Section 2

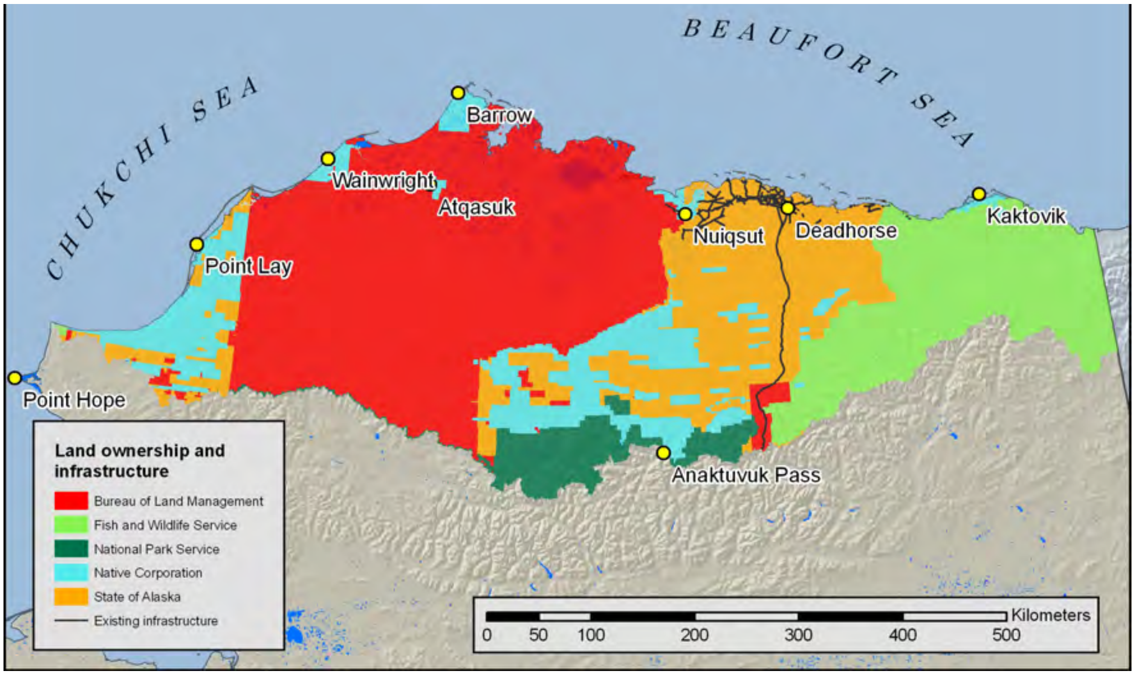
North Slope Ecoregions and Climate Scenarios

North Slope Ecoregions

The geographic/ecological scope of the workshop will be freshwater and terrestrial systems of the North Slope of Alaska, with a focus on the Arctic Coastal Plain and Foothills ecoregions. Montane areas and nearshore marine waters will also be included where there is an essential ecological or physical tie (e.g., glacial input of water into North Slope river systems; nearshore lagoons used by anadromous fish and molting/migrating water birds).

The North Slope covers approximately 204,000 km^2 of Alaska's arctic lands. Human population within the region is about 7,000 residents (2004 census), with activity and infrastructure concentrated within 6 small communities and the widespread industrial zone with a hub at Deadhorse. Land management and ownership is split among seven major entities (Figure 2.1). The Bureau of Land Management (Department of the Interior [DOI]) is responsible for management of a large portion for region—nearly 45% or the total area or roughly 91,000 km^2. The State of Alaska is the second largest landowner, responsible for 41,000 km^2 (20%). Fish and Wildlife Service (DOI) lands account for approximately 35,000 km^2 (17%), and Native lands encompass about 26,000 km^2 (13%). The remaining lands are held by the National Park Service (DOI), private owners, and the Department of Defense.

Figure 2.1. Land ownership and location of human infrastructure, Alaska North Slope.



The North Slope is divided into three ecoregions: Arctic Coastal Plain, Arctic Foothills, and Brooks Range (Figure 2.2). Information for each ecoregion is derived from the Circumpolar Arctic Vegetation Map (CAVM) Team (2003) and Gallant et al. (1995).

Arctic Coastal Plain

The 50,000 km^2 Arctic Coastal Plain is the northernmost ecoregion in Alaska. The Coastal Plain is bounded on the west and north by the Chukchi and Beaufort seas and extends east nearly to the U.S.-Canada border. The region is underlain by thick permafrost, up to 660 m deep (at Prudhoe Bay). Permafrost-related surface features, such as pingos, ice-wedge polygons, oriented lakes, peat ridges, and frost boils, are common. The major vegetation communities on the Coastal Plain are:

- nontussock sedge, dwarf-shrub, moss tundra;
- tussock-sedge, dwarf-shrub, moss tundra;
- sedge/grass, moss wetland; and
- sedge, moss, dwarf-shrub wetland.

The Arctic Coastal Plain contains a large portion, roughly 22%, of all the sedge, moss, dwarf-shrub wetland habitat mapped by the CAVM Team (2003). Most major streams originate from other ecoregions in the south. Streams west of the Colville River are interconnected with lakes and tend to be sluggish and meandering while those east of the Colville River are braided and build deltas in the Arctic Ocean. Most of the smaller streams dry up or freeze during winter.

Arctic Foothills

The Arctic Foothills is a 96,000 km^2 band of rolling hills and plateaus that grades from the Coastal Plain to the Brooks Range. The Foothills stretch from the Chukchi Sea on the west to the U.S-Canada border on the east. The ecoregion is underlain by permafrost, and permafrost-related surface features are common on the landscape. Vegetation communities in the Arctic Foothills are described as:

- nontussock sedge, dwarf-shrub, moss tundra;
- tussock-sedge, dwarf-shrub, moss tundra;
- erect dwarf-shrub tundra;
- low-shrub tundra;
- sedge, moss, dwarf-shrub wetland; and
- sedge, moss, low-shrub wetland.

The ecoregion also contains both noncarbonate and carbonate mountain complexes. The Arctic Foothills represent a large portion, roughly 16.8%, of all the tussock-sedge, dwarf-shrub, moss tundra mapped by the CAVM Team. The Foothills have better defined drainage networks than the Arctic Coastal Plain. Most streams tend to be swift, but portions may be braided and smaller streams dry up or freeze during winter. Flooding and channel shifting is common during breakup of river ice. Oxbow lakes, located along major streams, are the predominant type of lake in the region.

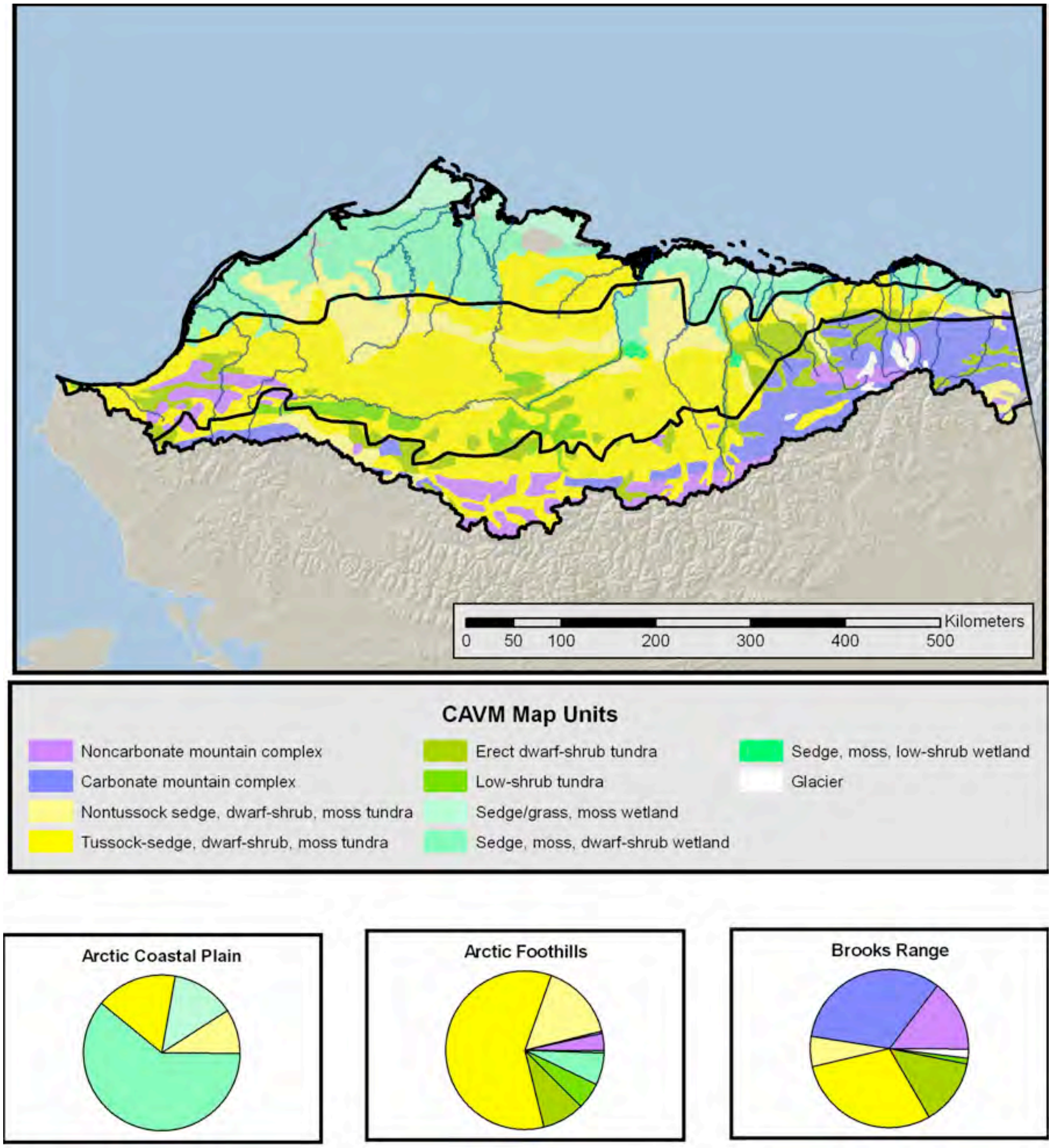
Brooks Range

The Brooks Range is the Alaskan extension of the Rocky Mountains, of which 58,000 km^2 lies north of the continental divide. The ecoregion covers most of the east-west extent of Alaska—from the U.S.-Canada border to within 100 km of the Chukchi Sea. In contrast to the Arctic Coastal Plain and Arctic Foothills, this ecoregion was extensively glaciated during the Pleistocene epoch. However, only a few scattered glaciers still persist. The terrain is dominated by steep, rugged mountain complexes, and continuous permafrost underlies the region. The combination of harsh climate, shallow soils, and highly erodible slopes result in sparse vegetation cover that is generally limited to valleys and lower hill slopes. Those vegetation communities present are described as:

- nontussock sedge, dwarf-shrub, moss tundra;
- tussock-sedge, dwarf-shrub, moss tundra;
- erect dwarf-shrub tundra; and
- low-shrub tundra.

In general, the ecoregion has few lakes. These lakes tend to occur in rock basins at the mouths of large glaciated valleys, in areas of ground and terminal moraines, and on floodplains of major rivers. Streams in the Brooks Range often have braided drainage patterns.

Figure 2.2 Vegetation of arctic Alaska based on the Circumpolar Arctic Vegetation Map (CAVM).



The North Slope of Alaska contains approximately 26% of all of sedge, moss, dwarf-shrub wetlands and 24% of all tussock-sedge, dwarf-shrub, moss tundra habitats present in the circumpolar region.

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CAVM Team. 2003. Circumpolar Arctic Vegetation Map. Scale 1:7,500,000. Conservation of Arctic Flora and Fauna (CAFF) Map No. 1. U.S. Fish and Wildlife Service, Anchorage, Alaska.

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Climate Scenarios

For the purpose of discussion, the workshop will consider two provisional climate change scenarios, consistent with projections based on a composite of the five best-performing General Circulation Models for the Arctic (Walsh et al 2008, http://www.snap.uaf.edu/about), based on the IPCC A1B scenario (IPCC 2007), an intermediate emissions scenario that assumes a steady increase in CO_2 emissions for several decades, followed by a gradual decline as more efficient technologies are implemented. Model outputs were applied to a baseline dataset consisting of a 2-km resolution PRISM (Parameter-elevation Regressions on Independent Slopes Model) grid of mean monthly temperature and precipitation data for the period 1961–1990. This effectively "down-scaled" the GCM output to a 2-km resolution. There is considerable uncertainty associated with the point estimates for projected temperature and precipitation, deriving from both within- and among-model variation.

Projected average temperature and precipitation values (The Wilderness Society, unpublished) for the decade 2075–2084 are presented in Table 2.1. Climate scenario II is most consistent with these projections. Although precipitation is forecast to increase, there is considerable uncertainty associated with this prediction, and therefore we have chosen to also consider Scenario I, in which precipitation remains constant.

I. Warming Temperatures, Precipitation Constant

Mean annual temperatures increase 5–6 °C by the year 2080. Warming is more pronounced in winter (7.6–8.6 °C) than in summer (2.5–2.9 °C), with the range representing variation among ecoregions. Growing season length is expected to increase at a rate of 1.3, 2.4, and 3.0 days per decade for the northern Brooks Range, Arctic Foothills, and Arctic Coastal Plain, respectively, with a skew toward greater change in the fall (Table 2.2).

II. Warming Temperatures, Precipitation Increase

Mean annual temperatures increase 5–6 °C by the year 2080. Warming is more pronounced in winter (7.6–8.6 °C) than in summer (2.5–2.9 °C), with the range representing variation among ecoregions. Mean annual precipitation increases by 22%, 35%, and 43% for the northern Brooks Range, Arctic Foothills, and Arctic Coastal Plain, respectively. Precipitation increase is more pronounced in winter (31–60%) than in summer (16–30%), with the range representing among-ecoregion variation that mirrors the pattern for annual precipitation. Change in growing season as in the above scenario.

Table 2.1. Projected magnitude of change from historic[1] values for temperature and precipitation, Year 2080, by ecoregion and season[2].

Ecoregion	**Temperature (Δ °C)**		
	Winter	Summer	Annual
Arctic Coastal Plain	8.6	2.5	6.1
Arctic Foothills	8.1	2.8	5.9
N. Brooks Range	7.6	2.9	5.6
	Precipitation (% increase)		
	Winter	Summer	Annual
Arctic Coastal Plain	60	30	43
Arctic Foothills	45	27	35
N. Brooks Range	31	16	22

1. Baseline temperature and precipitation values are based on the Parameter-Elevation Regression on Independent Slopes Model (PRISM) dataset created by the PRISM Group (Oregon State University, www.prism.oregonstate.edu). These data consist of 12 gridded mean maximum temperature, mean minimum temperature, and total precipitation files at 2-km resolution, one for each month averaged over 1961–1990 for the state of Alaska. This dataset was created using observational data from weather stations across the state and spatially interpolated over Alaska using weighted regression incorporating elevation and terrain effects on climate (Daly et al. 2002, Simpson et al. 2005). We averaged the minimum and maximum temperature grids together to create a dataset of mean monthly temperatures.

2. Summer (growing-season) is calculated as the average of May through September. Winter is calculated as the average of October through March.

Table 2.2. Modeled change in growing season, from 2010 to 2080, rounded to nearest day.

Ecoregion	Growing Season Length	Advance in First Date Above Freezing (Spring)	Delay in First Date Below Freezing (Fall)
Arctic Coastal Plain	21	5	16
Arctic Foothills	17	6	11
N. Brooks Range	15	6	9

References

IPCC. 2007. http://www.ipcc.ch/ipccreports/ar4-syr.htm

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Section 3
Hydrology

Hydrologic processes will play a pivotal role in directing climate-influenced habitat change. This section illustrates the processes that determine overall water balance and seasonal fluxes and features typical of arctic environments. Figure 3.1 is a generalized representation of the current condition (baseline). Specific features of the illustration are labeled and keyed to the accompanying text. Figure 3.2 and accompanying text outlines the changes expected under a scenario of rising temperature. Figure 3.3 and accompanying text outlines changes expected under a scenario of increased temperature and precipitation. Predicted change can be interpreted in the figures by comparing baseline condition (grayed out) with predicted (white for snow, blue for surface storage).

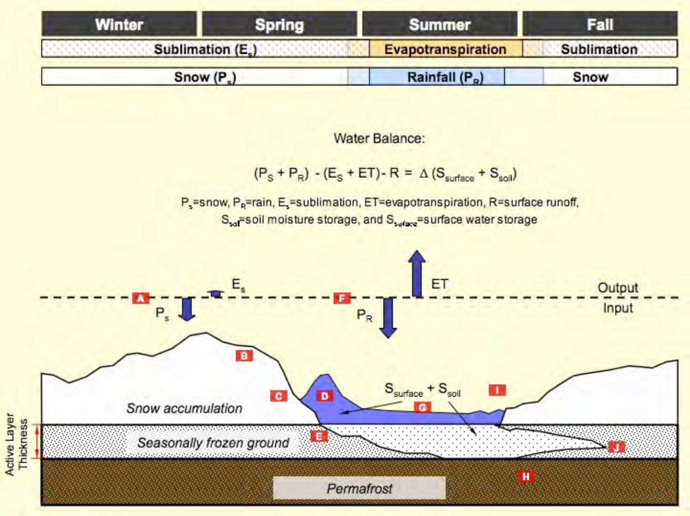


Figure 3.1. Baseline hydrological conditions.

Note: Figures 3.1–3.3 are reproduced in larger size on the following pages.

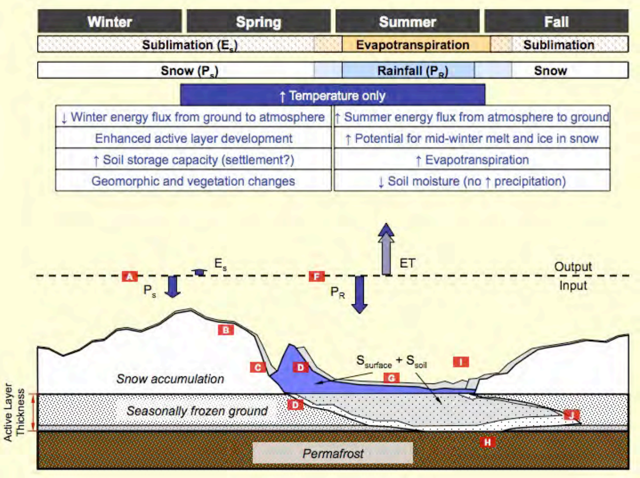


Figure 3.2. Hydrological changes expected under Scenario I (increased temperature).

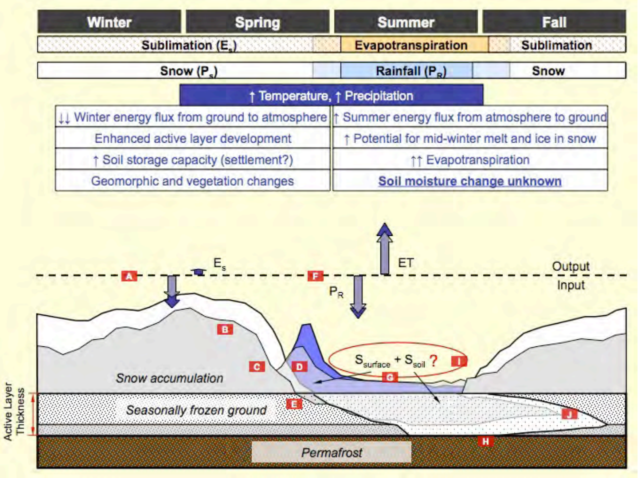


Figure 3.3. Hydrological changes expected under Scenario II (increased temperature and increased precipitation).

Baseline Case (Current Condition)

A) Winter precipitation less sublimation (PS-ES)

During the cold season, precipitation falls as snow and is temporarily stored in the snow pack at the ground surface. During the winter months, the surface energy balance yields a net loss of energy from the ground to the atmosphere, thus lowering soil temperatures. Snow cover, and snow depth in particular, helps to insulate the underlying ground surface from the cold winter temperatures. Therefore, with all else being equal, increasing snow accumulation would lead to higher surface soil temperatures, and decreasing snow accumulation will lead to lower surface soil temperatures. Snow accumulation is reduced to some extent by sublimation (water changing from the solid to gaseous state). Snowfall represents approximately 40% of annual North Slope precipitation.

Occasionally, air temperature will rise sufficiently to cause mid-winter snow melt. The resulting liquid water then moves downward in the snow pack before refreezing as an ice layer.

B) End-of-winter snow water equivalent (SWE)

The winter snow pack represents an effective seasonal surface water storage reservoir. Precipitation falling during this season, minus sublimation losses, remains in storage until the spring freshet when it is released. Consequently, the water stored in the snow pack at the end of winter is an important hydrologic quantity and is referred to as the end-of-winter snow water equivalent (SWE).

C) Spring snow ablation

During spring, the snow pack that developed over the course of the previous winter melts in a short period of time. Snow ablation (depletion via melting and evaporation) typically occurs within a one to two week period. During the melt period, incoming energy from the atmosphere leads to increasing snow temperatures. Once the snow pack reaches the freezing point, it becomes isothermal, and additional energy input is stored as latent heat associated with the water phase change from solid to liquid form. Once ablation is complete and the ground surface is no longer covered with snow, surface soil temperatures begin to increase. In addition, the loss of snow cover leads to a sudden and dramatic decrease of surface albedo that leads to more rapid warming and greater positive net energy flux at the surface.

D) Spring water storage and runoff

Water released from the snow pack during spring melt saturates surface soils, recharges local lakes, ponds, and emergent wetlands, and runs off the surface into streams. Shortly following ablation, streamflow rises sharply and then gradually recedes over the subsequent few weeks. Although much of the snowmelt drains into the Arctic Ocean, a considerable portion is at the surface in the form of lakes, wetlands, and soil moisture. Over the course of a few weeks following peak streamflow, the inundated land surface area, and thus surface water storage, rapidly decreases. This is largely due to lake and wetland drainage down slope until water surface elevations fall below their outlets. Surface water begins to infiltrate into the soil column as soil storage capacity increases with thaw and at the same time, surface and soil-stored water is lost to the atmosphere through evapotranspiration.

E) Soil thaw

Loss of snow cover and increasing energy flux from the atmosphere to the land surface causes thawing of surface soils. As soils thaw they become much more permeable. Consequently, water can more readily enter the soil column and drain vertically and laterally.

F) Summer precipitation less evapotranspiration (PR-ET)

During the warm season (average temperatures above 0 °C), precipitation occurs in the form of rain and condensation. The energy flux from the atmosphere to the ground during late spring and early summer is at its maximum and represents a net gain of energy for the ground surface. Unlike winter sublimation, the loss of surface moisture to the atmosphere is very close to precipitation inputs.

G) Summer water storage

During the summer months, rainfall and condensation tend to be equal or less than evapotranspiration. Therefore, there is a gradual drying of wetlands and soils that received snow melt recharge in the spring.

H) Active layer thickness (ALT)

The top portion of the soil column that thaws during the summer season is referred to as the active layer. The maximum depth to which the ground thaws is called the active layer thickness (ALT), and the lower extent of the active layer is defined by the permafrost table. The active layer plays a paramount role in hydrologic response as depth of thaw is directly related to the maximum soil water storage capacity.

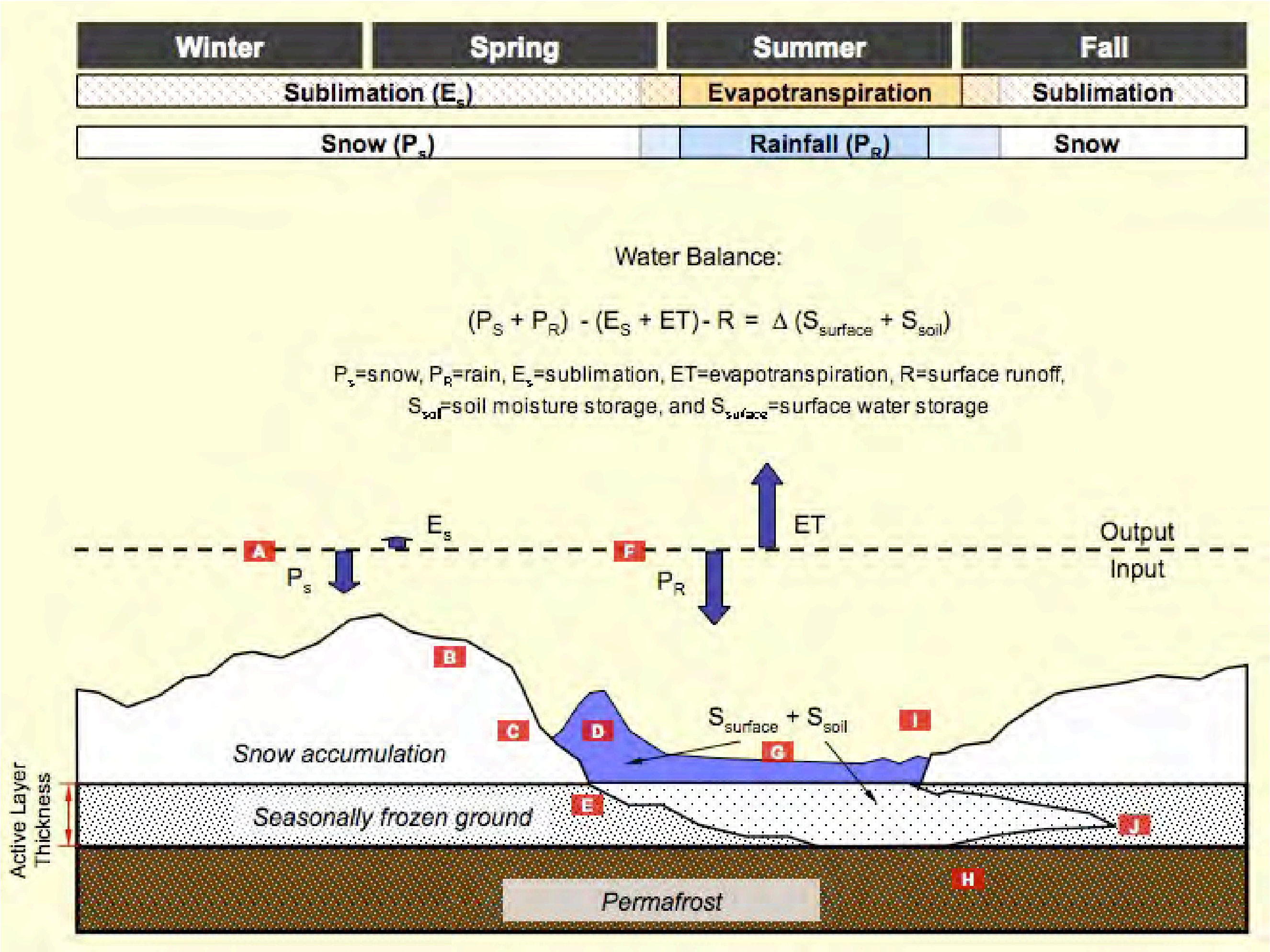
I) End-of-summer water storage

Late summer water storage is a function of total available basin storage (surface + soil), the sign and magnitude of PR-ET, and topographic gradients. The coastal plain is dominated by surface storage effects, while the foothills are more influenced by topographic gradients. As depicted in feature (G), surface water storage gradually decreases throughout the summer months. Although there is some summer recharge from storms, it tends to be minor, and end-of-summer surface storage is considerably below the maximum storage capacity. During the following spring, snowmelt will again recharge the surface storage.

J) Soil freeze-back

In early fall, surface soils begin to cool and eventually reach the freezing point. Between mid and late fall, the active layer undergoes freeze-back, primarily at the surface but also at the interface with the permafrost table.

Figure 3.1. Baseline hydrological conditions.



Future Scenario I: Increased Temperature Only

A) Winter precipitation less sublimation (PS-ES)

Assuming no change in precipitation, there would be little change in snow minus sublimation. Changes in sublimation will likely be small.

Increasing temperatures, particularly in late fall and early winter may lead to increased frequency of mid-winter snow melt, rain on snow events, and ice formation.

B) End-of-winter snow water equivalent (SWE)

As with feature (A), the change in sublimation will be small, and end-of-winter SWE will change little.

C) Spring snow ablation

Increasing winter and spring temperatures will lead to earlier and more rapid snow ablation. However, changes in cloudiness may either enhance snow ablation (e.g., reduced cloudiness results in higher short wave radiation at the surface) or retard ablation (e.g., increased cloudiness reduces short wave radiation at the surface).

D) Spring water storage and runoff

Earlier snow melt will lead to earlier surface storage recharge and peak streamflow. If it is assumed that snow melt rate changes are only minor, then peak flows and inundated areas can be expected to be similar during the initial runoff response.

E) Soil thaw

Surface soils begin to thaw following the end of snow cover. Earlier loss of snow cover will, therefore, lead to earlier onset of active layer thawing.

F) Summer precipitation less evapotranspiration (PR-ET)

Increasing air temperature will lead to increases in potential evapotranspiration (PET), which is a function of the energy available to drive evapotranspiration. PET is the rate of evapotranspiration that may be expected under saturated surface conditions. Actual evapotranspiration will increase as long as surface moisture is available. Because the baseline scenario (current condition) indicates that summer evapotranspiration already exceeds rainfall and condensation, a warming scenario that does not include increased rainfall suggests increasingly drier conditions and more rapid depletion of surface and soil water storage.

G) Summer water storage

As stated above [feature (F)], the rate of moisture loss to the atmosphere will increase under a warming scenario. Consequently, the rate at which surface and soil water storage decreases throughout the summer is likely to increase. This is represented on the schematic as a steeper decline of the surface and soil water storage throughout the summer months.

H) Active layer thickness (ALT)

Warmer winter temperatures will reduce the energy flux from soils to the atmosphere, and winter soil temperatures will not be as cold as in the baseline case. Increasing temperatures during the warm season will lead to greater energy flux to the soil from the atmosphere. Warmer soil temperatures and earlier onset of active layer thaw will enhance the potential depth of seasonal thaw. Other things being equal, increased depth of thaw will lead to greater soil water storage capacity and the conversion of surface ponding into subsurface storage. It is important to note, however, that this effect may be offset by ground settlement that tends to reduce ALT.

Increasing soil storage capacity and more rapid moisture export through evapotranspiration will lead to decreased hydrologic response to summer storms. Currently, the coastal plain exhibits very little or no stream response to summer rainfall events. This is due to the high surface storage capacity, low topographic gradient, and increasing storage deficits during summer. As rainfall arrives at the surface, it replenishes storage deficits and does not result in short-term streamflow increases. In contrast, significant rainfall events do result in streamflow response in the Arctic Foothills ecoregion. As the active layer and surface storage deficits increase, the foothills will have muted hydrologic response to storms but greater base flow due to suprapermafrost groundwater flow from soil moisture.

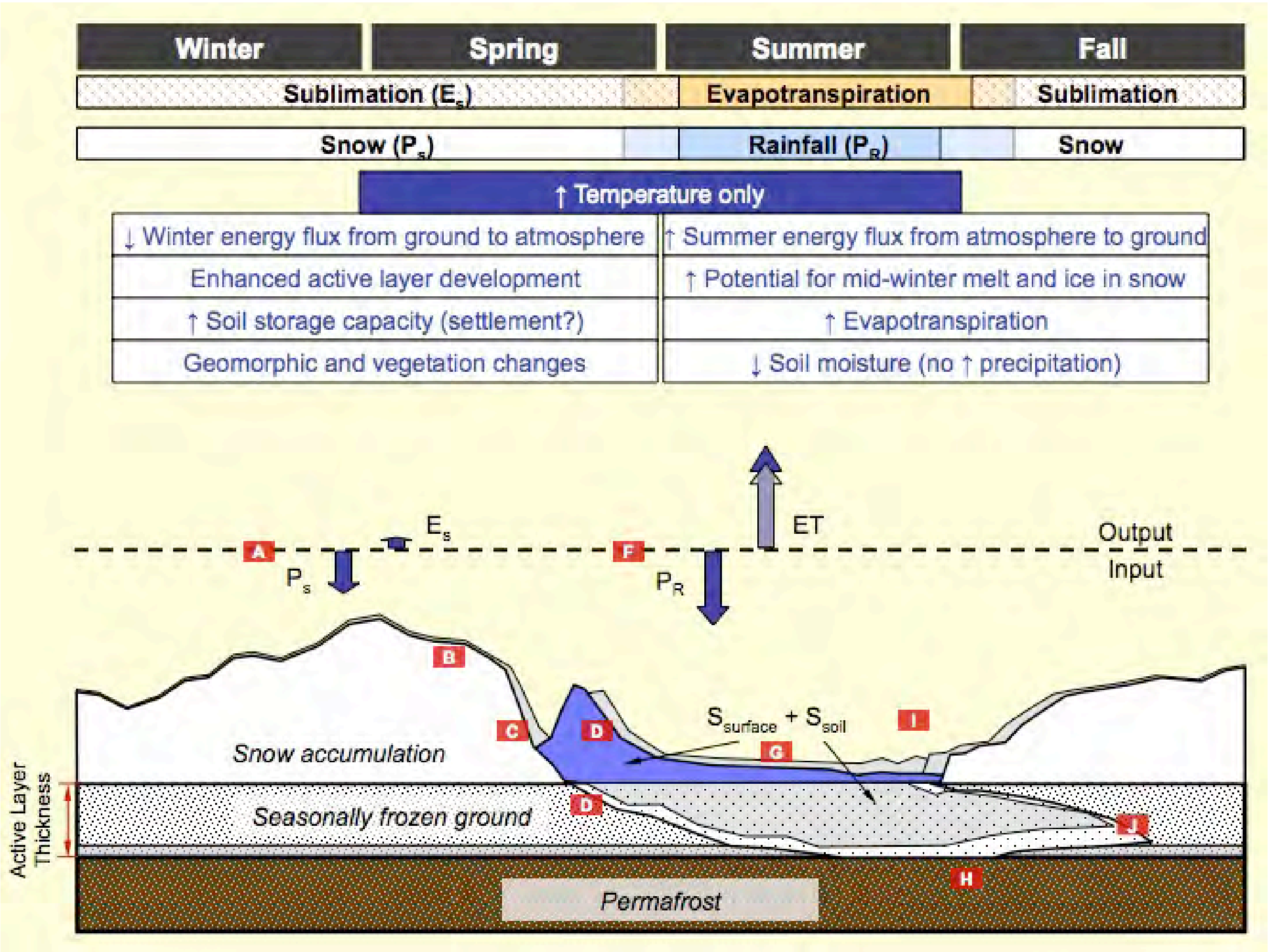
I) End-of-summer water storage

Although initial surface inundation and peak streamflows may be similar to current conditions, increasing evapotranspiration will lead to more rapid surface and soil water depletion. Furthermore, increasing ALT may convert more surface water storage into subsurface storage (soil moisture). Larger fall storage deficits will require a larger proportion of spring snow melt to recharge storage reservoirs. This will reduce peak streamflow the following spring to some extent.

J) Soil freeze-back

Warmer soil temperatures and a prolonged fall season will lead to later and more gradual soil freezing. In extreme scenarios this may even lead to talik formation if the active layer cannot fully freeze-back. In the foothills, prolonged thaw may lead to increased soil water drainage to streams. On the coastal plain, topographic gradients may be insufficient for soil water to drain.

Figure 3.2. Hydrological changes expected under Scenario I (increased temperature).



Future Scenario II: Increased Temperature and Increased Precipitation (Across All Seasons)

A) Winter precipitation less sublimation (PS-ES)

Increases in winter precipitation will dominate the snow storage, while changes to sublimation are likely to be minor. This scenario assumes a general increase in annual precipitation. However, most global climate models project that increasing arctic precipitation will be more pronounced in the winter.

B) End-of-winter snow water equivalent (SWE)

Increasing snowfall will result in higher end-of-winter SWE. As a result, there will be a greater volume of water released during the spring melt.

C) Spring snow ablation

Although higher temperatures favor earlier onset of snowmelt, the advance of melt is limited by the availability of radiation to drive the process. Furthermore, increased end-of-winter SWE will require additional energy to melt the snow pack. Consequently, the timing of melt and total snow ablation may not be significantly earlier than the current condition.

D) Spring water storage and runoff

The volume of water released from the snow pack will increase with increasing winter precipitation. If end-of-summer storage deficits are unchanged, the result will be increased surface storage and increased peak streamflow. If end-of-summer storage deficits are higher (i.e., drier conditions in fall), then a larger portion of SWE will be necessary to fill surface and soil moisture deficits.

Following the initial hydrologic response (e.g., peak flows and maximum inundated area), surface storage will still decrease rapidly according to the water surface elevation with respect to the elevation of drainage outlets. The rate of evaporative losses from water surfaces will be greater due to increased temperatures. However, total loss from evaporation and transpiration will depend on 1) total inundated area, 2) near-surface soil moisture, and 3) the timing of summer rainfall with respect to seasonally changing radiation and plant senescence.

E) Soil thaw

Soils will begin to thaw following snow cover loss. Although the start of thaw may not be different from the baseline case, the rate of thaw may be greater due to 1) warmer end-of-winter soil temperatures, 2) increased summer temperatures, and 3) increased heat transfer associated with summer rainfall.

F) Summer precipitation less evapotranspiration (PR-ET)

Increasing summer precipitation along with increasing summer temperatures will result in increased evapotranspiration. However, evapotranspiration is limited by soil and surface moisture. Soil moisture under changing climate is highly uncertain and the subject of many ongoing research efforts. It is not clear if increasing summer precipitation will be sufficient to outpace evapotranspiration.

G) Summer water storage

Increasing summer rainfall may reduce the rate of summer surface drying. However, it is unknown if rainfall will increase enough to outpace increasing evapotranspiration. Total summer storage is comprised of both surface water storage (e.g., lakes, ponds, and emergent wetlands) and soil moisture in the active layer.

H) Active layer thickness (ALT)

More rapid active layer thaw and a prolonged warm season will increase the potential soil thaw depth. As the active layer thaws more rapidly and to greater depth, the distribution of storage between surface water and soil moisture may shift downward. As a result, some surface water may become soil moisture and result in less inundated area, shallow soil moisture may percolate deeper in the soil column, and uplands may become drier despite overall higher soil water storage at the landscape scale.

The increased soil storage capacity associated with greater ALT serves to attenuate streamflow response to summer storms. As rainfall arrives at the surface, a greater volume can enter the soil column before saturating the soil and generating direct runoff. Soil water is then gradually released to the drainage network, resulting in lower peak flows and longer streamflow recession.

Although increased heat flux to the ground will cause a deepening of the active layer, a number of potentially opposing processes can also occur. The load-bearing capacity of frozen soils is greater than thawed soils. As a result, increasing active layer thickness may result in soil compaction that effectively reduces the maximum depth of thawed soil. Vegetation plays a strong role in controlling terrestrial-atmospheric energy and moisture fluxes. As temperature and active layer thickness increase, vegetation may respond in such a way as to insulate the ground and create a new stable state for the active layer. These feedbacks illustrate just how difficult it is to predict arctic hydrologic response to changing climate.

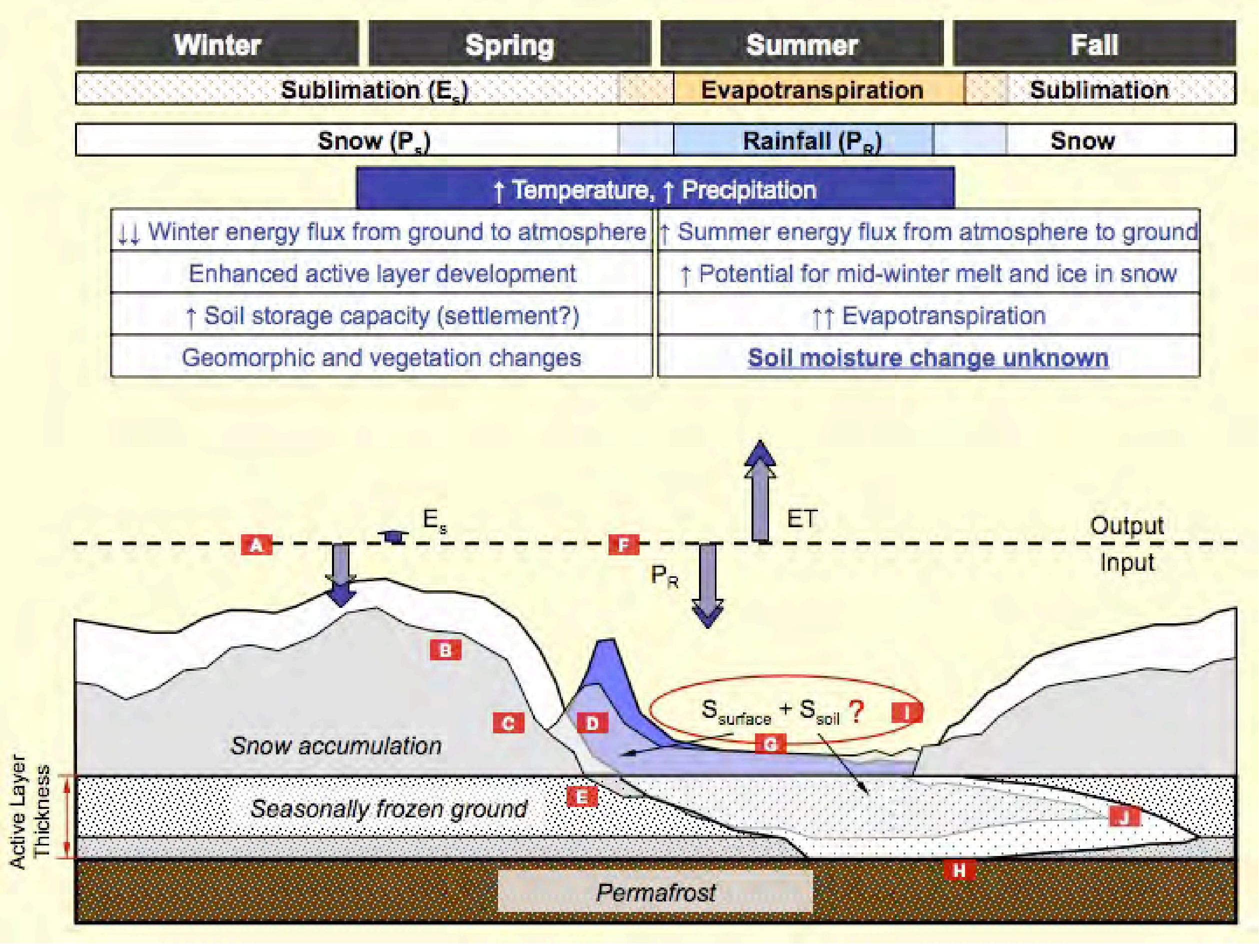
I) End-of-summer water storage

As the warm season is prolonged due to arctic warming, so too is the period for soil moisture to move down gradient and into drainage networks. This may lead to late summer and early fall soil drying, while stream baseflows increase due to additional shallow groundwater flow. If rainfall in early fall increases, much of the depleted storage may be recharged prior to winter freeze-back.

J) Soil freeze-back

As with Scenario I (temperature only), soil re-freeze will be delayed due to higher temperatures. In this scenario, however, the active layer thickness is greater, so the time to total freeze-back will take longer. In the extreme case, the active layer may become too thick to completely re-freeze in winter, and a talik will form. In the foothills, such an occurrence could mean continued soil drainage throughout winter and a larger spring soil moisture deficit. This winter drainage may lead to higher under-ice streamflow. The effect may be less important on the coastal plain where soil moisture may not have sufficient gradients along which to drain. Consequently, overall soil moisture distribution on the coastal plain will be largely determined by microtopography.

Figure 3.3. Hydrological changes expected under Scenario II (increased temperature and increased precipitation).



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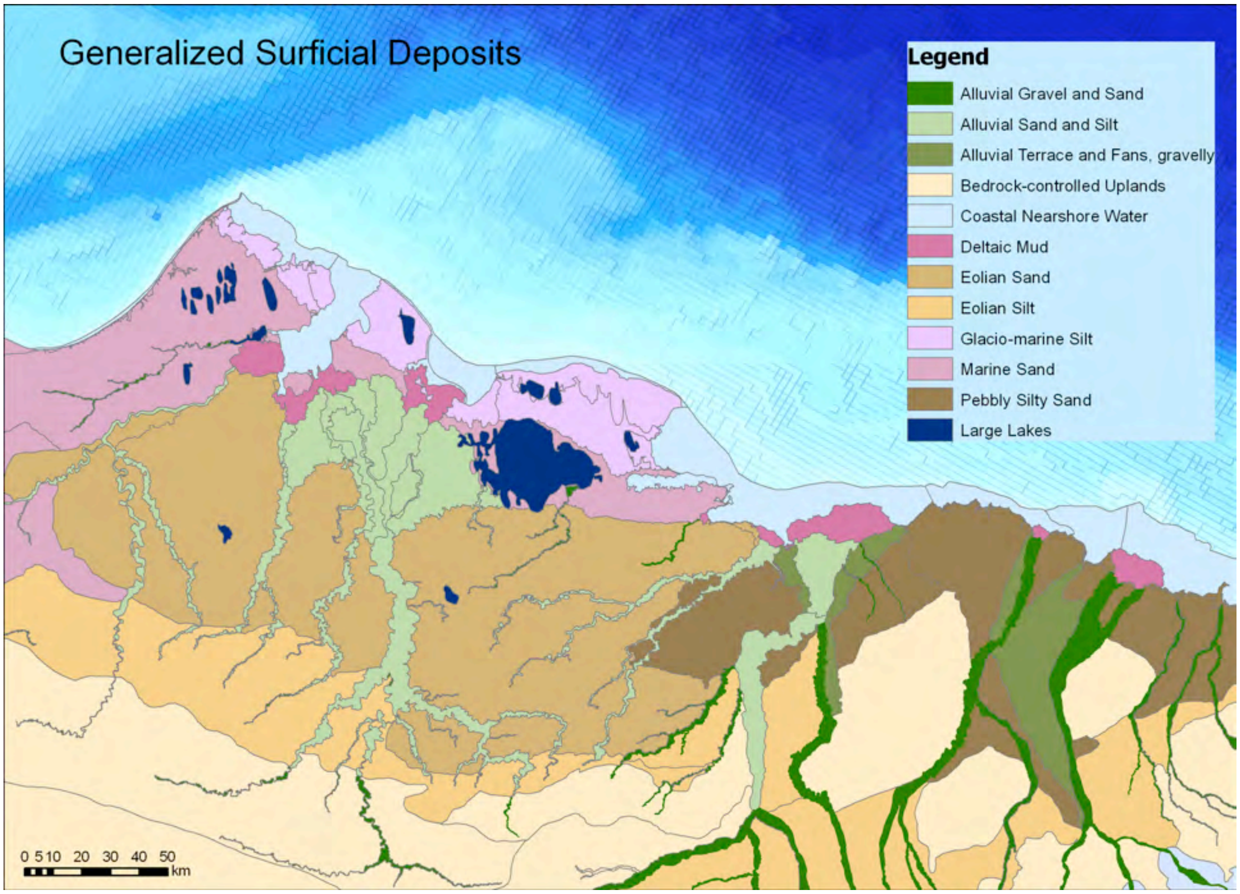
Section 4

Permafrost-influenced Geomorphic Processes

Geomorphic processes vary greatly among ecoregions in northern Alaska, extending from the Beaufort Sea coast to the Brooks Range (Figure 4.1). Regional differences in the distribution of surficial deposits, all of late Pleistocene origin, are a reflection of various past processes. The coastal areas are characterized by glaciomarine pebbly silt, glacial deposition of slightly pebbly silty sand from a northern ice sheet, and deposition of marine sand by marine transgression. The western portion of the Arctic Coastal Plain is covered by an eolian sand. The lower portion of the Arctic Foothills is blanketed by thick loess (silt). The upper foothills are underlain by bedrock near the surface; ridges typically have rocky residual soils, slopes are mantled with organic-rich colluvium (accumulations of sediment transported downslope by gravity), and basins are filled with organic-rich fine-grained colluvium. Floodplains dissect these deposits and tend to be gravelly in the foothills and the eastern portion of the Arctic Coastal Plain and sandy on the Arctic Coastal Plain in the western portion of northern Alaska.

Figure 4.1. Surficial deposits of the central portion of northern Alaska.

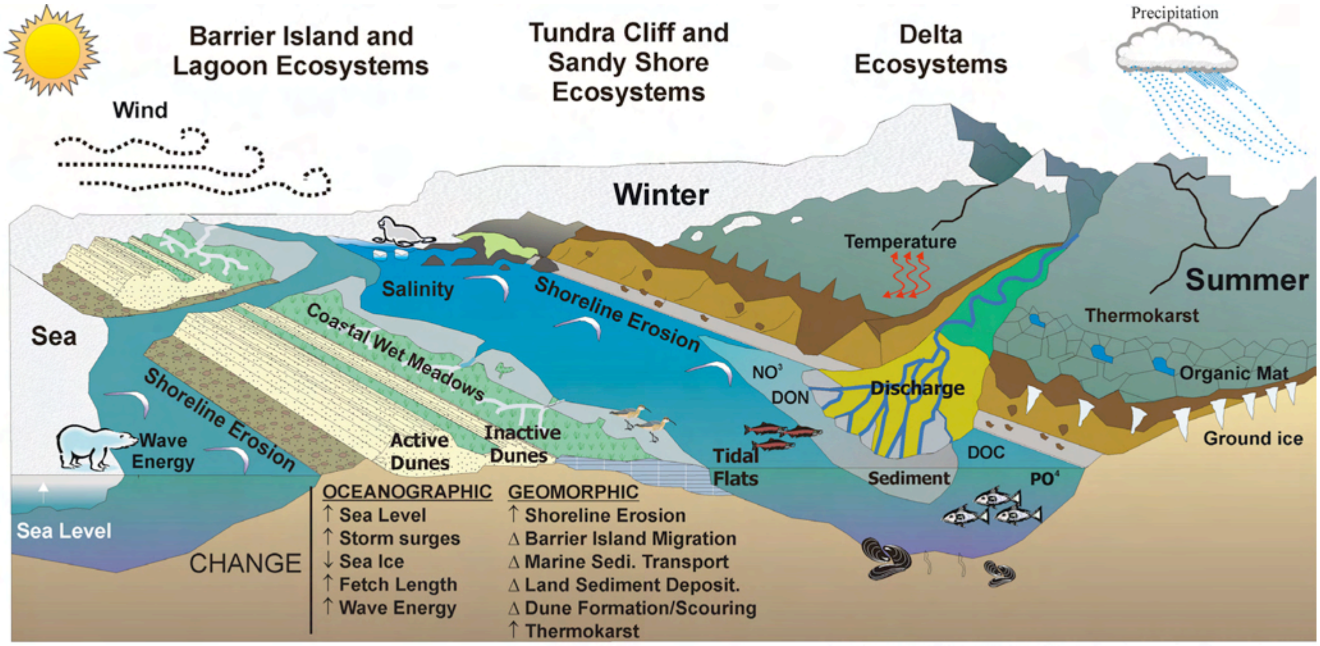


Beaufort Coast

The Beaufort Sea coast is dominated by lagoons with sandy barrier islands, exposed coast with high-eroding bluffs, deltas, and low-lying drained-lake basins that are occasionally flooded by storm surges (Figure 4.2). These are dynamic environments that are greatly affected by sea ice, wind-driven waves and storm surges, coastal erosion, sedimentation by rivers and eroding coastal bluffs, and long-shore currents.

The most prominent changes associated with global warming will be the decrease in sea ice, increase in wave energy, and increase in storm surges related to increased fetch across the open Arctic Ocean. Sea level is currently rising at 3 mm/yr and projected to rise 0.5–1.0 m by the end of the century. Due to recent sea ice retreat, there has already been a substantial increase in erosion rates at Cape Halkett and Barter Island. Erosion rates along most of the Beaufort Sea coast are 1–2 m/yr, but recent observation reveal that erosion can be as high as 15 m/yr along some extremely ice-rich coastlines. A noticeable change in bank profiles from banks mantled with slumping soil material to steep undercut banks with collapsing blocks has also been observed. The increase in storm heights, accompanied by the projected sea-level rise, will cause additional flooding and salinization of low-lying terrain. This will likely increase the distribution of coastal barrens and meadows. Coastal ecosystems on deltas probably will remain in equilibrium with sea-level rise due to frequent sedimentation, which will maintain the ground surface near sea level. Changes in precipitation will likely have only minor effects, primarily on the inputs of sediment and organic carbon into lagoons and nearshore water.

Figure 4.2. A geomorphic and ecological conceptual model of the coastal ecoregion of northern Alaska illustrating the relationships among climatic, geomorphic processes, and biotic distributions.



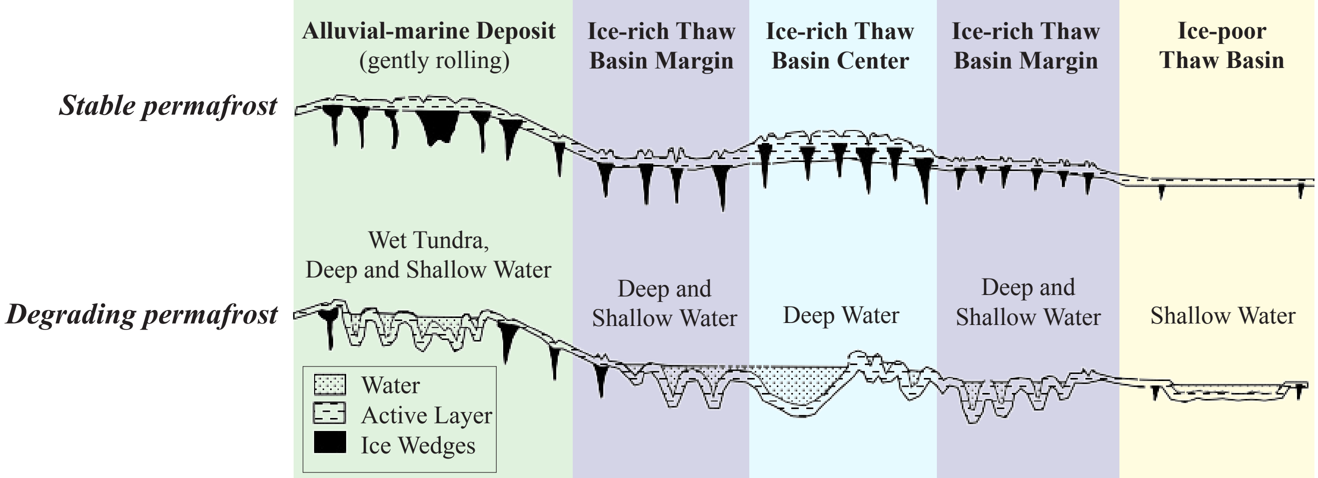
Produced for ARCN-NPS by M. T. Jorgenson and D. M. Sanzone

Coastal Plain

The coastal plain has numerous surficial deposits related to initial coastal plain formation and subsequent lake development and drainage (Figure 4.1). Ice-rich deposits, such as delta and glacio-marine deposits have abundant thaw lakes and drained basins. In deposits where the ground-ice volume is not sufficient to allow development of thaw lakes, such as eolian sand and slightly pebbly sand till, the lakes formed in low-lying swales during the early Holocene and expanded through erosion of fine-grained sediments. The development and expansion of a drainage network during the Holocene has contributed to drainage of some of the large lakes. Once lakes are tapped and drained the exposed sediments are subject to permafrost aggradation. The sandy margins tend to aggrade little ice, while ice segregation and ice wedge development in the organic-rich silty centers is prevalent. This differential ice accumulation typically causes the drained centers to dome up and shift water to the lower-lying sandy margins. Small ponds created by this hydrologic shift are abundant around the margins. The small ponds typically fill in with limnic sediments in the center and sedge peat around the margins.

The response of coastal plain deposits to warming (5 °C increase) and wetting (25% precipitation increase) will have a dramatic effect on the stability of ice wedges and will result in a redistribution of water. The redistribution of water, however, will depend on landscape position: whether the site is a water-shedding slope or a water-gathering basin. Because ice wedges are formed just below the active layer and are in close equilibrium with the existing climate, an abrupt warming will cause nearly all ice wedges to degrade. The degradation will cause impounding of water in thermokarst troughs and pits, draining of the adjacent polygon centers, and an increase in the water storage capacity of the tundra (Figure 4.3). At later stages of degradation, the thermokarst troughs will form drainage networks to further lower the water table. Thawing of ice wedges in ice-rich deposits may induce development of thermokarst ponds. Eventual integration of the thermokarst troughs and pits into drainage networks should further lower the water table and cause increased drying on the centers of the high-centered polygons created by the thawing ice wedges. In the low-lying basins, the water of deep lakes and shallow ponds will be fully recharged by spring snow melt with excess water running off. Under a warming scenario where precipitation is unchanged, increased evaporation during mid-summer should cause deeper draw downs of lakes and ponds in mid-summer, but water levels should increase again with fall rains and subsequent spring snow melt. Thermokarst of ice wedges in basins will create more capacity for water storage but should have little effect on water levels. Lake shoreline erosion by wind-driven waves and lake expansion from thermokarst is expected to continue and may increase with a longer ice-free season and warmer water. Lake expansion may affect ~1–3% of the landscape. Most drained-lake basins formed during a period of extensive drainage during the mid-Holocene, and contemporary lake drainage is uncommon. With expected warming, however, degradation of ice-wedges, which can integrate into drainage channels with a lower base elevation, may increase the drainage of lakes.

Figure 4.3. A cross-sectional profile of the coastal plain in northern Alaska illustrating the role of permafrost degradation in the redistribution of water.



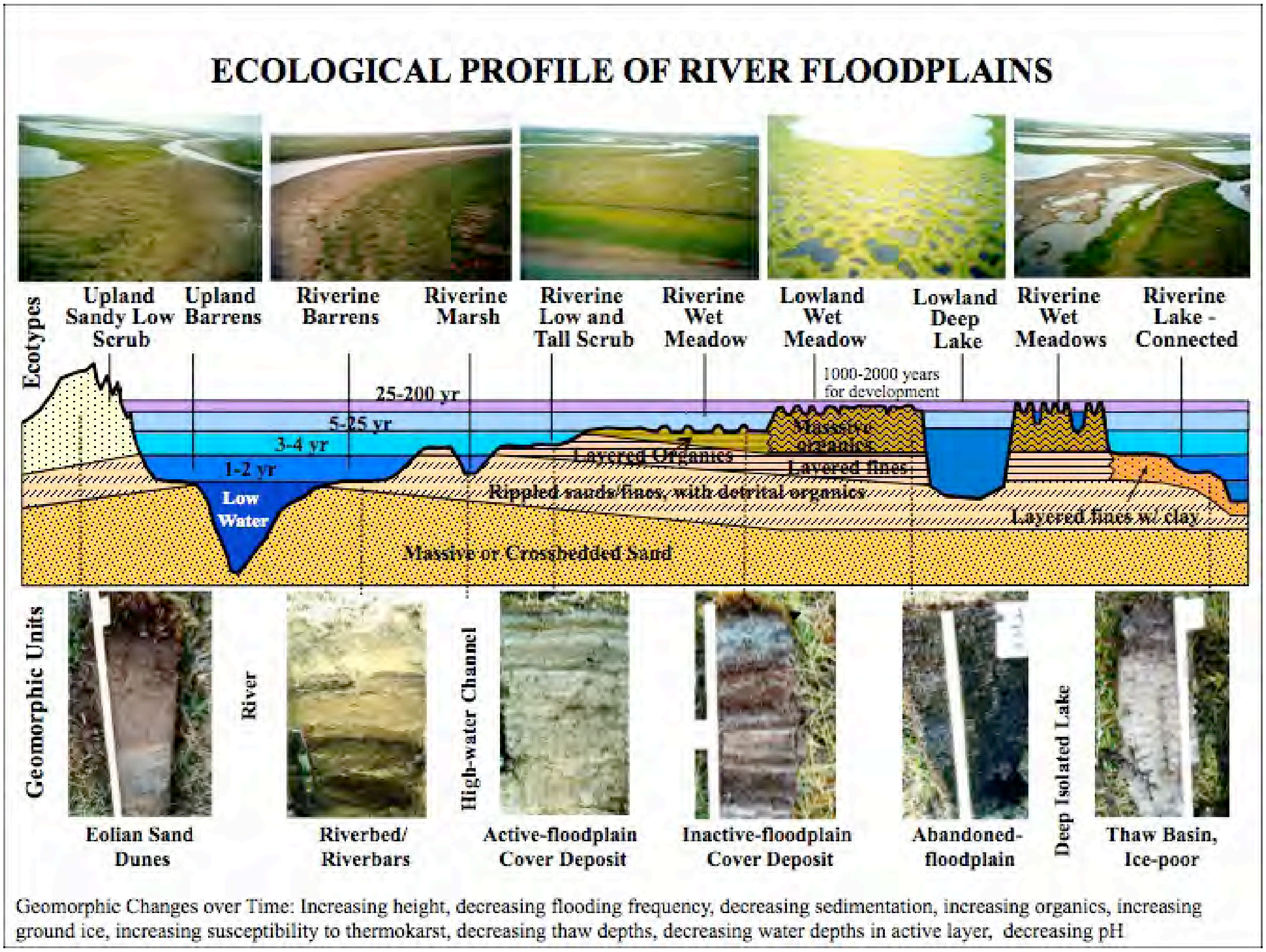
	Alluvial-marine Deposit (gently rolling)	Ice-rich Thaw Basin Margin	Ice-rich Thaw Basin Center	Ice-rich Thaw Basin Margin	Ice-poor Thaw Basin
Before Disturbance					
Active Layer (m)	0.3	0.4	0.3	0.4	0.4
Segregated Ice (% vol)	71	64	64	64	60
Wedge Ice (% vol)	20	15	20	15	0
After Disturbance					
Active Layer (m)	0.8	0.8	0.8	0.8	0.8
Mound Settlement (m)	0.6 ± 0.3	0.4 ± 0.3	0.3 ± 0.1	0.4 ± 0.3	0.4 ± 0.3
Trough Settlement (m)	1–2	1–2	1–3	1–2	0
Drainage	partial	none	none/partial	none	none

Floodplains

Floodplains are active geomorphic environments because of sedimentation caused by flooding, erosion caused by channel migration, and deposition of sand blown off of barren riverbars (Figure 4.4). The varying flooding regime creates a sequence of deposits that include massive or crossbedded sand in the active channel, rippled interbedded sands and fines with distinctive detrital organics that are the remains of peat banks eroded upstream, layered fines caused by vertical accretion of silts during overbank flooding, layered organics and silts created by the accumulation of organic matter in between infrequent flooding events, and massive organics that accumulate on higher floodplains that are rarely flooded. During floodplain evolution, the deposits are modified by the aggradation of segregated and wedge ice, which deforms the surface, affects water runoff, and increases the susceptibility of older terrain to thermokarst. These deposits support a successional sequence of ecotypes from river to riverine barrens, tall shrub, low shrub, dwarf shrub, and wet sedge meadows. Although riverine ecosystems are not abundant(~8% of the Arctic Coastal Plain and ~4% of the Arctic Foothills), they are highly productive ecosystems, conduits of water, sediments, and nutrients, and used by a wide range of fish, bird, and mammal species.

Riverine ecosystems will respond to climate change in a variety of ways depending on the amount of warming and whether precipitation will increase or remain about the same. The response will be affected by reduced or increased sedimentation, delayed permafrost aggradation during early floodplain development, and degradation of permafrost in ice-rich late floodplain stages. In response to warming, permafrost aggradation will be slightly delayed in the barren portion of active floodplains, and degradation will be accelerated on the inactive and abandoned floodplains. Ice wedges formed in the later stages of floodplain development will degrade. This degradation will help lower the water table and will help form drainage networks that will accelerate drainage of riverine lakes. Assessing the consequences of altered precipitation (magnitude, seasonality, frequency, extreme events), discharge, flooding, sedimentation, and erosion is more uncertain. Many of the processes are more affected by extreme events rather than average conditions. Under higher precipitation, flooding, sedimentation, and erosion should increase favoring more productive, early successional ecosystems. In contrast, decreased runoff associated with drying during mid-summer may lead to increased channel stability and increased shrub growth on the stabilized active floodplain.

Figure 4.4. An ecological profile of sandy floodplains in northern Alaska illustrating the relationships among hydrology, geomorphology, soils, and vegetation.



Geomorphic Changes over Time: Increasing height, decreasing flooding frequency, decreasing sedimentation, increasing organics, increasing ground ice, increasing susceptibility to thermokarst, decreasing thaw depths, decreasing water depths in active layer, decreasing pH

Foothills

The upland ecosystems of the Arctic Foothills have four distinctive geomorphic environments (Figure 4.5):

- rocky residual soils on ridges;
- gentle slopes mantled with ice- and organic-rich colluvium over bedrock;
- Pleistocene loess on the lower foothills; and
- ice-cored moraines, which occur at the outlets of glaciated mountain valleys but are of limited extent and are not included in this discussion.

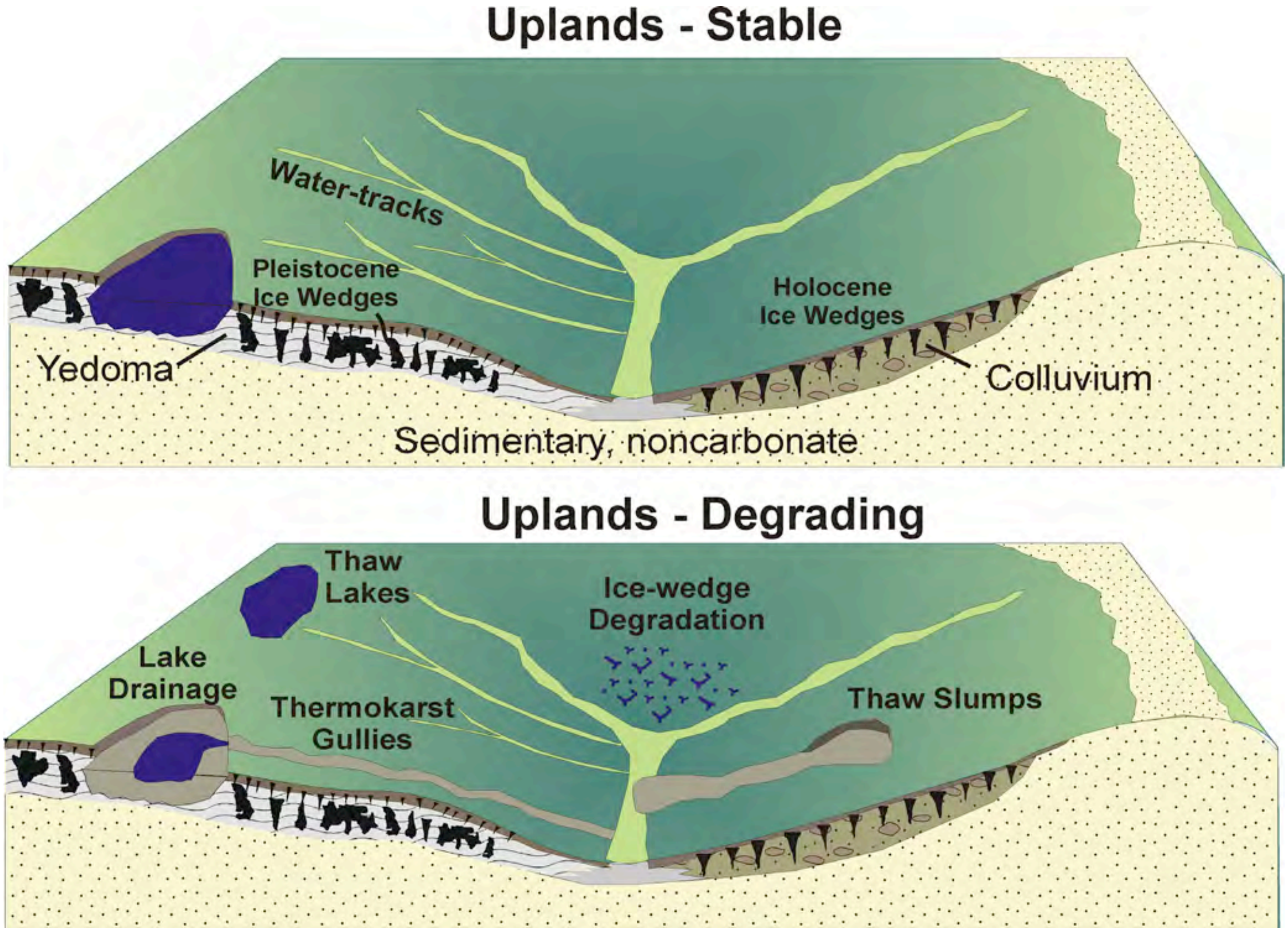
The rocky residual soils are well-drained, have deep active layers, and are relatively thaw stable. The soils on colluvium, typical of mid to lower slopes, tend to be highly organic, saturated, and have abundant ice wedges and segregated ice near the permafrost table. Pleistocene loess tends to be extremely ice-rich with massive ice extending to depths of 20–30 m. Because of the massive ice, deep thermokarst lakes are common. Probable response of each of these specific environments is discussed separately below.

Rocky ridges probably will undergo little geomorphic change under a warmer and wetter climate. The already well-drained soils will remain well-drained and thaw stable. The active layer will likely increase, and taliks may develop on some south-facing slopes, but this will have little effect on surface hydrology. Under drying conditions, little change is expected.

Colluvium-mantled hillsides are likely to be very sensitive to climate warming. Because the active layer is underlain by ice-rich permafrost, thaw slumps are likely to become abundant on the sloping surfaces. The slumping will expose new soil to plant colonization and contribute abundant sediment to small streams. Gullies are likely to become common where water flow through ice-wedge networks causes the ground surface to collapse. The gullies will then contribute to channelization of flow and drying of intervening ridges. In some areas, water-tracks may deepen without deeper gully formation, but still serve to channel suprapermafrost groundwater flow. On very gentle slopes, ice-wedges are likely to degrade without prominent gully formation.

Landscapes characterized by the presence of extremely ice-rich loess (yedoma) of late Pleistocene age are highly sensitive to warming and have the potential for drastic change. Yedoma is abundant across the lower foothills and may occupy roughly 20% of the overall foothills landscape. In places, such as along the lower Colville River, the yedoma has only 0.5–1 m of soil covering 10–25 m of ice. The degraded yedoma landscape of the Seward Peninsula may provide a good example of how the landscape could be altered by widespread degradation. First, thermokarst develops in the network of shallow Holocene ice wedges near the surface of the permafrost. Second, the thermokarst troughs and pits expand into thermokarst ponds and lakes that thaw into the underlying massive ice. Expansion of the thermokarst lakes and drainage networks cause the lakes to drain, forming a thaw lake plain. The process is likely to take hundreds to thousands of years.

Figure 4.5. A conceptual model of the Arctic Foothills region of northern Alaska illustrating the potential consequences of permafrost degradation on hillslope processes.



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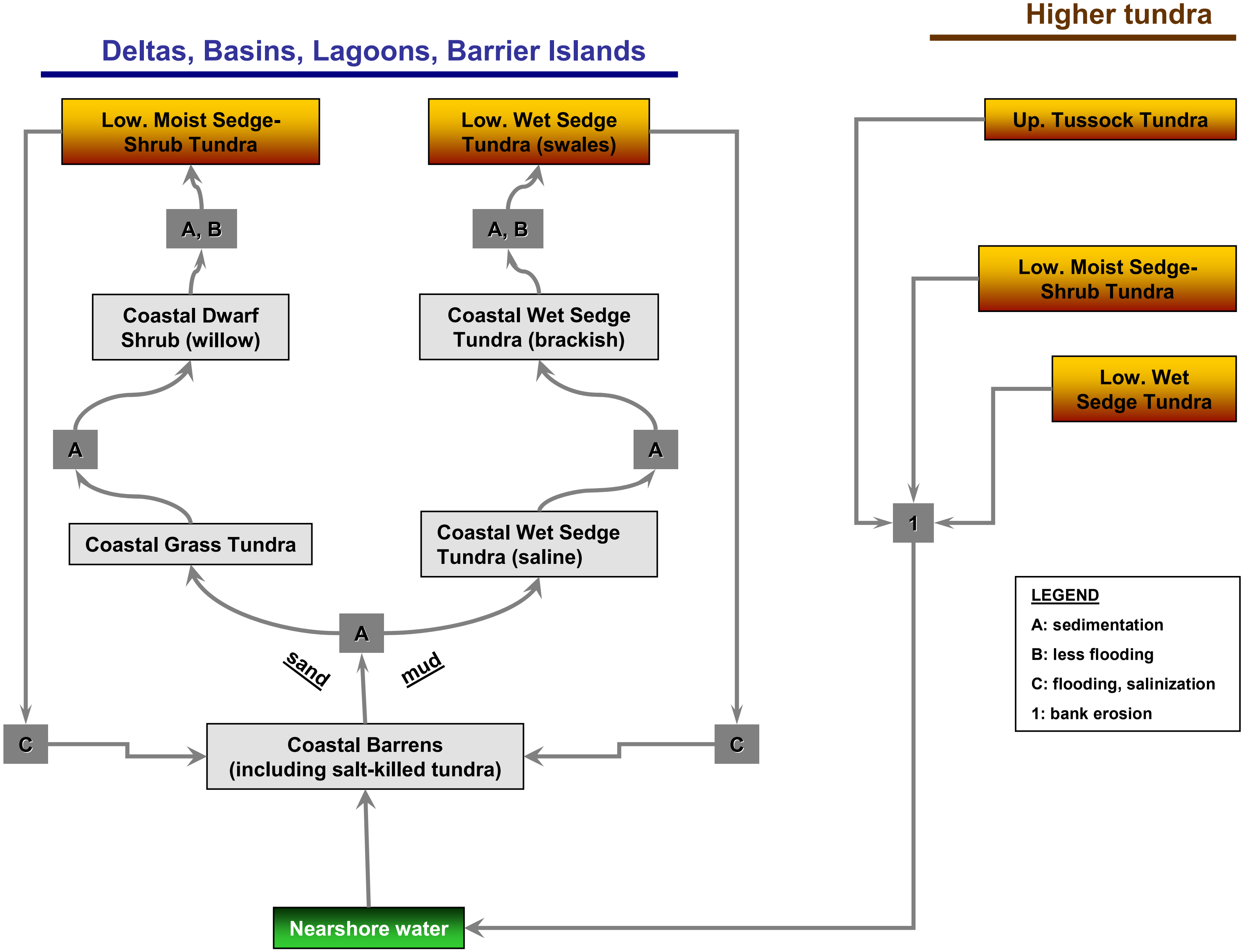
Coastal Pathways



Section 5

Pathways of Ecosystem Change

Ecosystems will change in response to vegetation succession over time, soil development, erosional and depositional processes associated with geomorphic processes, permafrost dynamics, hydrologic shifts, and climate change. Assessment of the potential changes in vegetation and associated ecosystem characteristics can be organized by ecoregion, or broad physiographic characteristics, to better partition the variability in ecosystem responses. Presented below are conceptual models of ecological pathways, or the shifts from one ecosystem to another in response to environmental changes, for the coast, coastal plain, floodplain (riverine), and foothill (uplands) physiographic environments of northern Alaska. The pathway diagrams identify the patterns (classes of ecotypes) and processes responsible (indicated by arrows and accompanying text). The diagrams illustrate what we can expect to be “winners” and “losers” from predicted climate change.

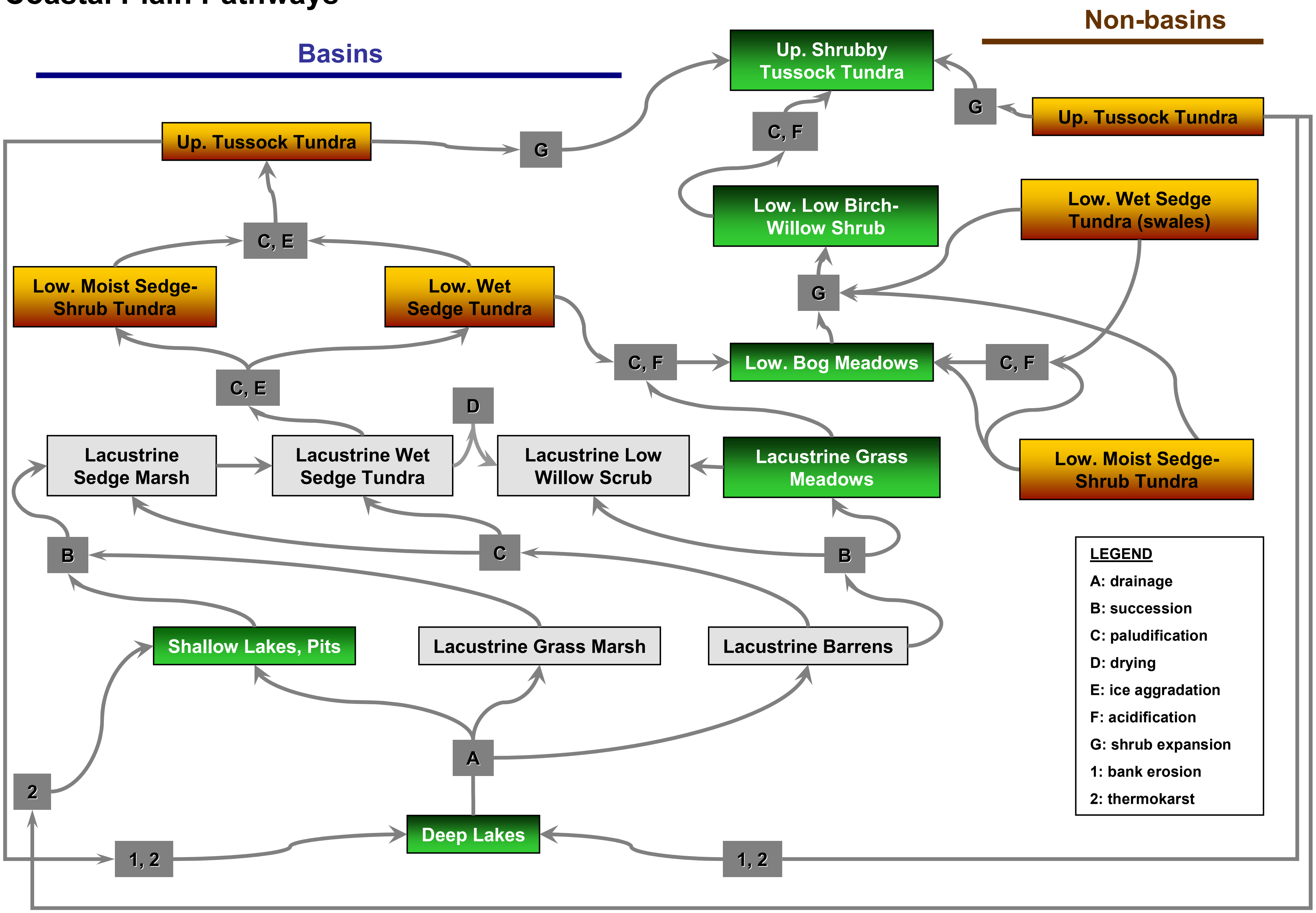
Coastal Ecosystems

Coastal ecosystems are dominated by coastal water, coastal barrens (mudflats, barrier islands, spits, sand dunes), coastal wet sedge tundra (saline, dominated by *Carex subspathaceae* and *Pucinellia phryganodes*), coastal sedge tundra (brackish, dominated by *Carex aquatilis, Dupontia fisheri*), coastal grass tundra (*Leymus mollis*), and coastal dwarf shrub (*Salix ovalifolia*). Distribution of these ecotypes are affected by shoreline erosion, flooding from storms and sea-level rise, salinity, sedimentation, and soil drainage related to soil texture and topographic position (Figure 5.1).

Coastal water is expected to expand in area, at the expense of lowland wet sedge tundra, lowland moist sedge-shrub tundra, and upland tussock tundra, as a result of shoreline erosion. Accelerated shoreline erosion is anticipated in response to decreased sea ice, increased open-water fetch, and longer ice-free season. Lacustrine wet sedge tundra and lacustrine moist sedge-shrub tundra in low-lying drained-lake basins also will decrease due to flooding and salinization of inland habitats. Most coastal ecosystems are likely to maintain current abundance, however, because they are well adapted to the highly dynamic coastal margin.

Figure 5.1 (facing page). Predicted pathways of changes in coastal ecosystems in response to climate change and geomorphic processes. For ecotypes, green boxes indicate an increase, grey boxes indicate little change, and orange boxes indicate a decrease.

Coastal Plain Pathways



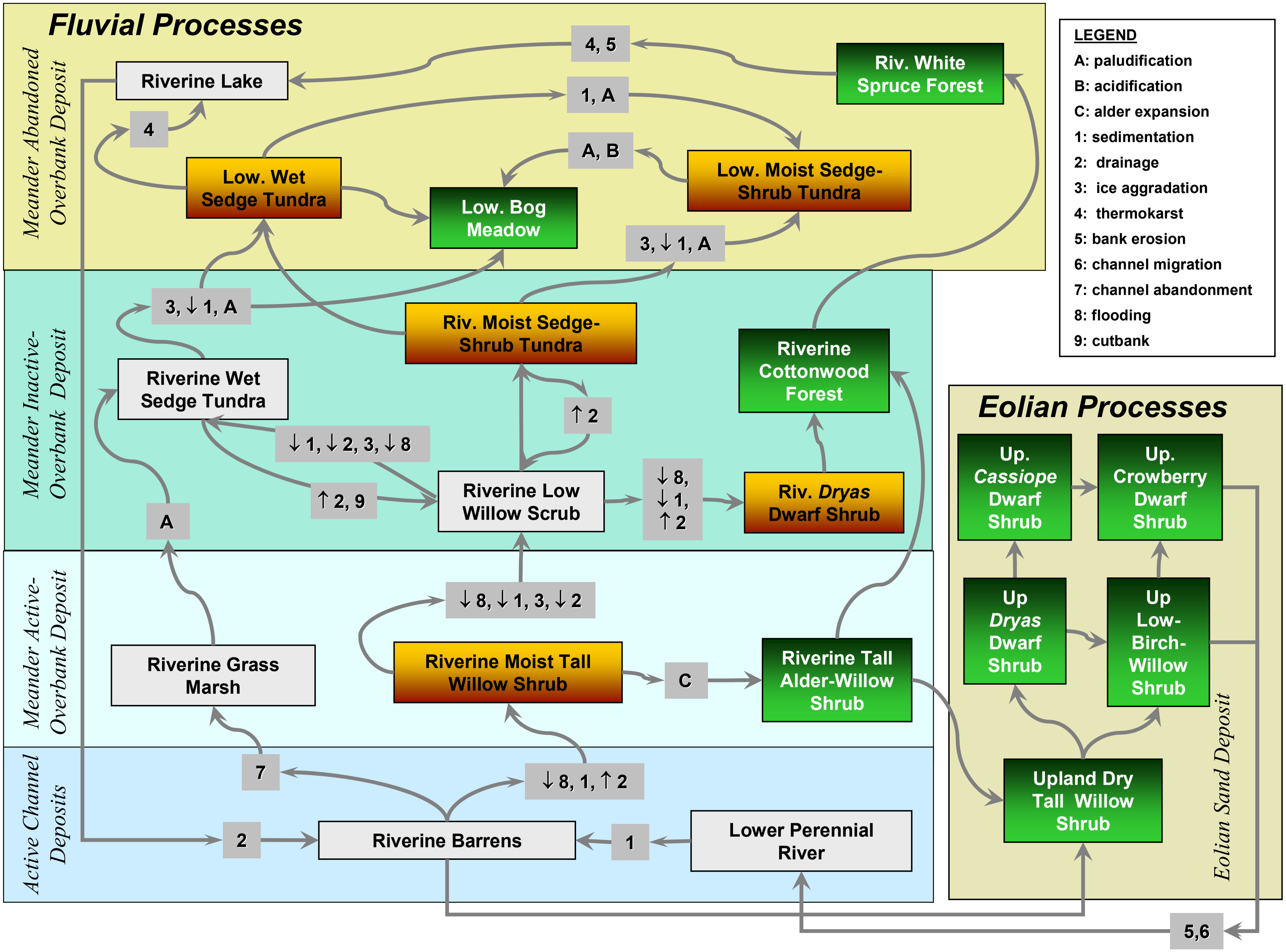
Coastal Plain Ecosystems

The coastal plain has a wide diversity of ecosystems that includes early successional lacustrine ecosystems that are closely linked to fluctuating lake levels and recently exposed sediments in drained-lake basins. Lacustrine ecosystems evolve into late-successional lowland ecosystems that develop in ice-rich drained lake basins, where polygonal networks of ice-wedges impede surface-water and nutrient flow and create higher microsite variability (Figure 5.2). The higher terrain in between the lakes and basins support both upland and lowland ecosystems. Lacustrine ecosystems include deep lakes (>1.5 m), shallow lakes and ponds (<1.5 m), lacustrine grass marsh (dominated by *Arctophila fulva* in water >0.3 m deep), lacustrine sedge marsh (*Carex aquatilis* and *Eriophorum angustifolium* in water 0.1–0.3 m deep), lacustrine wet sedge tundra (*Carex aquatilis, Eriophorum angustifolium*, forbs and mosses in water <0.1 m deep), lacustrine low willow shrub (*Salix lanata, S. planifolia*). In warmer regions, lacustrine grass meadows (*Calamagrostis canadensis*) are abundant in moist, recently drained lake basins. Lowland ecotypes in older basins characterized by well developed ice-wedge polygons include lowland wet sedge tundra and lowland moist sedge-shrub tundra (*C. aquatilis, C. bigelowii, Dryas integrifolia, S. lanata, S. planifolia*). Where ice-aggradation causes substantial surface heave, such as in the silt-rich centers of old, drained lake basins, upland tussock tundra (*Eriophorum vaginatum*) can replace earlier ecotypes. The older, higher terrain between basins also support lowland wet sedge tundra in swales, lowland moist sedge-shrub tundra on lower slopes, and upland tussock tundra on upper slopes and gentle ridges.

Ecosystems on the coastal plain are likely to be seriously affected by shoreline erosion and lake drainage, thermokarst, changing hydrologic regimes, paludification and acidification, and shrub expansion. Shoreline erosion by wind-driven waves and lake expansion from thermokarst is expected to continue and may increase with a longer ice-free season and warmer water. Lake expansion may affect ~1–3% of the landscape. Most drained-lake basins formed during a period of extensive drainage during the mid-Holocene, and contemporary lake drainage is uncommon. With expected warming, however, degradation of ice-wedges, which can integrate into drainage channels with a lower base elevation, may increase the drainage of lakes. Degradation of ice wedges creates thermokarst pits and troughs that are initially filled with open water, later colonized by lacustrine sedge marsh, and eventually by lacustrine wet sedge tundra. In terrain where ice wedges are particularly abundant, 20–30% of the landscape could be affected. An increase or decrease in precipitation is likely to have only minor effects on coastal plain ecosystems. The above- and below-ground water storage capacity is filled during snow melt each year, so water levels mostly will be affected during mid-summer. The mid-summer changes probably are not sufficient to alter the distribution of lowland and lacustrine ecotypes. Paludification and acidification are likely to have major effects. Organic-matter accumulation alters micro-topography and can raise the ground surface relative to the water level. Soils can be leached and acidified by increased precipitation or by colonization by *Sphagnum* mosses. *Sphagnum* moss, which can contribute to rapid acidification, is abundant in wet habitats in warmer climates, such as on the Seward Peninsula, and has been observed to be colonizing recent thermokarst pits. Acidification impedes nutrient availability, lowers productivity, and creates habitat for slower growing sedges and ericaceous shrubs. Most lowland wet sedge tundra is likely to shift to lowland bog meadows. Warmer temperatures likely will lead to increased growth of shrubs, although the change will involve a complex interaction of soil temperature, drainage, snow depth, competition, and herbivory.

Figure 5.2 (facing page). Predicted pathways of changes in lowland and lacustrine ecosystems on the coastal plain in response to climate change and geomorphic processes. For ecotypes, green boxes indicate an increase, grey boxes indicate little change, and orange boxes indicate a decrease.

Riverine Pathways



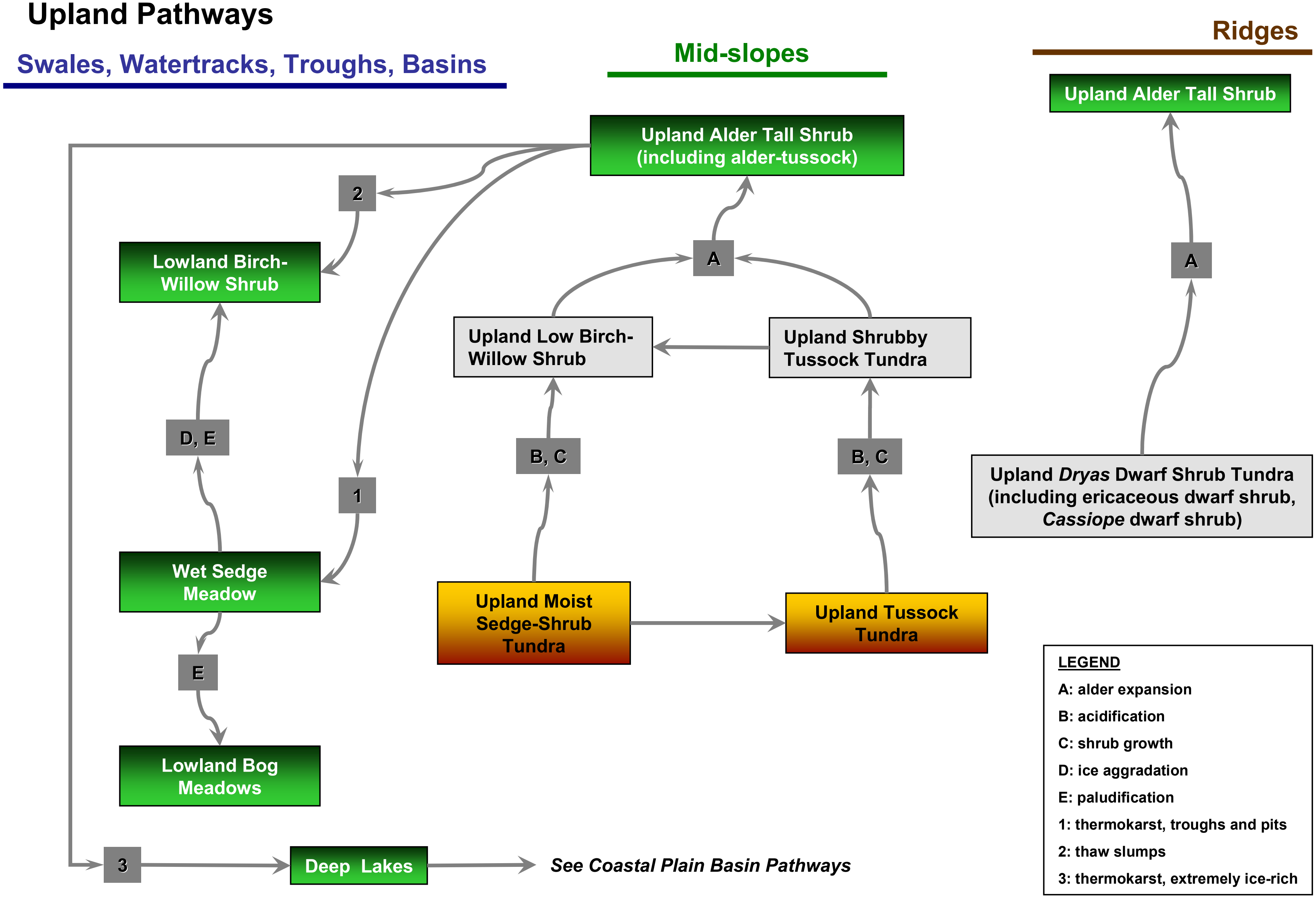
Riverine Ecosystems

Riverine ecosystems that develop on floodplains include: early to mid-successional ecosystems that develop on active and inactive floodplains subject to frequent flooding and sedimentation; late successional lowland ecosystems that develop on abandoned floodplains that are rarely flooded; and upland ecosystems that develop on well-drained dunes that develop downwind of barren riverbars (Figure 5.3). Riverine ecotypes include: flowing rivers; riverine lakes and riverine grass marsh (*Arctophila fulva*) that form in abandoned channels; riverine barrens; riverine tall alder-willow shrub (primarily *Salix alaxensis* on North Slope) with well-drained soils; riverine low shrub (*Salix lanata, S. planifolia*) on moderately drained soils, riverine wet sedge tundra on wet soil, riverine moist sedge-shrub on moist soils, and riverine *Dryas* dwarf shrub (*D. integrifolia, D. drummondii*). Lowland ecotypes on older, abandoned floodplains include lowland wet sedge tundra and lowland moist sedge-shrub tundra. Sand dunes with active deposition of wind-blown sand support upland dry tall willow shrub and inactive dunes support the late-successional ecotypes upland *Dryas* dwarf shrub and upland *Cassiope* dwarf shrub. In warmer climates, such as the lower Noatak valley, riverine tall alder-willow shrub (*Alnus crispa, A. tenuifolia, Salix alaxensis*), riverine cottonwood forest (*Populus balsamifera*), and riverine white spruce forest (*Picea glauca*) develop on active and inactive floodplains.

Riverine ecotypes are affected by channel migration and bank erosion, flooding and sedimentation, ice aggradation during floodplain evolution, thermokarst, paludification, and tree and shrub migration. Channel migration erodes late successional riverine and lowland ecotypes and converts terrestrial ecosystems to water. Flooding, sedimentation, and nutrient input are closely interrelated; lower floodplains receive more flooding and coarser-textured sediment, and higher floodplains receive less flooding and finer-textured sediments. As the sediments build up, flooding, sedimentation, and nutrient input are reduced. Ice aggradation during floodplain development under cold climates also raises the surface and, thus, affects flooding frequency. The ice aggradation also makes the ground more sensitive to thermokarst, and thermokarst lakes are abundant on older floodplains. Vegetation development on floodplains contributes to organic matter accumulation. Organic-matter accumulation and leaching over time contribute to acidification of late-successional ecotypes. Lowland wet sedge tundra and lowland moist sedge-shrub tundra are likely to be colonized by *Sphagnum* mosses and replaced by lowland bog meadows. Thermokarst on ice-rich abandoned floodplains is likely to increase and create more riverine lakes and riverine barrens after the lakes are tapped and drained. Floodplains make good corridors for rapid migration of alder, cottonwood, and white spruce because of the transport of seed by flowing water. With climate warming, riverine moist low willow shrub common on the North Slope is likely to be replaced by riverine tall alder-willow shrub common in the southern Brooks Range. Riverine cottonwood forests are likely to expand quickly, while the migration of riverine white spruce forests likely will be slow.

Figure 5.3 (facing page). Predicted pathways of changes in riverine ecosystem types in response to climate change and geomorphic processes. For ecotypes, green boxes indicate an increase, grey boxes indicate little change, and orange boxes indicate a decrease.

Upland Pathways



LEGEND

A: alder expansion
B: acidification
C: shrub growth
D: ice aggradation
E: paludification
1: thermokarst, troughs and pits
2: thaw slumps
3: thermokarst, extremely ice-rich

Upland Ecosystems

Upland ecosystems in the Arctic Foothills are dominated by shrub-dominated vegetation. Dominant ecotypes include upland *Dryas* dwarf shrub (*Dryas octopetala, D. integrifolia*, and also lumps together ericaceous- and *Cassiope*-dominated dwarf shrub communities) on dry rocky ridges, upland low birch-willow shrub (*Betula nana, S. planifolia, S. glauca*) on better drained soils, upland shrubby tussock tundra (*Betula nana, S. planifolia, Eriophorum vaginatum*) and upland tussock tundra (*E. vaginatum*) on saturated organic-rich soils, and upland moist sedge-shrub tundra (*C. bigelowii, Dryas integrifolia*) on circum-alkaline soils (Figure 5.4). Less common are lowland wet sedge tundra and lowland low birch-willow shrub that occur in swales, toe-slopes, and basins. Upland tall alder shrub is relatively rare but has been expanding slowly over the past century.

Upland ecosystems are strongly affected by soil drainage, ice aggradation at the top of the permafrost, slope failure, thermokarst, leaching and acidification, and shrub expansion on better-drained soils. Hillsides have a steep soil moisture gradient from dry rocky ridges through moderately drained slopes to poorly drained swales and basins. This gradient will be sensitive to changes in summer precipitation and snow redistribution. Increased air and soil temperatures, and possibly improved soil drainage with thicker active layers, probably will lead to conversion of upland tussock tundra to upland shrubby tussock tundra and to upland tall alder shrub. Upland *Dryas* dwarf shrub will mostly persist but in places could be converted to upland low birch-willow shrub and upland tall alder shrub. Slopes are sensitive to active-layer detachment slides and thaw slumps because of the formation of an ice-rich layer at the top of the permafrost. Sudden thawing of this layer during warm summers can lead to supersaturation of soil at the base of the active layer and downhill saturated flow of the active-layer soil. Once exposed, the permafrost can continue to thaw in retrogressive thaw slumps. Sediments released from these slides usually are transported to streams and alter water quality. Upland tussock tundra and upland shrubby tussock tundra will be highly susceptible to thaw slumps. In areas of extremely ice-rich loess, which is common along the lower foothills, thawing can lead to 10–25 m of ground collapse. In these areas, where upland tussock tundra, upland shrubby tussock tundra, and upland moist sedge-shrub predominate, thermokarst will lead to the formation of deep thaw lakes. Soil chemistry is sensitive to leaching from precipitation inputs. Consequently, soils tend to be alkaline on the coastal plain and lower foothills, where summer precipitation is low, and acidic in the upper foothills, where precipitation is higher. Increased precipitation can increase leaching, but the process is likely to be very slow. *Sphagnum* expansion will accelerate acidification. Upland moist sedge-shrub tundra will be somewhat susceptible to leaching and conversion to upland low birch-willow shrub. Shrub infilling (increased height and coverage) and expansion (colonization of new habitats) will likely be substantial in warming and drying soils as described above for soil drainage effects.

Figure 5.4 (facing page). Predicted pathways of changes in upland ecosystem types in response to climate change and geomorphic processes. For ecotypes, green boxes indicate an increase, grey boxes indicate little change, and orange boxes indicate a decrease.

Section 6

Habitat Models for Fish and Wildlife

Description and Map of Northern Alaska Ecotypes

Terrestrial habitat types adapted from the ecotypes described by Jorgenson and Heiner (2003) are described in Table 6.1. The distribution of ecotypes is depicted in Figure 6.1. Distribution of ecotypes among ecoregions of the North Slope is presented in Table 6.2.

Table 6.1. Description of ecotypes (local-scale ecosystems) for northern Alaska.

Class	Description
Alpine Ecotypes	
Alpine Glaciers	Perennially frozen snow and ice at high elevations in the Brooks Range, typically on north-facing slopes.
Alpine Non-carbonate Barrens	Barren (<5% plant cover) to partially vegetated (5–30%) areas on noncarbonate bedrock and talus slopes above treeline in the Brooks Range. Bedrock includes felsic intrusive (e.g., granite, granodiorite), noncarbonate metamorphic (e.g., slate, schist), and noncarbonated sedimentary (e.g., conglomerate, sandstone, shale) rocks that generally have low calcium and sodium and high aluminum concentrations that lead to acidic soils. Soils are rocky, excessively drained, lacking in surface organic accumulations, and strongly acidic (pH <5.5). At high elevations, common species include *Geum glaciale, Saxifraga bronchialis, S. flagellaris, S. nivalis, S. eschscholtzii,* and crustose and fruticose lichens. Lower elevations have species similar to Alpine Noncarbonate Dwarf Shrub Tundra.
Alpine Carbonate Barrens	Barren (<5% plant cover) to partially vegetated (5–30%) areas on carbonate bedrock and talus slopes above treeline in the Brooks Range. Bedrock includes both sedimentary (limestone, dolostone) and metamorphic (marble) carbonate rocks. Soils are rocky, excessively drained, lacking in surface organics, and alkaline (pH >7.3). Common pioneering plants include *Dryas integrifolia, D. octopetala, Saxifraga oppositifolia, Potentilla uniflora, Oxytropis nigrescens, O. arctica,* and *Carex rupestris*.
Alpine Mafic Barrens	Barren areas on intermediate, mafic, and ultramafic plutonic rocks above treeline in the Brooks Range that typically have dark-colored mineral assemblages with abundant iron and magnesium. Soils are rocky, excessively drained, lacking in surface organic accumulations, and are neutral to alkaline. Some areas have high levels of trace metals. Areas usually are devoid of vegetation.

Alpine Non-carbonate Dwarf Shrub Tundra	Areas on noncarbonate bedrock and talus slopes above treeline in the Brooks Range with dwarf shrub vegetation. Soils are rocky, excessively drained, have very thin surface organic accumulations, and are strongly acidic. Vegetation is dominated by dwarf shrubs including *Dryas octopetala* (mostly south slopes), *Salix phlebophylla, S. arctica, Loiseleuria procumbens, Diapensia lapponica, Arctostaphylos alpina, Empetrum nigrum, Vaccinium uliginosum,* and *Cassiope tetragona* (north slopes). Other species include *Carex podocarpa, C. bigelowii, Hierochloe alpina, Cladina mitis, C. rangiferina,* and *Rhizocarpon geographicum*.
Alpine Carbonate Dwarf Shrub Tundra	Areas on carbonate bedrock and talus slopes above treeline in the Brooks Range with dwarf shrub vegetation. Soils are rocky, excessively drained, rich in humus, and alkaline. Vegetation is dominated by dwarf shrubs including *Dryas integrifolia* (mostly south slopes), *D. octopetala, Cassiope tetragona* (north slopes), *Salix arctica,* and *Arctostaphylos alpina.* Other species include *Carex rupestris, C. bigelowii, Saxifraga oppositifolia, Potentilla uniflora, Oxytropis nigrescens, O. arctica, Nephroma arcticum, Rhytidium rugosum, Flavocetraria cucullata,* and *Thamnolia vermicularis.*
Alpine Mafic Dwarf Shrub Tundra	Areas on intermediate, mafic, and ultramafic plutonic rocks above treeline in the Brooks Range with dwarf shrub vegetation. Rocks have dark-colored mineral assemblages with abundant iron and magnesium. Soils are rocky, excessively drained, lacking in surface organic accumulations, and are neutral to alkaline. Some areas have high levels of trace metals. Vegetation is poorly described for this type but it probably is similar to that described for Alpine Noncarbonate Dwarf Shrub Tundra.
Upland Ecotypes	
Upland Spruce Forest	Upland areas on mid- to upper slopes on weathered bedrock, colluvium, and glacial till with vegetation dominated by needleleaf trees. Soils are loamy to rocky, well-drained, have moderately thick organic horizons, are acidic, and may or may not have permafrost. This late-successional forest is dominated by an open to closed canopy of *Picea glauca*, but can include minor amounts of *Betula papyrifera* and *P. mariana*. Understory plants include *Alnus crispa, Vaccinium vitis-idaea, Ledum groenlandicum, Empetrum nigrum, Rosa acicularis, Cornus canadensis, Shepherdia canadensis, Spiraea beauverdiana, Linnaea borealis, Calamagrostis canadensis, Hylocomium splendens,* and *Pleurozium schreberi*.
Upland Birch-Aspen-Spruce Forest	Upland areas on mid- to upper slopes on weathered bedrock, colluvium, and glacial till with vegetation co-dominated by broadleaf and needleleaf trees. Soils are well-drained, have thin organic horizons, are moderately acidic, and usually lack permafrost. This mid-successional mixed forest is dominated by an open to closed canopy of *Betula papyrifera, Populus tremuloides,* and *Picea glauca.* Understory plants include *Alnus crispa, Salix glauca, Vaccinium vitis-idaea, Ledum groenlandicum, Rosa acicularis, Cornus canadensis, Shepherdia canadensis, Linnaea borealis, Calamagrostis canadensis,* and feathermosses.
Upland Birch-Aspen Forest	Upland areas on mid- to upper slopes on weathered bedrock, colluvium, and glacial till with vegetation dominated by broadleaf deciduous trees. Soils are loamy to rocky, well-drained, have thin organic horizons, are acidic, and usually lack permafrost. The mid-successional forest is dominated by an open to closed canopy of *Betula papyrifera* and *Populus tremuloides.* Understory plants include *Alnus crispa, Salix glauca, Vaccinium vitis-idaea, Ledum groenlandicum, Rosa acicularis, Cornus canadensis, Shepherdia canadensis, Spiraea beauverdiana, Linnaea borealis, Calamagrostis canadensis*, and feathermosses.

Upland Tall Alder Shrub	Upland areas on mid- to upper slopes on weathered bedrock, colluvium, and glacial till with vegetation dominated by tall shrubs. Soils are loamy to rocky, well-drained, have thin organic horizons, are acidic, and usually lack permafrost. Vegetation is dominated by an open to closed canopy of *Alnus crispa,* although *Salix pulchra, Salix glauca,* and *Betula glandulosa* occasionally are abundant. Understory species include *Vaccinium uliginosum, Vaccinium vitis-idaea, Betula nana, B. glandulosa, Ledum groenlandicum, Empetrum nigrum, Equisetum arvense, Spiraea beauverdiana, Calamagrostis canadensis,* and *Petasites frigidus*. Mosses include *Sphagnum* spp., *Hylocomium splendens*, and *Dicranum* spp.
Upland Low Birch-Willow Shrub Tundra	Upland areas on mid- to upper slopes on weathered bedrock, colluvium, and glacial till with vegetation dominated by low shrubs. Soils are loamy to rocky, well-drained, have moderately thick organic horizons, are acidic, and usually have permafrost. Vegetation has an open to closed canopy of *Betula nana* and/or *Salix pulchra*. Other species include *Salix glauca, Vaccinium uliginosum, V. vitis-idaea, Ledum decumbens, Empetrum nigrum, Arctostaphylos alpina, Dryas octopetala, D. integrifolia, Salix reticulata, Equisetum arvense, Carex bigelowii,* and the mosses and lichens *Hylocomium splendens, Tomentypnum nitens, Sphagnum* spp.*, Aulacomnium palustre, Dicranum* spp.*, Cladina rangiferina,* and *Flavocetraria cucullata*.
Upland Dryas Dwarf Shrub Tundra	Upland windswept ridges and upper slopes on weathered bedrock, colluvium, inactive sand dunes, and coastal plain deposits with vegetation dominated by dwarf shrubs. Soils are well-drained, loamy to rocky, have thin organic horizons, and are circumneutral to acidic. Common dwarf shrubs include *Dryas octopetala* (mostly south slopes)*, D. integrifolia, Salix phlebophylla, S. arctica, S. reticulata, Loiseleuria procumbens, Diapensia lapponica, Arctostaphylos alpina, Empetrum nigrum, Vaccinium uliginosum, Ledum decumbens,* and *Cassiope tetragona* (north slopes). Other common species include *Carex bigelowii, C. scirpoidea, Arctagrostis latifolia, Equisetum variegatum, Tomentypnum nitens, Hylocomium splendens,* and *Cladina stellaris.*
Upland Shrubby Tussock Tundra	Gently sloping uplands and ridges on loess and colluvium over bedrock and glacial till, primarily within the Brooks Foothills (>120 m elevation), with vegetation co-dominated by tussock-forming sedges and low shrubs. Soils are somewhat poorly drained, loamy, have moderately thick surface organics, are acidic, and are underlain by ice-rich permafrost. The open low shrub canopy of *Betula nana* and *Salix pulchra* usually overtop the *Eriophorum vaginatum* tussocks. Other dominant plants include *E. angustifolium, Carex bigelowii, Ledum decumbens, Vaccinium vitis-idaea, V. uliginosum, Rubus chamaemorus, Hylocomium splendens, Sphagnum* spp.*, Aulacomnium palustre, Cladina rangiferina, C. arbuscula, C. mitis,* and *Flavocetraria cucullata*.
Upland Tussock Tundra	Gently sloping uplands and ridges on loess, colluvium, and coastal plain deposits, primarily within the Beaufort Coastal Plain (<120 m elevation), with vegetation dominated by tussock-forming sedges. Soils are moist, somewhat poorly drained, loamy, and have moderately thick surface organics, are circumneutral to acidic, and are underlain by ice-rich permafrost. Vegetation is dominated by *Eriophorum vaginatum*. On circumneutral soils, *Carex bigelowii, Dryas integrifolia, Salix pulchra, Cassiope tetragona, S. reticulata, Tomentypnum nitens,* and *Hylocomium splendens* are common. On acidic soils, dominant plants include *E. angustifolium, Betula nana, Salix pulchra, Ledum decumbens, Vaccinium vitis-idaea, Rubus chamaemorus, Hylocomium splendens, Sphagnum* spp.*, Aulacomnium palustre,* and *Cladina rangiferina.*

Upland Moist Sedge-Shrub Tundra	Upland ridges and upper slopes on weathered bedrock, loess-mantled bedrock, colluvium, and glacial till, with vegetation co-dominated by sedges and low and dwarf shrubs. Soils are loamy to rocky, somewhat poorly drained, have moderately thick surface organics, and are alkaline to acidic depending on substratum. On acidic soils more common in the upper foothills and mountains, dominant plants include *Betula nana, Salix pulchra, Carex aquatilis, Eriophorum angustifolium,* and *Sphagnum* spp. On circumneutral to alkaline soils more common on the coastal plain and lower foothills, dominant plants include *Salix lanata richardsonii, Dryas integrifolia, S. reticulata, Arctostaphylos rubra, Rhododendron lapponicum, Equisetum arvense, Carex bigelowii, Tomentypnum nitens,* and *Thamnolia vermicularis*.
Lowland Ecotypes	
Lowland Spruce Forest	Low-lying flats and gentle slopes on colluvium and abandoned floodplains with vegetation dominated by needleleaf forests. Soils are wet, somewhat poorly drained, have moderately thick surface organics, are acidic, and usually are underlain by permafrost. The open tree canopy (usually 5–10 m high) is dominated by *Picea mariana,* although *P. glauca, Larix laricina,* and *Betula papyrifera* occasionally can be present in small amounts. In the wettest areas the trees can be very stunted. Common understory plants include *Salix pulchra, Betula nana, Vaccinium uliginosum, Ledum groenlandicum, Potentilla fruticosa, Rubus chamaemorus, Equisetum arvense, and Carex bigelowii*. Mosses and lichens include *Sphagnum* spp., *Hylocomium splendens, Pleurozium schreberi, Cladonia* spp., *Nephroma* spp., *Cetraria* spp., and *Peltigera* spp.
Lowland Low Birch-Willow Shrub Tundra	Low-lying flats and lower slopes on drained-lake basins, abandoned floodplains, colluvium, and coastal plain deposits with vegetation dominated by low shrubs. Soils typically are poorly drained, loamy, have moderately thick surface organics, are acidic, and are underlain by permafrost. The open to closed low shrub canopy is dominated by *Salix pulchra* and *Betula nana.* On acidic soils other common species include *Ledum decumbens, Vaccinium uliginosum, V. vitis-idaea, Empetrum nigrum, Petasites frigidus, Rubus chamaemorus, Eriophorum angustifolium, Carex aquatilis, Calamagrostis canadensis,* and *Sphagnum* spp. On circumneutral to alkaline soils, *Salix lanata richardsonii, S. reticulata, Dryas integrifolia, Arctostaphylos rubra, Equisetum arvense, Eriophorum angustifolium, and Carex aquatilis* are common.
Lowland Moist Sedge-Shrub Tundra	Low-lying flats and gentle slopes on drained lake basins, abandoned floodplains, colluvium, and coastal plain deposits, particularly on the Beaufort Coastal Plain, with vegetation co-dominated by sedges and low or dwarf shrubs. Soils are saturated at intermediate depths (>15 cm), loamy with moderately thick surface organics, are circumneutral to alkaline, and are underlain by ice-rich permafrost. Sites generally are free of surface water during summer. Vegetation is dominated by *Carex aquatilis, C. bigelowii, Eriophorum angustifolium,* and *Dryas integrifolia.* Other common species include *Salix lanata richardsonii, S. pulchra, S. reticulata, Tomentypnum nitens,* and *Hylocomium splendens*. Acidic vegetation could not be adequately differentiated from non-acidic vegetation on the Beaufort Coastal Plain.

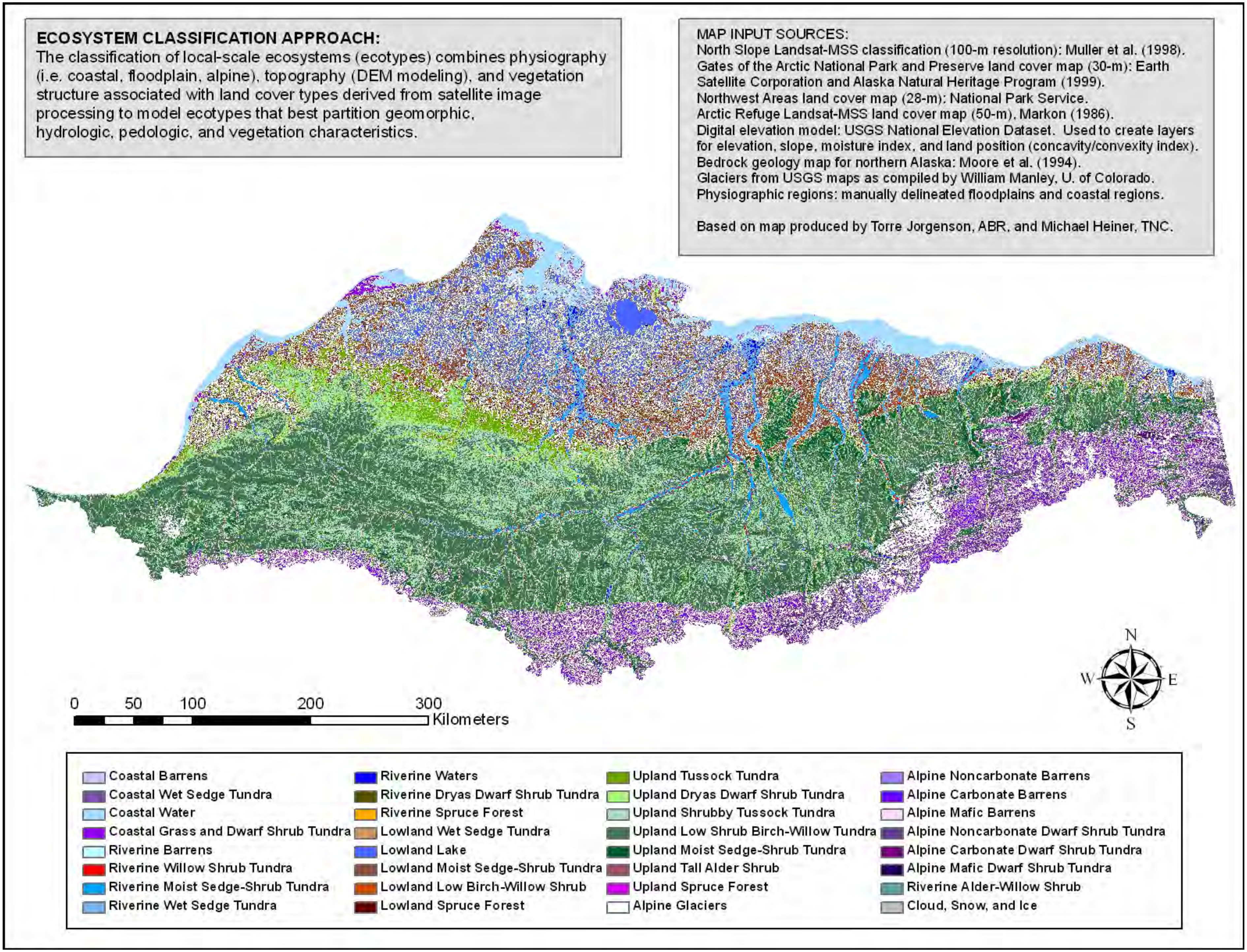
Lowland Wet Sedge Tundra	Low-lying flats and drainages on drained lake basins, abandoned floodplains, colluvium, and coastal plain deposits, particularly on the Beaufort Coastal Plain, with vegetation dominated by sedges. Soils are poorly drained, have moderately thick to thick (10–50 cm) surface organics over silt loam, usually circumneutral, and are underlain by ice-rich permafrost. Ice-wedge development in older landscapes creates distinctive low-centered polygons. The surface generally is flooded during early summer (depth <0.3 m) and drains later, but soils remain saturated ≥15 cm from the surface throughout the growing season. Vegetation is dominated by *Carex aquatilis* and *Eriophorum angustifolium*, while willows, including *Salix lanata richardsonii* and *S. pulchra*, often are present but usually not co-dominant. Other common species include *Dryas integrifolia, S. reticulata, C. bigelowii,* and *Equisetum scirpoides* on higher microsites and polygon rims.
Lowland Lake	Shallow (<1.5 m) ponds and deep (≥1.5 m) lakes resulting from thawing of ice-rich permafrost, primarily on the coastal plain and distal portions of abandoned floodplains. In shallow ponds, water freezes to the bottom during winter, thaws by early to mid-June, and is warmer than water in deep lakes. In deep lakes, water does not freeze to the bottom during winter in deeper portions of the lake. Sediments are loamy to sandy. These lakes lack riverine influences (flooding), but they may have distinct outlets or connections to rivers.
Lacustrine Ecotypes	
Lacustrine Barrens (not mapped)	Barren or partially vegetated (<30% cover) areas on newly exposed sediments in recently drained lake basins. The surface form generally is nonpatterned due to the lack of ice-wedge development. Soils are saturated to well-drained, sandy to loamy, lack surface organics, and are alkaline. Typical colonizers are *Arctophila fulva, Carex aquatilis, Dupontia fisheri, Scorpidium scorpioides,* and *Calliergon* spp. on wet sites and *Poa alpigena, Senecio congestus, Salix ovalifolia,* and *Salix arctica* on drier sites.
Lacustrine Marsh (not mapped)	Shallow (depth <1 m), permanent waterbodies with emergent aquatic sedges and grasses. Water and bottom sediments freeze completely during winter, but the ice melts in early June. The sediments range from sands to organics (10–50 cm deep) overlying silt loam. In deeper water (30–100 cm), *Arctophila fulva* can form sparse to dense stands and is the predominant vegetation. In shallower (<30 cm) water, *Carex aquatilis* and *Eriophorum angustifolium* are dominant, and *Utricularia vulgaris* is common. This ecosystem type is important to waterbirds but could not be mapped separately and is included in both Lowland Lakes and Lowland Wet Sedge Tundra.
Riverine Ecotypes	
Riverine Spruce Forest	Flat areas on inactive floodplains subject to infrequent flooding with vegetation dominated by needleleaf trees. The late-successional forest has an open to closed tree canopy dominated by *Picea glauca*. Soils are well-drained, loamy to gravelly, have moderately thick surface organics, and are acidic. The understory is dominated by *Alnus crispa, Vaccinium uliginosum, V. vitis-idaea, Arctostaphylos rubra, Cornus canadensis, Viburnum edule, Rosa acicularis, Mertensia paniculata,* and feathermosses *(Hylocomium splendens, Rhytidiadelphus triquetrus,* and *Pleurozium schreberi)*.

Riverine Spruce-Balsam Poplar Forest	Flat areas on inactive floodplains subject to infrequent flooding with mixed forests co-dominated by needleleaf and broadleaf trees. The mid-successional forests have an open to closed tree canopy dominated by *Picea glauca* and *Populus balsamifera*. Soils are well-drained, loamy to gravelly, have moderately thick surface organics, and are circumneutral to acidic. The understory is dominated by *Alnus crispa, Vaccinium uliginosum, V. vitis-idaea, Arctostaphylos rubra, Cornus canadensis, Viburnum edule, Rosa acicularis, Equisetum arvense, Epilobium angustifolium, Calamagrostis canadensis,* and feathermosses *(Hylocomium splendens, Rhytidiadelphus triquetrus,* and *Pleurozium schreberi)*.
Riverine Balsam Poplar Forest	Flat areas on inactive floodplains subject to infrequent flooding and that have vegetation dominated by broadleaf forests. Soils are well-drained, loamy to gravelly, have thin surface organics, and are circumneutral. The mid-successional forest has an open to closed canopy dominated by *Populus balsamifera* or occasionally *Betula papyrifera*. The understory has *Alnus crispa, Rosa acicularis, Equisetum arvense, Epilobium angustifolium, Hedysarum alpinum, Calamagrostis canadensis, Galium boreale,* and *Rhytidiadelphus triquetrus*.
Riverine Tall Alder-Willow Shrub	Flat areas on active floodplains subject to frequent flooding that have vegetation dominated by tall shrubs in the boreal region. Soils are well-drained, loamy to gravelly, have very thin surface organics, and are circumneutral. The early succession community has an open to closed tall shrub canopy dominated by *Salix alaxensis, S. arbusculoides, S. monticola,* and *Alnus crispa*. The understory is dominated by *Vaccinium uliginosum, Artemisia tilesii, Calamagrostis canadensis, Petasites frigidus,* and *Equisetum arvense*. Mosses and lichens are not abundant.
Riverine Low Willow Shrub Tundra	Flat to gently sloping areas on active and inactive floodplains in arctic regions subject to variable flooding frequency and that have vegetation dominated by tall and low shrubs. On the narrow zone close to the river, soils are frequently flooded, well-drained, lack organic accumulations, and have vegetation dominated by open tall (>1.5 m) *Salix alaxensis, S. arbusculoides,* and *S. glauca. Alnus crispa* is uncommon. In the understory, *Equisetum arvense, Astragalus alpinus, Aster sibericus,* and *Festuca rubra* are common. On inactive floodplains, where soils have interbedded organic layers and are seasonally saturated, *Salix lanata richardsonii* and *S. pulchra* are dominant. Common understory species include *Salix reticulata, Arctostaphylos rubra, Dryas integrifolia, Arctagrostis latifolia, Equisetum* spp., legumes, *Tomentypnum nitens,* and other mosses.
Riverine Dryas Dwarf Shrub Tundra	Flat areas on inactive floodplains subject to infrequent flooding and that have vegetation dominated by dwarf shrubs. Soils are well-drained, sandy to rocky, have thin surface organics, are alkaline, and are underlain by ice-poor permafrost. The dwarf shrub *Dryas integrifolia* is dominant, and *Salix reticulata, S. lanata richardsonii, Carex bigelowii, Arctagrostis latifolia, Astragalus* spp., *Oxytropis deflexa,* and *Equisetum scirpoides* are common. *Tomentypnum nitens* and *Distichium capillaceum* are common mosses.
Riverine Moist Sedge-Shrub Tundra	Flat areas on inactive floodplains subject to infrequent flooding and that have vegetation co-dominated by sedges and low and/or dwarf shrubs. Soils are moderately well-drained, loamy, have moderately thick surface organics, are circumneutral and underlain by ice-rich permafrost. Vegetation is dominated by *Carex aquatilis* and *Eriophorum angustifolium* with *Dryas integrifolia, Salix lanata richardsonii, S. reticulata,* and *Carex bigelowii, Equisetum* spp., *Tomenthypnum nitens,* and *Campylium stellatum* as common associates

Riverine Wet Sedge Tundra	Flat areas on active and inactive floodplains subject to frequent or infrequent flooding and that have vegetation dominated by sedges. Soils are poorly drained, loamy with moderately thick to thick surface organics, are circumneutral to alkaline, and are underlain by ice-rich permafrost. Surface forms vary from nonpatterned to low-relief, low-centered polygons; the latter are indicative of progressive ice-wedge development. Vegetation is dominated by *Carex aquatilis* and *Eriophorum angustifolium*, although occasionally the willow *Salix lanata richardsonii* is a co-dominant. Other species include *Dupontia fisheri, Equisetum variegatum, Pedicularis sudetica, Campylium stellatum, Scorpidium scorpioides,* and *Limprichtia revolvens*.
Riverine Marsh (not mapped)	Shallow waterbodies (0.1–1.0 m) on active and inactive floodplains subject to occasional flooding with vegetation dominated by emergent aquatic grasses and sedges. Due to shallow water depths, the water freezes to the bottom in the winter, and the ice melts by early June. *Arctophila fulva* usually is found in deeper water while Carex aquatilis is usually found in very shallow water. *Hippuris vulgaris* occasionally is present.
Riverine Barrens	Barren or partially vegetated (<30% cover) areas on active river channel deposits associated with meandering or braided rivers. Frequent sedimentation and scouring restricts establishment and growth of vegetation. Soils are poorly to excessively drained, sandy to gravelly, lack surface organics, are alkaline, and usually have ice-poor permafrost in arctic regions and lack permafrost is boreal regions. Typical pioneer plants include *Salix alaxensis, Deschampsia caespitosa, Chrysanthemum bipinnatum, Epilobium latifolium, Artemisia arctica, Festuca rubra, Arctagrostis latifolia,* and *Trisetum spicatum*.
Riverine Waters	Permanently flooded channels of freshwater rivers and streams, and lakes on inactive floodplains that are subject to occasional flooding. Some stream water flows throughout the year. Peak flooding generally occurs during spring breakup, and the lowest water levels occur during mid-summer. Riverbed materials can be either sand or gravel. Shallow (<1.5 m) or deep lakes usually are associated with old river channels, point bars, and meander scrolls, although some result from thawing of ice-rich permafrost on large floodplains. Some may have connecting channels that flood during high water. Shorelines usually are smooth (lack polygonization).
Coastal Ecotypes	
Coastal Grass and Dwarf Shrub Tundra	Low-lying, salt-affected areas along the coast with vegetation dominated by either grasses or dwarf shrubs. Soils are well-drained, slightly saline, and alkaline. This class includes three vegetation types. On active dunes and beaches, vegetation includes *Elymus arenarius, Chrysanthemum bipinnatum, Puccinellia* spp., *Artemisia tilesii,* and *Salix ovalifolia*. Well-drained inactive tidal flats dominated by dwarf shrub vegetation have *S. ovalifolia, Stellaria humifusa, E. arenarius, Deschampsia caespitosa, Dupontia fisheri, Carex subspathacea,* and *A. tilesii*. Inactive dunes along the Chukchi Sea with slightly saline sandy soils have dwarf shrub vegetation dominated by *Empetrum nigrum, S. ovalifolia, E. arenarius, Lathyrus maritimus, C. bipinnatum*, and lichens. Substantial areas of this mapped class would have been more accurately mapped as Lowland Moist Sedge-Shrub Tundra but could not be adequately differentiated spectrally or by modeling.

Coastal Wet Sedge Tundra	Low-lying, salt-affected areas on tidal flats, deltas, and muddy beaches along the coast that are frequently flooded and have vegetation dominated by sedges. The surface is nonpatterned. Soils are poorly drained, clayey to loamy, usually lack surface organics, and are brackish and alkaline. The soils are underlain by ice-poor permafrost. Vegetation is dominated by *Carex subspathacea, Carex ursina,* and *Puccinellia phryganodes,* with *Dupontia fisheri, Puccinellia andersonii, Cochlearia officinalis,* and *Stellaria humifusa* also common. Non-vascular plants usually are absent. Substantial areas of Lowland Wet Sedge Tundra are included in these mapped areas but could not be adequately differentiated.
Coastal Barrens	Barren or partially vegetated, low-lying, salt-affected areas on tidal flats, deltas, and muddy beaches along the coast that are frequently flooded. Soils are poorly drained, clayey to loamy, usually lack surface organics, and are brackish and acidic to alkaline. The soils are underlain by ice-poor permafrost. Common colonizing plants include *Deschampsia caespitosa, Elymus arenarius, Salix ovalifolia,* and *Stellaria humifusa* in well-drained areas, and *Puccinellia phryganodes, Dupontia fisheri,* and *Carex subspathacea* in wetter areas. This class also includes tundra that has been killed by saltwater intrusions from storm surges and is being colonized by salt-tolerant plants. Newly deposited sediments typically are found on top of a thick organic horizon. These areas have low pH, high salinity, and shallow thaw depths. Common colonizing plants include *Puccinellia phryganodes, Stellaria humifusa, Cochlearia officinalis,* and *Salix ovalifolia*.
Coastal Water	Shallow (~<2 m) estuaries, lagoons, embayments, and tidal ponds along the coast of the Beaufort and Chukchi Seas. Winds, tides, river discharge, and icing create dynamic changes in physical and chemical characteristics. Salinity ranges widely from nearly fresh near rivers to saline in unprotected areas. Tidal ranges normally are small (<0.2 m) along the Beaufort and moderate (0.5–1 m) along the Chukchi Seas, but storm surges produced by winds may raise sea level as much as 2–3 m. Bottom sediments are mostly unconsolidated mud and sand. The ice-free period extends from July until October. Winter freezing generally begins in late September.
Other Ecotypes	
Marine Water (not mapped)	Deep (~>2 m) marine waters of the Beaufort and Chukchi Seas outside of lagoons and barrier islands. Ice coverage is highly variable from permanent pack ice to seasonally ice free areas. Small areas of Marine Water included in Coastal Water for mapping purposes.
Human Modified	Barren or partially vegetated areas resulting from human disturbance. As mapped, the human-modified areas are predominantly roads, pads, and mine pits and overburden.
Cloud, Snow and Ice	Areas with clouds, snow, and ice. The Clouds and Ice Class was combined with the Shadow classes for the final map. Most of the original shadow classes in the input maps in the Brooks Range were recoded to alpine classes based on modeling. Remaining shadow areas are primarily due to clouds in the Brooks Foothills. Aufeis on rivers was classified as Riverine Barrens to avoid creation of a separate Riverine Ice class.

Figure 6.1 Distribution of ecotypes in northern Alaska (Jorgenson and Heiner 2003)



ECOSYSTEM CLASSIFICATION APPROACH:
The classification of local-scale ecosystems (ecotypes) combines physiography (i.e. coastal, floodplain, alpine), topography (DEM modeling), and vegetation structure associated with land cover types derived from satellite image processing to model ecotypes that best partition geomorphic, hydrologic, pedologic, and vegetation characteristics.

MAP INPUT SOURCES:
North Slope Landsat-MSS classification (100-m resolution): Muller et al. (1998).
Gates of the Arctic National Park and Preserve land cover map (30-m): Earth Satellite Corporation and Alaska Natural Heritage Program (1999).
Northwest Areas land cover map (28-m): National Park Service.
Arctic Refuge Landsat-MSS land cover map (50-m), Markon (1986).
Digital elevation model: USGS National Elevation Dataset. Used to create layers for elevation, slope, moisture index, and land position (concavity/convexity index).
Bedrock geology map for northern Alaska: Moore et al. (1994).
Glaciers from USGS maps as compiled by William Manley, U. of Colorado.
Physiographic regions: manually delineated floodplains and coastal regions.

Based on map produced by Torre Jorgenson, ABR, and Michael Heiner, TNC.

Table 6.2. Distribution of ecotypes on the North Slope. More abundant (>5% of area) ecotypes are highlighted in grey. Aquatic habitats (riverine, lake, and coastal water) are further defined and modified in Section 7, under "Freshwater Resident and Anadromous Fish."

Ecotype	**Coastal Plain**		**Foothills**		**Brooks Range**		**North Slope (Total Area)**	
	Area (km²)	**%**	**Area (km²)**	**%**	**Area (km²)**	**%**	**Area (km²)**	**%**
Coastal Barrens	507.7	0.9	9.5	0.0	0.0	0.0	517.2	0.2
Coastal Wet Sedge Tundra	1253.8	2.3	40.9	0.0	0.0	0.0	1294.7	0.6
Coastal Water	6741.6	12.1	301.4	0.3	0.0	0.0	7043.0	3.4
Coastal Grass and Dwarf Shrub Tundra	1320.0	2.4	79.2	0.1	0.0	0.0	1399.2	0.7
Riverine Barrens	548.4	1.0	921.1	1.0	228.3	0.4	1697.8	0.8
Riverine Willow Shrub Tundra	75.9	0.1	920.9	1.0	146.9	0.3	1143.7	0.5
Riverine Moist Sedge-Shrub Tundra	1374.4	2.5	2948.2	3.1	579.5	1.0	4902.1	2.3
Riverine Wet Sedge Tundra	951.3	1.7	914.4	1.0	135.3	0.2	2000.9	1.0
Riverine Waters	554.2	1.0	610.9	0.6	132.1	0.2	1297.2	0.6
Riverine Dryas Dwarf Shrub Tundra	0.0	0.0	4.8	0.0	270.2	0.5	275.0	0.1
Riverine Spruce Forest	0.0	0.0	0.0	0.0	1.8	0.0	1.8	0.0
Lowland Wet Sedge Tundra	11239.0	20.2	3511.4	3.7	643.6	1.1	15394.0	7.4
Lowland Lake	7983.2	14.4	1665.3	1.7	246.3	0.4	9894.9	4.7
Lowland Moist Sedge-Shrub Tundra	12671.0	22.8	6923.7	7.2	0.0	0.0	19595.5	9.4
Lowland Low Birch-Willow Shrub	683.2	1.2	1293.7	1.4	297.6	0.5	2274.6	1.1
Lowland Spruce Forest	0.0	0.0	0.0	0.0	11.5	0.0	11.5	0.0
Upland Tussock Tundra	7480.6	13.5	9682.7	10.1	0.0	0.0	17163.7	8.2
Upland Dryas Dwarf Shrub Tundra	891.5	1.6	551.7	0.6	1089.5	1.9	2532.9	1.2
Upland Shrubby Tussock Tundra	17.6	0.0	33469.3	34.9	10448.6	18.2	43938.2	21.0
Upland Low Shrub Birch-Willow Tundra	1199.5	2.2	23831.6	24.9	11357.8	19.8	36390.4	17.4
Upland Moist Sedge-Shrub Tundra	18.1	0.0	7869.5	8.2	5621.5	9.8	13510.1	6.5
Upland Tall Alder Shrub	0.0	0.0	0.0	0.0	211.8	0.4	211.8	0.1
Upland Spruce Forest	0.0	0.0	0.4	0.0	41.2	0.1	41.6	0.0
Alpine Glaciers	0.0	0.0	0.0	0.0	198.6	0.3	198.6	0.1
Alpine Noncarbonate Barrens	0.0	0.0	62.7	0.1	8133.0	14.2	8195.8	3.9

Alpine Carbonate Barrens	0.0	0.0	0.0	0.0	103.2	0.2	103.2	0.0
Alpine Mafic Barrens	0.0	0.0	0.0	0.0	103.1	0.2	103.1	0.0
Alpine Noncarbonate Dwarf Shrub Tundra	0.0	0.0	51.5	0.1	16060.3	28.0	16112.0	7.7
Alpine Carbonate Dwarf Shrub Tundra	0.0	0.0	0.0	0.0	129.5	0.2	129.5	0.1
Alpine Mafic Dwarf Shrub Tundra	0.0	0.0	0.0	0.0	185.4	0.3	185.4	0.1
Riverine Alder-Willow Shrub	0.0	0.0	0.0	0.0	2.0	0.0	2.0	0.0
Cloud, Snow, and Ice	5.4	0.0	123.7	0.1	1071.7	1.9	1200.8	0.6
Total	**55516.4**		**95788.7**		**57450.1**		**208762.5**	

Figure 6.2. Habitat model for birds in summer.

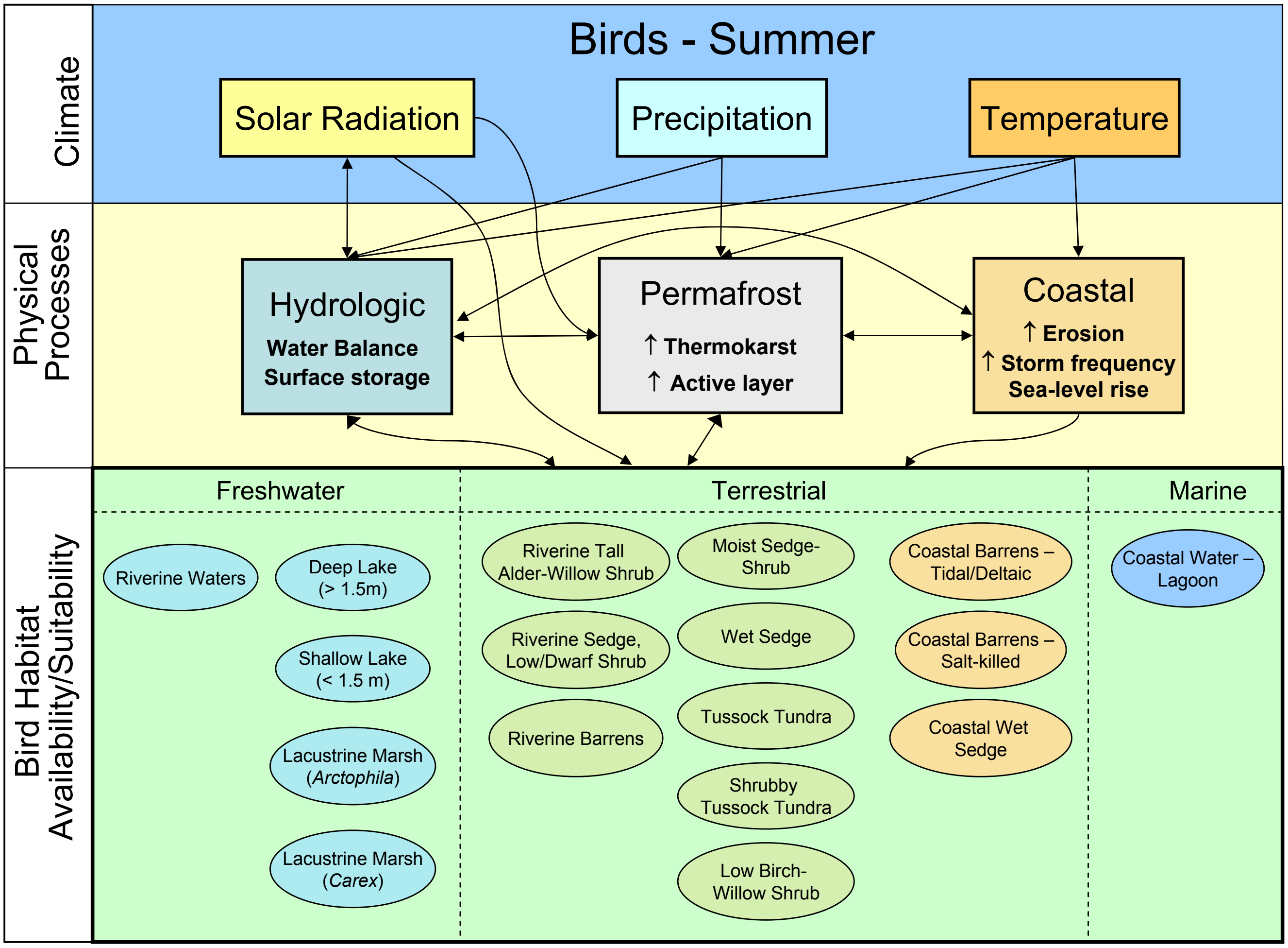


Figure 6.3. Habitat models for fish in summer (above) and winter (below)..

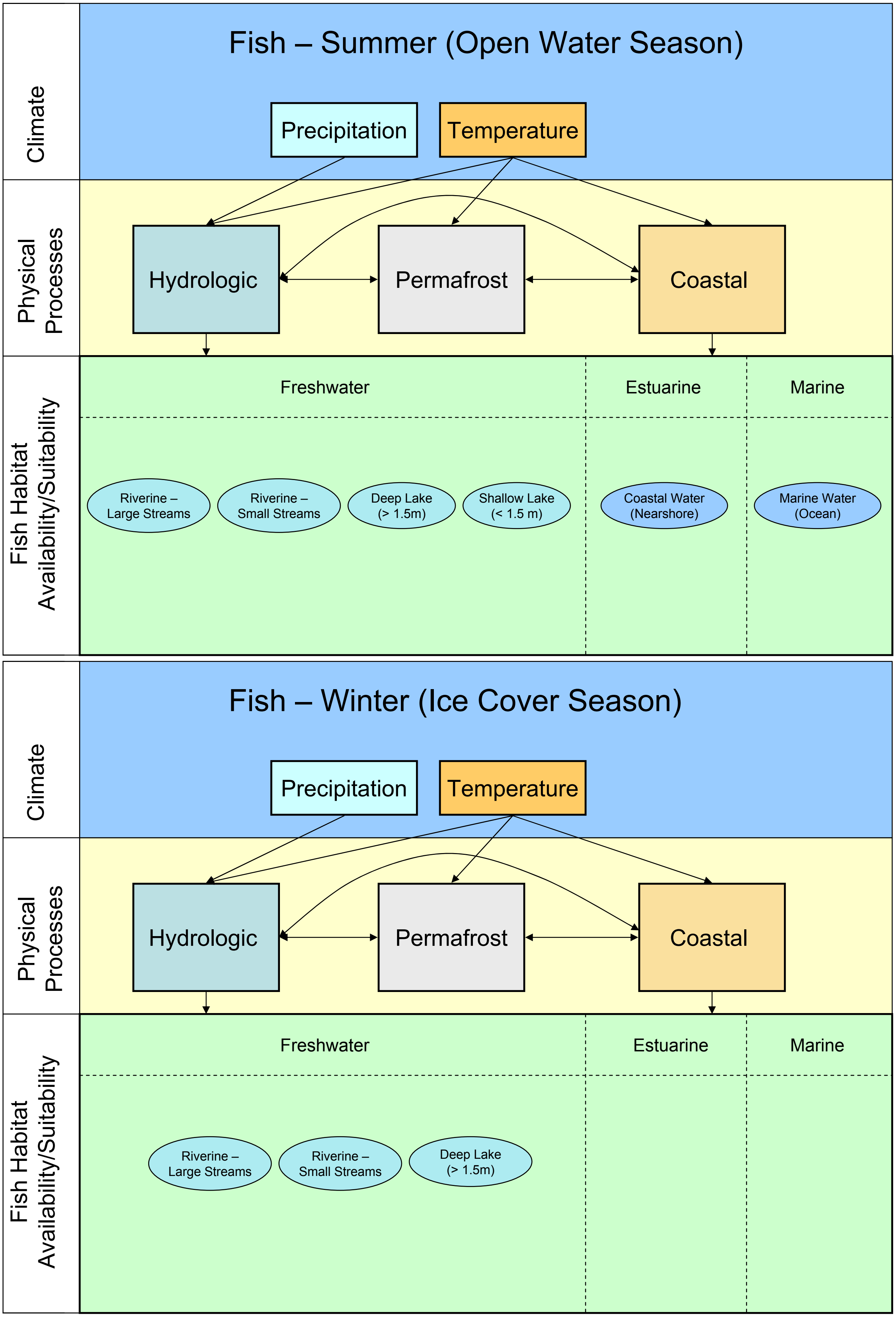
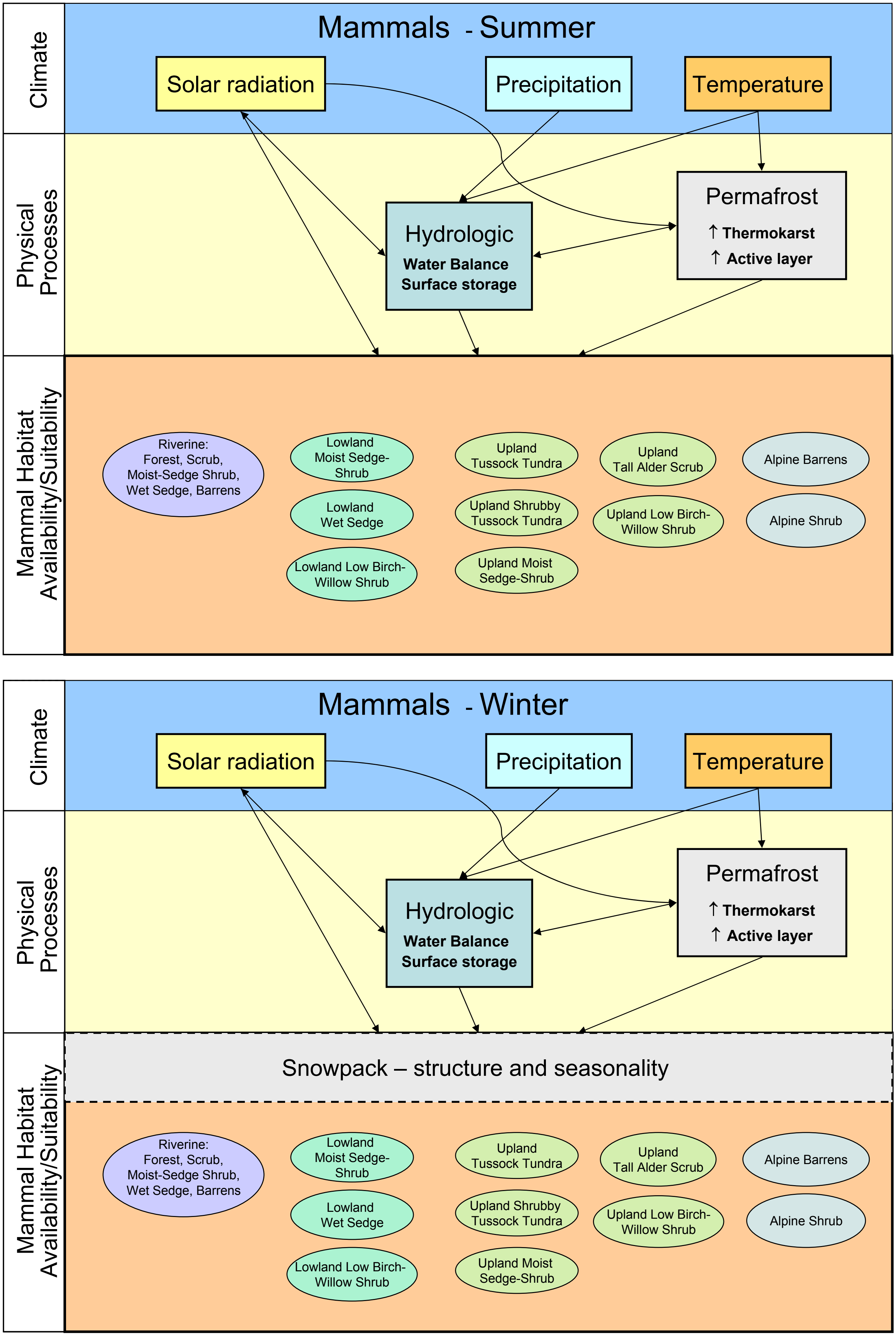


Figure 6.4. Habitat models for mammals in summer (above) and winter (below).



Section 7

Climate Effects on Fish and Wildlife

Birds

Over 80 species of birds regularly use terrestrial and aquatic (non-marine) habitats of the Alaska North Slope for nesting, brood-rearing, and fall staging. Nearly all are migratory, occupying the region for a portion of the interval between May and mid-November, but with the majority present June through August. Some species, such as the arctic tern and red phalarope, migrate over 10,000 km each year from wintering grounds in Antarctica and southern Africa, respectively. Other species arrive from wintering grounds in the Far East, Aleutian Islands, and the Americas. A few species, however, such as ptarmigans and the common raven, will overwinter on the North Slope.

Table 7.1 lists 80 species regularly found on the North Slope and provides basic information related to general diet and habitat preferences. Most of the species (waterfowl, shorebirds, loons, gulls, and terns) that use the Arctic Coastal Plain are wetland-dependent. The diversity of songbirds is greatest in the Brooks Range and Arctic Foothills, where shrub-associated species with taiga affinities (e.g., gray-cheeked thrush, American tree sparrow, white-crowned sparrow, and fox sparrow) reach the northern limits of their range. The Alaska breeding range of many tundra-associated species extends along the Chukchi Sea coast and as far south as the Yukon-Kuskokwim delta; populations of several species, however, are concentrated in northern Alaska. These include: yellow-billed loon, snow goose, king eider, spectacled eider, Steller's eider, red phalarope, stilt sandpiper, ruddy turnstone, red knot, white-rumped sandpiper, pectoral sandpiper, buff-breasted sandpiper, glaucous gull, black guillemot, pomarine jaeger, snowy owl, and Smith's longspur.

Potential Climate Impacts on Birds

The potential for warmer summers and delayed freeze-up would likely improve reproductive success for some bird species. For example, there is evidence suggesting shorebird chick growth and survival is constrained by cold weather conditions (Soloviev et al. 2006), thus a warming climate could increase productivity in these species. A longer open water season should also improve fledging success for species like red-throated loons, for which early freezing temperatures are a significant source of mortality for pre-fledging juveniles (Dickson 1983).

If warmer summers result in drying of wetlands, however, species that rely on shallow lakes and ponds and wet meadows could be profoundly affected. Low-gradient wetlands and shallow lakes on the Arctic Coastal Plain are recharged largely by spring snow melt. As summer progresses, water loss through evapotranspiration is greater than input from precipitation, leading to lake drawdown (Bowling et al. 2003). Without a coincident increase in precipitation, warmer summer temperatures would result in drying. It is not only the net amount of precipitation input but also the timing of those events that will influence wetland habitats. If precipitation increases occur predominantly in winter, then most could be lost to spring runoff, and summer drying of the surface may still occur. A long-term drying trend would likely lead to changes in vegetation community composition and productivity of invertebrates, affecting herbivorous species as well as those dependent on arthropods.

The invertebrate community within arctic lakes is heavily influenced by the presence or absence of fish (Stross et al. 1980); therefore prey availability for aquatic birds is also affected. Changes in flow regimes that prevent fish from entering lakes (see Fish) would be detrimental to piscivores, but reduced competition for invertebrate prey would likely benefit other bird species. Furthermore, increased water temperatures and longer open-water season could increase primary and secondary productivity in aquatic systems, thus increasing food availability.

Despite overall increases in productivity, changes in seasonal patterns of food quantity and quality could be detrimental. The timing of breeding activities for many species of arctic birds appears closely linked to peak insect emergence (Hurd and Pitelka 1954, Holmes 1966, MacLean 1980). Juveniles, in particular, depend on the synchronous seasonal activity peak of surface-available arthropods for growth and survival (Tulp 2008). The timing of insect emergence is closely related to the timing of snowmelt, and might advance with warmer spring temperatures (Høye and Forchhammer 2008, Tulp 2008). If birds can not adjust migration and breeding schedules to optimize exploitation of food resources, a condition of "trophic mismatch" would develop, whereby the phenology of a consumer is out-of-phase with critical food resources (Coppack and Both 2002). Figure 7.1 illustrates some of the potential climate effects on birds, mediated through availability of invertebrate prey.

Beyond short-term phenological response to changing climate, seasonality may have profound long-term consequences for the distribution and abundance of arctic arthropods. Multi-year life cycles occur in many arctic invertebrates (MacLean 1980, Chernov 1985) as an adaptation to temperature-constrained growth rates. The prevalence of multi-year life cycles results in a large standing biomass of larval invertebrates available to predators throughout the summer season. A shift to shorter, even annual, life cycles could substantially influence the availability of larval biomass available to birds during portions of the breeding season, although the relationship is complex (MacLean 1980). In northern Alaska, species diversity of soil invertebrates increases substantially along a climatic gradient away from the colder coastal zone (MacLean 1975), suggesting that longer summer seasons will result in range shifts and changes in the composition of the soil invertebrate fauna.

Observed changes in coastal habitats will likely have a continued influence on bird habitat availability. A longer ice-free season for the Beaufort and Chukchi seas increases the probability of occurrence of storms with high erosive capacity. Indeed, recent studies confirm an increase in coastal erosion rates in the Beaufort Sea region (Mars and Houseknecht 2007, Jones et al. in press). Coastal erosion, accompanied by lake-breaching and salinization of adjacent low-lying areas, may result in changes in vegetation that influence habitat suitability differentially for bird species (Mars and Houseknecht 2001, Flint et al. 2008). Accelerated erosion rates may also be expected to increase the carbon and nutrient input into coastal lagoons (Jorgenson and Brown 2005). Increased stream sediment loads may result from thermokarst-associated bank erosion (Walsh et al. 2005); the persistence of deltaic mud-flat habitat is dependent on the balance of deposition rate vs. inundation from sea level rise. Hypothesized climate effects on the availability of coastal bird habitat are illustrated in Figure 7.2.

Figure 7.1. Hypothesized climate influences on birds, as mediated via invertebrate prey availability.

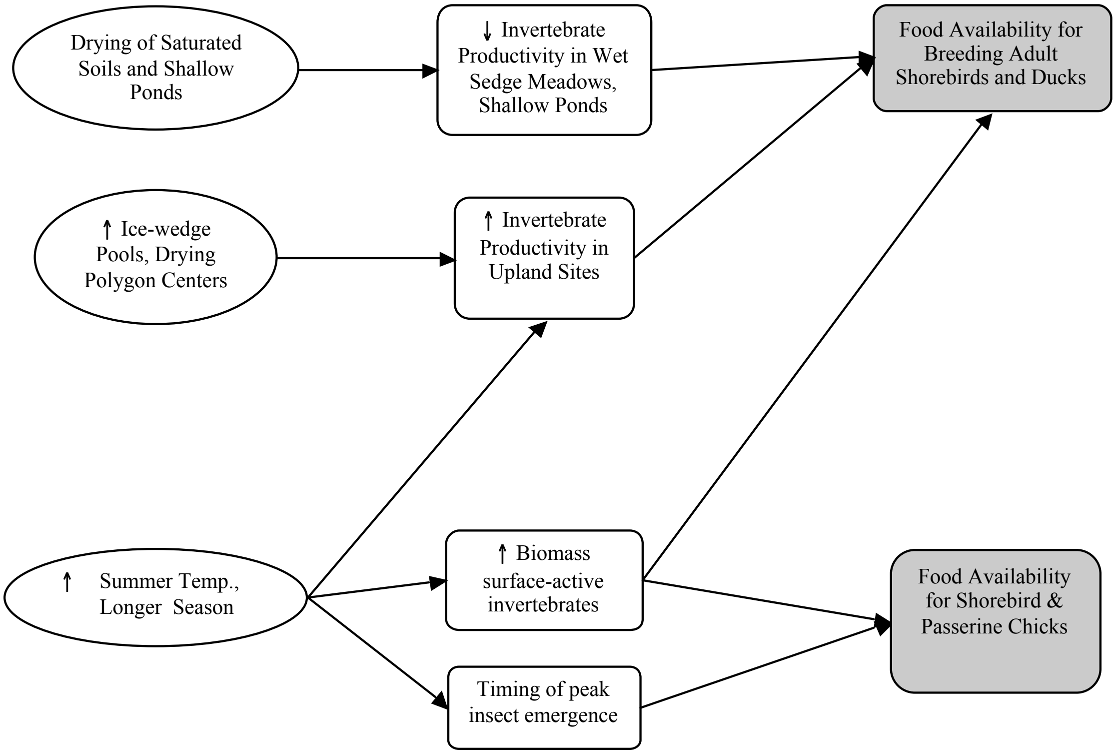


Figure 7.2. Hypothesized climate influences on coastal bird habitat availability.

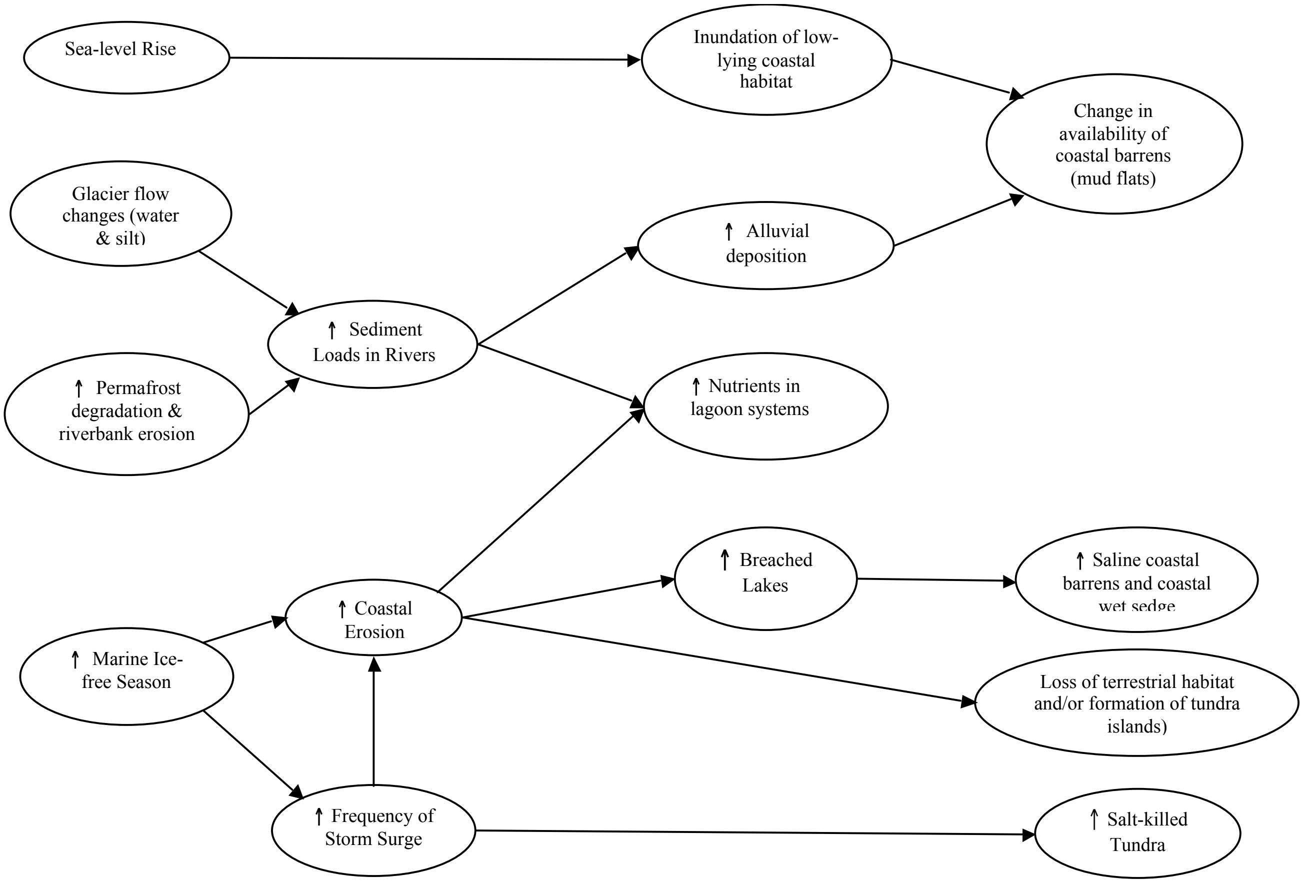


Table 7.1. Diet (Poole 2005) and principal habitat affinities (TNC and ABR Inc., unpublished) of birds typical of arctic Alaska.

Common Name	**Diet[1]**	**Habitat**
Red-throated Loon	P	Lowland Wet Sedge Tundra, Lacustrine Marsh, Riverine Marsh
Pacific Loon	P	Lacustrine Marsh, Lowland Wet Sedge Tundra, Lowland Lake
Yellow-billed Loon	P	Lowland Lake, Riverine Waters, Lacustrine Marsh
Red-necked Grebe	P, I	Lacustrine Marsh, Lowland Lake
Tundra Swan	H	Lowland Moist Sedge-Shrub Tundra, Lowland Lake, Lowland Wet Sedge Tundra
Gr. White-fronted Goose	H	Lowland Wet Sedge Tundra, Lacustrine Marsh, Lowland Lake
Snow Goose	H	Coastal Wet Sedge Tundra, Lowland Wet Sedge Tundra
Canada Goose	H	Lowland Moist Sedge-Shrub Tundra, Lowland Wet Sedge Tundra, Lowland Lake
Brant	H	Coastal Wet Sedge Tundra, Lowland Lake, Lowland Wet Sedge Tundra
Green-winged Teal	H, I	Lowland Moist Sedge-Shrub Tundra, Lowland Wet Sedge Tundra
Mallard	H, I	Lowland Wet Sedge Tundra, Lowland Lake
Northern Shoveler	H, I	Coastal Wet Sedge Tundra, Riverine Marsh, Lowland Lake
Northern Pintail	H, I	Lowland Moist Sedge-Shrub Tundra, Lacustrine Marsh, Lowland Wet Sedge Tundra
Greater Scaup	H, I	Riverine Wet Sedge Tundra, Lacustrine Marsh, Lowland Lake
Lesser Scaup	I	Lowland Lake, Lowland Wet Sedge Tundra
Steller's Eider	I	Lacustrine Marsh, Lowland Lake, Lowland Wet Sedge Tundra
Spectacled Eider	H, I	Lowland Wet Sedge Tundra, Lacustrine Marsh, Lowland Lake
King Eider	H, I	Lacustrine Marsh, Lowland Wet Sedge Tundra, Coastal Wet Sedge Tundra
Common Eider	I	Coastal Water, Coastal Barrens, Lowland Wet Sedge Tundra
Harlequin Duck	I	Riverine Waters, Riverine Low Willow Shrub Tundra, Riverine Tall Alder-Willow Shrub
Long-tailed Duck	H, I	Lowland Wet Sedge Tundra, Lowland Lake, Lacustrine Marsh
White-winged Scoter	I	Lowland Lake, Riverine Waters
Red-breasted Merganser	I, P	Riverine Waters, Coastal Barrens
Northern Harrier	C	Riverine Dryas Dwarf Shrub Tundra
Rough-legged Hawk	C	Upland Bluffs, Upland Moist Sedge-Shrub Tundra, Upland Dryas Dwarf Shrub Tundra
Golden Eagle	C	Upland Bluffs, Alpine Mafic Dwarf Shrub Tundra
Peregrine Falcon	C	Upland Bluffs, Riverine Dryas Dwarf Shrub Tundra
Gyrfalcon	C	Upland Bluffs, Lowland Wet Sedge Tundra, Alpine Dryas Dwarf Scrub Tundra
Willow Ptarmigan	H	Lowland Moist Sedge-Shrub Tundra, Lowland Wet Sedge Tundra, Upland Shrubby Tussock Tundra
Rock Ptarmigan	H	Lowland Wet Sedge Tundra, Lowland Moist Sedge-Shrub Tundra, Upland Moist Sedge-Shrub Tundra
Sandhill Crane	H, I, C	Lowland Wet Sedge Tundra, Lowland Moist Sedge-Shrub Tundra

Black-bellied Plover	I	Lowland Wet Sedge Tundra, Lowland Moist Sedge-Shrub Tundra, Coastal Barrens
American Golden-Plover	I	Lowland Wet Sedge Tundra, Lowland Moist Sedge-Shrub Tundra, Alpine Mafic Dwarf Shrub Tundra
Semipalmated Plover	I	Riverine Barrens, Coastal Barrens, Upland Dryas Dwarf Scrub Tundra
Wandering Tattler	I	Riverine Waters, Riverine Barrens
Upland Sandpiper	I	Lowland Wet Sedge Tundra, Upland Moist Sedge-Shrub Tundra
Whimbrel	I, F	Upland Moist Sedge-Shrub Tundra, Upland Dryas Dwarf Shrub Tundra, Upland Shrubby Tussock Tundra
Bar-tailed Godwit	I, F	Lowland Wet Sedge Tundra, Coastal Barrens, Lowland Moist Sedge-Shrub Tundra
Ruddy Turnstone	I	Coastal Barrens, Lowland Moist Sedge-Shrub Tundra, Lowland Wet Sedge Tundra
Surfbird	I	Alpine Mafic Dwarf Shrub Tundra, Alpine Noncarbonate Dwarf Shrub Tundra
Red Knot	I, H	Coastal Barrens, Upland Dryas Dwarf Shrub Tundra, Lowland Wet Sedge Tundra
Sanderling	I	Coastal Barrens, Lowland Wet Sedge Tundra
Semipalmated Sandpiper	I	Coastal Barrens, Lowland Wet Sedge Tundra, Lowland Moist Sedge-Shrub Tundra
Western Sandpiper	I	Coastal Barrens, Lowland Moist Sedge-Shrub Tundra, Upland Moist Sedge-Shrub Tundra
Least Sandpiper	I	Coastal Barrens, Lowland Moist Sedge-Shrub Tundra, Lowland Wet Sedge Tundra
White-rumped Sandpiper	I	Lowland Moist Sedge-Shrub Tundra, Lowland Wet Sedge Tundra, Coastal Wet Sedge Tundra
Baird’s Sandpiper	I	Lowland Moist Sedge-Shrub Tundra, Coastal Wet Sedge Tundra, Riverine Barrens
Pectoral Sandpiper	I	Lowland Wet Sedge Tundra, Lowland Moist Sedge-Shrub Tundra, Upland Moist Sedge-Shrub Tundra
Dunlin	I	Lowland Wet Sedge Tundra, Lowland Moist Sedge-Shrub Tundra, Upland Moist Sedge-Shrub Tundra
Stilt Sandpiper	I	Lowland Wet Sedge Tundra, Lowland Moist Sedge-Shrub Tundra, Coastal Wet Sedge Tundra
Buff-breasted Sandpiper	I	Lowland Moist Sedge-Shrub Tundra, Upland Moist Sedge-Shrub Tundra, Lowland Wet Sedge Tundra
Long-billed Dowitcher	I	Lowland Wet Sedge Tundra, Lowland Moist Sedge-Shrub Tundra, Coastal Wet Sedge Tundra
Wilson’s Snipe	H, I	Lowland Wet Sedge Tundra, Lowland Spruce Forest, Upland Moist Sedge-Shrub Tundra
Red-necked Phalarope	I	Lowland Wet Sedge Tundra, Lowland Moist Sedge-Shrub Tundra, Lowland Lake
Red Phalarope	I	Lowland Wet Sedge Tundra, Lowland Moist Sedge-Shrub Tundra, Lowland Lake
Pomarine Jaeger	C	Lowland Wet Sedge Tundra, Upland Moist Sedge-Shrub Tundra, Lowland Moist Sedge-Shrub Tundra

Parasitic Jaeger	C	Lowland Wet Sedge Tundra, Lowland Moist Sedge-Shrub Tundra, Upland Moist Sedge-Shrub Tundra
Long-tailed Jaeger	C, I	Lowland Wet Sedge Tundra, Lowland Moist Sedge-Shrub Tundra, Upland Moist Sedge-Shrub Tundra
Glaucous Gull	C, P, A	Lowland Lake, Lowland Wet Sedge Tundra, Lowland Moist Sedge-Shrub Tundra
Sabine’s Gull	H, I, P	Lowland Lake, Lowland Wet Sedge Tundra, Coastal Wet Sedge Tundra
Arctic Tern	I, P	Coastal Barrens, Coastal Wet Sedge Tundra, Lowland Moist Sedge-Shrub Tundra
Snowy Owl	C	Lowland Wet Sedge Tundra, Upland Moist Sedge-Shrub Tundra
Short-eared Owl	C	Lowland Wet Sedge Tundra, Riverine Wet Sedge Tundra
Common Raven	H, C, P, A	Human Modified, Upland Bluffs
American Dipper	I, P	Riverine Waters
Bluethroat	I	Riverine Willow Scrub Tundra, Upland Shrub Birch-Willow Tundra
Northern Wheatear	H, I	Riverine Dryas Dwarf Shrub Tundra, Upland Dryas Dwarf Shrub Tundra, Alpine Carbonate Barrens
Gray-cheeked Thrush	I, F	Riverine Low Willow Shrub Tundra, Upland Tall Alder Shrub, Upland Spruce Forest
Yellow Wagtail	I	Riverine Low Willow Shrub Tundra, Riverine Tall Alder-Willow Shrub
American Pipit	I	Alpine Carbonate Barrens, Alpine Noncarbonate Barrens, Alpine Noncarbonate Dwarf Shrub Tundra
Northern Shrike	I, C	Riverine Low Willow Shrub Tundra, Upland Tall Alder Shrub, Upland Low Birch-Willow Shrub Tundra
American Tree Sparrow	I	Riverine Low Willow Shrub Tundra, Upland Tall Alder Shrub,Upland Low Birch-Willow Shrub Tundra
Savannah Sparrow	I, S	Lowland Moist Sedge-Shrub Tundra
Fox Sparrow	I	Upland Tall Alder Shrub, Riverine Low Willow Shrub Tundra, Riverine Tall Alder-Willow Shrub
White-crowned Sparrow	I, S	Upland Tall Alder Shrub, Riverine Low Willow Shrub Tundra
Lapland Longspur	I, S	Lowland Moist Sedge-Shrub Tundra, Lowland Wet Sedge Tundra,Upland Dryas Dwarf Shrub Tundra
Smith’s Longspur	I, S	Lowland Wet Sedge Tundra, Riverine Low Willow Shrub Tundra, Lowland Moist Sedge-Shrub Tundra
Snow Bunting	I, S	Human Modified, Lowland Wet Sedge Tundra, Coastal Barrens
Common Redpoll	I, S	Riverine Low Willow Shrub Tundra, Lowland Low Birch-Willow Shrub
Hoary Redpoll	I, S	Riverine Low Willow Shrub Tundra, Upland Low Birch-Willow Shrub Tundra,Upland Shrubby Tussock Tundra

1. H = herbivore (shoots, leaves), F = herbivore (fruit), S = herbivore (seeds), I = invertebrates, C = carnivore (mammals/birds), P = piscivore, A = anthropogenic

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Freshwater Resident and Anadromous Fish of the North Slope of Alaska

Aquatic habitats on the North Slope are extreme environments for fish. North Slope streams and lakes are characterized by low average temperatures, low prey densities, short open water periods each year, and limited overwintering habitat for fish (Craig 1989). During summer, strong freshwater flow from North Slope rivers mixes with coastal waters to produce a narrow nearshore band of relatively warm, brackish water that provides rich foraging opportunities for anadromous fishes. During winter, however, only the two largest rivers (Colville and Sagavanirktok), maintain sufficient flow to create a brackish water interface with the marine system (Craig and McCart 1975). The temperature of the marine water during winter falls to about -2 °C (O'Rourke 1974, Craig and Haldorson 1981), which is too cold for any of the anadromous species (Black 1957, DeVries and Cheng 2005). These environmental factors act together to impose unique constraints on fish populations in the region. A number of species, however, have adapted to thrive in these habitats.

Species in the family Salmonidae are perhaps the most diverse group of fishes that use North Slope freshwater habitats. They include lake trout *Salvelinus namaycush* and Arctic char *S. alpinus* that live exclusively in freshwater lake systems (Morrow 1980, Reist et al. 1997). Arctic grayling *Thymallus arcticus* and round whitefish *Prosopium cylindraceum* live in lakes and rivers and are rarely encountered in coastal waters. Many Dolly Varden *S. malma* populations are anadromous, migrating into nearshore coastal waters to feed during the summers and returning to freshwater rivers to spawn in the fall and to overwinter (McCart 1980). Other Dolly Varden populations, however, live entirely in freshwater. Similar to Dolly Varden, both anadromous and freshwater resident populations of least cisco *Coregonus sardinella* exist on the North Slope (Seigle 2003, Moulton et al. 1997). Broad whitefish *C. nasus*, and humpback whitefish *C. pidschian* populations are apparently all anadromous, although freshwater populations may exist in certain lakes or in upstream reaches of the Colville River (Craig 1989). Arctic cisco *C. autumnalis* encountered on the North Slope of Alaska are entirely anadromous and return to the Mackenzie River in northern Canada to spawn (Fechhelm et al. 2007). Chum salmon *Oncorhynchus keta*, pink salmon *O. gorbuscha*, and other Pacific salmon species are encountered in low numbers in nearshore coastal waters of the Beaufort Sea each summer (Stephenson 2005). Small numbers of spawning chum and pink salmon are regularly observed in the Colville River and occasionally observed in other streams as well. It is not clear at this time whether Pacific salmon in North Slope drainages are self sustaining populations or strays from populations in Kotzebue Sound or farther south.

A number of non-salmonid fishes of several families have also adapted to aquatic habitats on the North Slope. Ninespine stickleback *Pungitius pungitius* populations can be either resident or anadromous (Morrow 1980). They are found in freshwater and nearshore habitats across the North Slope, but never too far inland, and they play a critical role in the food webs of piscivorous birds (Poole 2005) and fish. Burbot *Lota lota* are common in stream and lake habitats of the western North Slope (Morris 2003), but they are rarely captured in coastal waters. Blackfish *Dallia pectoralis*, northern pike *Esox lucius*, slimy sculpin *Cottus cognatus*, and longnose sucker *Catostomus catostomus* are also found in freshwater habitats of the western North Slope.

Table 7.2 lists North Slope freshwater fish species and categorizes their use of major habitat classes, as defined below:

- Large streams are those with sufficient flow to allow instream (springs and deep areas) and estuarine (river delta) overwintering habitat. On the North Slope, only two rivers, the Colville and Sagavanirktok Rivers, fall into this habitat category.
- Small streams are those waterbodies that do not have sufficient flow to develop estuarine habitats. Some of these streams may provide instream overwintering habitat in the form of springs and deep pools.
- Deep lakes are those lakes whose depth allows for year-round use by fish. These lakes may be isolated or stream-connected.
- Shallow lakes do not provide overwintering habitat but may be used by fish during the open water season if there is access.
- Coastal water (Nearshore) is marine water that is somewhat warmer and of lower salinity than the ocean, due to fresh water inflow during the open water season (e.g., lagoons, river deltas, and marine waters close to shore). These habitats take on fully marine characteristics of salinity and temperature during winter, which

precludes their use by freshwater or anadromous species during that season. Lagoon systems may actually reach higher salinity and colder temperatures than open marine systems during winter.
- Coastal water (Ocean) is fully marine habitat that does not allow overwintering of any salmonid species because of low water temperatures.

Potential Climate Impacts on Fish

The Intergovernmental Panel on Climate Change (IPCC) and the Arctic Climate Impact Assessment (ACIA) both identified the Arctic as an area where climate effects will most readily be observed (IPCC 2007, ACIA 2005). Furthermore, they suggest that aquatic systems within the region will act as keystone indicators of the timing, rate, intensity, and effects of the change. Both freshwater and anadromous fish are important components of these aquatic systems and are particularly vulnerable to effects from climate change (Reist et al. 2006a).

The insight gained from monitoring climate impacts to fish and their habitats will facilitate greater understanding of possible impacts to other aquatic biota and the humans that use these resources.

A warming climate is likely to increase ecosystem productivity and result in increased biomass and yields of many targeted species (Reist et al. 2006b). The magnitude of change in ecosystem productivity and fish biomass will depend on local conditions and population tolerances. Freshwater resident fish in lakes may potentially show increased production in comparison to those populations in flowing water. Increased productivity in nearshore areas could boost returns of anadromous fish. However, increased productivity in freshwater systems could lead to a decrease in the frequency of anadromy followed by a decrease in population production. An anadromous life history strategy provides for larger individual and population sizes (Gross et al. 1988), but increased freshwater productivity may allow some populations to forego migration to saltwater and switch to a freshwater resident form. Although the resident population would be sustainable, it would not likely attain the production levels attained from the anadromous strategy.

As water temperatures rise past optima, biomass and yields could decrease and lead to differing rates and locations of colonization, extinction, competition, and productivity (Tonn 1990). Increasing temperatures will have a direct effect on available habitats, most notably in populations reliant on thermal refugia below the thermocline in lakes (Reist et al. 2006c). Warmer waters may also affect the prevalence of diseases and parasites (Reist et al. 2006b). Longer term changes may also lead to a decoupling of environmental cues, such as photoperiod and water temperature, that may drive major life history actions, including gonadal maturation and fertilization success (Reist et al. 2006c). Changes in groundwater flows may affect the type and amount of instream sediment and substrate, alter chemical composition, and change temperature of the water. Changes to the physical and chemical properties of water may lead to changes in incubation success and availability of overwintering habitat. In addition, groundwater can alter instream habitat structure by its influence on ice formation. Changes in both groundwater and precipitation runoff may affect the flow regimes of rivers and streams and result in changes to the migration patterns of freshwater and anadromous fish (Prowse et al. 2006). An increase in sea level and coastal erosion may also disrupt traditional migration patterns or make current habitats unavailable (ACIA 2005).

Fisheries that rely on North Slope species must also change as the fish populations adapt to new conditions (Reist et al. 2006b). With changes in the local environment, fish abundance, species composition, and individual sizes of targeted fish, traditional access may not be feasible and harvest methods and timing may need to change. These changes could negatively impact small scale fisheries within local villages. Alternatively, changing environment and fish abundance may provide better access to fishing sites or opportunities for new fisheries that target colonizing species. Flexible and adaptive approaches will be critical to future successful management (Peterson et al. 1997).

Table 7.2 Life history strategy[1] and seasonal habitat use by North Slope freshwater fish.

Species[2]		**LC**		**AC**	**RW**	**BW**	**HW**	**LT**	**CH**	**DV**		**PS**	**CS**	**AG**	**NS**		**Total species & life histories by habitat**
	Life history	A	R	A	R	A	A	R	R	A	R	A	A	R	A	R	
Season	**Habitat[3]**																
Open water	Large streams	X		X	X	X	X			X	X	X	X	X	X	X	**12**
	Small streams				X					X	X			X	X	X	**6**
	Deep lakes	X	X		X	X	X	X	X					X	X	X	**10**
	Shallow lakes	X				X	X								X	X	**5**
	Coastal water (Nearshore)	X		X		X	X			X		X	X		X	X	**9**
	Coastal water (Ocean)			X						X		X	X				**4**
Ice cover	Large streams	X		X	X	X	X			X	X	X	X	X	X	X	**12**
	Small streams				X					X	X			X	X	X	**6**
	Deep lakes		X		X	X	X	X	X					X	X	X	**9**
Total habitats by species & life history		**5**	**2**	**4**	**6**	**6**	**6**	**2**	**2**	**6**	**4**	**4**	**4**	**6**	**8**	**8**	

1. Generalizations include adult and juvenile life stages. Least cisco, Dolly Varden char, and ninespine stickleback populations exhibit two life history strategies (R = freshwater resident, A = anadromous). Other species are considered to exhibit only one life history strategy.
2. Species codes:
   LC = Least cisco
   AC = Arctic cisco
   RW = Round whitefish
   BW = Broad whitefish
   HW = Humpback whitefish
   LT = Lake trout
   CH = Arctic char
   DV = Dolly Varden char
   PS = Pink salmon
   CS = Chum salmon
   AG = Arctic grayling
   NS = Ninespine stickleback
3. See text for description of habitat types.

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Figure 7.3 Generalized examples of hypothesized influences from a deepening active layer (A) and a decrease in aufeis (B) on adult fish riverine habitat during summer and fall under increased temperature and increased precipitation scenarios (length of arrows unrelated to degree of influence). Freshwater input to rivers based on: 1) precipitation (direct and from runoff); 2) groundwater (precipitation filtered through the active layer); 3) springs (groundwater from below the permafrost); 4) aufeis (in channel frozen precipitation, groundwater, and spring water released during the open water season); and 5) glaciers.

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Mammals

Table 7.3 lists 26 mammal species found in the Alaskan Arctic from the crest of the Brooks Range north to the Beaufort Sea. The mammals are grouped into 7 classes based on life history strategies, including food strategies (herbivore or carnivore/omnivore), winter strategies (active surface, active subnivean, dormant), and reproductive strategies (relative length of gestation/lactation, relative number and size of litters per year and whether offspring are altricial or precocial). Four classes are herbivores (H1, H2, H3 and H4), and 3 are carnivore/omnivores (C1, C2, C4). The table lists mammal species associated with each class, the attributes used to define each class, and summarizes ecological requirements in the winter and growing seasons for each class.

Table 7.4 uses these class designations to summarize hypothesized effects of climate change on classes of mammals in the winter and summer (growing) season.

Figures 7.4 and 7.5 graphically summarize possible effects of climate change on arctic mammals (grouped by species class from Table 7.3) in winter and during the growing season respectively

Table 7.3. Arctic mammals grouped by life history strategy.

Class	Species	Diet[1]	Winter Strategy[2]	Reproductive Strategy[3]	Class Attributes	Requirements for Survival and Successful Reproduction
H1	Collared lemming Brown lemming Red backed vole Singing vole Tundra vole	H	S	SMA	Small herbivore, subnivean in winter, short gestation + lactation, multiple medium to large litters, altricial young.	Winter: access to stored food, hoar frost layer, snow cover. Summer: access to abundant forage, natal nests, escape cover.
C1	Shrews (3 species) Least weasel	C	S	SMA	Small carnivore, active/subnivean in winter, short gestation + lactation, single/multiple medium to large litter, altricial young.	Winter: constant access to numerous prey; natal nests. Summer: constant access to numerous prey; natal nests.
H2	Arctic ground squirrel Arctic marmot	H	D	MSA	Medium-sized herbivore, dormant in winter, medium gestation + lactation, single medium to large litter, altricial young.	Winter: winter/natal denning habitat, adequate snow. Summer: access to forage, escape cover (burrows).
C2	Ermine Mink Arctic fox Red fox River otter Wolverine Wolf	C	A	MSA	Medium to large carnivore, active in winter, medium lactation + gestation, single medium to large litter, altricial young	Winter: access to prey, natal dens. Summer: access to prey, natal and post natal dens.

H3	Snowshoe hare	H	A	SSP	Medium sized herbivore, active in winter, short to long gestation + short lactation, single/ multiple small to medium litters, precocial young.	Winter: access to forage, shelter. Summer: access to forage, shelter.
	Porcupine					
H4	Caribou	H	A	LSP	Medium to large herbivore, active in winter, long gestation + lactation, single birth of 1-2 offspring, precocial young.	Winter: access to forage; energy conserving conditions (low snow). Summer: access to high quality abundant forage and insect relief
	Moose					
	Dall sheep					
	Muskox					
C4	Grizzly bear	C	D	VSA	Large carnivore/ omnivore, dormant in winter, delayed implantation + very long lactation, single birth of 1-3 offspring, altricial young.	Winter: access to winter/natal denning habitat. Summer: access to food resources
	Polar bear					

1. Diet:

H = Herbivore

C = Carnivore/omnivore

2. Winter strategy:

A = Active in winter on surface

S = Active under snow (subnivian)

D = Dormant in winter den

3. Reproductive strategy:

SMA = short gestation/lactation; multiple medium to large litters; altricial young

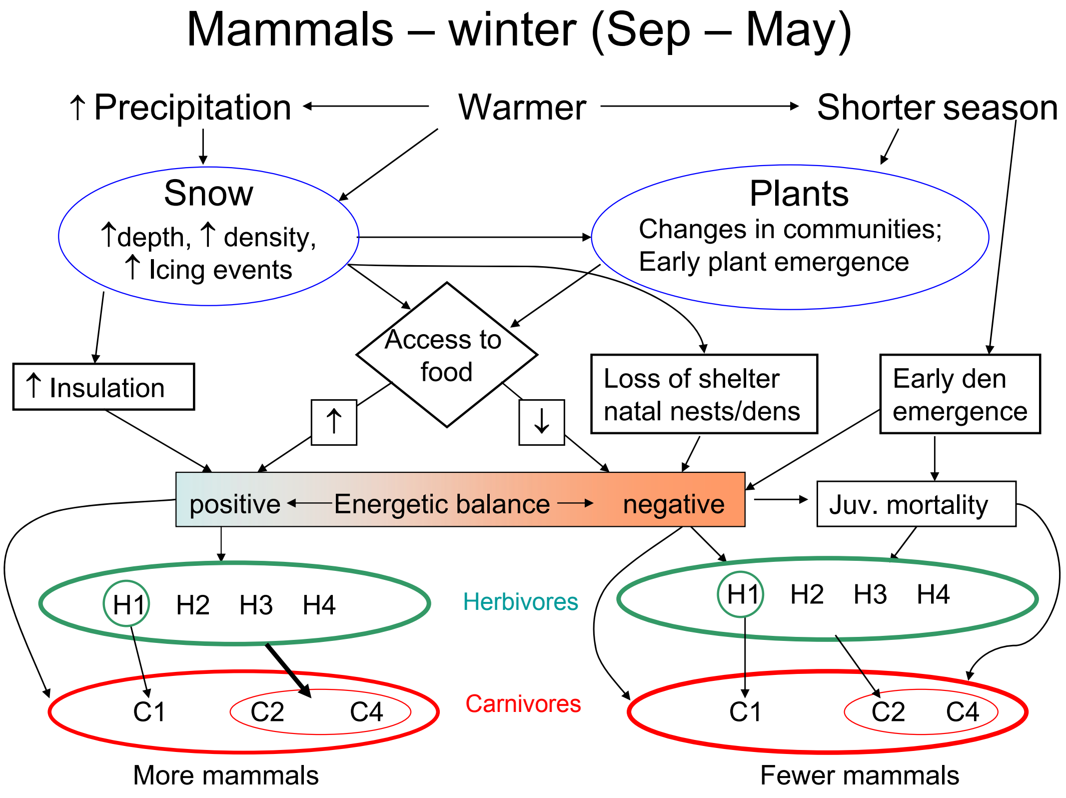
MSA = medium gestation/lactation; single medium/large litter; altricial young

SSP = short to long gestation+short lactation; single/multiple small to medium litters; precocial young

LSP = long gestation/lactation; single birth of 1-2 offspring; precocial young

VSA = delayed implantation + very long lactation and period of parental care; single birth of 1-3 offspring; altricial young

Figure 7.4 Possible effects of climate change on arctic mammals in winter (above) and the growing season (below).



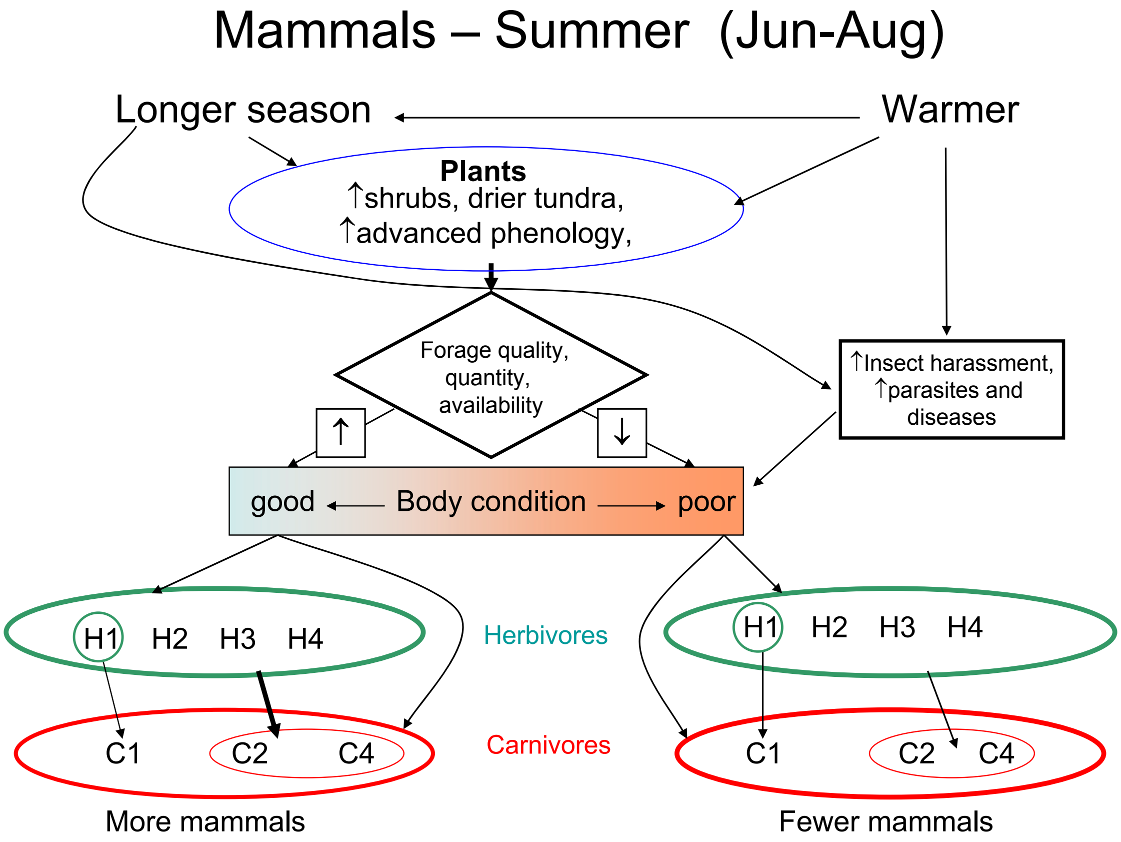


Table 7.4. Possible effects on arctic mammals under scenarios of changing climate.

Class[1]	**Winter: warmer, deeper snow, shorter season:**	**Summer: warmer, drier, longer season:**
H1	• More icing events, deeper dense snow, reduced snow in early and late winter • Loss of hoar frost layer = habitat loss; reduced access to stored food, runways, natal nests. • Lack of insulation in early and late winter = lower survival and reproduction	• Shifts in plant communities; shifts in phenology, increased plant biomass, degrading permafrost, shifts in hydrology, early summer flooding, more diseases and parasites, reduction in insect relief habitat (aufeis and snow fields). • Drier plant communities= benefit red-backed + singing voles, collared lemmings, but hurt tundra voles + brown lemmings. • Flooded burrows = lower survival + reproduction. • More disease/parasites = lower survival + reproduction.
C1	• Change in access to prey = low reproduction and survival. • Prey loss critical: small carnivores need constant access to food.	• Change in access to prey = low reproduction and survival. • Prey loss critical: small carnivores need constant access to food. • Increase in disease/parasites = lower reproduction+survival.
H2	• Early den emergence = death of offspring, decreased survival of adults.	• Change in food types and/or availability = change in abundance. • Shifts in phenology may reduce access to high quality forage. • Increased parasites/disease = lower production + survival.
C2	• Less food during pregnancy+ lactation = smaller litters + lower survival.	• Less summer food = lower production + survival. • Increased parasites/disease = lower production + survival.
H3	• Reduced forage availability = smaller + fewer litters.	• Increased plant biomass + shift to shrubs = increased productivity + survival • Increased parasites/disease = lower production + survival
H4	• Reduced access to forage, increased energy expenditure = fewer calves born and increased adult mortality.	• Increased plant biomass = increased production + survival. • Shift in plant composition to shrubs = increase summer forage but decrease winter forage. • Shifts in phenology may reduce access to high quality forage during calving season = decreased successful reproduction • Increase in lungworm infections + other diseases = lower reproduction + survival • Reduced access to insect relief habitat (snow + aufeis) = stress + reduced body condition + increased parasites.
C4	• Early den emergence: death of neonatal cubs; lower survival of adults. • Loss of denning habitat:	• Changes in plant communities and prey populations = shifts in diet which may or may not affect successful reproduction and survival. • Increase in parasites/disease = lower production + survival.

1. Species class codes from Table 7.3.