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Soil productivity in the Arctic environments of Canada.

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Arctic regions are characterized by low temperatures and low precipitation. These conditions combine to create habitats where distinctive arctic plant communities develop. The generalized description of polar regions is usually based on broad vegetation and soil features, and further characterized by climatic parameters.

In Canada, the most northerly region is the High Arctic (Fig. 1), characterized by scant vegetation and little soil development (Fig. 2A), although local conditions combine to create considerable variations. In upland Polar Deserts, the plant cover is less than 10%, but up to 50% in Polar Semideserts (Bliss 1975). In many lowlands, sedge and grass communities form a nearly complete vegetation cover. The Low Arctic Region is characterized by closed vegetation cover formed by wet sedge-grass meadows and lichen-shrub communities on the better-drained areas. The Mid-Arctic Region is transitional between these two regions, with sedge-grass meadows in the lowlands and dwarf shrub-moss communities on the better-drained areas forming a 50-90% ground cover (Fig. 2B).

The Subarctic regions are characterized by the presence of trees occurring in open stands. In the High Subarctic Region, the trees are stunted, with lichen and mosses growing on the forest floor. In some areas such stunted, open forests occur as patches in treeless tundra, but in other areas the open forests dominate. Permafrost is

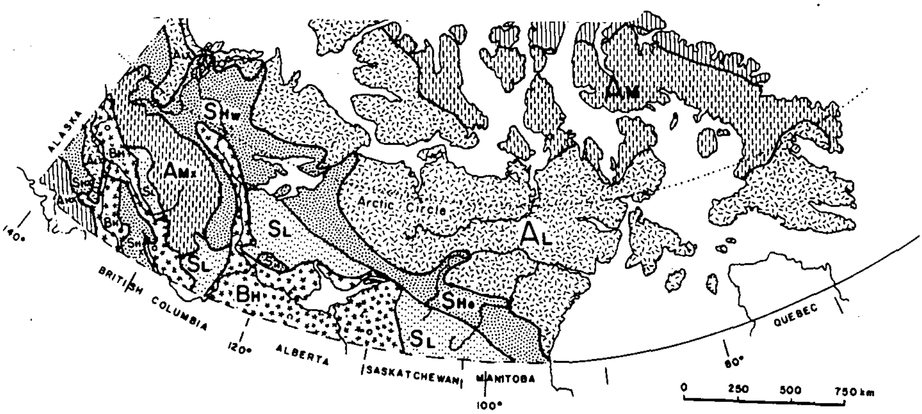

Figure 1. Ecological regions of northern Canada

A_H - High Arctic	A_{Hx} - High Alpine complex	S_H - High Subarctic
A_M - Mid-Arctic	A_{Mx} - Mid-Alpine complex	S_L - Low Subarctic
A_L - Low Arctic	A_{Lx} - Low Alpine complex	B_H - High Boreal

found within 1.5 m of the surface. In the Low Subarctic Region, the trees are taller, reaching heights over 5 m, but the stands are still open with many lichens and mosses on the ground. Although permafrost occurs within 1.5 m of the surface in most areas, it may be absent on coarse-grained soils or on hillsides exposed to the south. In the Boreal Region, tree crowns form a closed canopy. Permafrost is generally absent, except for discontinuous patches in some bogs.

The climate of the Arctic and Subarctic regions is cold, with short growing seasons. The climatic data along a north-south transect in Canada (Table 1) show a gradual warming southward and an increase in the frost-free season. Annual precipitation is very low in the north, but increases southward. Annual net radiation is from 5 to 15 kly in the Arctic, 16 to 19 kly in the Subarctic, and increasing to 28-31 kly at the northern limit of the Boreal forest (Hare and Ritchie 1972).

Table 1. Climatic data from selected northern Canadian weather stations (Atmospheric Environment Service 1975)

Region	Station	Mean annual temperature °C	Mean July temperature °C	Mean no. frost-free days	Annual precip. mm
High Arctic	Resolute	-16.4	4.3	44	136
Mid-Arctic	Spence Bay	-15.4	7.1	73	153
Low Arctic	Baker Lake	-12.3	10.7	60	213
High Subarctic	Ennadai Lake	-9.5	12.8	102	285
Low Subarctic	Brochet	-5.2	15.3	131	426
High Boreal	Wabowden	-2.2	16.8	139	466

PRODUCTIVITY

In natural ecosystems, the primary producers are plants that utilize the incoming energy to produce plant tissue. The rate at which the plant tissue production takes place is dependent on a number of factors in addition to solar radiation. These factors may be related to soil conditions and to the vegetation itself. Among the soil conditions, nutrients, soil texture and temperature, soil fauna and flora, and the availability of mositure are prominent. The presence of vegetation that is well-adapted to the local environment greatly enhances the rate of production. Portions of the produced plant material will decompose and hence be available for future growth. Animals may consume some of the plant materials and export them from the site of production. Much of the plant matter, however, will remain undecomposed under Arctic conditions as peat, either on the surface or mixed into the soil by cryoturbation.

Primary productivity can be estimated by measuring the plant biomass of aboveground standing crop. When production on a fully vegetated High Arctic meadow community (Table 2) is compared with graminoid vegetation of other northern regions, a similarity in the amount of the standing crop is apparent. Standing crop figures are much higher in wooded areas, where many years of growth are stored in the trunks and branches of trees.

Table 2. Primary productivity in various regions. Mean values of live and dead plant biomass of aboveground standing crop (g m^{-2})

Region	Plant community			Reference
High Arctic	Meadow	Semidesert	Desert	
	977	18	5	Wein & Rencz 1976
Low Arctic	Cottongrass	Meadow		
	532			Wein & Bliss 1973, 1974
		215		Dennis & Johnson 1970
		628		Shamurin *et al.* 1972
Low Alpine	Dwarf shrub	Meadow		
	475	527		Chepurko 1972
		570		Østbye 1974
High Subarctic	Open larch forest			
	2308			Ignatenko *et al.* 1972
Boreal Forest	Pine			
	10127			Foster & Morrison 1976
Prairie Grassland	Agropyron-Koeleria			
	724			Coupland *et al.* 1975

Standing cropsin a High Arctic meadow and in a semiarid Prairie grassland are similar (Table 2). However, decomposition is rapid in the grassland, where cellulose was 50% decomposed in 24 weeks (Coupland *et al.* 1975), but slow in the High Arctic meadow, where filter paper was only 17% decomposed after 2-1/2 growing seasons (Bliss 1975). The standing crop in the High Arctic meadow therefore includes growth that may be several years old, while much less dead plant matter is present in the Prairie grassland community.

Another measure of plant productivity is the annual net plant production, including the above- and belowground growth. There are vast differences in the net plant production in different ecosystems in the High Arctic Region (Table 3). This table also shows that the production at the most productive High Arctic site is in the same order of magnitude as the less productive ecosystems of more southerly regions. However, a comparison of net plant production on similar sites in different regions shows (Table 4) that the High Arctic meadow has a far lower rate of productivity than the more southerly graminoid wetlands. Furthermore, most of the net production in the High Arctic meadow was in the root system: 130 g m^{-2} yr^{-1} belowground and 50 g m^{-2} yr^{-2} aboveground (Bliss 1975). In the *Carex* wetland of the temperate region, the belowground production was 208 g m^{-2} yr^{-1}, whilst aboveground was 965 g m^{-2} yr^{-1} (Bernard and Solsky 1977).

SOIL-PLANT INTERRELATIONSHIPS

At a broad level of generalization, the different plant ecosystems in the Canadian High Arctic appear to be controlled by

Table 3. Annual net plant production in various regions. Mean values of yearly above- and belowground increment (g m^{-2} yr^{-1})

Region	Plant community			Reference
High Arctic	Meadow 232	Semidesert 54	Desert 7	Bliss 1975
Low Arctic		Meadow 260		Bunnell *et al.* 1974
Low Alpine	Wet meadow 837	Dry meadow 534	Lichen 276	Østbye 1974
Boreal forest (trees only)	Populus tremuloides Juvenile 474*	Mature 210*		Pollard 1972

* Includes an estimate of 20% for root growth (Pollard 1972)

Table 4. Annual net plant production in graminoid wetlands in various regions. Mean values of yearly above- and belowground (g m^{-2} yr^{-1})

Region	Production	Reference
High Arctic	280	Bliss 1975
Subalpine (maritime)	837 868	Østbye 1974 Heal et al. 1974
Temperate	1173	Bernard & Solsky 1977

elevation and, by inference, macroclimate. Graminoid tundra and dwarf shrub tundra occur generally in coastal lowlands, while Polar Semi-deserts occur from sea level to 100-200 m elevation. Polar Deserts are found at higher elevations (Bliss *et al.* 1973). A closer scrutiny reveals, however, that soil materials and profile development play a large role in the distribution of High Arctic ecosystems. On Somerset and Prince of Wales islands, fully vegetated tundra occurs in lowlands where soil materials were entirely or largely deposited by a postglacial marine inundation (Woo and Zoltai 1977). The finer soil texture and lowland topography provide better moisture conditions than prevail in the till-like materials of the surrounding areas. Chemical composition of marine sediments is also different from the till. Thus, the Scarp Brook Association, derived from till and local bedrock, is extremely calcareous ($CaCO_3$ equivalent up to 70%), while the marine sediments (Transition Bay and Garnier Bay Associations), occurring in small pockets in the till area, are less calcareous (12-45%, Woo and Zoltai 1977). The vegetation on the Scarp Brook Association is a Polar Desert, with less than 1% vascular plant cover, but the sediments are fully vegetated. Similarly, soil profile development on Scarp Brook

Association is negligible (Regosolic Turbic Cryosol). On the marine sediments, a structural B horizon is present, developing Orthic or Gleisolic Turbic Cryosols.

The mineral composition of soil materials derived from till and local bedrock mixture greatly influences the vegetation. On Somerset and Prince of Wales islands, the proportion of surface covered by vegetation can be related to the carbonate content, and especially to the calcite content of the parent materials. Soils with the lower calcite content (1-15%) had a more complete vegetation cover (30-100%) and were therefore Polar Semideserts than soils with high (26%) calcite content, where Polar Deserts are common (Woo and Zoltai 1977).

Soil nutrient status is extremely important in determining its productivity. Throughout the Canadian Arctic well vegetated spots develop in the Polar Desert around lemming burrows, wolf and fox dens, skeletal remains of animals, rocks serving as fox stations or bird perches, and old Inuit habitations (Fig. 3A). Such sites are marked by vigorously growing vegetation (Babb and Bliss 1974, Batzli 1975). On Somerset Island the top 10 cm of the soil at a fox stop (Fig. 3B) was analyzed both outside and inside the enriched area (Woo and Zoltai 1977). The soils were extremely calcareous (66-76% carbonate equivalents) with pH of 8.0. The available phosphorus was 108.8 ppm in the enriched area, as compared with 2.5 ppm outside. Similarly, nitrate nitrogen was 7.8 ppm inside and only 0.9 ppm outside the enriched area in the Polar Desert.

Many such enriched spots occur on excessively drained ridges or along scarps that are exposed to wind. This eliminates sheltering or increased moisture from seepage or snow beds as the reason for lush vegetation growth. The lushness of the vegetation at such spots substantiates observations that plant production in the High Arctic is largely limited by lack of nutrients (Bliss 1971; Savile 1972) rather than lack of moisture.

The effect of local enrichment can be long lasting under some circumstances. Lush vegetation was found around old whalebones about 20 m above the present sea level on the east coast of Somerset Island. The rate of uplift following deglaciation of the High Arctic indicates that the sea level stood at this elevation some 5000-6000 years ago (Dyke 1974). On other parts of Somerset Island old muskox skulls were found surrounded by well-vegetated patches. Muskoxen were exterminated on this island by whalers around the turn of the century (Russell and Edmonds 1977), at least 75 years ago. These examples indicate that the extraneous nutrients may be recycled through several generations of plants, with only small losses.

Soil enrichment and consequent change in the vegetation can induce further changes in nutrient-poor soils. An abandoned wolf den was found on a small kame in the Low Arctic, near Tha-Anne River. The soil material was acid (pH 4.1) sand and gravel, derived from Precambrian granite. The vegetation consisted of a continuous carpet of a dwarf (less than 5 cm high) ericaceous shrubs and lichens. Around the wolf den near the summit of the hill, however, a tall (up to 50 cm), dense

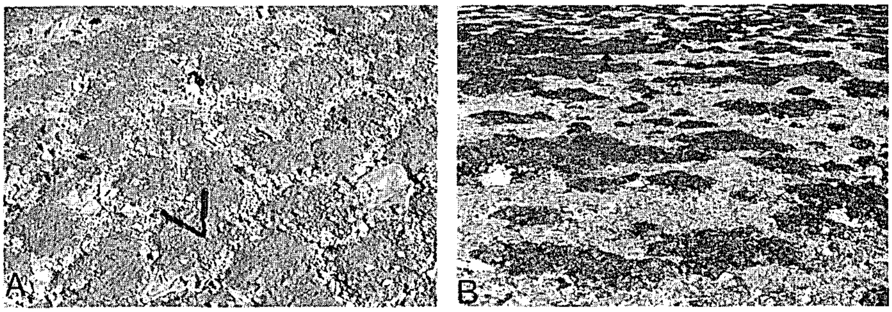

Figure 2. A - Almost bare surface of Polar desert in the High Arctic
B - Sparse vegetation cover in the Polar Semidesert of the Mid-Arctic

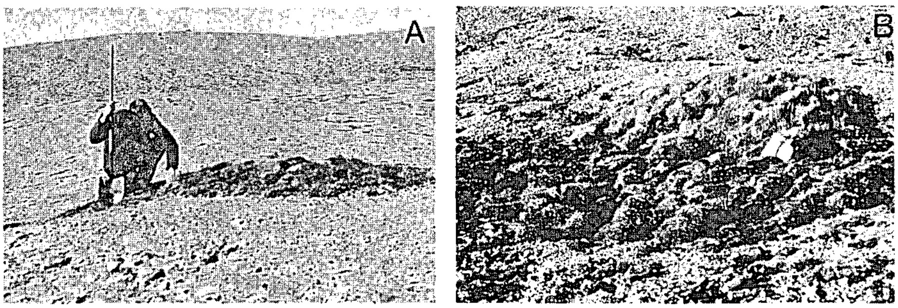

Figure 3. A - Vegetated spot around a bird perch in the Polar Desert
B - Vegetated fox stop in the Polar Desert; site of soil analyses

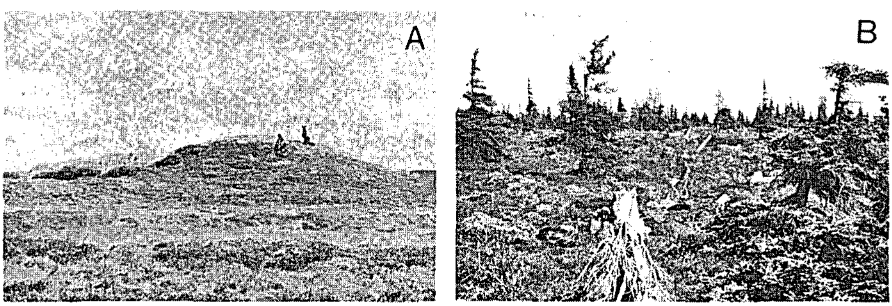

Figure 4. A - Kame in the Low Arctic tundra, with tall grass over wolf den
B - Stumps of trees cut about 75 years ago in the High Subarctic

stand of polar grass (*Arctagrostis latifolia*) grew (Fig. 4A). Excavation showed that a 25 cm layer of humus-rich material covered the original Brunisolic Static Cryosol profile; this material was the spoil excavated from the den and contained a few caribou bones. The humus-rich material was absent from the undisturbed part of the kame. Permafrost was 28 cm from the surface under the grass, but 75 cm under the dwarf shrub-lichen cover, only 1 m away. It appears that the increased nutrient status allowed the thick growth of grass to eventually insulate the soil with mulchlike accumulation of dead leaves and stems and prevent the deep thawing of the soil. The lushness of the vegetation on the enriched area indicates that the effect of added nutrients far outweighed the effect of induced colder soil temperatures.

PRODUCTIVITY AND MAN

Primary productivity in the Arctic and Subarctic regions is inherently low and plant production potentially useable by man is lower still. Berries such as *Vaccinium uliginosum* (bilberry), *V. vitis-idaea* (cranberry), and *Rubus chamaemorus* (baked-apple berry) growing in the Subarctic and Low Arctic were utilized in the diet of aboriginal peoples (Porsild 1964), but present-day consumption is not known.

Trees growing in the Subarctic regions and driftwood carried northward by rivers were extensively utilized for construction and fuel by the aboriginal population. Even the short (3-4 m), excessively tapering trees of the High Subarctic were harvested, as shown by stumps found in the Henik Lake area of central Canada (Fig. 4B). The condition of the stumps suggested that the trees had been cut in the winter some 80 to 100 years ago. The timber was probably transported by sleds to the nearest settlement at Padlei across two watersheds, some 50 km distant. The present use of trees is far more limited, as construction materials and fuels are usually imported from the south.

Most of the harvestable products of the north are derived from animals feeding on the primary producers. Animals, feeding on large areas, are concentrating in their own tissues the energy and organic matter produced by the scattered, slow growing vegetation. Herbivores such as caribou, moose, muskox and snow geese have been the staple food of native people of the Arctic and Subarctic regions in the past. Although the monetary value of country food is difficult to estimate, it accounts for a major source of protein in the diet of the present inhabitants of the north (Usher 1976). Reindeer herding, a long established practice in northern Europe and Asia, is pursued in the Low Arctic of Canada on a very modest scale, with the number of animals ranging between 2000 and 9000 (Scotter 1972). Fur-bearing animals such as muskrat, white fox, and beaver contribute significantly to the economy of northern regions. On Banks Island in the Low Arctic Region, the mean catch of white fox per man year was 183 animals during 1928-1967 (Usher 1970). This provided an income for the trappers that was equal to the average national wage.

Management for red meat production may offer prospects for the future. Caribou are better adapted to North American conditions than reindeer and may have the same potential for domestication as reindeer (Scotter and Telfer 1975). Muskoxen are now largely restricted to the Arctic regions, but indications are that they ranged well into the Subarctic regions until the late 19th Century (Burch 1977). Caribou and muskoxen may be produced in the same area, as they utilize different habitats, and hence interspecific competition for food is minimal (Russell and Edmonds 1977).

The ultimate limit on game management is the primary productivity of the ecosystem. Determination of the carrying capacity of rangelands is very difficult, especially when distinctive summer and winter ranges are involved (Scotter and Telfer 1975). Thus the caribou of Prince of Wales and Somerset islands comprise a single population, as the majority winters on Somerset Island and summers on the neighbouring Prince of Wales Island. Summer ranges are essentially unlimited, but the availability of winter range is critical for the maintenance of the herd (Russell and Edmonds 1977). Management practices therefore should concentrate on improving the critical habitats after determining whether food, its availability, shelter, deep snow, or a number of other biotic, topographic, or climatic factors control the survival of game populations.

Increased utilization of northern areas will cause a great impact on the northern environment. Certain attributes of the plants and terrain make this region particularly vulnerable to the interference by man. Much has been said about the fragility of the Arctic ecosystems (Bliss *et al.* 1973), manifested in the length of time required for a return to a steady state following a disturbance of plant communities or the terrain. In a study of *Luzula*, an arctic rush (Addison 1977), it was found that the plants were 110 years old. The plants spread by tillers from subsurface rhizomes, but no seedlings were found, nor were seeds produced during the 3 years of study. It is implied that seed production and seedling establishment by this and possibly other species growing at the northern limit of their range is sporadic. Possibly several years of favorable weather conditions are necessary for reproduction by seed: a season for the storage of plant nutrients and setting the reproductive primordia, production of seeds the following year, and establishment of seedlings in the third season (Addison, personal communication).

Another aspect of the northern environment that contributes to their sensitivity to disturbance is the presence of icy layers in the near-surface permafrost (Mackay 1970). This is especially prevalent in the Subarctic and Low Arctic regions where the vegetative mat serves as insulation and prevents the deep thawing of the soil. When a disturbance such as forest fire, or vehicular traffic, bulldozing, etc. destroys or disrupts the insulating layer, the permafrost table drops, and the moisture held in the permafrost is released. Under some circumstances this initiates the thawing of thick icy beds, releasing large quantities of water and mud (Fig. 5A). If the water released by thawing can drain by seepage, the ground surface subsides, creating uneven, karstlike topography (Fig. 5B). If the water cannot escape, it collects in depressions, forming permanent ponds. This process, thermokarst development, can substantially change the soil surface for many years (Mackay 1970, French 1975). In the High Arctic where little insulation is provided by the thin vegetation layer, thermokarst development is a

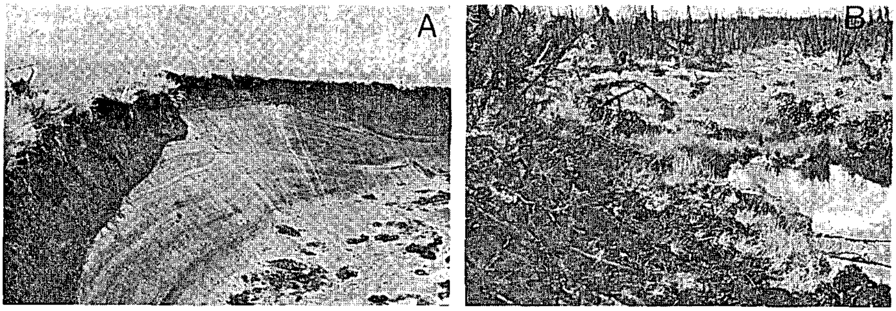

Figure 5. A - Highly icy subsoil exposed after fire in the High Subarctic
B - Subsided surface on winter road in the Low Subarctic

relatively minor problem (Babb and Bliss 1974). In all areas, the rehabilitation of the surface is a long process. In forested areas, if the subsidence did not result in a water-filled depression, the vegetation and permafrost conditions are restored within about 100 years (Zoltai 1975). On more severely altered sites, recovery is far slower, especially if the raw subsoil was exposed by thermal erosion.

The low productivity of the arctic ecosystem and the slow recovery rates from disturbances combine to impose extreme caution in exploiting the renewable natural resources. Although the use of such resources may be possible by range and game management, such programs must be undertaken with a full knowledge of the intricate interactions among the soil, vegetation, and fauna of these regions, for mistakes heal very slowly.

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SUMMARY

Primary productivity of the Arctic and Subarctic regions of Canada is low, due to servere climatic conditions and nutrient-poor soils. Harvestable products of the land are mainly the meat and furs of wild animals. Game and range management practices may ensure a continuing flow of renewable resource products. However, any increased development of the north should consider the very slow rehabilitation rate of disturbed soils and vegetation.

RÉSUMÉ

La productivité primaire des régions de l'arctique et du subarctique au Canada est faible à cause de la rigueur du climat et de la faible teneur des sols en éléments nutritifs. Les principaux produits de la région sont la viande et la fourrure des animaux sauvages. L'aménagement des parcours et du gibier peut garantir un écoulement continuel de produits provenant des ressources renouvelables. Toutefois, toute intensification de la mise en valeur du nord devra tenir compte de la très faible vitesse de rétablissement des sols et de la végétation, une fois qu'ils ont été perturbés.

ZUSAMMENFASSUNG

Aufgrund der strengen Witterungsverhältnisse und des niedrigen Nährstoffgehalts des Bodens ist die primäre Ertragsfähigkeit der arktischen und subarktischen Gebiete Kanadas gering. Die wichtigsten erntefähigen Güter sind das Fleisch und die Felle wilder Tiere. Geeignete Methoden zur Bewirtschaftung des Wildbestandes und des Weidelandes können eine stete Produktion aus erneuerbaren Quellen gewährleisten. Jede intensivierte Entwicklung der Nordgebiete sollte jedoch die äußerst langsame Rehabilitierung gestörter Böden und Vegetationen berücksichtigen.