flow of water and material from the frost boil to the inter-frost boil) and by cryosuction (movement of water from the inter-boil area to the frost boil during winter). Within each element, the thin arrows indicate interactions between the components. The interactions between the soil and the ice lenses are primarily related to the influence of soil texture on ice segregation and the organic soil horizons on the insulation properties of the soil, which reduce heat flux into and out of the soil. Effects of the ice lenses on the soil include changes to soil structure and chemistry, soil aeration, mineralization, and sorting of soil particles. The interactions between the soil and the vegetation include supply of nutrition and water. Vegetation effects on the soil are primarily related to the accumulation of organic material and nutrients. The interaction between the vegetation and the ice lenses is mainly the insulation effects that affect the active-layer thickness and the rate of freezing. Finally, the ice lenses influence the vegetation through frost heave.

The strength of the interactions between components of the system is controlled to large extent by the prevailing climate (Figure 13). In the coldest parts of

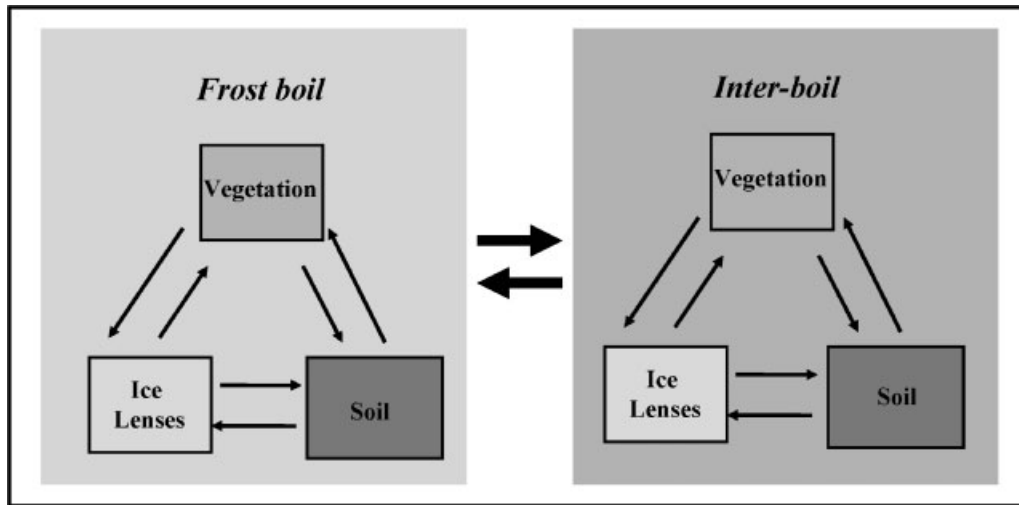


Figure 12 The frost-boil system. The arrows indicate interactions and feedbacks between *elements* (frost boils and inter-boils), and between *components* of each element (ice lenses, soils, and vegetation). See text for explanation of the interactions between the elements and components.

the High Arctic (Subzone A), biological processes are weak. The physical processes governing frost heave and soil formation are dominant in both the frost boils and the inter-boil elements. The vegetation component has little effect on the system in either element. There is little differential heave and poor development of frost boils. In Middle-Arctic (Subzone C) climates, the vegetation component is quite active in the inter-boil element, but conditions similar to those in the High Arctic are maintained on the frost boils. Physical processes dominate on the frost boil element creating barren habitats, but there is a nearly complete cover of plants in the inter-frost-boil areas. The strong contrast between the boils and inter-boils creates conditions for maximum differential heave, and frost boils are well expressed (Figure 1). In the relatively warm southern Low-Arctic climates (Subzone E), biological processes dominate in both elements of the frost-boil system. There is a longer growing season, warmer soils, and a greater diversity of plants, with more above-ground and below-ground biological activity. As a consequence, plants are able to counteract the effects of frost heave and needle-ice formation. There is a nearly-complete cover of plants on both elements (see Figure 9) and there is usually poor surface expression to the frost boils because of thick vegetation mats.

The Role of Frost Boils in Tundra Ecosystem Dynamics

Recent studies have noted that frost boils are linked to a wide variety of ecosystem properties, including

regional patterns of thaw-layer thickness (Nelson *et al.*, 1997), nutrients (Broll *et al.*, 1999; Jonasson and Skold, 1983), carbon sequestration (Bockheim *et al.*, 1998; Ping *et al.*, 1998), fluxes of energy and water (Walker *et al.*, 1998), plant species richness (Gough *et al.*, 2000; Walker *et al.*, 1998), and forage quality for wildlife (Walker *et al.*, 2001) (Figure 14). In the Low Arctic frost boils help to maintain high soil pH. Paleoecological studies of Arctic landscapes recognize the important role of changes in soil pH that led to the transition from a mineral-rich environment during the Pleistocene to the modern day paludified ecosystems that cover much of northern Alaska (Mann *et al.*, 2002; Oswald *et al.*, 2003; Walker *et al.*, 2001).

Soils in the frost boils have surprisingly large stores of carbon and nutrients frozen in the permafrost. This carbon is of concern in studies of global climate change because it represents a possible source of additional greenhouse gases to the atmosphere (Chapin *et al.*, 1997; Oechel *et al.*, 1997; Rastetter and Shaver, 1992). In addition to being a large store of carbon, tundra soil organic matter contains substantial quantities of nitrogen, which when mineralized to an inorganic form (ammonium or nitrate), or in some cases to amino acids, provides a nutrient source for plants and soil organisms. Because of the generally cold and saturated soils of the tundra, the mineralization process is slow (Giblin *et al.*, 1991), and arctic ecosystems tend to be strongly limited by available nitrogen (Shaver *et al.*, 2001). Differences in the soil environment between frost boils and inter-boil areas, including differences in soil moisture, temperature,

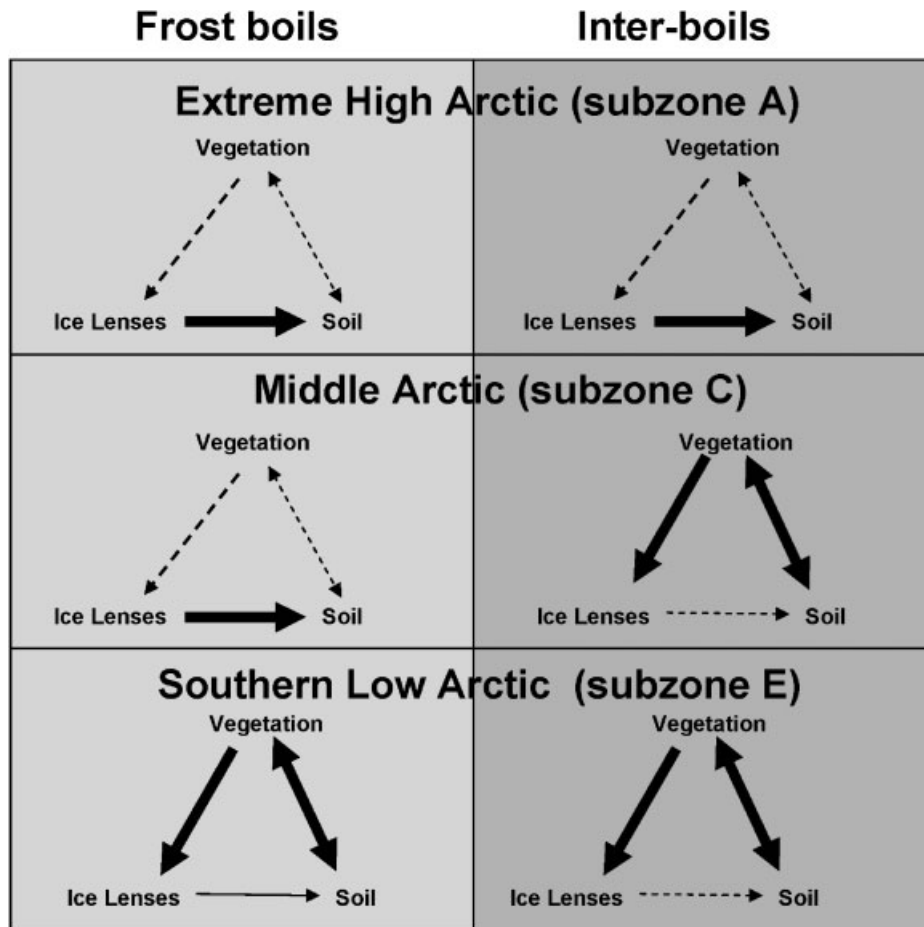


Figure 13 Hypothesized response of the frost-boil system along the Arctic bioclimate gradient. Arrows indicate strength and direction of primary interaction between components of the system. Bold arrows indicate dominant interactions, dashed arrows are weak interactions. See text for details of interactions in the three subzones.

active layer depth, and the quantity and quality of the soil organic matter, are due largely to the presence or absence of vegetation. Nitrogen cycling is likely to be quite different on frost boils compared to inter-boil areas and probably plays an important role in the succession of vegetation on frost boil soils.

Most studies indicate that climate warming will promote thicker active layers, which would mobilize carbon and nitrogen because of increases in heterotrophic respiration (Rastetter *et al.*, 1991). If the availability of nitrogen increases in the soil, particularly in areas with extremely low soil nitrogen, plant growth would be promoted. However, a related study (Walker *et al.*, 2003) indicates that in the zonal areas of Subzone E, air temperature has a diminished influence on soil temperatures and the thickness of the thaw layer because of the confounding influences

of the vegetation mat. Warmer temperatures do promote deeper thaw, but they also promote more plant growth, which tends to insulate the soil and prevent deep thaw. Warmer temperatures also reduce the effect of cryoturbation, which stirs the soil carbon to deeper levels in the thaw layer, where it can be incorporated into the permafrost table. These complex interactions between climate, cryoturbation, vegetation, soil carbon, and permafrost make the net effect on carbon and nutrient cycling far from clear.

The response of frost-boil systems to climate change will differ in each subzone. In the High Arctic (subzones A and B), organic-matter accumulation would focus in the inter-boil areas, but probably not on the frost boils. Landscape heterogeneity would, therefore, likely increase in Subzones A and B. In subzones C and D, a long-term increase of soil organic

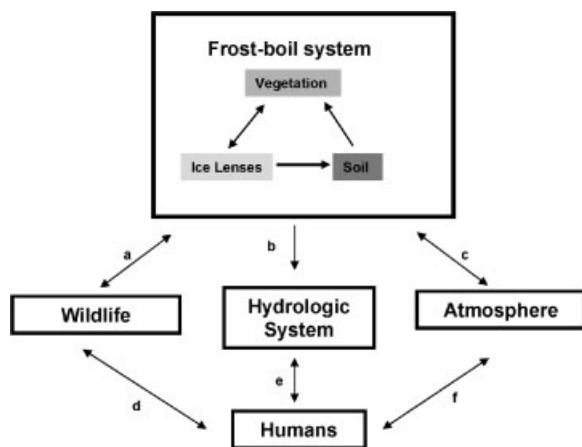


Figure 14 Linkages between the frost-boil system and components of the greater Arctic system and biosphere. Arrows that indicate the linkages between subsystem components *within* the frost-boil system are shown more explicitly in Figure 12 and described in the text. The linkages to the greater Arctic system are (a) effects on forage quality and wildlife habitat, (b) effects on water flux and water quality, and (c) fluxes and energy and trace gases to the atmosphere. These components are important to humans because of their effects on (d) availability of game, (e) fish and water resources, and (f) climate change.

matter on zonal sites would likely increase the growth of the plants on the frost boils and the inter-boil areas, and decrease the thickness of the thaw layer.

In Subzone E, warmer temperatures would probably not have immediate effects on the frost-boil patterns because they are already masked by thick vegetation mats. In some parts of Subzone E, shrub growth may convert tussock tundra to shrub tundra (Sturm, 2001; Silapaswan, 2001) where frost boils are usually not abundant. In some areas, permafrost may vanish altogether leaving only relict frost boils.

CONCLUSION

Frost-boil ecosystems are widespread throughout the Arctic, but little is known about their role in the functioning of the total Arctic system. The frost boils along the climate gradient in Alaska are typical of zonal situations on ice-rich fine-grained soils elsewhere in the Low Arctic. The conceptual model of frost boil ecosystems presented here is a hypothesis of frost-boil morphology-soil-vegetation-heave interactions along a complete climate gradient. Studies of other frost-boil ecosystem components and processes are needed, including but not limited to, (a) energy and trace gas fluxes, (b) water and nutrient flux to streams, (c) effect of cryoturbation on the carbon in

the intermediate layer (near-surface), and (d) nutrient cycling, especially in relationship to studies of animal habitat at several scales.

ACKNOWLEDGEMENTS

Marilyn Walker's contributions to the ideas leading to the conceptual diagrams in Figures 14 and 15 are much appreciated. The Geophysical Institute, the Institute of Arctic Biology, and Veco Polar Resources, Inc. provided considerable cooperative logistic support. Funding was provided by the National Science Foundation grants OPP-0120736 and OPP-9908829 and a grant from the International Arctic Research Center. Additional support was provided by several NSF Research Experience for Undergraduate (REU) supplements. This work would not have been possible without the help of several field assistants and students who participated in the field studies including Lindsey Kiez, David Wirth, Amber Moody, Erica Edwards and Corinne Munger.

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