

Obtaining baseline data to assess the potential for tree-line and shrub advance in Gates of the Arctic Park and Preserve and Noatak National Preserve

Project report to the ARCN, US NPS

Final report submitted: December 2009

M. Sydonia Bret-Harte^{1,*} and Martin Sommerkorn^{2,*},

Gregory R. Goldsmith¹, Peter M. Ray¹, Kenneth D. Tape¹, Lis Süfke², Laura S. Brosius¹, Andrew W. Balser¹, Kumi L. Rattenbury³, Andrew McCarthy⁴, Jacqueline M. Potts⁵, and Diane M. Sanzone³

(1) Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, AK 99775, USA

(2) The Macaulay Institute, Aberdeen, AB15 8QH, Scotland, UK

(3) National Park Service, Fairbanks, AK 99775, USA

(4) National Park Service, Anchorage, AK 99501, USA

(5) Biomathematics and Statistics Scotland, Aberdeen AB15 8QH, Scotland, UK

(*) These authors contributed equally to this report

Executive Summary

Shrub expansion and treeline advance are probably the largest land surface changes expected with climate warming in arctic tundra ecosystems, and have occurred in the past. A transition from tundra to shrubs or shrubs to forest changes fundamental ecosystem functions such as productivity, surface energy balance and regional climate, C and N dynamics, hydrology, and habitat for sustaining wildlife populations. Vegetation transitions inherently change the character of a landscape and may affect visitor perceptions.

This collaborative project had two main goals. The first was to establish a long-term monitoring tool for the assessment of future shrub expansion in the upper Noatak River Basin in Gates of the Arctic National Park and Preserve and Noatak National Preserve. To address this goal, we carried out four activities. First, transects were established within existing shrub populations between 12-Mile Slough and Kavachurak Lake and their positions geo-referenced and depicted to enable long-term re-sampling. Second, protocols were developed and documented to characterize plant community composition and structure, and accompanying soil characteristics. Third, these protocols were applied to collect data on the current status of vegetation and soils along these transects that will serve as a baseline for future monitoring. Fourth, low-altitude aerial pictures documenting the current distribution of shrubs were taken that included the transect locations, but integrated them into the larger landscape of the upper Noatak basin. The second main goal of the project was to analyze the data we obtained on vegetation and soils to detect indicators of recent shrub advance and its potential impact on soil characteristics. The project also aimed to contribute to the floristics of the upper Noatak basin by collecting specimens of plants not previously described for the area.

The 9 transects that were established and sampled in the upper Noatak contain a highly diverse understory of forb and prostrate deciduous shrub species, with relatively few evergreen shrub species, on permafrost-affected soils storing significant amounts of C as soil organic matter. 109 different species of plants were collected, of which 64 were not previously identified as occurring along the upper Noatak River, and 5 were not previously identified as occurring anywhere in the non-maritime Noatak Basin.

Of the sites investigated in the upper Noatak, those dominated by alder, bog birch, and balsam poplar all showed evidence of relatively recent expansion via seedling establishment. Saplings of all 3 species were encountered, but were not abundant. Alder saplings were most evident in hillslope areas, where solifluction had occurred and soils showed signs of cryoturbation and the mixing of organic and mineral horizons. Birch saplings were less frequent, and were primarily seen on river terraces. Poplar saplings were seen on soils with a minimal organic horizon. In contrast, willow parklands were dominated by mature, often senescent individuals, and we found no seedlings or saplings. The soil organic layer in willow parklands was thick and highly decomposed.

Our data analysis suggests that willow parklands are less likely to undergo shrub expansion by sexual reproduction than areas dominated by alder, poplar, or birch. Alder sites on the Noatak appear to share some understory vegetation characteristics with sites on the North Slope where alder expansion is known to have occurred, maybe indicating that the Noatak alder sites have recently expanded. Although shrub expansion may affect soil C storage, the cover of canopy shrubs does not control soil C across the range of landscape types that we sampled. Instead, soil pH appears to be an important predictor of shrub cover and biomass, but not of recent shrub reproduction from seed. Soil pH and average shrub ramet age are important predictors of soil C, but high variance exists in the data.

Table of Contents

<i>Section</i>	<i>Page</i>
Executive Summary	2
Introduction	4
Methods	6
Expedition and fieldwork format	6
Study sites	6
Low altitude aerial photography	9
Sampling methods and protocols	9
Data analysis	16
Comparison with sites of known expansion history	17
Results	18
Transect 1	18
Transect 2	23
Transect 3	28
Transect 4	33
Transect 5	38
Transect 6	43
Transect 7	48
Transect 8	53
Transect 9	58
Comparative transect analysis	63
Floristics	68
Discussion	72
A long-term resource to assess shrub expansion and potential effects on soil carbon	72
Indicators for shrub dynamics	73
Indicators for shrub effects on soil characteristics	77
Outlook for the future	78
References	80
Appendix	83

Introduction

Gates of the Arctic Park and Preserve (GAAR) and the Noatak National Preserve (NOAT) are national treasures protected in the interest of the public for future generations and the common good. The Noatak River and its surrounding watershed is an internationally recognized UNESCO Biosphere Reserve, established for its unique contribution to the conservation of biological diversity and biological resources (UNESCO 1976). The first step in conserving biological resources and diversity is to conduct baseline surveys using an ecosystem approach, to better understand (a) existing species and their distribution, (b) biotic community composition, (c) species of concern, and (d) the ecosystems that sustain them (Secretariat of the Convention on Biological Diversity). The United States government officially supports the suggested recommendations of the Secretariat (CBD SBSTTA 9 2003).

Understanding and forecasting the impacts of current and future change on biodiversity and ecosystem function in the Noatak Basin will depend on understanding the ecosystems of this unique and relatively undisturbed area. While a number of studies have documented plant species present in GAAR and NOAT (e.g. Young et al., 1973), less is known about how susceptible the vegetation is to environmental change, and how quickly it may already be changing. For example, little is known about the effects of climate warming, arctic haze and airborne pollutants on species and ecosystems in the parks.

Shrub expansion and tree-line advance are probably the largest land surface changes expected with climate warming in arctic tundra ecosystems (Epstein et al., 2004) and have occurred in this region in the past (Edwards et al., 2003). A transition from tundra to shrubs or shrubs to forest changes fundamental ecosystem functions such as productivity, surface energy balance (Sturm et al., 2005) and regional climate (McFadden et al., 1998; Beringer et al., 2005), ecosystem C and N dynamics (Mack et al., 2004), hydrology (Sturm et al., 2001) and habitat for sustaining wildlife populations. In addition, vegetation transitions inherently change the character of a landscape and may affect visitor perceptions.

A point of specific interest in shrub expansion and tree line advance is the interaction of the encroaching vegetation element with soil carbon stocks, especially in the light of a potential feedback to atmospheric CO₂ concentrations. There are several mechanisms by which plants can affect soil carbon stores, ranging from decreased soil moisture following increased transpiration, to increased substrate availability for soil microbial communities stemming from soluble plant assimilates or litter, to changes in soil chemistry caused by plant ion uptake patterns that affect soil organic matter stability. All these mechanisms potentially apply in the case of shrub expansion; however, the effect of their advance onto tundra soils has so far not been researched. Tree line advance has been shown to affect soil carbon in contradictory ways even within the Noatak catchment. While Wilmking et al. (2006) reported a loss of soil carbon with tree line advance, Steltzer (2004) showed that tree establishment had increased soil carbon storage. However, the abovementioned studies, similar to most others dealing with the topic, infer the observed changes from a “space-for time” substitution approach using chronosequences of trees, without a clearly established *status quo ante*, i.e., a first point in the soil carbon stock time series. Because soil carbon stocks can vary substantially even under the same vegetation type, it is clearly desirable to establish the soil and vegetation status of locations that can be re-sampled in the future.

Widespread shrub expansion has already been observed across the Alaskan Arctic, including the Brooks Range (Tape et al., 2006). Likewise, tree-line is generally advancing northward and to higher elevations under climate warming (Lloyd and Fastie, 2003, Wilmking et al., 2004). Both shrub expansion and tree-line advance have been documented in the western Noatak Basin, along the Kugururok and Nimiuktuk Rivers (Tape et al., 2006).

However, local environment and soil characteristics have been shown to modulate the response of vegetation to climate warming, and a variety of factors have been implicated in controlling tree-line advance and shrub expansion (Epstein et al., 2004). For example, though shrubs have expanded across the Alaskan Arctic in many places, in some locations no changes have been observed (Tape et al., 2006). Similarly, it has been suggested that in drier areas, tree-line has actually retreated with recent climate warming (Wilmking et al., 2004). Understanding what characteristics make areas susceptible to vegetation change under climate warming is crucial for designing a vegetation monitoring program in NOAT and GAAR.

Much of the Noatak River lies along the line of contact between the sub-arctic boreal forest and the arctic tundra, and as such is particularly susceptible to tree-line or shrub expansion caused by climate change. Although repeat aerial photography has revealed shrub expansion and tree-line advance in the western Noatak basin (Tape et al., 2006, Sturm et al., 2001), the extent and potential for vegetation change along the entire Noatak River has not been fully assessed.

This collaborative project had two main goals. The first goal was to establish a long-term monitoring tool for the assessment of future shrub expansion in the upper Noatak River Basin in Gates of the Arctic National Park and Preserve and Noatak National Preserve within the U.S. National Park Service (NPS) Inventory and Monitoring Program. For this purpose we carried out four activities. First, transects within existing shrub populations were established between 12-Mile Slough and Kavachurak Lake and their position geo-referenced and depicted to enable long-term retrieval and re-sampling. Second, protocols were developed and documented to characterize plant community composition and structure, and accompanying soil characteristics along these transects. Third, these protocols were applied to produce a dataset of the current status of vegetation and soils on these transects that will serve as a baseline for future monitoring. Fourth, low-altitude aerial pictures documenting the current distribution of shrubby vegetation were taken that contained the transect locations, but integrated them into larger proportions of the landscape of the upper Noatak basin.

The second main goal of the project was to detect indicators of recent shrub advance and potential impacts on soil characteristics, by analyzing the dataset obtained on vegetation and soils. The project also aimed to contribute to the floristics of the upper Noatak basin by collecting specimens of plants not previously described for the area.

We report here: i) the information on transect location and layout, ii) the protocols we used to characterize the transect vegetation and soils, and iii) the results of this baseline inventory identifying shrub, understory vegetation and soils. This body of work will provide the necessary baseline for a future monitoring of shrub expansion and tree-line advance in GAAR and NOAT by the NPS.

Methods

Expedition and fieldwork format

The data described here were collected in the upper Noatak River basin between July 16 and 31, 2006. A crew of eight people, including two NPS personnel, was dropped off by fixed-wing aircraft at 12-Mile Slough (67°35'59.14"N, 155°13'18.06"W) in Gates of the Arctic National Park and Preserve, and picked up, also by fixed-wing aircraft, at Lake Kavachurak (67°53'24.69"N, 156°53'30.59"W) in Noatak National Preserve. Except for arrival and departures, no motorized transport was used. We traveled between campsites by means of three smaller and two larger inflatable boats, and accessed sampling locations in the valley floor and on the slopes of the valley by foot. In general, we camped two nights at each location, with one day to establish and document transects, and sample their vegetation and soils before moving on to the next site by boat the following day. The crew worked in two teams of four, one for sampling vegetation and one for soils. The process of site selection and of laying out the transects was performed by all crew members, after initial reconnaissance and discussion. Most camping sites were selected prior to the field season, with the guidance of NPS personnel. All camping sites were located on unvegetated gravel bars next to the Noatak River. We adhered to the “leave no trace” camping ethic, and all sites were left as undisturbed as possible.

Study sites

We established a total of 9 transects along the upper Noatak between 12-Mile Slough (67°35'59.14"N, 155°13'18.06"W) and Lake Kavachurak (67°53'24.69"N, 156°53'30.59"W) (Table 1, Fig. 1). Of these, 2 transects were positioned on relatively shallow slopes (approximately 10°; transects 2 and 7), three on moderate slopes (approximately 25°; transects 1, 4, and 6), one on a steep slope (approximately 45°; transect 5), one on a flood plain (transect 3), and two transects along river terraces (transects 8 and 9). We classified three transects as being dominated by alder (*Alnus crispa*; transects 1, 4 and 5), three by willow (primarily *Salix glauca*; transects 2, 6, and 7), two by bog birch (*Betula glandulosa*; transects 8 and 9), and one by poplar (*Populus balsamifera*; transect 3). This classification was based on the identity of the most conspicuous species in the tallest layers of the overstorey vegetation. The most common shrub species in a given sampling location was not always the species classified as dominant for that transect, because our sampling was systematic, not continuous.

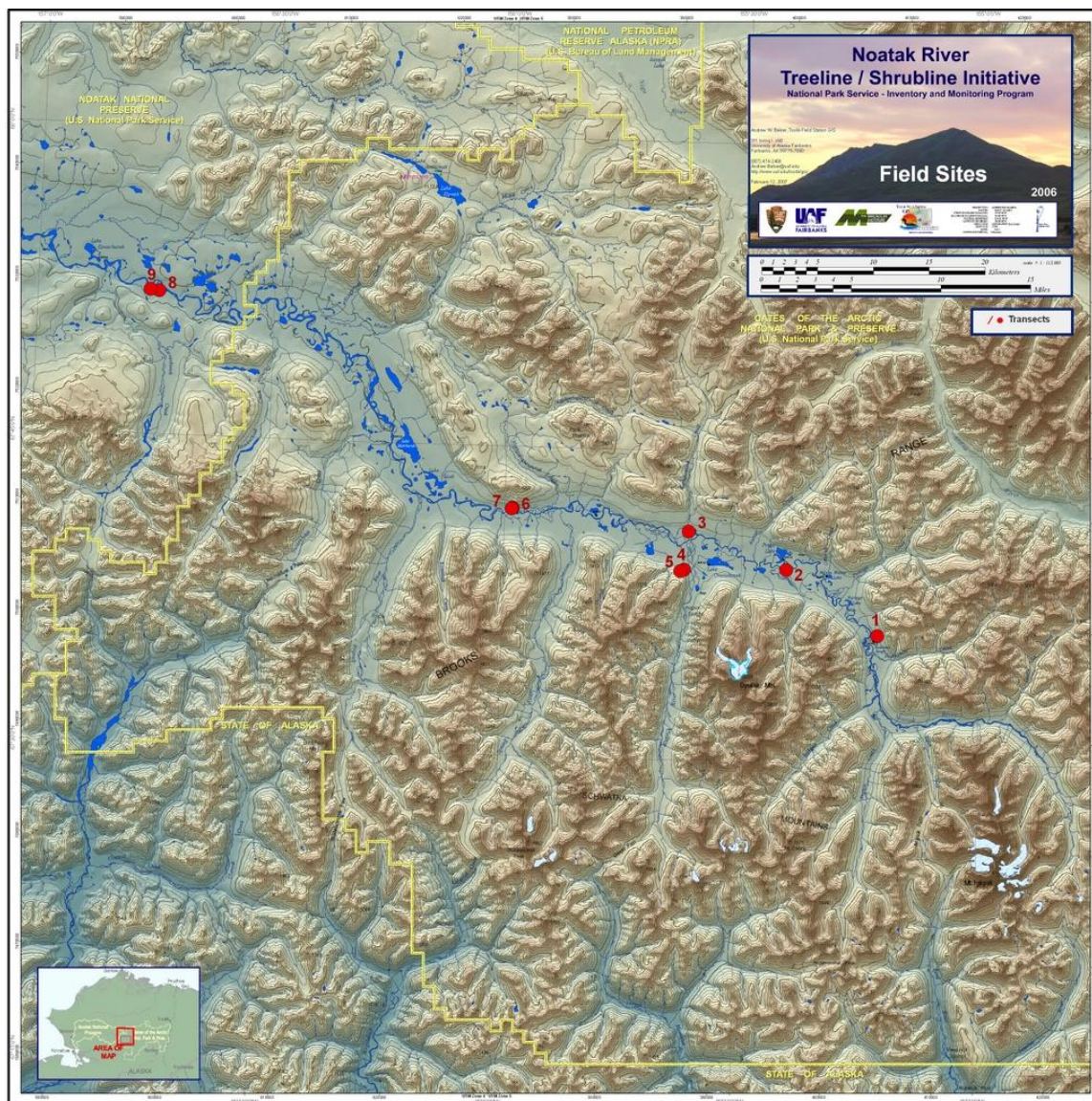


Figure 1. Transect locations in the upper Noatak valley

Table 1 Transect locations. Noatak transect locations: Geographic Coordinates, Datum NAD27 Alaska. GPS error was estimated by the instrument; “n/a” indicates that data were not available for a parameter at that location.

Origin of Transect				End of Transect			
Transect #	Coordinates	Elevation (m)	Estimated	Coordinates	Elevation (m)	Estimated	Bearing from Origin (° true)
			GPS Error (m)			GPS Error (m)	
1	67° 36' 13.5"N, 155° 12' 45.7"W	603	n/a	67° 36' 08.6"N, 155° 12' 42.5"W	611	n/a	155
2	67° 39' 21.2"N, 155° 24' 22.8"W	556	n/a	67° 39' 19.8"N, 155° 24' 17.4"W	567	n/a	n/a
3	67° 41' 06.8"N, 155° 36' 45.6"W	546	7	67° 41' 09.0"N, 155° 36' 49.4"W	545	n/a	330
4	67° 39' 15.7"N, 155° 37' 13.7"W	594	7	67° 39' 13.4"N, 155° 37' 09.9"W	589	19	149
5	67° 39' 11.1"N, 155° 37' 39.8"W	n/a	7	67° 39' 11.1"N, 155° 37' 46.2"W	n/a	8	280
6	67° 42' 02.1"N, 155° 59' 00.6"W	n/a	5	67° 42' 04.1"N, 155° 58' 58.5"W	n/a	6	15
7	67° 42' 00.8"N, 155° 59' 06.2"W	n/a	5	67° 42' 01.0"N, 155° 59' 12.4"W	n/a	5	277
8	67° 51' 59.3"N, 156° 44' 37.8"W	n/a	6	67° 52' 01.5"N, 156° 44' 34.2"W	n/a	6	30
9	67° 52' 01.9"N, 156° 45' 44.6"W	451	7	67° 52' 00.6"N, 156° 45' 50.4"W	452	7	220

Low-altitude aerial photography

On September 1, 2006, between 11:24AM and 11:50AM ADT, we obtained 30 vertical (90°) high-resolution, real-color aerial photographs covering the section of the upper Noatak River basin where expedition field work was conducted. Photographs were taken 5000 feet above the ground level. Individual photo frames were taken within five airphoto lines, with each line developed to specifically cover established transects from 2006 fieldwork. These five separate airphoto lines provide coverage for eight of the nine transects (see Appendix for location information).

Cumulatively, these photographs cover an area of roughly 26km². As digital products they do not have a fixed scale, but rather a recommended maximum scale of use. It is recommended that these photos not be used for mapping at scales larger than 1:500. It is estimated that the spatial resolution of these photographs, post-georectification, is about 35 cm. Camera equipment included a Nikon D2X digital camera, set at *f*/4.0, 200 speed with a 24.0mm focal length for all transects. Each individual photo frame also includes GPS coordinate estimates (NAD27, lat/long) for the principal point of that frame in an EXIF header. All of these photographs and a location map are included in the electronic appendix to this report, on an accompanying CD.

Sampling Methods and Protocols

Transect establishment

Site selection

Over the course of the expedition, we established nine permanent transects in shrubby vegetation in the upper Noatak River valley (Figure 1). The overall process of selecting transect locations was motivated by the intention to cover as many shrub-dominated community types of the upper Noatak valley as feasible. Initial planning was guided by the report of Young (1973), high-altitude photographs taken during U-2 aircraft overflights in the 1970s, satellite imagery obtained with Google Earth, and oblique photographs obtained by A. Balser during a limnological expedition to the upper Noatak in 2005. While on the ground, a practical constraint was distance to, and time required to walk to, the transect from the Noatak river channel, where all camps were established. On-site reconnaissance was guided by landscape position (e.g. physiographic features such as floodplain, slope, or aspect), dominant overstory shrub type, accessibility, and how representative the vegetation appeared relative to its surroundings. Fine-scale transect establishment was done by subjectively defining a starting point and a direction for each transect within each dominant overstory vegetation type. The subsequent layout of sampling locations along the transect was systematic, defined by distance from transect origin. Transects were 80 m

long and comprised of five regularly spaced sampling locations each, originating at 0 m, 20 m, 40 m, 60 m, and 80 m distance from the transect's starting point.

Transects were geo-referenced by taking GPS readings with handheld devices (Garmin ETrex, Garmin, KS, USA) at origin and end of each transect (Table 1). Wherever possible, transects were established so that the zero meter point was at the lower elevation of the transect, and 80 meter at the higher elevation. A person holding a red umbrella was positioned at the origin and end of each transect and an oblique photograph of the transect was taken from nearby, making the transect position in the landscape clearly visible. To aid future relocation, transect origins were positioned close to conspicuous locations (e.g., prominent boulders) wherever possible, and four photographs were taken, one in each cardinal direction, centered at both the origin and end of each transect. All photographs are included in the electronic appendix, on accompanying CD. A 20 cm (8") piece of rebar was buried at shallow depth at both origin and end of each transect to guarantee precise relocation of the transects by means of a metal-detector. Through this combination of markers the precise future re-sampling of transect locations should become possible.

Sampling plots

A tape measure was run in a straight line between origin and end of the transect. On the left side of the tape moving from 0 to 80 m five sampling locations ("locations" from here on) measuring 6 m by 6 m were established along the transect, originating at 0 m, 20 m, 40 m, 60 m, 80 m, in such a way that the location's bottom axis ran along the transect (e.g. the bottom axis of location "0" ran from 0 m to 6 m along the transect's length) (Fig. 2).

The location contained the assessment and sampling sites for understory vegetation and soils and formed in itself the area used for assessment and sampling of shrubs. A photograph was taken of the location while standing at its origin (i.e. at the transect's line 0 m, 20 m, 40 m, 60 m, 80 m mark), looking diagonally across to the far corner of the 6 by 6 m area. All photographs are included in the electronic appendix, on accompanying CD.

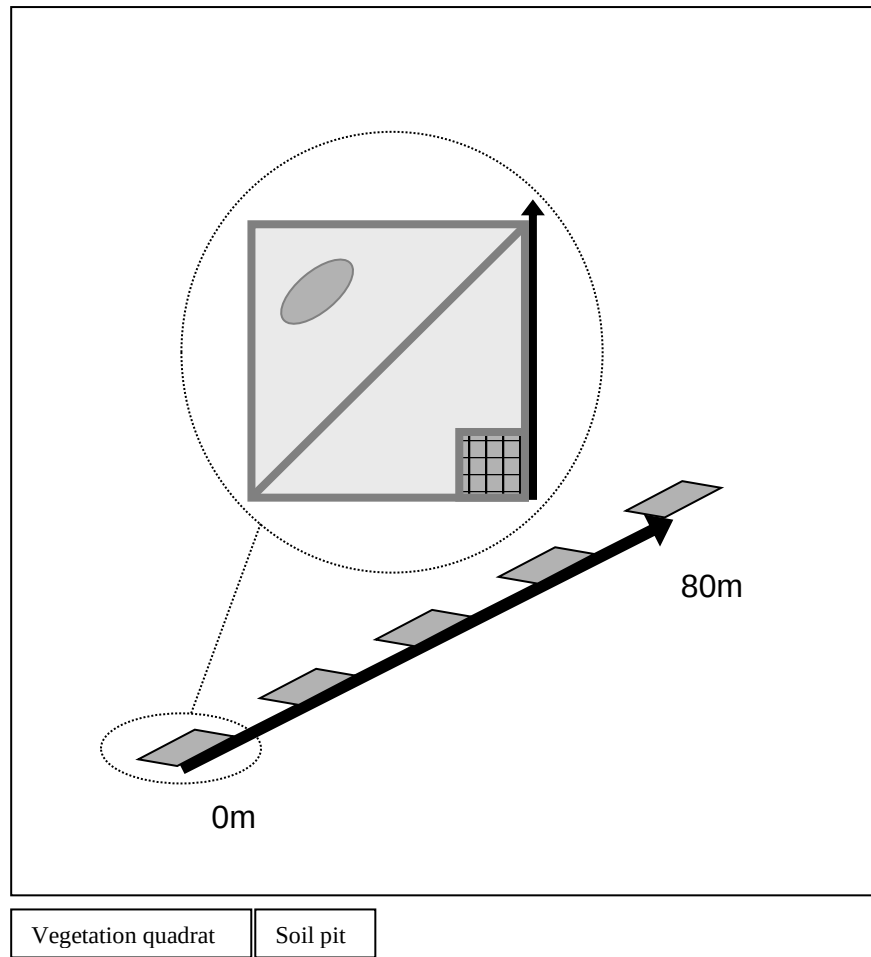


Figure 2. *Transect and plot layout (NB not to scale). The arrow depicts the transect line with locations at 0 m, 20 m, 40 m, 60 m, 80 m. Magnified is one 6x6 m location plot with transect line (arrow), shrub assessment diagonal, understory vegetation quadrat and soil pit area. See text for details.*

At the origin of the location a 1 m² grid for the assessment of understory vegetation species and cover was placed with its lower left corner at the location's origin extending on the same side of the tape as the location (e.g. at location "0" the grid would extend from 0-1 m on the transect, and be placed on the left side of the tape moving from 0 to 80 m).

A corridor of 1 m width for shrub assessment was established along the diagonal of the location that did not cut through the origin, extending 0.5 m on each side of the diagonal. This zone extended only to the point where its edges crossed the boundary of the 6 x 6 m location (i.e., not all the way to the corners).

The soil sampling location was established at a suitable point in the far segment of the location as separated by the shrub sampling diagonal (i.e., the triangular half of the location away from the transect line), between the location's top right corner and the corridor used to assess shrub characteristics.

Understory vegetation

At the origin of each location, vegetation composition and percent cover was assessed in a 1 x 1 m plot. This was predominantly, but not exclusively, the composition and percent cover of the understory vegetation, because the taller overstory shrubs rarely occupied part of the 1 x 1 m plot.

A 1 x 1 m grid divided into 100, 10 x 10 cm, squares by strings was laid down with its lower left corner at the origin of the location. Each 1 x 1 m plot and its grid were photographed from above. All these photographs are included in the electronic appendix, on accompanying CD. Then, the area covered by each vascular plant species within the grid was estimated visually by counting the number of 10 x 10 cm squares (1% each), to the nearest 1/2 square (0.5%), that would be occupied by that species if all of the individuals were clumped together in one part of the 1 x 1 m grid (sometimes referred to as “optical cramming”). Species occupying less than 1/2 of a 10 x 10 cm square were assigned a cover of 0.5%. In some cases, it was not possible to estimate the area of a species, because most individuals were not flowering, and there was more than one species in the same genus with similar vegetative morphology (e.g., several species of *Carex*). In this case, the area occupied by the genus was estimated. The percent cover of all mosses, all lichens, mushroom caps, vascular plant litter (irrespective of species), and bare ground were also estimated, using the same method as above. The identities of the most common moss and lichen species were noted where they could be identified.

Vascular species occurring within the 1 x 1 m plot that were initially unknown were identified subsequently by collecting and identifying nearby flowering individuals located outside the 1 x 1 m grid. Besides identifying the species found within the sampled quadrats in each transect, we observed, and in many cases collected specimens of other plant species that we thought might not have been previously collected in the upper Noatak. We collected these specimens in the vicinity of the transects and of our camps, along the routes between these two, and on a few explicitly botanically-exploratory excursions. All specimens were pressed, dried, identified, and mounted on herbarium sheets following the expedition. The species identity of the collected specimens was later determined by the collector (Peter Ray), and subsequently checked, and in some cases revised, by University of Alaska Museum of the North Herbarium botanist Dr. Carolyn Parker. Specimens are housed in the National Park Service Arctic Inventory and Monitoring collection, which is located in the UAF Museum of the North Herbarium.

Total cover (including all categories) within each 1 x 1 m grid was 100%, but the sum of all categories for a given grid was not always 100, for two reasons. First, rare species present in the 1 x 1 m grid were not assigned cover values less than 0.5%, which tended to overestimate total cover if many rare species were present. Second, there was some uncertainty in the estimation of cover, particularly for graminoids, due to the needle-like nature of their leaves. For these reasons, we chose not to normalize total cover values to 100% for each location. In the understory composition tables for each transect, blank values for a species at a given location indicate that

this species was not found in the 1x1 m grid at that location, though it was found elsewhere on the transect.

Shrubs

A number of characteristics of the overall vegetation and the overstory shrubs were sampled within the 6 x 6 m location, at a coarser resolution than was used in the 1 x 1 m grid. We measured leaf area index (LAI; area of leaves per unit area of ground) as a measure of overall vegetation cover, and also measured the length, width, and height of the canopy of all the overstory shrubs in either 1/4 or 1/2 of the 6 x 6 m location, depending on their density. The density of shrub ramets and their basal diameter within shrub patches was measured, and samples were taken to determine the C and N concentrations in foliage, and the age, of overstory shrub ramets, as explained below.

LAI was measured optically (LAI 2000; LiCor, Inc., Lincoln Nebraska) under diffuse light at each meter point along the diagonal. Measurements were always taken starting at the point on the diagonal farthest from the main transect tape, then moving toward the transect tape. The maximum height of the vegetation at each point sampled for LAI was also recorded.

The number of ramets of each of the three most common overstory shrub species that occurred within 50 cm of either side of the diagonal tape were recorded. In addition, the basal diameter was measured using calipers for the first 10 ramets of each of the three most common species encountered in this 1 x 8 m corridor. The number and height of small shrub seedlings/saplings within this corridor was also recorded if they occurred, however, this happened rarely.

Within the half of the 6 x 6 m location that was not used for soil sampling, the approximate size of all the individual overstory shrubs present was assessed. If the density of overstory shrubs was so high that it would take a long time to measure all of them in this area, sizes were assessed in half this area, which was the quarter of the 6 x 6 m location that did not contain the 1 x 1 m understory vegetation grid. We measured the maximum length, width, and height of each shrub canopy. The species of each measured shrub was also recorded. Area (A) of overstory canopy within the sampled portion of the location was calculated from maximum length (l) and width (w) measurements, using the formula for an ellipse,

$$A = \pi * (l/2) * (w/2).$$

Approximately 10 understory and 10 canopy leaves were collected into Ziploc bags from each of the three most common shrub species within the location, for determination of %C and %N. Leaves were taken from multiple shrubs of each species. Leaf samples were transferred to paper bags at camp and were air-dried in the field. Upon return to Fairbanks, samples were dried at 60°C for 72 h, then ground for carbon, hydrogen, and nitrogen (CHN) content analysis in a roller ball mill, using 9.5 mm (3/8") steel balls in scintillation vials. Approximately 10 mg of each

sample was rolled into steel tins and combusted on a LECO TruSpec CN analyzer (LECO, Inc. St. Joseph, MI) in the Forest Soils Laboratory at the University of Alaska, Fairbanks.

One large, representative ramet of each of the three most common shrub species was cut as close to the base of the shrub as possible, and the basal 10-20 cm of stem was placed in a Ziploc bag. The upper side of the stem (i.e. away from the ground) and its distal end were marked with an indelible pen, so that its orientation in the field would be clear (in some shrub species, there was not a large difference in diameter between the basal and distal ends of the stem segments). Upon return to Fairbanks, stem segments were refrigerated until their ages could be determined. Ramet age was determined by cutting sections from the basal end of the stem segment by hand (i.e., not using a microtome) with a razor blade, staining these sections with 1% phloroglucinol in 20% HCl, and counting annual growth rings at 40-100x magnification in a compound microscope.

Near transect 3 and within a poplar population near the Kugurak springs, we collected increment cores from four of the larger balsam poplar (*Populus balsamifera*) individuals, to assess the approximate ages of the stands. Increment cores were taken at breast height using a 6" increment borer (Haglöf Sweden AB, Långsele, Sweden).

Soils

Soil sampling in the field

At each location along the transect a soil pit was opened to sample soil material to assess bulk density, loss on ignition (LOI) of organic carbon and carbonate, carbon (C) and nitrogen (N) content, depth of organic horizon, rock content, pH and soil moisture. Thaw depth and soil temperatures were measured at the soil pit and where applicable the distance of the soil pit to the nearest overstory shrub was recorded.

If any soil micro-topography was present the type of micro-topography was described and a soil profile was dug for a high (H) and a low (L) point in the respective relief. In some cases this was done within one soil pit, in other cases two separate soil pits were dug. The soil pits were dug down to either permafrost or to a depth allowing for the sampling for bulk density of the mineral horizon (see below).

Depth of thaw was sampled by inserting a probe-rod into the ground to permafrost three times and averaging the readings. Where the active layer depth exceeded the length of the permafrost probe (60 cm), or where the soil was too rocky to establish a reliable reading, no data were recorded. Soil temperatures at 5 cm and 10 cm were measured by means of a digital thermometer with a steel-mantled thermistor probe (Trace 10 memory thermometer; Fisher Scientific, Inc.).

After the pit wall designated for sampling was cleaned with trowel or knife a vertical cm scale was positioned in front of it and a digital photo was taken. All photographs are included in the electronic appendix, on accompanying CD. In this picture the position of the scale, the trowel, and the knife depict the vertical lines where the three replicate soil samples were taken (see below). The depth of the soil pit and of the organic horizon next to the scale was recorded.

From the middle of the vertical extent of the organic horizon, three replicate defined volumes of soil were sampled from the side-wall of the excavated pit without compression by pushing small steel cylinders horizontally into the soil. The steel cylinders were 62.5 mm in length, with an inner diameter of 57.5 mm and wall thickness of 1.6 mm. In many organic horizons the texture made it necessary to cut around the steel cylinder with a knife to recover the sample.

The organic soil samples were then homogenized on a metal tray and any rocks larger than 4 mm diameter present were picked out by hand and saved. Their volume was later determined in the laboratory by water displacement in a graduated cylinder. Rock volume was then subtracted from the volume of the entire soil sample to correct the estimates of bulk density for each of the three replicate soil samples. In the field, the soil samples were immediately weighed to determine their total fresh weight (FW) on a battery-operated balance (Scout Pro, Ohaus, Inc., Pine Brook, NJ USA). Because the soil samples were heavy and bulky in the aggregate, once the volume and FW of the entire soil sample was determined, approximately 10 g of each replicate sample were sub-sampled and weighed into a Zip-lock bag for laboratory analysis of dry weight (DW), LOI and C and N content. Another sample of approximately 5 g was taken from each replicate sample and pooled in another zip-lock bag to yield a 15 g sample for laboratory analysis of pH.

Using the same steel cylinders as for the organic horizon, three replicate defined volume of soil was sampled from the side-wall of the excavated pit at the top of the mineral horizon. The soils were sieved through a 4 mm soil sieve onto a metal dish and immediately weighed for a determination of FW. The rocks were collected from the sieve and sampled for analysis of volume and subsequent sample volume correction in the laboratory, using the same procedure described for rocks from the organic soil sample. Two separate samples were again sub-sampled from the mineral soil sample, one of approximately 10 g for determination of DW, LOI, C and N content from each of the three replicates, and a second of approximately 15 g (pooled from 5 g from each replicate) for determination of pH.

All soil pits were re-filled again after sampling was complete, and the sod containing vegetation was replaced on top of the pit.

Soil analyses in the laboratory

Determination of soil pH was done using de-ionized water as the extractant and applying a soil : extractant ratio of 1:3 by volume. After the water was added the soil slurries were placed on a

shaker table for one hour, after which the pH was determined by means of a calibrated pH electrode.

Determination of soil dry weight was done by drying soil aliquots of approximately 10 g FW in pre-dried and pre-weighed tins for 24 hours at 105°C in a drying oven. The fresh weight (FW) / dry weight (DW) ratio of the soil samples was established as

$$(FW - W_{\text{tin}}) / (DW - W_{\text{tin}})$$

with W_{tin} being the weight of the pre-dried tin.

Loss on ignition (LOI) and carbonate content of soils was established by consecutive combustion steps of dried soil material in a muffle furnace. Approximately 5 g of the oven-dried soil material was weighed on a pre-dried and pre-weighed crucible and placed in a muffle-furnace at 550°C for 12 hours. After cooling in a desiccator the samples were weighed and the LOI (% weight) was calculated as

$$(W_{\text{C+S}} - W_{\text{A+C}}) / (W_{\text{C+S}} - W_{\text{C}}) * 100$$

with $W_{\text{C+S}}$ being the weight of the crucible plus oven-dried soil, $W_{\text{A+C}}$ the weight of the crucible with the remaining ash, W_{C} being the weight of the dried crucible.

Thereafter, the crucible with the ash was placed in a muffle furnace set at 850°C for another 5 hours to burn off carbonates. After cooling in a desiccator the carbonate content (% weight) of the soils was determined by weighing using the formula

$$(W_{\text{A+C}} - W_{\text{A-CO3+C}}) / (W_{\text{C+S}} - W_{\text{C}}) * 100$$

with $W_{\text{A+C}}$ being the weight of the crucible with the ash following muffling at 550°C, $W_{\text{A-CO3+C}}$ being the weight of the crucible with the carbonate-free ash, $W_{\text{C+S}}$ being the weight of the crucible plus oven-dried soil, W_{C} being the weight of the dried crucible.

C and N content of dried and ground soil samples was determined using a CHN-analyzer.

Aliquots of the remainder of the three replicate dried soils from each horizon were pooled and ground on a roller ball mill, using 9.5 mm (3/8") diameter steel balls in scintillation vials. On a 4-digit balance, 10 mg of target soil mass was weighed into tin capsules and analyzed on a CHN analyzer (LECO TruSpec, LECO, Inc., St. Joseph, MI).

Data Analysis

All data were collected along transects, and it would be expected *a priori* that data from locations within a transect would be more similar to each other than to data from locations on other transects. Thus, the data from individual locations could not be assumed to be independent, and our statistical analyses included transect as a random factor within the mixed models. Data on soil carbon content, percent cover of overstory shrubs, leaf area index, ramet density, and ramet age were analyzed by linear mixed models using restricted maximum likelihood (REML) variance components analysis, with transect as a random factor and soil or vegetation variables as

fixed factors (Genstat 10th edition, VSN International Limited). Whereas linear regression estimates fixed effects only, REML estimates effects and variance components for a linear model that also includes both fixed and random effects (Patterson and Thompson, 1971). A backwards stepwise approach was used to identify the most significant fixed factors in these models, and only the significance levels associated with those fixed factors are presented here. Because many of our variables were highly correlated, not all variables could be included in the initial stepwise procedure. The composition of the understory vegetation at each of the locations (i.e., percent cover values for each of the species from each of the 1 x 1 m grids) was analyzed by ordination using canonical variates (Genstat 10th edition, VSN International Limited), with transect as the grouping factor. Ordination by canonical variates maximizes the separation amongst groups, and is the most appropriate ordination technique for this dataset, where the individual locations on a transect cannot be assumed to be independent of each other.

Comparison with sites with a known history of shrub expansion

We also collected data on soils and vegetation, observing identical protocols, from two sites on the Alaskan North Slope where repeat photography has demonstrated substantial expansion of alder in the last 50 years at one site (69°24.624'N, 148°38.027'W; transects 12 and 13), and no apparent expansion of alder in the same time period at the other site (69°5.189'N, 148°44.638'W; transects 10 and 11; Tape et al., 2006). We do not include all of these data in this report, but we performed a separate ordination of understory composition including all nine Noatak transects and these additional transects for purposes of comparison with sites with a known shrub expansion history. Again, we performed the ordination by canonical variates, with transect as the grouping factor.

Results

Transect 1

Location

This transect is located on a southwest-facing toe-slope to the north of the Noatak River above Twelve Mile Slough. The transect is composed primarily of mixed shrub and semi-heath tundra.



Figure 3. Oblique photograph of Transect 1

Shrub structure

The overstory shrubs in the vicinity of transect 1 were spaced fairly far apart. Although the dark green of alders (*Alnus crispa*) were prominent from a distance (Fig. 3) and caused transect 1 to be classified as an alder transect, no alders were encountered at the sampling locations. The most common overstory shrub species encountered were several species of *Salix*, and *Betula glandulosa* (Table 2). Overstory shrub cover in the 6 x 6 m sampling locations ranged from 7.8-48.5%, while mean height ranged from 37.6-124.8 cm. Optical measures of leaf area index were well below 1 at all sampling locations. The maximum age of the overstory shrub ramets sampled on this transect was 39 years. No seedlings were encountered during the sampling, although

some of the ramets sampled were less than 5 years old. The N content of overstory shrub leaves ranged from 2.2% to 2.7%, which is fairly typical for deciduous shrubs.

Understory vegetation

The understory vegetation on transect 1 was dominated by prostrate or low-growing deciduous shrubs, with comparatively low abundances of graminoids, evergreen shrubs, and forbs (Table 3). The most abundant single species was the prostrate, tardily deciduous (Cody 1996) shrub *Dryas integrifolia*, which is typical of non-acidic heath vegetation. Other common species included *Vaccinium uliginosum*, *Betula nana*, and *Arctostaphylos rubra*. Evergreen shrubs (*Rhododendron lapponicum*, *Empetrum hermaphroditum*, *Vaccinium vitis-idaea*) were present in low abundance. Mosses were abundant at some of the sampling locations. Although no single forb species was particularly abundant, there was a fairly high diversity of forbs, with 12 different species encountered in the sampling on this transect.

Soils

The soils of transect 1 were characterized by a 10-20 cm deep organic layer showing comparatively high LOI values of up to 79% DW, and high C-contents of up to 43% (Table 4). Carbon storage in the organic horizon ranged from 3 to 9.6 kg m⁻², with C:N ratios around 20. Both organic and mineral horizons showed a neutral pH, and the mineral horizon had very low carbonate contents. The organic matter in the mineral horizon showed LOI values between 10 and 22% DW, and carbon contents between 2 and 12%, with C:N ratios ranging from 10-15.

Table 2. Shrub variables from transect 1

Location	LAI along diagonal	Vegetation height along diagonal	Rel. cover overstory shrubs in 6 x 6 m	Mean height overstory shrubs	N- content canopy	C:N ratio canopy	N-content understory	C:N ratio understory	Ramets in 1 x 8 m diagonal	Mean ramet age	Maximum ramet age	Most common shrub species
<i>m from origin</i>	<i>m² leaf per m² ground</i>	<i>cm</i>	<i>%</i>	<i>cm</i>	<i>%</i>	<i>mol/mol</i>	<i>%</i>	<i>mol/mol</i>	<i>#</i>	<i>yr</i>	<i>yr</i>	
0	0.25	24.4	25.0	51.6	2.2	20.1	2.2	21.2	29	19.7	27	<i>S. lanata</i>
20	0.79	43.3	48.5	62.4	2.6	19.2	2.4	20.0	52	26.5	38	<i>S. glauca</i> & <i>B. glandulosa</i>
40	0.67	95.4	28.9	124.8	2.2	18.1	2.5	18.7	43	22.5	27	<i>S. alaxensis</i>
60	0.33	17.7	7.8	37.6	2.3	17.7	2.2	22.3	3	29.0	39	<i>S. glauca</i>
80	0.30	26.1	14.6	42.7	2.6	15.3	2.7	17.0	25	3.5	5	<i>S. glauca</i>

Table 3. Understory vegetation composition, transect 1. A blank indicates that a given species or category was not encountered in the 1 x 1 m grid at that location.

Species/category	Location along transect (m)				
	0	20	40	60	80
	%	%	%	%	%
<i>Arctostaphylos rubra</i>	19	5	18	0	10
<i>Astragalus umbellatus</i>	0.5				1.5
<i>Betula nana</i>	12	2.5	13		2
<i>Bistorta plumosa</i>			0.5		
<i>Boykinia richardsonii</i>				8	
<i>Carex</i> spp. other than <i>C. bigelowii</i>	5	4	3		
<i>Dryas integrifolia</i>	6	14	4	37	18
<i>Empetrum hermaphroditum</i>			3		
<i>Epilobium latifolium</i>			4		
<i>Eriophorum angustifolium</i>					2
<i>Festuca altaica</i>				2	2
<i>Hedysarum alpinum</i> ssp. <i>americanum</i>	1				
<i>Oxytropis koyukukensis</i>	4	1			
<i>Oxytropis maydelliana</i>					4
<i>Pedicularis labradorica</i>					3
<i>Pedicularis langsдорffii</i>	0.5				
<i>Poa</i> spp.		6			
<i>Pyrola grandiflora</i>				1	0.5
<i>Rhododendron lapponicum</i>		6.5	3		
<i>Salix alaxensis</i>			4		
<i>Salix glauca</i>	6	4	2	3	
<i>Salix richardsonii</i>	2	2		2	
<i>Saussurea angustifolia</i>	0.5	1		0.5	0.5
<i>Shepherdia canadensis</i>			1		
<i>Stellaria laeta</i>		0.5			
<i>Vaccinium uliginosum</i>	11	5	22		
<i>Vaccinium vitis-idaea</i>					1
Moss	5	22	1.5	4	17
Lichens	1	1	1.5		1
Litter	11.5	7	8	33	7
Bare soil			2		

Table 4. Soil characteristics of transect 1. Where no microtopography was specified, only one soil pit was sampled. Other blank positions indicate no data, for example where no mineral soil samples could be obtained.

Loca- tion	Mic ro- top o- gra phy	Po si- tio n	Depth of thaw <i>cm</i>	Organic horizon								Mineral horizon						
				Depth of horizon <i>cm</i>	Bulk Densit y <i>g / cm3</i>	p H <i>W</i>	LO I <i>D</i> <i>W</i>	Carbon content <i>% DW</i>	Nitrogen content <i>% DW</i>	C:N Ratio <i>mol / mol</i>	C-org-mass of horizon <i>g / m2</i>	Bulk Densit y <i>g / cm3</i>	p H <i>W</i>	LO I <i>D</i> <i>W</i>	Carbonat e content <i>% DW</i>	Carbon content <i>% DW</i>	Nitrogen content <i>% DW</i>	C:N Ratio <i>mol / mol</i>
<i>m from origin</i>	<i>Type</i>																	
0			58	10	0.11	7. 4 9	78. 8	41.5	2.0	21.1	4416	0.57	7. 5 5	10. 1	0.31	1.9	0.2	10.4
20				13	0.10	4. 9 0	53. 9	23.2	0.9	25.9	2993	0.42	6. 7 4	21. 7	0.12	12.6	0.8	15.1
40			95	20	0.11	7. 2 5	76. 4	42.9	2.0	21.7	9560		6. 8 8					
60			53	11	0.16	6. 7 8	70. 7	37.5	2.1	18.1	6710	0.24	7. 4 2	15. 2	0.18	8.4	0.6	14.6
80			58	14	0.13	6. 8 3	75. 6	42.7	2.3	19.0	7907	0.71	6. 8 2	9.9	0.07	4.0	0.3	13.1

Transect 2

Location

This transect is located on a north-facing, slightly sloping hill to the south of the Noatak River. The transect is composed primarily of willow parkland with some evidence of old sorted circles.

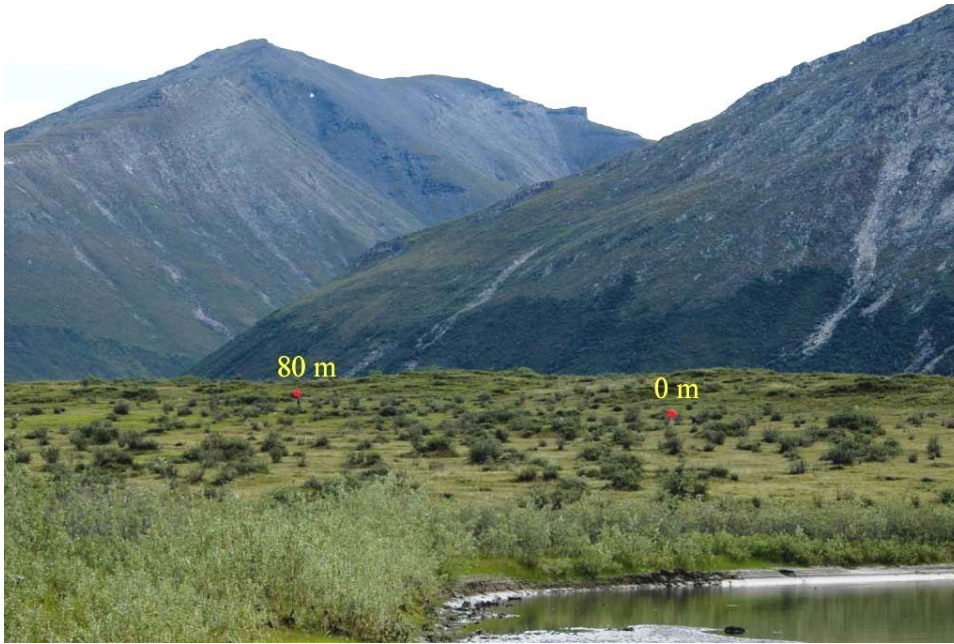


Figure 4. Oblique photograph of Transect 2

Shrub structure

Transect 2 was located in an open willow parkland, where discrete overstory shrubs were spaced fairly far apart. Overstory shrubs consisted entirely of large individuals of *Salix glauca*. No *Salix* seedlings or saplings were seen in the vicinity of this transect. The percent cover of overstory shrubs in the 6 x 6 m sampling locations ranged from 1.8% to 17.5% (Table 5), lower than in transect 1. Ramet density was also lower than in transect 1. Mean height of the overstory shrubs ranged from 51 to 100 cm, while the vegetation in general ranged from 13 to 34 cm in height. Leaf area index was low, generally less than 0.5. Overstory shrub leaves had N concentrations varying from 1.9-3.1%, a wider range than in many other transects. The maximum age of ramets sampled on this transect was 46 years, which probably underestimates the age of the shrubs in this area, some of which can be seen in Steve Young's photographs from his 1973 expedition. This was the only area we sampled that could be positively identified to be the same as that sampled by Steve Young and collaborators in 1973.

Understory vegetation

Understory vegetation was dominated by low or prostrate deciduous shrubs, but with a relatively higher abundance of graminoids (mostly *Carex* spp) and lichens than was seen in transect 1 (Table 6). The deciduous shrub *Dryas integrifolia* was again the most common single species. Several other prostrate deciduous shrub species were encountered, including several *Salix* species and *Arctostaphylos rubra*, but no *Betula nana* or *Vaccinium uliginosum* was encountered. The only evergreen shrub present was *Rhododendron lapponicum*, and it was not abundant. Ten species of forbs were encountered in the 1 x 1 m sampling plots, many of which were different than were found on transect 1.

Soils

In parts of transect 2 the soils showed a sorted circles frost-pattern. The soils were characterized by a 6-32 cm deep organic layer mostly showing LOI values between 42 and 53% DW, and C-contents of up to 29% (Table 7). Carbon storage in the organic horizon ranged from 0.9 to 7.6 kg m⁻² with C:N ratios between 16 and 25. Both organic and mineral horizons showed a pH between 6.8 and 7.6, and some of the mineral horizons had carbonate contents of up to 2% DW. The organic matter in the mineral horizon mostly showed LOI below 10% DW, and carbon contents below 5%, with relatively high C:N ratios ranging up to 39.

Table 5. Shrub variables from transect 2

Location	LAI along diagonal	Vegetation height along diagonal	Rel. cover overstory shrubs in 6 x 6 m	Mean height overstory shrubs	N- content canopy	C:N ratio canopy	N-content understory	C:N ratio understory	Ramets in 1 x 8 m diagonal	Mean ramet age	Maximum ramet age	Most common shrub species
<i>m from origin</i>	<i>m² leaf per m² ground</i>	<i>cm</i>	<i>%</i>	<i>cm</i>	<i>%</i>	<i>mol/mol</i>	<i>%</i>	<i>mol/mol</i>	<i>#</i>	<i>yr</i>	<i>yr</i>	
0	0.27	12.8	17.5	78.0	3.1	15.5	2.5	19.0	0	34.0	34	<i>S. glauca</i>
20	0.57	33.9	15.9	86.7	2.6	18.9	2.4	20.3	17	29.0	33	<i>S. glauca</i>
40	0.15	25.0	1.8	100.0	1.9	26.2	2.0	24.6	0	28.0	28	<i>S. glauca</i>
60	0.26	14.4	15.2	51.4	2.6	18.9	2.4	20.0	11	27.0	46	<i>S. glauca</i>
80	0.30	21.7	11.7	93.8	2.6	18.0	2.4	18.9	31	31.5	33	<i>S. glauca</i>

Table 6. Understory vegetation composition, transect 2. A blank indicates that a given species or category was not encountered in the 1 x 1 m grid at that location

Species/category	Location along transect (m)				
	0	20	40	60	80
	%	%	%	%	%
<i>Androsace chamaejasme</i>				0.5	
<i>Anemone parviflora</i>	0.5	0.5			
<i>Arctagrostis latifolia</i>	0.5				
<i>Arctostaphylos rubra</i>		0.5	0.5	2.5	2.5
<i>Bistorta plumosa</i>	0.5	1	0.5	0.5	0.5
<i>Carex</i> spp. other than <i>C. bigelowii</i>	13	15	12		6
<i>Chrysanthemum integrifolium</i>	0.5				
<i>Dryas integrifolia</i>	25	20	20	18	28
<i>Equisetum arvense</i>				7	
<i>Hedysarum alpinum</i> ssp. <i>americanum</i>	7	0.5	3		
<i>Kobresia sibirica</i>				6	
<i>Oxytropis tananensis</i>	1.5		1	0.5	0.5
<i>Oxytropis viscida</i>		1	3	1	5
<i>Papaver</i> sp.				0.5	
<i>Pedicularis capitata</i>	0.5			1	3
<i>Rhododendron lapponicum</i>	0.5				
<i>Salix arctica</i>		1	0.5	2.5	
<i>Salix glauca</i>			2		7
<i>Salix reticulata</i>		0.5	6		0.5
<i>Senecio lugens</i>	0.5				
<i>Tofieldia pusilla</i>		0.5	0.5	0.5	0.5
Moss	6	4	25	1	7
Lichens	15	10	6	5	8
Litter	20	35	25	55	31

Table 7. Soil characteristics of transect 2. Where no microtopography was specified, only one soil pit was sampled.

				Organic horizon								Mineral horizon						
Loca- tion	Micro- topo- graphy	Posi- tion	Depth of thaw	Depth of horizon	Bulk Density	pH	LOI	Carbon content	Nitrogen content	C:N Ratio	C-org- mass of horizon	Bulk Density	pH	LOI	Carbonate content	Carbon content	Nitrogen content	C:N Ratio
<i>m from origin</i>	<i>type</i>		<i>cm</i>	<i>cm</i>	<i>g / cm3</i>		% <i>DW</i>	% <i>DW</i>	% <i>DW</i>	<i>mol / mol</i>	<i>g / m2</i>	<i>g / cm3</i>		% <i>DW</i>	% <i>DW</i>	% <i>DW</i>	% <i>DW</i>	<i>mol / mol</i>
0	old sorted circles	H	82	6	0.16		21.4	15.9	0.9	17.6	1459	0.51	7.26	4.2	0.02	4.7	0.2	22.8
0	old sorted circles	L	42	11	0.06	7.19	52.3	24.9	1.3	19.5	1499	0.39	7.39	4.4	0.16	5.2	0.2	25.1
20	Sorted circles /stripes	H	57	15	0.11	7.52	42.2	25.1	1.4	18.0	3939	0.22		12.3	1.98	6.8	0.3	19.9
20	Sorted circles /stripes	L	51	10	0.12	7.39	44.2	24.6	1.3	19.2	2400	0.62	7.52	4.1	0.30	3.5	0.1	38.8
40			60	32	0.08	7.48	50.7	29.1	1.2	24.9	7604	0.35	7.62	7.2	0.50	4.7	0.3	14.8
60			45	19	0.10	6.79	51.8	28.4	1.7	16.3	5127	0.37	7.50	10.4	0.18	5.8	0.4	13.5
80			66	5	0.08	7.18	52.8	24.0	1.5	15.8	912	0.55	7.14	3.0	1.31	2.6	0.1	17.7

Transect 3

Location

This transect is located on a flood plain to the north of the Noatak River. The transect is composed primarily of poplar. It is to the east of Karumnalina Creek adjacent to a riparian zone.



Figure 5. Oblique photograph of Transect 3

Shrub structure

Transect 3 was located in a fairly dense stand of poplar (*Populus balsamifera*) and other shrubs, mostly large individuals of *Salix glauca*, but with some *Shepherdia canadensis* and *Betula glandulosa*. Saplings and small individuals of *P. balsamifera* were abundant, and it was clear that the population has been expanding in recent decades. The cover of overstory shrubs (which included the poplars) ranged from 15-36%, with a mean height between 48 and 124 cm (Table 8). Leaf area index of the vegetation was considerably higher than in transects 1 and 2, with many values close to 1, and the height of the general vegetation reflected the high density of the overstory shrubs. The maximum age of the overstory shrub ramets was 62; this did not include the largest poplars, whose age has not yet been determined from tree increment cores. Leaf N concentrations were similar to those seen in other transects, ranging from 2.4 to 2.8%.

Understory vegetation

The understory vegetation along this transect was dominated by mosses, which made up from 12 to 70% of the cover in the various locations (Table 9). There was relatively low cover of prostrate deciduous shrubs and graminoids, and no prostrate evergreen shrubs were encountered. Ten species of forbs were encountered in the 1 x 1 m plots, some of which were quite abundant. *Pyrola grandiflora* and *Oxytropis viscida* together comprised more than 10% of total cover in most locations on this transect, and were more common here than on any of the other transects.

Soils

The soils of transect 3 were characterized by the shallowest organic layer found in this study, only 3-9 cm in extent. Some samples of this transect were lost, the remaining one shows an LOI value of 67% DW, and a C-content of 29% (Table 10). Carbon storage in the organic horizon ranged from 0.6 to 2.5 kg m⁻², the lowest of the whole study, with C:N ratio of 18. The organic mineral horizon showed a pH of 6.5, the mineral ranged from 6.9 to 7.4, and there was virtually no carbonate found in the mineral horizon. The organic matter in the mineral horizon showed LOI of about 4% DW, and carbon contents below 1%.

Table 8. Shrub variables from transect 3.

Location	LAI along diagonal	Vegetation height along diagonal	Rel. cover overstory shrubs in 6 x 6 m	Mean height overstory shrubs	N- content canopy	C:N ratio canopy	N-content understory	C:N ratio understory	Ramets in 1 x 8 m diagonal	Mean ramet age	Maximum ramet age	Most common shrub species
<i>m from origin</i>	<i>m² leaf per m² ground</i>	<i>cm</i>	<i>%</i>	<i>cm</i>	<i>%</i>	<i>mol/mol</i>	<i>%</i>	<i>mol/mol</i>	<i>#</i>	<i>yr</i>	<i>yr</i>	
0	0.56	22.7	25.8	69.9	2.6	17.0	2.4	17.0	12	17.7	20	<i>S. canadensis</i>
20	0.48	140.0	22.7	47.8	2.5	18.2	2.6	17.7	21	22.3	29	<i>P. balsamifera</i>
40	1.03	119.6	36.0	124.4	2.6	17.6	2.5	19.1	36	28.0	40	<i>P. balsamifera</i>
60	0.95	107.3	29.0	69.8	2.8	17.1	2.7	16.9	49	20.3	40	<i>P. balsamifera</i>
80	0.90	141.0	14.9	87.9	2.6	17.4	2.5	18.0	18	36.3	62	<i>P. balsamifera</i> and <i>S. glauca</i>

Table 9. Understory vegetation composition, transect 3. A blank indicates that a given species or category was not encountered in the 1 x 1 m grid at that location.

Species/category	Location along transect (m)				
	0	20	40	60	80
	%	%	%	%	%
<i>Arctostaphylos rubra</i>	2			1.5	
<i>Arnica griseomii</i> ssp. <i>frigida</i>			9		
<i>Aster sibiricus</i>		6	2		
<i>Astragalus aboriginum</i>		0.5	1.5	1	
<i>Bromus pumellianus</i>	1.5	1	7	1.5	1.5
<i>Bupleurum americanum</i>	1				
<i>Calamagrostis purpurascens</i>	1.5	1	7	1.5	1.5
<i>Dryas integrifolia</i>					27
<i>Festuca altaica</i>			4	3	0.5
<i>Gentiana propinqua</i>	0.5				
<i>Hedysarum alpinum</i> ssp. <i>americanum</i>	2			4	
<i>Juncus castaneus</i>				0.5	
<i>Oxytropis koyukukensis</i>	1				
<i>Oxytropis viscida</i>	11	9.5		0.5	6
<i>Poa glauca</i>	1	0.5			
<i>Populus balsamifera</i>		5	5	1	
<i>Pyrola grandiflora</i>	3	3	17	5.5	4
<i>Salix glauca</i>		1			
<i>Senecio lugens</i>		5.5			
<i>Shepherdia canadensis</i>	2	0.5	1.5	13	
Moss	70	60	11.5	44	30
Lichens	2	7	2	7	14
Litter	3	8	41	12	22.5

Table 10. Soil characteristics of transect 3. Where no microtopography was specified, only one soil pit was sampled.

Loca- tion	Micro- topo- graphy	Posi- tion	Depth of thaw	Organic horizon								Mineral horizon						
				Depth of horizon	Bulk Density	pH	LOI	Carbon content	Nitrogen content	C:N Ratio	C-org- mass of horizon	Bulk Density	pH	LOI	Carbonate content	Carbon content	Nitrogen content	C:N Ratio
<i>m from origin</i>	<i>Type</i>	<i>cm</i>	<i>cm</i>	<i>g / cm3</i>		<i>% DW</i>	<i>% DW</i>	<i>% DW</i>	<i>mol / mol</i>	<i>g / m2</i>	<i>g / cm3</i>		<i>% DW</i>	<i>% DW</i>	<i>% DW</i>	<i>% DW</i>	<i>mol / mol</i>	
0			3							695	1.03	6.86	3.6	0.06	0.7	0.1	9.0	
20			9	0.08	6.51	67.0	34.3	1.9	17.6	2501	0.73	7.42	4.0	0.03	0.9	0.1	9.9	
40			4							973								
60			2							556								
80			3							834								

Transect 4

Location

This transect is located on a north-facing hillslope south of the Noatak River, and west of the Kugurak River. The transect is composed primarily of alder parkland showing past solifluction (currently inactive) and active frostboils.



Figure 6. *Oblique photograph of Transect 4*

Shrub structure

This transect was set up to cross the boundary of an alder area. Location 0 was outside of the alder area, and contained no overstory shrubs. The other locations all contained some overstory shrubs, although the most common overstory shrub species was alder only at location 20. No seedlings or saplings of alder were seen within the locations, but small individuals (saplings) of alder were seen in the vicinity of the boundary, farther up the hill. Leaf area index of the general vegetation ranged from 0.26 to 1.31 (Table 11). Overstory shrub cover ranged from 0 (outside the shrub area) to 28.3%, with mean heights from 51.4-105 cm. The N content of canopy leaves ranged from 2.3-2.7%. The maximum ramet age was 74, indicating that at least some overstory shrubs had been growing here for a long time.

Understory vegetation

Understory vegetation on transect 4 was dominated by mosses, prostrate deciduous shrubs (including *Arctostaphylos rubra*, *Dryas integrifolia*, *Salix reticulata*, and *Vaccinium uliginosum*), and graminoids, mostly *Carex bigelowii* (Table 12). Similar to the other alder transects, several species of evergreen shrubs (*Rhododendron lapponicum* and *Cassiope tetragona*) were encountered, though they were not abundant. Ten species of forbs were encountered on this transect, including *Boschniakia rossica*, which is parasitic on the roots of alder and was not seen on any other transect.

Soils

The soils of transect 4 comprised a variety of frost-patterns from frost boils with solifluction to hummock / hollow structures. At some locations *Eriophorum vaginatum* tussocks were present. Consequently, the depth of the organic layer was highly variable and ranged from 1 to 21 cm (Table 13). This resulted in carbon storage values in the organic horizon to range from 0.1 to 4.7 kg m⁻². LOI values were consistently high and reached up to 81% DW, and associated with C-content of 22-44% and C:N ratios ranging from 19 to 34. The soils showed pH values of 6.8 to 7.9, and there was some carbonate, up to 1.3% DW, found in the mineral horizon. The organic matter in the mineral horizon generally showed LOI values between 3 and 6% DW, and carbon contents between 4 and 1% at C:N ratios around 15.

Table 11. Shrub variables from transect 4

Location	LAI along diagonal	Vegetation height along diagonal	Rel. cover overstory shrubs in 6 x 6 m	Mean height overstory shrubs	N- content canopy	C:N ratio canopy	N-content understory	C:N ratio understory	Ramets in 1 x 8 m diagonal	Mean ramet age	Maximum ramet age	Most common shrub species
<i>m from origin</i>	<i>m² leaf per m² ground</i>	<i>cm</i>	<i>%</i>	<i>cm</i>	<i>%</i>	<i>mol/mol</i>	<i>%</i>	<i>mol/mol</i>	<i>#</i>	<i>yr</i>	<i>yr</i>	
0	0.26	10.8	0.0	.					0			
20	0.40	7.6	21.6	105.0	2.7	16.3	2.4	18.5	0	27.0	31	<i>A. crispa</i>
40	0.89	23.2	14.2	51.4	2.3	20.2	1.8	23.5	49	48.5	74	<i>Betula</i> hybrid
60	0.95	18.9	15.7	57.3	2.3	19.8	1.6	22.3	16	16.3	18	<i>S. barclayi</i>
80	1.31	44.6	28.3	68.5	2.5	18.4	2.3	19.5	52	29.3	57	<i>S. glauca</i>

Table 12. Understory vegetation composition, transect 4. A blank indicates that a given species or category was not encountered in the 1 x 1 m grid at that location.

Species/category	Location along transect (m)				
	0	20	40	60	80
	%	%	%	%	%
<i>Anemone parviflora</i>				0.5	
<i>Arctostaphylos rubra</i>	8	15.5	5.5	19	
<i>Astragalus umbellatus</i>			0.5	4.5	22.5
<i>Bistorta vivipara</i>			1		
<i>Boschniakia rossica</i>		0.5			
<i>Carex bigelowii</i>	13	16	20	3	6
<i>Cassiope tetragona</i>	2	1			
<i>Dryas integrifolia</i>	10	3	4	7.5	8
<i>Dryas octopetala</i>		3	3.5	7	
<i>Equisetum arvense</i>	5	11			
<i>Eriophorum angustifolium</i>				2	
<i>Eriophorum vaginatum</i>				6	
<i>Hedysarum alpinum</i> ssp. <i>americanum</i>		0.5			
<i>Orthilia secunda</i>					0.5
<i>Oxytropis koyukukensis</i>			0.5		
<i>Pedicularis capitata</i>	2			0.5	
<i>Pyrola grandiflora</i>				0.5	2
<i>Rhododendron lapponicum</i>		1	1	0.5	
<i>Salix arctica</i>	3	2			
<i>Salix richardsonii</i>				12	
<i>Salix reticulata</i>		10	8.5	4.5	
<i>Saussurea angustifolia</i>		0.5	1.5		
<i>Tofieldia pusilla</i>				0.5	
<i>Vaccinium uliginosum</i>	4		5	3	5.5
Moss	30	20	21	10	30
Lichens	2	1	0.5	0	7
Litter	20	13	20	15	15

Table 13. Soil characteristics of transect 4.

Loca- tion	Micro- topo- graphy	Posi- tion	Depth of thaw	Organic horizon								Mineral horizon						
				Depth of horizon	Bulk Density	pH	LOI	Carbon content	Nitrogen content	C:N Ratio	C-org- mass of horizon	Bulk Density	pH	LOI	Carbonate content	Carbon content	Nitrogen content	C:N Ratio
<i>m from origin</i>	<i>Type</i>		<i>cm</i>	<i>g / cm3</i>		<i>% DW</i>	<i>% DW</i>	<i>% DW</i>	<i>mol / mol</i>	<i>g / m2</i>	<i>g / cm3</i>		<i>% DW</i>	<i>% DW</i>	<i>% DW</i>	<i>mol / mol</i>		
0	frost boils, solifluction	L		21	0.05	7.33	67.2	41.3	1.5	27.9	4721	0.56	7.49	4.7	0.02	3.9	0.2	17.1
0	frost boils, solifluction	H	90	3							430	0.35	7.85	4.1	0.32	3.3	0.2	16.7
20	frost boils, solifluction	L	51	15	0.04	7.19	76.4	37.2	1.9	19.4	2128	0.55	7.58	2.8	0.31	2.4	0.1	16.9
20	frost boils, solifluction	H	51	15	0.03	6.87	81.0	44.3	1.9	23.9	2149	0.18	7.36	24.0	0.86	13.6	0.8	16.8
40	Turf hummocks	L	55	1							142	0.56	7.27	3.0	1.32	1.5	0.1	11.0
40	Turf hummocks	H	52	1							130	0.46	7.42	5.0	0.14	1.6	0.2	10.3
60	tussock on solifluction	L	27	18	0.05	7.15	68.7	36.6	1.1	34.1	3137							
60	tussock on solifluction	H	43	4							519	0.46	7.07	4.9	0.32	2.7	0.2	12.8
80	Turf hummocks	H	36	20	0.06	6.81	54.5	22.1	1.2	19.1	2596	0.40	7.05	6.4	0.36	4.2	0.3	14.0
80	Turf hummocks	L	29	20	0.05	6.89	60.3	33.5	1.7	19.2	3371							

Transect 5

Location

This transect is located on a north-facing hillslope south of the Noatak River and immediately west of transect 4. This transect is composed of alder parkland with apparently infilling alder.



Figure 7. Oblique photograph of transect 5

Shrub structure

This transect runs up a fairly steep hill through alder parkland composed of large individual shrubs with smaller ones growing between them. This suggested that infilling of alder may have occurred recently here. Although no seedlings, saplings, or very small individual alders were encountered within sampling locations, a number were seen in the vicinity of this transect. Despite the visual prominence of alder, it was not as common as *Salix* overstory species in any of the locations. The vegetation was relatively dense, with leaf area index values close to one at all locations (Table 14). Overstory shrub cover ranged from 4.5-40.4%, with mean heights from 35-71.4 cm. N content of canopy leaves ranged from 2.3-2.7%. Maximum ramet age was 54.

Understory vegetation

The understory vegetation on this transect was dominated by low-growing or prostrate deciduous shrubs, especially *Arctostaphylos rubra*, *Dryas octopetala*, and *Vaccinium uliginosum* (Table 15). However, several evergreen shrub species (*Andromeda polifolia*, *Cassiope tetragona*, and *Ledum palustre* ssp. *decumbens*) were present, and were sometimes quite abundant. The graminoid *Carex bigelowii* was the single most abundant species, but no other graminoids were encountered. Eight species of forbs were found on this transect, none of which were very abundant. Mosses and lichens both made up an appreciable proportion of the cover.

Soils

The soils of transect five comprised a variety of frost-patterns from frost boils to hummock / hollow structures. Compared to transect 4 the steeper slope resulted in more active solifluction patterns. At some locations *Eriophorum vaginatum* tussocks were present, as were segregated ice lenses in the soil. The depth and carbon storage of the organic layer was therefore highly variable and ranged from 3 to 25 cm and 1 to 8.5 kg m⁻², respectively (Table 16). LOI values were relatively high and ranged from 40 to 81% DW. They were associated with C-content of 15-45% and C:N ratios ranging from 16 to 31. The soil's pH values were the lowest found in this study and ranged from 5.5-6.5 in the organic horizon and from 5 to 6.7 in the mineral horizon. There was no carbonate found in the mineral horizon, except in one sample, however, one of the samples had a confirmed spill during analysis and maybe others were affected as well. The organic matter in the mineral horizon showed variable LOI values (8-30% DW) and carbon contents (3-16%), but consistent C:N ratios of around 15.

Table 14. Shrub variables from transect 5

Location	LAI along diagonal	Vegetation height along diagonal	Rel. cover overstory shrubs in 6 x 6 m	Mean height overstory shrubs	N- content canopy	C:N ratio canopy	N-content understory	C:N ratio understory	Ramets in 1 x 8 m diagonal	Mean ramet age	Maximum ramet age	Most common shrub species
<i>m from origin</i>	<i>m² leaf per m² ground</i>	<i>cm</i>	<i>%</i>	<i>cm</i>	<i>%</i>	<i>mol/mol</i>	<i>%</i>	<i>mol/mol</i>	<i>#</i>	<i>yr</i>	<i>yr</i>	
0	1.20	28.7	20.4	57.5	2.6	18.7	2.3	21.2	23	33.7	46	S. glauca
20	0.91	29.4	40.4	71.4	2.3	21.2	2.1	23.0	20	30.7	54	S. glauca
40	1.24	12.9	4.5	39.2	2.3	20.1	2.3	19.8	16	12.0	17	S. lanata
60	1.25	21.0	8.5	35.0	2.4	20.5	2.0	24.0	25	26.3	46	S. glauca
80	1.45	39.8	13.2	64.5	2.7	19.0	2.7	18.0	30	33.0	33	S. glauca

Table 15. Understory vegetation composition, transect 5. A blank indicates that a given species or category was not encountered in the 1 x 1 m grid at that location.

Species/category	Location along transect (m)				
	0	20	40	60	80
	%	%	%	%	%
<i>Alnus crispa</i>	17			6	
<i>Andromeda polifolia</i>		1			
<i>Arctostaphylos rubra</i>	3.5	5.5	2	16.5	0.5
<i>Bistorta plumosa</i>		2	3	8	1
<i>Bistorta vivipara</i>	0.5				
<i>Boykinia richardsonii</i>			4		3
<i>Carex bigelowii</i>	5.5	15	10	40	6
<i>Cassiope tetragona</i>	19.5	8	6	5	8
<i>Dryas octopetala</i>	22.5	4	3	5	8
<i>Equisetum arvense</i>				0.5	3
<i>Ledum palustre</i> ssp. <i>decumbens</i>	0.5	0.5			
<i>Orthilia secunda</i>	0.5				
<i>Pedicularis albolabiata</i>				0.5	
<i>Platanthera obtusata</i>					0.5
<i>Pyrola grandiflora</i>	1.5	0.5	2		0.5
<i>Salix glauca</i>	7.5	12		0.5	3
<i>Salix richardsonii</i>					4
<i>Saussurea angustifolia</i>	0.5	0.5	1.5	1.5	3
<i>Vaccinium uliginosum</i>	11	3.5	12	8.5	6
Moss	16	5	20	1	25
Lichens	2	8	5	0.5	4
Mushroom Caps	0.5			0.5	
Litter	25	20	35	10	25

Table 16. Soil characteristics of transect 5.

Loca- tion	Micro- topo- graphy	Posi- tion	Depth of thaw	Organic horizon								Mineral horizon						
				Depth of horizon	Bulk Density	pH	LOI	Carbon content	Nitrogen content	C:N Ratio	C-org- mass of horizon	Bulk Density	pH	LOI	Carbonate content	Carbon content	Nitrogen content	C:N Ratio
<i>m from origin</i>	<i>type</i>	<i>cm</i>	<i>cm</i>	<i>g / cm3</i>		<i>% DW</i>	<i>% DW</i>	<i>% DW</i>	<i>mol / mol</i>	<i>g / m2</i>	<i>g / cm3</i>		<i>% DW</i>	<i>% DW</i>	<i>% DW</i>	<i>mol / mol</i>		
0	Turf hummocks	H	47	23	0.18	5.51	40.9	20.5	1.0	20.3	8487	0.75	6.54	7.6	0.00	3.3	0.2	14.0
0	Turf hummocks	L	19	15	0.18	5.86	57.7	15.1	1.0	15.9	3970							
20	tussock on solifluction	H	70	10	0.09	6.48	61.6	44.6	1.7	26.3	4029	0.76	6.33	8.0	0.00	3.8	0.3	14.8
20	tussock on solifluction	L	20	12	0.11	6.32	70.8	38.6	1.8	21.5	5026	0.84	6.69					
40	hummock on solifluction	H	46	4							1612	0.39	6.31	29.9	0.00	16.0	1.0	16.0
40	hummock on solifluction	L	35	25	0.13	6.44	71.5	32.9	1.4	23.5	10324	0.59	6.20	23.6	0.00	10.4	0.7	15.3
60	Turf hummocks	H	44	8	0.12	6.25	53.4	29.1	1.5	20.1	2763	0.77	6.15	9.1	0.00	3.6	0.3	13.0
60	Turf hummocks	L	25	23	0.25	6.54	39.5	18.7	1.1	17.8	10691							
80	hummock on solifluction	H	48	3							1036	0.30	5.08	11.7	0.96	6.6	0.5	14.3
80	hollow on solifluction	L	11	13	0.07	5.85	81.0	41.7	1.3	31.4	3809							

Transect 6

Location

This transect is located on a south southeast-facing hillslope to the north of the Noatak River. It is composed primarily of willow parkland transitioning to sorted lichen-rich stripes.



Figure 8. *Oblique photograph of transect 6*

Shrub structure

This transect was set up to cross the boundary of a willow parkland into an area of lichen-covered sorted stripes. Overstory willow shrubs were present even in the sorted stripes area, but they were much less common there. No seedlings, saplings, or small individuals of overstory willows were encountered in the vicinity of this transect. Percent cover of overstory shrubs was low even within the willow parkland, ranging from 1-13% over the entire transect, but mean overstory shrub height ranged from 54.6-84 cm (Table 17). Leaf area index was generally low, ranging from 0.17-0.6. N content of canopy leaves varied from 2.3-3.5%, a larger range than was seen on most other transects. The maximum age of ramets on this transect was 53.

Understory vegetation

Understory vegetation on this transect was dominated by lichens and the prostrate deciduous shrub *Dryas integrifolia* (Table 19). Other low-growing deciduous shrubs were present, but were not generally abundant, except for *Betula glandulosa x nana* in one location. No evergreen shrubs were encountered other than *Rhododendron lapponicum*, which was not abundant. A higher variety of graminoid species was encountered here than on most other transects, including *Arctagrostis latifolia*, *Kobresia simpliciuscula*, and several sedges (including *Carex scirpoidea*, *Carex membranacea*, *Carex capillaris*, and *Carex petricosa*), whose cover could not be determined separately. Ten species of forbs were encountered, none of which were very abundant.

Soils

The soils of some locations of transect six showed a sorted stripes frost pattern. The depth of the organic layer was generally deep, but highly variable and ranged from 3 to 33 cm (Table 19). This caused a similar pattern in the carbon storage values, which ranged between 3.6 and 20.7 kg m⁻², by far the highest values found in this study. LOI values were very low and ranged from 29 to 39% DW. C-content were mid-range between 16 and 29%, and C:N ratios were found between 15 and 18. The soil's pH values were comparatively high and ranged from 6.5 to 7.8, with very little carbonate present in the mineral horizon. The mineral horizon showed low LOI values (3-8% DW) and carbon contents (1-5%), but generally had comparatively high C:N ratios (up to 35).

Table 17. Shrub variables from transect 6

Location	LAI along diagonal	Vegetation height along diagonal	Rel. cover overstory shrubs in 6 x 6 m	Mean height overstory shrubs	N- content canopy	C:N ratio canopy	N-content understory	C:N ratio understory	Ramets in 1 x 8 m diagonal	Mean ramet age	Maximum ramet age	Most common shrub species
<i>m from origin</i>	<i>m² leaf per m² ground</i>	<i>cm</i>	<i>%</i>	<i>cm</i>	<i>%</i>	<i>mol/mol</i>	<i>%</i>	<i>mol/mol</i>	<i>#</i>	<i>yr</i>	<i>yr</i>	
0	0.60	17.2	13.0	57.5	3.0	16.1	2.5	19.7	13	18.0	18	<i>Betula</i> hybrid & <i>S. lanata</i>
20	0.24	7.8	9.6	54.6	2.3	22.0	2.1	23.2	11	40.0	53	<i>B. glandulosa</i>
40	0.22	11.7	10.6	69.3					0			<i>S. glauca</i> & <i>Betula</i> hybrid
60	0.38	11.3	1.0	65.5	3.5	13.8	2.9	16.2	29	14.5	15	<i>S. glauca</i>
80	0.17	2.3	3.8	84.0	2.4	20.1	3.0	16.5	5	6.0	6	<i>S. glauca</i>

Table 18. Understory vegetation composition, transect 6. A blank indicates that a given species or category was not encountered in the 1 x 1 m grid at that location.

Species/category	Location along transect (m)				
	0	20	40	60	80
	%	%	%	%	%
<i>Anemone parviflora</i>	0.5		0.5		
<i>Arctagrostis latifolia</i>		8			
<i>Arctostaphylos rubra</i>		0.5	3		
<i>Betula glandulosa</i> x <i>nana</i>			45		
<i>Bistorta plumosa</i>	0.5	0.5			
<i>Bistorta vivipara</i>	0.5		0.5	0.5	0.5
<i>Carex</i> spp. other than <i>C. bigelowii</i>	6	8	7	3	10
<i>Chrysanthemum integrifolium</i>				0.5	
<i>Dryas integrifolia</i>	40	20	11	24	28
<i>Dryas octopetala</i>	10	5	2	6	7
<i>Hedysarum alpinum</i> ssp. <i>americanum</i>	4		1		
<i>Kobresia simpliciuscula</i>				3	
<i>Parnassia palustris</i>	0.5				0.5
<i>Potentilla fruticosa</i>		2			
<i>Rhododendron lapponicum</i>		10	1		
<i>Salix glauca</i>	11				
<i>Saussurea angustifolia</i>	0.5	4			
<i>Saxifraga oppositifolia</i>			0.5	0.5	0.5
<i>Senecio lugens</i>		0.5			
<i>Shepherdia canadensis</i>	1				
<i>Thalictrum alpinum</i>	0.5	0.5	0.5	0.5	0.5
Moss	12	1	0.5	0	
Lichens	2	7	1	50	40
Litter	10	25	27	15	15
Bare soil	1				1

Table 19. Soil characteristics of transect 6. Where no microtopography was specified, only one soil pit was sampled.

				Organic horizon							Mineral horizon							
Loca- tion	Micro- topo- graphy	Posi- tion	Depth of thaw	Depth of horizon	Bulk Density	pH	LOI	Carbon content	Nitrogen content	C:N Ratio	C-org- mass of horizon	Bulk Density	pH	LOI	Carbonate content	Carbon content	Nitrogen content	C:N Ratio
<i>m from origin</i>	<i>type</i>		<i>cm</i>	<i>cm</i>	<i>g / cm3</i>		% <i>DW</i>	% <i>DW</i>	% <i>DW</i>	<i>mol / mol</i>	<i>g / m2</i>	<i>g / cm3</i>		% <i>DW</i>	% <i>DW</i>	% <i>DW</i>	% <i>DW</i>	<i>mol / mol</i>
0				24	0.34	6.48	35.7	28.7	1.7	17.0	17237	1.06	6.81	6.4	0.10	1.2	0.2	8.1
20			70	17	0.21	7.19	38.6	28.0	1.6	17.9	7996	0.82	7.61	7.5	0.06	2.6	0.2	11.0
40			75	3							1411	0.92	7.30	4.5	0.11	3.5	0.1	25.1
60	sorted stripes	H	109	6		7.43					3637	1.14	7.70	3.2	0.42	4.0	0.2	24.7
60	sorted stripes	L	96	22	0.37	7.25	28.8	16.4	1.1	15.4	12875	0.93	7.81	3.9	0.00	4.6	0.1	34.5
80	sorted stripes	H	89	12	0.37	7.39	29.3	16.6	1.0	16.1	6970	0.86	7.78	5.1	0.20	3.1	0.1	22.9
80	sorted stripes	L	79	33	0.32	7.42	31.3	19.3	1.3	15.3	20684							

Transect 7

Location

This transect is located on a south-facing hillslope north of the Noatak River. It is immediately west of transect 6. This transect is composed primarily of willow parkland.



Figure 9. Oblique photograph of transect 7

Shrub structure

Similar to transect 2, this transect was characterized by large, discrete overstory shrubs that were widely separated from each other. Overstory shrubs consisted entirely of large individuals of *Salix glauca*. No *Salix* seedlings or saplings were seen in the vicinity of this transect. Overstory shrub cover was low, varying from 5.3-19.7%, but average shrub height was high, varying from 86.8-160 cm (Table 20). The number of shrub ramets was also low, varying from 0-16 in the 1 x 8 m strip along the diagonal. General vegetation ranged in height from 4.8-21.0 cm, and leaf area index was always less than 0.5. N content of canopy leaves ranged from 1.9-3.2%, a wider range than in many other transects. The maximum age of sampled ramets was 35.

Understory vegetation

Understory vegetation on this transect was dominated by low-growing or prostrate deciduous shrubs and graminoids (Table 21). The deciduous shrub *Dryas integrifolia* was the single most common species, with lesser amounts of *Arctostaphylos rubra*, *Potentilla fruticosa*, and *Salix reticulata* comprising the deciduous shrub understory. Graminoids were mostly represented by *Carex scirpoidea* and *Carex membranacea*, with some *Festuca altaica* and *Calamagrostis purpurascens*. No evergreen shrubs were encountered. In contrast, there was a high diversity of forbs, with sixteen different species encountered in the 1 x 1 m plots, the most of any transect. The forbs were generally not abundant, however.

Soils

Except for one location the soils of transect seven showed no patterned structure. Depth of the organic layer ranged from 9 to 24 cm (Table 22), and carbon storage values from 2.6 to 9.5 kg m⁻². LOI values were consistent and found between 29 to 37% DW. C-contents were lower than in many other transects sampled and ranged from 17 to 24%, with C:N ratios consistently around 16. pH values were the highest found in this study and ranged from 6.7 to 8.1, with carbonate contents in the mineral soil around 0.5% DW and up to 1.9% DW. The mineral horizon showed about average LOI values (3-8% DW) and carbon contents (2-4%), but comparatively very low C:N ratios (10-13).

Table 20. Shrub variables from transect 7

Location	LAI along diagonal	Vegetation height along diagonal	Rel. cover overstory shrubs in 6 x 6 m	Mean height overstory shrubs	N- content canopy	C:N ratio canopy	N-content understory	C:N ratio understory	Ramets in 1 x 8 m diagonal	Mean ramet age	Maximum ramet age	Most common shrub species
<i>m from origin</i>	<i>m² leaf per m² ground</i>	<i>cm</i>	<i>%</i>	<i>cm</i>	<i>%</i>	<i>mol/mol</i>	<i>%</i>	<i>mol/mol</i>	<i>#</i>	<i>yr</i>	<i>yr</i>	
0	0.47	8.3	19.7	108.3	1.9	25.8	1.6	30.9	2	35.0	35	<i>S. glauca</i>
20	0.29	21.1	5.5	160.0	2.7	17.9	2.9	16.5	9	29.0	31	<i>S. glauca</i>
40	0.28	5.6	7.5	95.8	3.2	15.2	2.9	16.5	16	16.0	16	<i>S. glauca</i>
60	0.33	7.9	5.3	98.3	3.2	15.1	2.6	18.0	6	16.0	16	<i>S. glauca</i>
80	0.18	4.8	6.4	86.8					0			<i>S. glauca</i>

Table 21. Understory vegetation composition, transect 7. A blank indicates that a given species or category was not encountered in the 1 x 1 m grid at that location.

Species/category	Location along transect (m)				
	0	20	40	60	80
	%	%	%	%	%
<i>Anemone parviflora</i>	0.5	0.5	0.5	0.5	0.5
<i>Arctostaphylos rubra</i>	14	5			
<i>Astragalus umbellatus</i>	0.5				
<i>Bistorta vivipara</i>	0.5		0.5	0.5	
<i>Calamagrostis purpurascens</i>				0.5	0.5
<i>Carex</i> spp. other than <i>C. bigelowii</i>	7	15	23	14	10
<i>Chrysanthemum integrifolium</i>	1				
<i>Dryas integrifolia</i>	25	20	20	30	45
<i>Festuca altaica</i>		3			
<i>Gentiana propinqua</i>		0.5	1		
<i>Hedysarum alpinum</i> ssp. <i>americanum</i>	2	0.5	1.5	1.5	1
<i>Oxytropis koyukukensis</i>			0.5	0.5	4
<i>Oxytropis deflexa</i>				0.5	0.5
<i>Parnassia palustris</i>				0.5	
<i>Parrya nudicaulis</i>	2	0.5	1	1	
<i>Pedicularis albolabiata</i>		1	0.5		
<i>Potentilla fruticosa</i>					0.5
<i>Salix glauca</i>	6			0.5	
<i>Salix reticulata</i>		1			
<i>Saussurea angustifolia</i>	12	11	3	6	3.5
<i>Senecio atropurpureus</i> ssp. <i>frigidus</i>	0.5				
<i>Senecio lugens</i>					0.5
<i>Stellaria laeta</i>			0.5		
<i>Thalictrum alpinum</i>	0.5		0.5		0.5
Moss	16	15	12	10	11
Lichens	2	5	4	5	4
Litter	12	15	35	30	15

Table 22. Soil characteristics of transect 7. Where no microtopography was specified, only one soil pit was sampled.

Loca- tion	Micro- topo- graphy	Posi- tion	Depth of thaw	Organic horizon								Mineral horizon						
				Depth of horizon	Bulk Density	pH	LOI	Carbon content	Nitrogen content	C:N Ratio	C-org- mass of horizon	Bulk Density	pH	LOI	Carbonate content	Carbon content	Nitrogen content	C:N Ratio
				<i>m from origin</i>	<i>g / cm3</i>		% DW	% DW	% DW	<i>mol / mol</i>	<i>g / m2</i>	<i>g / cm3</i>		% DW	% DW	% DW	% DW	<i>mol / mol</i>
0	Turf hummocks	L	68	17	0.15	7.35	29.3	17.0	1.1	15.3	3590	0.45	7.65	6.7	1.06	2.8	0.3	10.3
0	Turf hummocks	H	68	9	0.14	7.70	31.0	20.8	1.3	16.2	2553	0.37	6.65	8.6	0.51	3.7	0.3	11.7
20			53	22	0.18	7.52	35.8	24.1	1.5	15.7	9351	0.42	7.77	7.6	0.67	3.7	0.3	11.7
40			83	22	0.21	7.66	32.2	19.3	1.3	15.3	8641	0.54	8.13	2.8	0.44	2.2	0.2	11.0
60			65	11	0.16	7.63	35.6	21.3	1.3	15.9	3601	0.40	7.89	7.5	0.46	4.2	0.3	12.3
80			67	24	0.17	7.27	36.8	22.7	1.4	16.8	9470	0.28	7.81	7.3	1.86	4.4	0.3	13.4

Transect 8

Location

This transect is located on a young river terrace above an oxbow lake to the south of the Noatak River, east of a prominent moraine ridge. It is composed primarily of semi-heath tundra.



Figure 10. Oblique photograph of transect 8

Shrub structure

Although the dark green of *Betula glandulosa* was prominent from a distance (Fig. 10), this transect had low cover of a variety of different overstory shrubs, including *Betula glandulosa*, *Potentilla fruticosa*, and *Salix glauca*. Several saplings and small individuals of *Betula glandulosa* and *Potentilla fruticosa* were seen in the vicinity of this transect. Overstory shrub cover was low, varying from 2.1-7.3%, and the height of the overstory shrubs was also low, ranging from 20.3-39.6 cm (Table 23). N content of the canopy leaves was consistently lower than in most of the other transects, ranging from 1.7-1.8%. Leaf area index was always less than 0.5, and general vegetation height was less than 10 cm. Despite the low cover values, the maximum age of sampled ramets was 47, comparable to most other transects.

Understory vegetation

Understory vegetation on this transect was dominated by low-growing deciduous shrubs. The deciduous shrub *Vaccinium uliginosum* was the most abundant single species, followed by *Dryas integrifolia* (Table 24). The only evergreen shrub encountered was *Rhododendron lapponicum*, which was relatively abundant in some locations. Graminoids (mostly *Carex* spp.) were a relatively minor component. Forbs were quite diverse, with fourteen species represented. Mosses and lichens were abundant in some locations.

Soils

The soils of transect eight showed consistently shallow organic layer depth of 9-13 cm (Table 25). Carbon storage values were found similarly consistent between 2.6 and 4.3 kg m⁻². LOI values were consistent and found between 38 and 50% DW, as were C-contents (17 to 24%). C:N ratios ranged from 16-18. The soil's pH values were found between 6.7 and 7.9. The organic layer bordered straight onto a layer of coarse rock alluvium, so that only limited mineral material was sampled.

Table 23. Shrub variables from transect 8

Location	LAI along diagonal	Vegetation height along diagonal	Rel. cover overstory shrubs in 6 x 6 m	Mean height overstory shrubs	N- content canopy	C:N ratio canopy	N-content understory	C:N ratio understory	Ramets in 1 x 8 m diagonal	Mean ramet age	Maximum ramet age	Most common shrub species
<i>m from origin</i>	<i>m² leaf per m² ground</i>	<i>cm</i>	<i>%</i>	<i>cm</i>	<i>%</i>	<i>mol/mol</i>	<i>%</i>	<i>mol/mol</i>	<i>#</i>	<i>yr</i>	<i>yr</i>	
0	0.26	9.8	7.3	33.1					0	30.3	47	<i>B. glandulosa</i>
20	0.16	7.2	4.2	39.6	1.7	27.9	1.6	28.5	3	16.3	29	<i>S. glauca</i>
40	0.38	6.4	2.8	20.9	1.8	26.8	1.8	26.4	40	21.0	31	<i>P. fruticosa</i>
60	0.43	6.0	4.7	28.3	1.7	29.5	1.6	29.4	32	14.7	36	<i>P. fruticosa</i>
80	0.31	8.2	2.1	20.3	1.7	28.3	1.9	26.3	11	21.5	25	<i>P. fruticosa</i> & <i>B. glandulosa</i>

Table 24. Understory vegetation composition, transect 8. A blank indicates that a given species or category was not encountered in the 1 x 1 m grid at that location.

Species/category	Location along transect (m)				
	0	20	40	60	80
	%	%	%	%	%
<i>Androsace chamaejasme</i>			0.5	0.5	0.5
<i>Anemone parviflora</i>				0.5	0.5
<i>Arctostaphylos rubra</i>	2	3	7	8	1
<i>Astragalus umbellatus</i>			1	0.5	0.5
<i>Betula glandulosa</i>			0.5		
<i>Betula glandulosa</i> x <i>nana</i>		3		2	
<i>Bistorta plumosa</i>	0.5		1	3.5	
<i>Carex bigelowii</i>	9	3			
<i>Carex</i> spp. other than <i>C. bigelowii</i>	9	3	3	6	2
<i>Dryas integrifolia</i>	2	1.5	25	16	22
<i>Dryas octopetala</i>		1.5			
<i>Festuca altaica</i>		0.5			
<i>Gentiana propinqua</i>					0.5
<i>Hedysarum alpinum</i> ssp. <i>americanum</i>			0.5	1	0.5
<i>Kobresia sibirica</i>			3		2
<i>Minuartia elegans</i>			0.5		
<i>Oxytropis maydelliana</i>				0.5	0.5
<i>Pedicularis albolabiata</i>	0.5				
<i>Potentilla fruticosa</i>	0.5			2	
<i>Pyrola grandiflora</i>	1				
<i>Rhododendron lapponicum</i>	1	12	1	2	15
<i>Salix reticulata</i>	5	2	2		5
<i>Saussurea angustifolia</i>				1	1
<i>Senecio atropurpureus</i> ssp. <i>frigidus</i>					1
<i>Silene acaulis</i>			0.5	0.5	
<i>Thalictrum alpinum</i>	0.5	0.5	0.5	0.5	0.5
<i>Tofieldia pusilla</i>			0.5		
<i>Vaccinium uliginosum</i>	30	33	0.5	14	4
Moss	10	22	2	22	5
Lichens	12	7	8	7	5
Litter	16	5	50	17	30

Table 25. Soil characteristics of transect 8. Where no microtopography was specified, only one soil pit was sampled.

Loca- tion	Micro- topo- graphy	Posi- tion	Depth of thaw	Organic horizon							Mineral horizon							
				Depth of horizon	Bulk Density	pH	LOI	Carbon content	Nitrogen content	C:N Ratio	C-org- mass of horizon	Bulk Density	pH	LOI	Carbonate content	Carbon content	Nitrogen content	C:N Ratio
<i>m from origin</i>	<i>type</i>	<i>cm</i>	<i>cm</i>	<i>g / cm3</i>	<i>% DW</i>	<i>% DW</i>	<i>% DW</i>	<i>mol / mol</i>	<i>g / m2</i>	<i>g / cm3</i>	<i>% DW</i>	<i>% DW</i>	<i>% DW</i>	<i>% DW</i>	<i>% DW</i>	<i>mol / mol</i>		
0				12	0.13	6.66	41.8	21.1	1.1	18.4	3165							
20				13	0.13	6.91	48.1	27.0	1.5	17.5	4346							
40				11	0.14	7.48	37.5	20.3	1.1	17.8	3012	0.33	7.85	2.7	0.13	8.7	0.4	21.9
60				12	0.15	6.95	39.1	21.8	1.3	16.6	3934							
80				9	0.12	7.18	49.5	25.9	1.6	16.3	2556							

Transect 9

Location

This transect is located on a river terrace to the south of the Noatak River, west of a prominent moraine ridge. It is composed primarily of *Betula* scrub with semi-heath tundra openings.



Figure 11. Oblique photograph of Transect 9

Shrub structure

This transect runs through semi-heath vegetation with large dense clumps of *Betula glandulosa* x *nana* hybrids that were widely spaced. Several small individuals of *Betula* were seen in the vicinity of this transect. Overstory shrub cover was relatively low, ranging from 2.6-21.9%, with mean shrub heights of 35-57.5 cm (Table 26). Leaf area index was generally less than 0.2, except at location 40, where a clump of *Betula* was sampled along the diagonal, in which case it was 0.7. The height of the general vegetation was also very low (<5 cm), except where overstory shrubs were encountered. N content of canopy leaves varied from 2.1-2.9%. The maximum age of ramets sampled on this transect was 38.

Understory vegetation

Vegetation on this transect, outside of the dense clumps of overstory *Betula*, was dominated by low-growing deciduous shrubs, especially *Dryas integrifolia* and *Vaccinium uliginosum* (Table 25). The only evergreen encountered was *Rhododendron lapponicum*, and it was not very abundant. Graminoids were also present, but not abundant. Fourteen species of forbs were encountered. Lichens comprised a prominent part of the understory cover in most locations. The 1 x 1 m plot at location 60 was located in the midst of a dense clump of *Betula glandulosa* x *nana*, and had no understory other than mosses, lichens, and some *Vaccinium uliginosum*.

Soils

In the soils of transect nine, depth of organic layer ranged from 3 to 14 cm (Table 26), LOI values from 30 to 40% DW and carbon content from 15-23%. This yielded carbon storage values from 0.9 to 4.1 kg m⁻², with C:N ratios around 15. The soil's pH values were found between 7.3 and 7.7, with low but consistent carbonate contents in the mineral soil averaging 0.14% DW. Similarly consistent were the mineral horizon's LOI values of 3-8% DW. The carbon contents ranged from 4-8% and the C:N ratios were generally found around 12.

Table 26. Shrub variables from transect 9

Location	LAI along diagonal	Vegetation height along diagonal	Rel. cover overstory shrubs in 6 x 6 m	Mean height overstory shrubs	N- content canopy	C:N ratio canopy	N-content understory	C:N ratio understory	Ramets in 1 x 8 m diagonal	Mean ramet age	Maximum ramet age	Most common shrub species
<i>m from origin</i>	<i>m² leaf per m² ground</i>	<i>cm</i>	<i>%</i>	<i>cm</i>	<i>%</i>	<i>mol/mol</i>	<i>%</i>	<i>mol/mol</i>	<i>#</i>	<i>yr</i>	<i>yr</i>	
0	0.09	4.6	2.6	35.0					0			<i>Betula</i> hybrid
20	0.10	4.7	5.4	40.0	2.9	17.3	3.1	16.3	14	22.0	22	<i>B. glandulosa</i>
40	0.70	14.8	21.9	38.3	2.1	23.4	2.2	23.4	6	38.0	38	<i>Betula</i> hybrid
60	0.06	3.9	10.3	57.5					0			<i>B. glandulosa</i> & <i>Betula</i> hybrid
80	0.13	3.4	6.1	39.0	2.6	19.3	2.2	23.0	1	33.0	33	<i>B. glandulosa</i>

Table 25. Understory vegetation composition, transect 9. A blank indicates that a given species or category was not encountered in the 1 x 1 m grid at that location.

Species/category	Location along transect (m)				
	0	20	40	60	80
	%	%	%	%	%
<i>Androsace chamaejasme</i>	0.5	0.5	0.5		0.5
<i>Anemone parviflora</i>			0.5		
<i>Astragalus umbellatus</i>	0.5	0.5	0.5		
<i>Betula glandulosa</i> x <i>nana</i>				80	11
<i>Bistorta plumosa</i>		0.5			
<i>Bistorta vivipara</i>	0.5		0.5		
<i>Bupleurum americanum</i>	0.5				
<i>Carex bigelowii</i>	3.5	8	7.5	2	6
<i>Carex</i> spp. other than <i>C. bigelowii</i>	3.5		7.5		2
<i>Chrysanthemum integrifolium</i>	0.5				
<i>Dryas integrifolia</i>	25	35	40		15
<i>Hedysarum alpinum</i> ssp. <i>americanum</i>					1
<i>Oxytropis maydelliana</i>	0.5	0.5			1
<i>Parrya nudicaulis</i>		0.5			
<i>Pedicularis albolabiata</i>			0.5		0.5
<i>Potentilla biflora</i>					12
<i>Rhododendron lapponicum</i>	1	1	1		0.5
<i>Salix reticulata</i>	0.5	0.5			2
<i>Saussurea angustifolia</i>		0.5	0.5		
<i>Silene acaulis</i>	3.5	6			
<i>Tofieldia pusilla</i>			0.5		
<i>Vaccinium uliginosum</i>	3.5	7	0.5	4.5	10
Moss	5	2	2	10	7
Lichens	20	17	23	4	15
Litter	35	30	20		25

Table 26. Soil characteristics of transect 9. Where no microtopography was specified, only one soil pit was sampled.

Loca- tion <i>m from origin</i>	Micro- topo- graphy <i>type</i>	Posi- tion	Depth of thaw <i>cm</i>	Organic horizon							Mineral horizon							
				Depth of horizon	Bulk Density	pH	LOI	Carbon content	Nitrogen content	C:N Ratio	C-org- mass of horizon	Bulk Density	pH	LOI	Carbonate content	Carbon content	Nitrogen content	C:N Ratio
				<i>cm</i>	<i>g / cm3</i>		%	% DW	% DW	<i>mol / mol</i>	<i>g / m2</i>	<i>g / cm3</i>		% DW	% DW	% DW	% DW	<i>mol / mol</i>
							DW											
0				14	0.11	7.28	39.8	22.5	1.5	15.2	3549	0.34	7.54	7.7	0.14	4.4	0.4	12.3
20				14	0.18	7.45	29.5	17.0	1.2	14.5	4119	0.27	7.65	8.1	0.18	4.6	0.3	16.2
40				10	0.14	7.38	36.8	15.1	1.0	15.5	1876	0.18	7.58	8.8	0.10	4.4	0.3	12.9
60				3							906	0.32	7.62	9.3	0.14	5.8	0.5	12.4
80				6	0.16	7.39	35.4	19.0	1.3	14.7	1662	0.27	7.61	13.9	0.13	7.9	0.6	12.7

Comparative transect analysis

Of the nine transects that we sampled, we classified three of them as being dominated by alder (*Alnus crispa*; transects 1, 4 and 5), three by willow (primarily *Salix glauca*; transects 2, 6, and 7), two by bog birch (*Betula glandulosa*; transects 8 and 9), and one by poplar (*Populus balsamifera*; transect 3). The cover of canopy shrubs was quite variable within and between transects, ranging from 0 - 48% over all of our sampling locations. Alder transects demonstrated the greatest variability in canopy cover. All of the willow parkland transects were characterized by large and widely-spaced individual shrubs. As such, these transects had low cover values for canopy shrubs, but the highest mean canopy shrub heights. Birch-dominated sites had the lowest canopy shrub heights and relatively low canopy shrub cover values.

Of the canopy shrub species, poplars showed the clearest evidence of recent expansion via seedling establishment. Numerous saplings and small individuals were encountered at the poplar transect and were also observed at a second population near the Kugurak Springs that was not sampled for the full suite of variables. A few saplings and small individuals of alder and birch were seen in the vicinity of two of their respective transects each. In contrast, no saplings or small individuals of canopy willow shrubs were seen in the vicinity of any of the willow parkland transects.

Understory vegetation was generally dominated by prostrate or low-growing deciduous shrubs and graminoids. Forbs were the most diverse component of the vascular vegetation, although they never composed a high proportion of the understory vegetation cover. Between 8 and 16 species of forbs were encountered in the 1 x 1 m sampling plots on each transect. Relatively few evergreen shrub species were encountered in the understory.

Soils showed a range of organic horizon development, with organic layers ranging from 1-33 cm in depth. The shallowest organic layers were consistently located in the poplar transect, while the deepest organic layers were located in the willow parkland transects. Carbon (C) storage in the organic layer varied from 0.1-20.7 kg m⁻², with the greatest C storage in soils of the willow parkland transects and the least in soils from the poplar transect. Birch and alder transects were intermediate, with birch transects tending to have lower carbon storage than the alder transects. However, there was high variability in C storage within most transects. C:N ratios ranged from 10-39, with the highest variation in the mineral horizon. Organic soils had C:N ratios from 15-20. Most soils were neutral in pH, although values ranged from 4.9-8.1. The highest pH values (6.7-8.1) were found on one of the willow parkland transects, while the lowest pH values (5.0-6.5) were found on one of the alder transects; however, there was noticeable overlap among the transects and vegetation types.

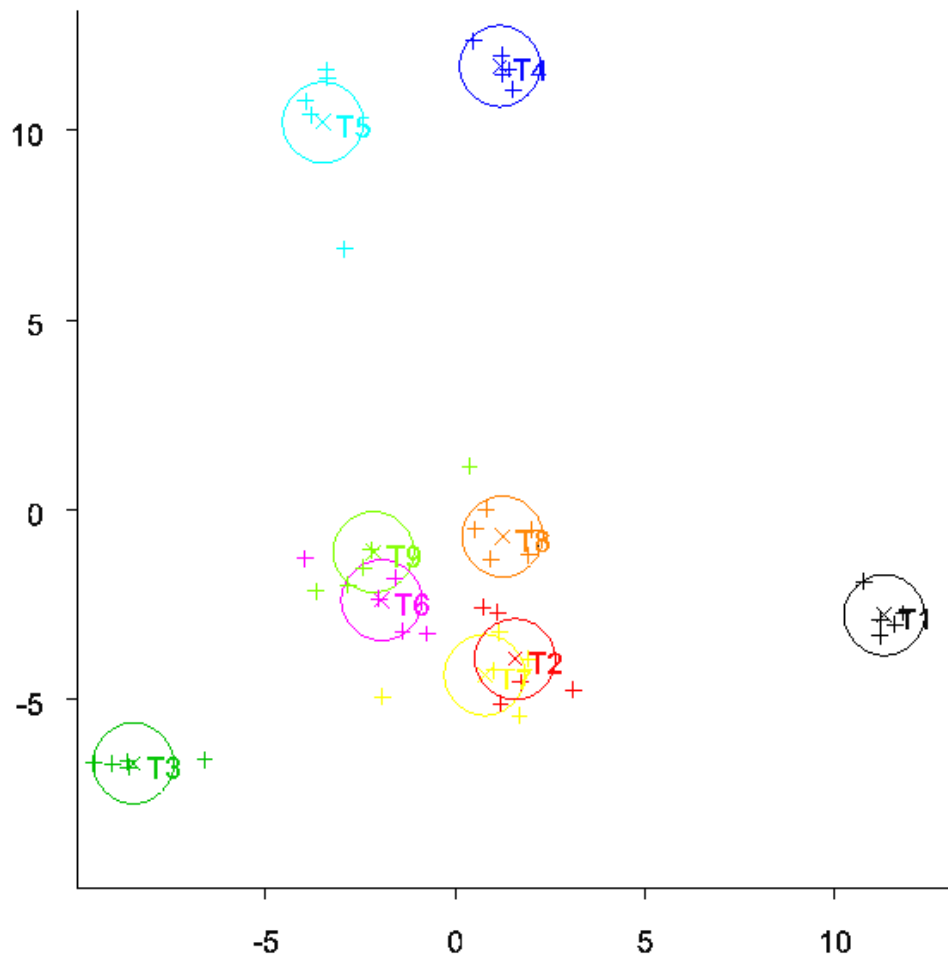


Figure 12. Ordination by canonical variates of understory vegetation composition, using transect as the grouping factor. Numbers refer to the individual transects. Transects 1, 4 and 5 were alder-dominated, transects 2, 6 and 7 were willow-dominated, transect 3 was dominated by poplar, and transects 8 and 9 were dominated by birch. +s indicate individual locations, Xs indicate the centroids of each transect, circles indicate 95% confidence intervals for that transect.

Ordination by canonical variates of understory vegetation composition, using transect as the grouping factor, revealed that the three alder transects and the poplar transect separated from those of the willow and birch transects (Fig. 12). However, the three alder transects did not group together. The greatest separation in this ordination was between transects 4 and 5, which are both alder transects, and the others. The five species that had the highest correlations with the scores for the first canonical variate were 1) *Carex bigelowii*, 2) *Cassiope tetragona*, 3) *Dryas*

octopetala, 4) *Dryas integrifolia*, and 5) *Carex* spp other than *C. bigelowii*. Of these species, *Carex bigelowii*, *Dryas octopetala*, and *Cassiope tetragona* were found in greater abundance or only occurred on transects 4 and 5. In contrast, *Dryas integrifolia* and other *Carex* species were very low in abundance on transects 4 and 5. Evergreen ericaceous shrubs, including *Cassiope tetragona*, were not abundant on any of our transects, but were found in higher abundance on the alder transects. These species are common in the climax vegetation of acidic tundra of the North Slope. *Carex bigelowii* and *Dryas octopetala* are also typically abundant in acidic tundra vegetation, while *Dryas integrifolia* is typically a major component of non-acidic tundra vegetation, and is common on calcareous soils.

REML variance component analyses suggest that pH is the abiotic variable that is most significant in explaining the variation in measured overstory shrub variables, including percent cover of overstory shrubs, shrub ramet density, total number of ramets in the 1 x 8 m diagonal strip, maximum ramet age, and leaf area index of the general vegetation (Table 27). There was a negative relationship between pH and all of these shrub variables. Sites with lower pH had greater cover of overstory shrubs, higher shrub ramet densities, more total ramets in the 1 x 8 m diagonal strip, and older ramets. Because leaf area index of the general vegetation was very low except when overstory shrubs were present, it also correlated with overstory shrub cover, and was highest at low pH. Because pH of the organic and mineral horizons was highly correlated, it was not possible to separate the effects of pH of the two horizons, and we present here only statistical analyses using pH of the organic horizon (Table 27). Generally speaking, alder transects had lower soil pH than was found in birch, willow, or poplar transects.

Table 27. Statistical parameters from REML variance component analysis of vegetation and soil variables, with transect as a random effect. Ndf, Ddf, approximate F-test values and P values are reported for nearly significant ($P \leq 0.1$) fixed effects only.

Dependent variable	Random effect	s.e.	Fixed effects	Effect	s.e.	Ndf	Ddf	F	P
Leaf area index	0.050	0.032	pH organic horizon	-0.26	0.083	1	43.0	9.64	0.003
Percent cover of overstory shrubs	18.5	17.1	pH organic horizon	-10.5	2.72	1	35.4	14.89	<0.001
Ramet density	53.5	48.3	pH organic horizon	-17.6	2.6	1	15.0	44.67	<0.001
Maximum ramet age	0		pH organic horizon	-7.08	3.92	1	38.0	3.26	0.079
Total ramets in 1 x 8 m diagonal strip	0		pH organic horizon	-11.6	3.95	1	43.0	8.60	0.005
Soil C content mineral horizon	111.7	67.0	pH organic horizon	-7.40	3.51	1	36.4	4.44	0.042
			Average ramet age	-0.30	0.176	1	31.8	2.87	0.100
Soil C mass of organic horizon	7587869	4423245	Average ramet age	-109	42.4	1	31.9	6.67	0.015

Shrub effects on soil characteristics

In our data set, we found no strong relationships between soil C and any variables that are linked directly to shrub biomass, such as canopy shrub cover. Soil carbon is affected by vegetation, but it is also controlled by a variety of abiotic factors, including soil moisture and pH, and time since disturbance. There was a negative relationship between pH and soil C content of the mineral horizon (Table 27), but the highest soil C that we found was in soils of intermediate pH, and there was a lot of unexplained variance. There was also a negative relationship between average ramet age and the soil C content of the mineral horizon, but average ramet age was not as significant a predictor as pH (Table 27). In contrast, soil C mass of the organic horizon was significantly negatively related to average ramet age in the REML analyses (Figure 13, Table 27).

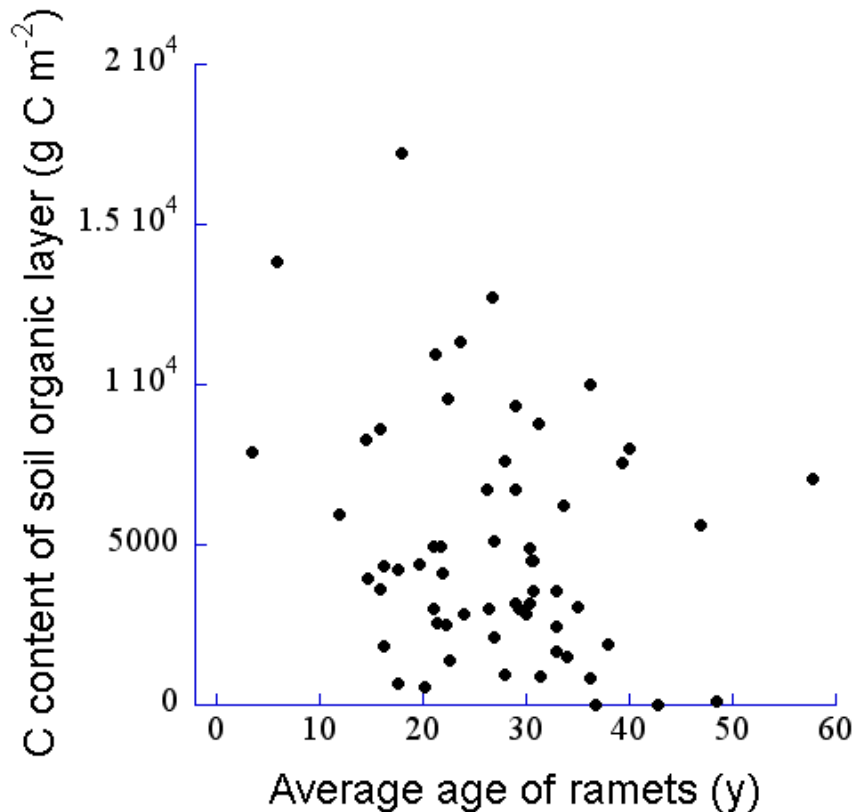


Figure 13. Relationship between soil C content of the organic horizon and average age of sampled shrub ramets.

Floristics

A total of 168 specimens were collected during this expedition, representing 107 vascular plant species and two Bryophytes (Table 28) (a number of less easily identified species were collected more than once). Of the collected species, 64 species were not previously identified to occur along the upper Noatak river, and we discovered 5 species that, so far as we can tell, have not previously been collected anywhere within the non-maritime Noatak drainage. Most notably, the specimens collected document a nearly 50% increase in the number of vascular plant species now known to occur in the Upper Noatak valley (the area from Kavachurak Lake east to the headwaters of the Noatak River). The possibly surprising extent of this increase in botanical information is probably due to only two previous botanically exploring expeditions having penetrated into the Upper Noatak at all, and these only having visited three localities within a rather vast total area.

The species that we observed and/or collected in the Upper Noatak in the course of the expedition span over a range of recognized growth forms or plant functional types (Table 29). Shrubs and graminoids are prominently represented, these constituting most of the dominants in this area's almost entirely non-arboreal vegetation. All of the dwarf shrubs or sub-shrubs (mostly Ericoids), which are also important vegetation components, are well-known tundra species that had previously been collected lower in the Noatak drainage and were not collected by us since they needed no identification work. Forb species (herbaceous, broad-leaved plants) were numerically the most prominent component of our collections, even though, as an understory they usually comprise a relatively minor part of the total plant biomass. No vines, and only two achlorophyllous flowering plants, were encountered, but one of these latter (*Boschniakia rossica* in the family Orobanchaceae), a root parasite, was conspicuous and abundant in areas where alder shrubs (*Alnus crispa*) occurred. We did not collect this species, as it had been collected in the Upper Noatak previously.

Table 30 summarizes the taxonomic distribution of collected species, and of the new species records noted above, among botanical families. Graminoid families (Poaceae, Cyperaceae) were prominently represented, while among non-graminoids the forb (in our area) families Fabaceae and Asteraceae were the most conspicuous.

Table 28. *Total numbers of vascular plant species collected and observed in the Noatak River Basin.*

	Entire Noatak ¹	Upper Noatak ²
Previously collected vascular plant species (before '06), according to records in the UAF Herbarium and Young (1974)	489 ³	132
Previously collected species observed by us but not collected, in '06	50	21
Previously collected species, collected again in '06	107 ⁴	43
New species collected by us in '06	5	64 ⁵

¹ Exclusive of its delta area (*i.e.*, not including maritime habitat)

² From Kavachurak Lake to Twelvemile Slough, plus Igning River (a tributary), and Kipmik Lake (in a tributary drainage near the western boundary of GAAR) where Young collected in 1973.

³ Includes 43 species that Young (1974) listed as having collected in the Noatak drainage but are not represented in the UAF Herbarium database, our primary data source for previous collections.

⁴ Grand total of 168 specimens collected in '06 includes ~55 vascular plant species that were collected more than once, plus 2 Bryophyte specimens.

⁵ Includes number to the left, those specimens being also records for the Upper Noatak

Table 29. *Functional types of species observed in Upper Noatak, 2006*

Functional type	collected	observed in '06 but not coll.	total species
non-seed vascular plants	4	1	5
trees	0	1	1
shrubs	11	4	15
dwarf shrubs (sub-shrubs)	0	9	9
vines	0	0	0
graminoids (grasses, sedges, rushes)	29	6	35
forbs (herbaceous, broad-leaved plants)	68	27	95
achlorophyllous flowering plants (heterotrophs)	0	2	2
total species	112	50	162

Table 30. Taxonomic distribution of species collected in the Upper Noatak in 2006, showing distribution of newly collected species as well as the distribution of our entire 2006 collection

Major group	Family¹	Our entire collection	New to Upper N.	New to Entire N.²
	“Pteridophytes” (ferns, <i>Equisetum</i>)	4	3	
Gymnosperms	(conifers, junipers, etc.)	1	1	
Monocots	Scheuchzeriaceae (arrowgrass f.)	2	2	1
	Poaceae (grasses)	10	4	
	Cyperaceae (sedges)	16	13	
	Juncaceae (rushes)	3		
	Liliaceae (lily family)	1	1	
	Orchidaceae (orchid family)	3	1	1
Dicots	Salicaceae (willow family)	6	3	1
	Betulaceae (birch family)	2		
	Caryophyllaceae (carnation fam.)	5	1	
	Ranunculaceae (buttercup family)	1		
	Brassicaceae (mustard family)	4	4	1
	Saxifragaceae (saxifrage family)	2	1	
	Rosaceae (rose family)	1	1	1
	Fabaceae (pea family)	10	5	
	Ericaceae (heath family)	1	1	
	Gentianaceae (gentian family)	2	1	
	Primulaceae (primrose family)	3	3	
	Polemoniaceae (phlox family)	1	1	
	Boraginaceae (borage family)	1	1	
	Scrophulariaceae (figwort family)	4	3	
	Caprifoliaceae (honeysuckle fam.)	2	2	
	Asteraceae (sunflower family)	15	7	

¹ A few minor families that are represented by a single collection are omitted from this table.

² Not previously reported from the entire Noatak Basin, exclusive of delta area (*i.e.*, maritime habitat). Entries in this column are included in the column to their left since they are of course records for the Upper Noatak also.

Discussion

A long-term resource to assess shrub expansion and potential impacts on soil carbon

The purpose of the NPS's Inventory and Monitoring Program is to “develop scientifically sound information on the current status and long term trend in the composition, structure, and function of the park ecosystem” (NPS, 2006). The program set out to achieve this by, among other measures, “determining the current condition of resources and how they are changing over time” (NPS, 2006). In the light of rapidly advancing climate change in the Arctic and the vast areas of arctic parklands it is more important than ever to understand the dynamic nature of arctic parkland ecosystems and to provide reference points for comparison between different time-points and ecosystems. Permanent plots that are revisited over time provide the most accurate opportunity to allow such comparisons and detect such changes. A fine-scale approach, using plots on the ground that can be revisited, is best-suited for the detection of changes in understory vegetation composition, soil conditions, and shrub seedling status. The vegetation and soil transects established for this study, in combination with the baseline dataset collected and the protocols documented in this report, provide this long-term inventory and monitoring resource. Because soil sampling took place in only a small portion of the 6 x 6 m locations, future soil sampling at other spots within the locations is possible so long as it is not done extremely often.

The sampling scheme that we developed and the permanent transects that we established will be useful for long-term monitoring in several ways. First, the specific locations on the ground can be revisited and analyzed in the future, greatly improving confidence in time-series analysis. The measures used to mark the transects guide a future field worker to the locations using a combination of basic tools such as a handheld GPS, a metal detector and a tape measure, together with the data contained in this report. Both mid-scale retrieval of sampled locations and detection of change on that scale are aided by a series of oblique photographs documenting the vegetation status in the proximity of the established transects as well as their position in the landscape. Buried metal markers (pieces of rebar) were chosen for small-scale retrieval of transect start and end points because, unlike wooden stakes, they are invisible in the landscape but will be detectable (by means of a metal detector) with precision for decades to centuries. Second, the protocols applied to analyze the status of vegetation and soils lend themselves to being applied by non-specialists with good, but not expert, knowledge of local plant species and average knowledge about local soils. Ocular percent cover assessments of understory vegetation are aided by using a 10 cm by 10 cm grid on square meter sized plots, greatly reducing the noise effect introduced by the individual surveyor. Only one organic and one mineral horizon of soils are sampled, greatly reducing the need for expert knowledge on soil development. Third, larger scale

shrub advances can be detected and monitored against a baseline established through a series of low-altitude aerial photographs, covering a substantial part of the upper Noatak valley. Because the aerial photographs taken incorporate the transects established on the ground, it will be possible to scale up aspects of the dataset obtained from the fine-scale transect assessment, using GIS techniques.

It was originally intended to establish and sample a more extensive number of transects. Having a higher number of locations to compare would have aided analysis of the present dataset and would undoubtedly aid the detection of change in future time-series analysis. The two main reasons for the slower than anticipated progress in the field were i) the time it took to walk to the transects even in this upper and comparatively narrow part of the Noatak valley, and ii) the sampling of soil material for bulk density analysis, which, in the absence of the possibility to carry vast amount of soil samples back to the laboratory for weight and volume reasons, required the weighing of soil samples of defined volumes recovered from soil pits in the field. For an assessment of soil carbon stocks, however, an assessment of bulk density cannot be avoided.

Indicators for shrub dynamics

The abiotic variable that most strongly predicted shrub cover and biomass was soil pH. This is perhaps not surprising. Tundra soils tend to acidify with time since deglaciation via chemical weathering and biotic succession (Walker et al., 1989). In a comparison of biomass on two North Slope soils of different pH and ages since deglaciation, the younger, higher pH soil responded less to nutrient addition, but supported a more diverse plant community with lower total biomass than the acidic, older soil (Hobbie et al., 2005). Across the circumpolar Arctic, carbonate-derived soils, which tend to have higher pH, show lower Normalized Difference Vegetation Index (NDVI) values for the same summer warmth than other soils (Raynolds et al., 2007). NDVI is a surrogate for plant biomass.

Shrub populations can expand either by reproduction from seed, or by clonal growth of existing individuals. These two mechanisms cannot be distinguished easily in large shrubs without obtaining genetic information, and it is likely that the shrub expansion observed in recent years by repeat photography (e.g. Tape et al., 2006) is due to both. We were unable to directly assess the contribution of clonal growth to any recent expansion in the shrub sites that we surveyed, although the aerial photographs that we took will allow total expansion to be measured in the future. However, the extent of clonality within a shrub population can be assessed with molecular markers, which would be interesting to do in the future (see *Outlook for the Future*, below). Nonetheless, it is of interest that the poplar, alder, and birch shrubs that we surveyed all showed some evidence of recent reproduction by seed, while the willows in the willow parkland transects did not. We inferred that willow colonization occurs only infrequently except on

floodplains with recently exposed mineral soil, but that large willows persist for a long time once they are established.

As another way of assessing whether the shrub populations we sampled had undergone recent expansion, we compared the understory vegetation composition of the Noatak sites with two North Slope sites dominated by alder, one of which showed expansion in the last 50 years, while the other did not (Tape et al., 2006). In a canonical variates ordination including all of these sites, the understory composition from the expanding North Slope alder site (transects 12 and 13) was more similar to the alder transects on the Noatak (transects 1, 4 and 5) than to the non-expanding North Slope alder site (transects 10 and 11; Fig. 14). Differences in understory composition at the alder sites were primarily responsible for the separation in this ordination, as the willow and birch transects clustered together and were not significantly different.

The primary differences in species abundance driving the separation among the alder sites were due to two ericaceous evergreen shrubs, *Ledum palustre* spp. *decumbens* and *Vaccinium vitis-idaea*. These species were very abundant in the non-expanding North Slope site, were at intermediate abundance in the expanding North Slope site, and were very low in abundance in the Noatak alder sites. The third most important species driving the difference was *Betula nana*, which occurred in high abundance in the non-expanding North Slope site, and at lower abundance in one of the Noatak alder transects. However, it was not seen at all in the expanding North Slope site or on the other Noatak transects. High abundance of these two ericaceous evergreen shrub species and *B. nana* are typical of the climax vegetation of acidic tussock tundra in the Brooks Range foothills (Walker et al., 1994). The two North Slope alder sites also fell on a gradient of soil pH relative to the Noatak sites, with the non-expanding site having the lowest pHs that we measured, and the expanding site being intermediate between the Noatak sites and the non-expanding North Slope alder site. This analysis of understory vegetation supports our inference, from the presence of seedlings, that alders may have expanded recently at our Noatak transects.

Inclusion of the two North Slope sites in our REML analyses did not qualitatively change their results (Table 31). Soil pH was still the abiotic variable that was most significant in explaining the variation in measured shrub overstory variables, and there was a negative relationship between soil pH and all of these vegetative variables. There was a somewhat stronger negative relationship between soil pH and ramet age when the North Slope sites were included than was seen in the Noatak data set alone (Tables 27, 31), because the North Slope sites had both lower soil pH and older ramets than the Noatak sites.

While soil pH is a good predictor of many variables that relate to overstory shrub biomass, it does not appear to be a good indicator of recent shrub expansion by itself. The lowest pH (and the highest shrub cover) were found in the non-expanding North Slope alder site, while the highest pH was found in willow parkland sites that showed no signs of recent shrub expansion by sexual reproduction. Recent shrub expansion, as inferred from either repeat photography (expanding

North Slope alder site) or the presence of saplings and small individuals (poplar, alder, and birch transects in the Noatak) was associated with soils of intermediate pH.

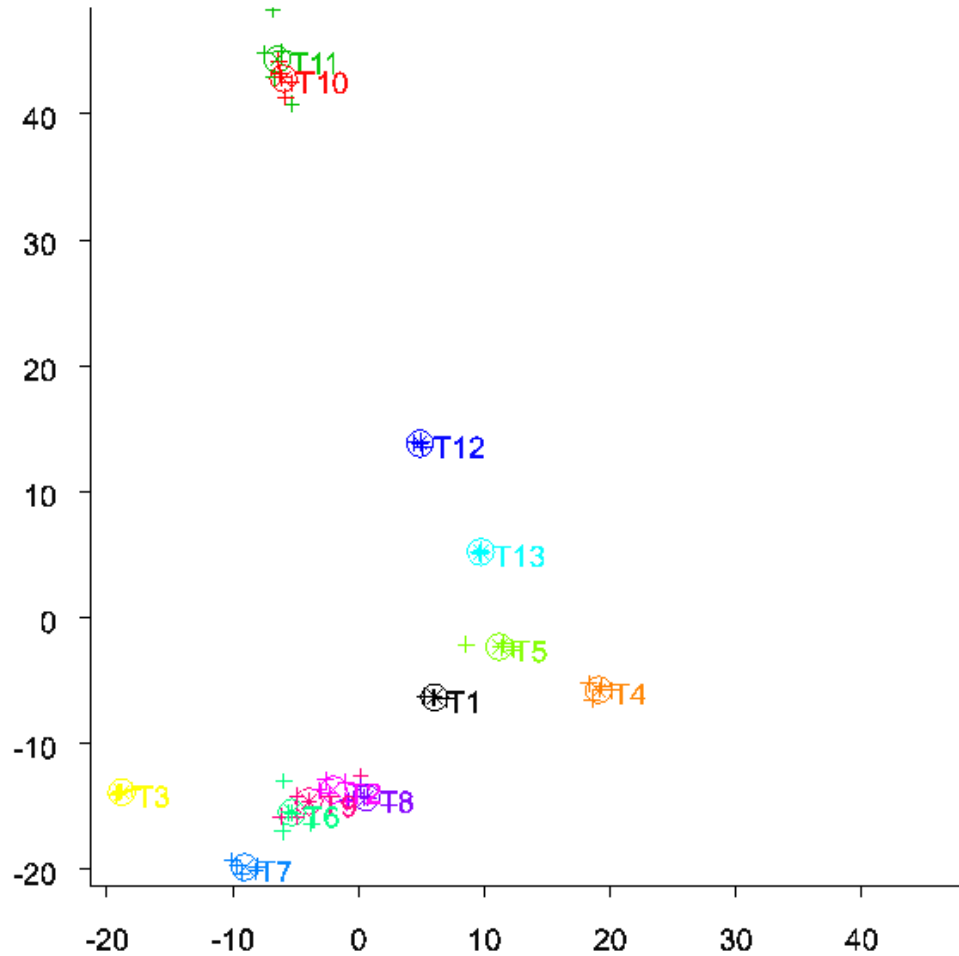


Figure 13. Ordination of understory vegetation composition by canonical variates, using transect as the grouping factor, and including all Noatak transects and 4 transects from two alder-dominated sites on the North Slope. Transect numbers 1-9 as in legend to Fig. 12, transects 10 and 11 were from the North Slope alder site where no expansion occurred in the past 50 years, while 12 and 13 were from the North Slope alder site where appreciable alder expansion occurred in the last 50 years. Symbols (+, X, circles) as in legend to Fig. 12.

Table 31. Statistical parameters from REML variance component analysis of vegetation and soil variables from Noatak and North Slope sites together, with transect as a random effect. Ndf, Ddf, F and P values are reported for nearly significant ($P \leq 0.1$) fixed effects only.

Dependent variable	Random effect	s.e.	Fixed effects	Effect	s.e.	Ndf	Ddf	F	P
Leaf area index	0.0411	0.0398	pH organic horizon	-0.22	0.077	1	15.3	8.61	0.010
Percent cover of overstory shrubs	30.7	22.4	pH organic horizon	-7.47	1.79	1	16.8	17.38	<0.001
Ramet density	53.5	48.3	pH organic horizon	-17.6	2.6	1	15.0	44.67	<0.001
Maximum ramet age	-15.5	16.7	pH organic horizon	-7.00	1.47	1	11.2	22.51	<0.001
Average ramet age	-1.10	8.57	pH organic horizon	-3.42	1.10	1	12.4	9.60	0.009
Soil C content mineral horizon	79.07	40.42	pH organic horizon	-6.08	2.19	1	27.5	7.67	0.010
			Average ramet age	-0.32	0.135	1	49.4	5.51	0.023
Soil C mass of organic horizon	5169661	2910447	Average ramet age	-82.1	42.5	1	53.7	3.72	0.059

Alder transects on the Noatak were associated with more disturbed soils (showing evidence of solifluction and cryoturbation) than the soils of other transects (birch, willow, or poplar). The soils at the expanding North Slope alder site also demonstrated signs of relatively recent solifluction, in contrast to soils at the non-expanding North Slope alder site. This suggests that soil disturbance may be an important factor mediating the expansion of shrub populations by seed reproduction, especially for alder. Soil disturbance opens up new sites for colonization by seedlings, and could improve access to mineral nutrients that limit plant growth, by exposing mineral soil and speeding up the decomposition of formerly buried organic matter. Shrub expansion in the Canadian Arctic has recently been strongly correlated with thermokarst development (T. Lantz, personal communication). Data collected by another NPS-sponsored inventory and monitoring project show that numerous thermokarst and solifluction events have occurred in the region around Feniak Lake in the upper Noatak River Basin since the 1980s (A. Balser, personal communication). Climate warming would be expected to increase rates of permafrost melt, leading to an increased frequency of thermokarst and solifluction events. Thus, increased soil disturbance may be an important indirect mechanism mediating the expansion of shrub populations as climate warms. While none of our transects were located in obvious areas of recent landscape disturbance, establishment of transects for monitoring vegetation in these areas is an important priority for the future.

Indicators for shrub effects on soil characteristics

In contrast to our initial expectation, there was no significant relationship between soil C content and any of our shrub variables that serve as proxies for shrub biomass, such as overstory shrub cover, ramet density, or LAI. The expansion of shrubs in graminoid-dominated ecosystems often leads to greater aboveground primary production and ecosystem carbon inputs across a wide-range of biomes, including arctic tundra (Knapp et al., 2008). However, effects of shrub expansion on carbon storage in soils can be negative or positive. There are several mechanisms by which plants can reduce soil carbon stores. First, plants can decrease soil moisture due to increased transpiration; this could speed up mineralization and reduce stored carbon in soils where decomposition is slow due to high moisture content. Second, plants can increase decomposition rates by stimulating soil substrate availability with inputs of soluble plant assimilates or litter that can be used by the microbial communities to break down recalcitrant soil organic matter. Third, plants can change soil chemistry to increase decomposition due to plant ion uptake patterns that negatively affect soil organic matter stability. On the other hand, increased plant litter production can lead to greater accumulation of soil organic matter when environmental factors constrain decomposition to a greater degree than can be offset by the vegetation-induced mechanisms mentioned above. Constraining environmental factors include moisture, temperature, pH, and time since disturbance. With respect to the latter, it is important to consider that soil organic matter represents a slow cycling carbon pool that is affected strongly by vegetation history, which can make changes over short periods of time hard to detect. Thus, in combination, it is not surprising that soil carbon dynamics across the locations investigated in this study in a comparative fashion, rather than in a time-series, appear somewhat uncoupled from shrub dynamics, because the controllers of shrub dynamics may be operating on a much shorter time scale than the controllers of soil C storage.

We did find that there was a negative relationship between average ramet age and soil C content, for both the mineral and organic soil horizons. This result must be interpreted with caution, because we sampled a very limited number of ramets from each location, and because we do not believe that ramet age as we measured it accurately reflects the total age of the individual shrubs. We did not cut down entire shrubs, as that would have been too destructive, and the ramet ages that we measured presumably reflect the aging and turnover of large branches, but not necessarily that of entire individual shrubs. Among the different vegetation types, ramets from the alder transects had a greater average age than ramets from the other transect types, while ramets from willow parkland and birch transects had lower average ages. This presumably reflects the more rapid turnover of willow branches compared to alder branches, although it is important to note that the sampled ramets on each transect came from a variety of species. As noted earlier, alder sites tended to have lower C storage than willow parkland transects, and greater evidence of recent soil disturbance. It is conceivable that, over time, alders may stimulate decomposition, through the positive feedback of their N-rich leaf litter. Decomposition is often limited by N

availability in cold tundra soils (e.g. Mack et al., 2004, Nowinski et al. 2008). In addition, with sufficiently long residence time, all of the canopy shrubs may reduce soil C storage through other mechanisms, such as those mentioned above, or the potential positive feedback to decomposition of increased winter soil temperature due to shrubs trapping more snow (Sturm et al., 2001). However, this potential mechanism seems at odds with our observations that the willow parkland sites, which had the greatest C storage, also had the most stable and oldest-appearing shrub populations and soils. To further evaluate and explore this relationship between ramet age and soil C, ramet age should be sampled more extensively in any future fieldwork.

Another reason for the noisy relationship between soil carbon and ramet age might come from the way we assessed soil carbon content and stock. We assessed carbon storage in the organic horizon from one sample only, taken at mid horizon depth, and assessed carbon content of the mineral horizon again from one sample only, taken from the top of the horizon. This protocol minimizes the number of samples as well as the sampling efforts (and was the only feasible one for the expedition format we used), and allows for least complicated re-sampling. However, it is also relatively insensitive for detecting very recent changes in organic matter storage in the organic horizon. This is because assessing carbon storage from mid-horizon samples assumes a systematic carbon content to depth relationship within the organic horizon, which would not be true if changes in carbon content initiated at the top of the horizon had not yet come into equilibrium with the entire horizon. Thus, recent changes at the top of the horizon would not be detected. Similarly, for the mineral horizon, our sampling method would not detect shrub-induced differences in the carbon content of deeper layers in the mineral soil.

Outlook for the future

Fieldwork in 2006 was successful in helping us to accomplish several important goals of the project, including the establishment of protocols and permanent transects for monitoring of vegetation and soils in areas dominated by shrubs. We also obtained high-resolution aerial photographs and GIS maps of the area that was studied. Our data analysis suggests that willow parklands are less likely to undergo shrub expansion by sexual reproduction than areas dominated by alder, poplar, or birch. Alder sites on the Noatak, in particular, appear to share some vegetation characteristics with sites on the North Slope where alder expansion is known to have occurred, including more evergreen ericaceous shrubs in the understory vegetation, and greater evidence of soil disturbance. It is possible that increased soil disturbance (solifluction, cryoturbation, thermokarst) due to climate change could mediate alder expansion. Although shrub expansion may affect soil C storage, the cover of canopy shrubs does not control soil C stocks across the range of landscape types that we sampled. Instead, soil pH and average ramet age appear to be important predictors of soil C, but high variance exists in the data. Soil pH predicts shrub cover and biomass, but not recent shrub reproduction from seed.

One limitation of our ground-truth data set is that it is relatively small. The data we collected are of high quality, but we need further replication and additional spatial data in order to establish an inventory and monitoring tool we can use to confidently determine the state of shrub expansion in arctic parks. Our ability to analyze the data statistically would be enhanced simply by having more transects in the Noatak Basin, particularly transects with a known history of shrub expansion or non-expansion. While we were able to make some useful comparisons with North Slope sites with known histories of alder expansion, the soils, vegetation and climatic setting of those sites are quite different from the montane sites in the Noatak Basin. It would improve our ability to develop predictive relationships if we were able to inventory shrub sites within the Noatak Basin where shrub expansion has been previously documented by repeat photography. Fortunately, several of these sites exist further west in the Noatak Basin (Hinzman et al., 2005, Tape et al., 2006).

Additionally shrubs may expand by sexual reproduction and dispersal, or by clonal growth. For sites of unknown expansion history, an understanding of the role of reproductive and dispersal method would aid in assessing possible future shrub expansion in the Noatak Basin. We have identified a collaboration with Vladimir Douhovnikoff (Simmons College) that will allow analysis of clonality using molecular markers (e.g. Douhovnikoff and Dodd, 2003; Douhovnikoff et al., 2005; 2007), which we would like to incorporate into fieldwork in the future.

Finally, if increased slope movement does mediate expansion of alder populations, it will be important to establish some vegetation monitoring transects in areas that have experienced recent soil disturbance due to solifluction or thermokarst. If possible, we would like to establish some transects in these types of areas during future fieldwork.

The biological mechanisms driving shrub expansion, and the susceptibility of different areas to this expansion, cannot be understood solely by remote sensing. Variables such as ramet age, the presence of shrub seedlings, fine-scale vegetation composition, and soil carbon storage must be measured on the ground. A combined approach that incorporates precise re-sampling of measurements of soil and vegetation characteristics on the ground, and that integrates these data with aerial photographs that include a bigger landscape, will be most effective over the long-term. The transects and protocols for study of vegetation and soils that we developed as part of this project, along with the aerial photographs and GIS-based maps, provide a long-term resource for monitoring future changes in vegetation in Gates of the Arctic National Park and Preserve and Noatak National Preserve. We trust that they will be useful to the Inventory and Monitoring Program of the Arctic Network, National Park Service.

References

- Beringer, J., Chapin F.S., III, Thompson, C.D., McGuire A.D. (2005): Surface energy exchanges along a tundra-forest transition and feedbacks to climate. *Agricultural and Forest Meteorology* 131: 143–161
- Bret-Harte, M.S., Shaver, G.R., Zoerner, J.P., Johnstone, J.F., Wagner, J.L., Chavez, A.S., Gunkelman, R.F. IV, Lippert, S.C., Laundre, J.A. (2001): Developmental plasticity allows *Betula nana* to dominate tundra subjected to an altered environment. *Ecology* 82: 18-32
- Cody, W.J. (1996) *Flora of the Yukon Territory* NRC Research Press, Ottawa, Ontario, Canada.
- Douhovnikoff, V. and Dodd, R.S. (2003) Intra-clonal variation and a similarity threshold for identification of clones: application to *Salix exigua* using AFLP molecular markers. *Theoretical and Applied Genetics* 106: 1307-1315.
- Douhovnikoff, V., Goldsmith, G.R., Huang, C., Bret-Harte, M.S. (2007): Genetic characterizations of clonality in expanding populations of arctic willow (*Salix* spp.) shrubs. Poster presentation at the Ecological Society of America annual meeting, August 2007.
- Douhovnikoff V., McBride J.R., Dodd, R.S. (2005): *Salix exigua* clonal growth and population dynamics in relation to disturbance regime variation. *Ecology* 86: 446-452.
- Edwards, M.E., Hamilton, T.D., Elias, S.A., Bigelow N.H., Krumhardt A.P. (2003): Interglacial extension of the boreal forest limit in the Noatak Valley, northwest Alaska: Evidence from an exhumed river-cut bluff and debris apron. *Arctic Antarctic and Alpine Research* 35, 460-468
- Epstein H.E., Beringer, J., Gould, W.A., Lloyd, A.H., Thompson, C.D., Chapin F.S., III, Michaelson, G.J., Ping, C.L., Rupp, T.S., Walker, D.A. (2004): The nature of spatial transitions in the Arctic. *Journal of Biogeography* 31: 1917-1933
- Hinzman, L.D., Bettez, N.D., Bolton, W.R., Chapin F.S., III, Dyurgerov, M.B., Fastie, C.L., Griffith, B., Hollister, R.D., Hope, A., Huntingdon, H.P., Jensen, A.M., Jia, G.J., Jorgensen, T., Kane, D.L., Klein, D.R., Kofinas, G., Lynch, A.H., Lloyd, A.H., McGuire, A.D., Nelson, F.E., Oechel, W.C., Osterkamp, T.E., Racine, C.H., Romanovsky, V.E., Stone, R.S., Stow, D.A., Sturm, M., Tweedie, C.E., Vourlitis, G.L., Walker, M.D., Walker, D.A., Webber, P.J., Welker, J.M., Winker, K.S., Yoshikawa, K. (2005): Evidence and implications of recent climate change in northern Alaska and other arctic regions. *Climatic Change* 72: 251-298.
- Hobbie, S.E., Gough, L., Shaver, G.R. (2005) Species compositional differences on different-aged glacial landscapes drive contrasting responses of tundra to nutrient addition. *Journal of Ecology* 93: 770-782.
- Knapp, A.K., Briggs, J.M., Collins, S.L., Archer, S.R., Bret-Harte, M.S., Ewers, B.E., Peters, D.P., Young, D.R., Shaver, G.R., Pendall, E., Cleary, M.B. (2008): Shrub encroachment in North American grasslands: shifts in growth form dominance rapidly alters control of ecosystem carbon inputs. *Global Change Biology* 14: 1-9, doi: 10.1111/j.1365-2486.2007.01512.x

- Lloyd, A.H. and Fastie, C.L. (2003): Recent changes in tree-line forest distribution and structure in interior Alaska. *Ecoscience* 10: 176-185.
- Mack, M.C., Schuur, E.A.G., Bret-Harte, M.S., Shaver, G.R., Chapin, F.S., III (2004): Ecosystem carbon storage in arctic tundra reduced by long-term nutrient fertilization. *Nature* 431: 440–443
- McFadden, J.P., Chapin, F.S., III, Hollinger, D.Y. (1998): Subgrid-scale variability in the surface energy balance of arctic tundra. *Journal of Geophysical Research*, 103-22: 28947–28961
- National Park Service (2006): Guidance for designing an integrated monitoring program. <http://science.nature.nps.gov/im/monitor/GoalsObjectives.cfm>
- Nowinski, N.S., Trumbore, S.E., Schuur, E.A.G., Mack, M.C., & Shaver, G.R. (2008) Nutrient addition prompts rapid destabilization of organic matter in an arctic tundra ecosystem. *Ecosystems*, **11**, 16-25.
- Patterson, H.D. and Thompson, R. (1971): Recovery of inter-block information when block sizes are unequal. *Biometrika* 58: 545-554.
- Raynolds, M.K., Comiso, J.C., Walker, D.A., Verbyla, D. (2007): Relationship between satellite-derived land surface temperatures, arctic vegetation types, and NDVI. *Remote Sensing of Environment*, in press (doi: 10.1016/j.rse.2007.09.008).
- Steltzer, H. (2004): Soil carbon sequestration with forest expansion in an arctic forest-tundra landscape. *Canadian Journal of Forest Research* 34: 1538-1542.
- Sturm, M., Douglas T., Racine, R., Liston, G.E. (2005): Changing snow and shrub conditions affect albedo with global implications. *Journal of Geophysical Research* 110: 1–13
- Sturm, M., Racine, C., and Tape, K. (2001): Increasing shrub abundance in the Arctic. *Nature*, 411: 546-547.
- Sturm, M., McFadden, J.P., Liston, G.E., Chapin, F.S., III, Racine, C.H., Holmgren, J. (2001): Snow-shrub interactions in Arctic tundra: a hypothesis with climatic implications. *Journal of Climate* 14: 336–344
- Tape, K., Sturm, M., Racine, C. (2006): The evidence for shrub expansion in northern Alaska and the pan-Arctic. *Global Change Biology* 12: 686–702.
- Walker, D.A., Binnian, E., Evans, B.M., Lederer, N.D., Nordstrand, E., Webber, P.J. (1989): Terrain, vegetation and landscape evolution of the R4D research site, Brooks Range Foothills, Alaska. *Holarctic Ecology* 12: 238-261.
- Walker, M.D., Walker, D.A., Auerbach, N.A. (1994): Plant communities of a tussock tundra landscape in the Brooks Range foothills, Alaska. *Journal of Vegetation Science* 5: 843-866
- Wilmking, M., Harden, J., Tape, K. (2006): Effect of tree line advance on carbon storage in NW Alaska. *Journal of Geophysical Research* 111: G02023

Wilmking, M., Juday, G.P., Barber, V.A., Zald, H.S.J. (2004): Recent climate warming forces contrasting growth responses of white spruce at tree-line in Alaska through temperature thresholds. *Global Change Biology* 10: 1724-1736.

Young, S.B. (1973): Vegetation of the Noatak Valley. In: Young, S. B. (ed.) *Biological Survey of the Noatak River Basin*. Wolcott, VT: The Center for Northern Studies: 11-24.

Appendix

All photographs are supplied on an accompanying CD. These include oblique photographs of the transects marked by red umbrellas, photographs taken at the end points of the transects, and photographs of the soil profiles, 1 x 1 m understory composition plots, and 6 x 6 m locations. The CD also includes the low-altitude aerial photographs taken in September 2006, that cover the larger area in which the transects were located.

Table 28. *Flight lines for low-altitude aerial photographs, and their locations.*

Airphoto Line	Transect(s) Covered	Start Point	End Point	No. of Frames	Individual Airphoto Frame Numbers	Nominal Direction	Base Ground Elevation	Airphoto Altitude
		Decimal ° NAD27	Decimal ° NAD27		file prefix is: “TT_0”		US feet	(Above Ground Level) US feet
1	1	67.615N 155.232W	67.592N 155.198W	7	710 – 716	W – E	2024’	5,000’
2	2	67.592N 155.436W	67.653N 155.372W	6	704 – 709	W – E	1807’	5,000’
3	4, 5	67.659N 155.671W	67.649N 155.606W	7	697 – 703	W – E	1955’	5,000’
4	6, 7	67.699N - 156.009W	67.702N - 155.976W	5	692 – 696	W – E	1965’	5,000’
5	8, 9	67.867N - 156.786W	67.864N - 156.732W	5	687 – 691	W – E	1420’	5,000’