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Alaska's Beaufort Coastal Corridor

Persistence of Ecological Values in a Changing Landscape

Benjamin Sullender

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I. Introduction

As development interest intensifies on the North Slope and in the nearshore waters of the Beaufort Sea, important areas need to be identified and prioritized to minimize impact to the highest-value habitats relied on by wildlife and subsistence hunters. Arctic wildlife increasingly faces broad-scale anthropogenic stressors, primarily oil and gas development, vessel traffic, and climate change.

This report builds on previous regional work such as the Ecological Atlas of Alaska's Western Arctic (Sullender and Smith 2016), the Habitat Conservation Strategy for the National Petroleum Reserve — Alaska (Smith et al. 2011), and the Ecological Atlas of the Bering, Chukchi, and Beaufort Seas (Smith et al. 2017). This report expands upon these efforts by integrating scientific information across terrestrial and marine ecosystems, combining quantitative and qualitative assessments of ecological importance, and providing a finer-scale, temporally explicit analysis. Ecological persistence is a focal theme: by downscaling biological data, examining observed changes in species distribution, and describing potential future changes through the lens of driving forces, this analysis seeks to address where, how, and why significant changes are occurring. Because stressors are also discussed, this report helps decision-makers, Arctic experts, and interested members of the general public understand regional conservation and development within the context of a rapidly changing landscape.

Study Area

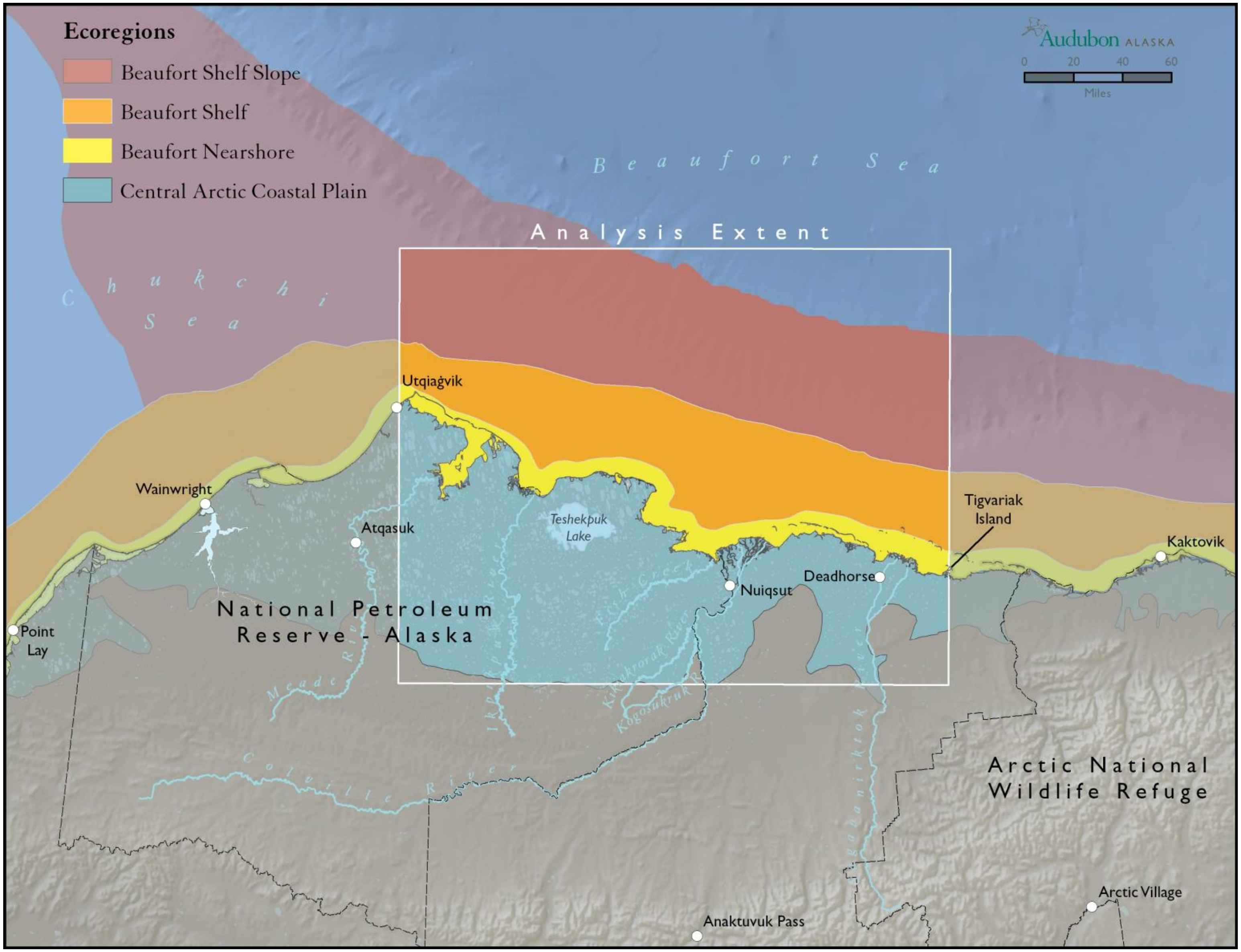
This report is geographically focused on the coastal and nearshore region of the Beaufort Sea, and includes adjacent terrestrial upland and marine offshore regions to look holistically at connectivity and potential impacts across ecoregions. This focal region extends east-west between the coastal features of Tigvariak Island and Utqiaġvik. The north-south extent includes areas south of the 200 m marine isobath and areas north of the 200 m terrestrial contour. The study area spans open-water marine, nearshore lagoons, coastal, tundra, and riverine habitats.

General Ecology, Management, and Conservation Threats

Although portions of several other ecoregions also overlap the study area, this analysis focuses on the four ecoregions described below and shown below. These four regions will be used to categorize similar ecological features and group key threats.

These are:

- Beaufort Slope
- Beaufort Shelf
- Beaufort Nearshore
- Central Arctic Coastal Plain



Selected ecoregions and study area of the Beaufort Coastal Corridor Analysis.

Beaufort Slope

The Beaufort Slope ecoregion is a component of the Beaufort-Chukchi Sea – Shelf Edge ecoregion as defined in Marine Ecoregions of Alaska (Piatt and Springer 2007). This region is characterized by upwelling along the shelf, and sits between two main currents: to the north, the Beaufort Gyre, which typically runs from east to west; and to the south, the Alaska Coastal Current, which typically runs from west to east. This entire region is under the jurisdiction of the U.S. federal government.

Currently, there is no oil and gas drilling activity in this region, but renewed efforts to open this area for oil and gas leasing could introduce development in the future.

Beaufort Shelf

The Beaufort Shelf ecoregion is a component of the Beaufort-Chukchi Coastal – Shelf ecoregion (Piatt and Springer 2007). This region is characterized by currents, upwelling, advection (lateral flow of seawater), and transport of major nutrient inputs. Seasonally and locally abundant zooplankton such as copepods are primarily transported by the Alaska Coastal Current from sources in the Chukchi and northern Bering Seas (Elliott et al. 2017) and are then concentrated in recurring but annually variable areas due to oceanographic fronts (Ashjian et al. 2010). Almost this entire region is under the jurisdiction of the U.S. federal government.

Aside from Liberty (a project proposed by Hilcorp Alaska), there is very limited oil and gas development in federal waters. Vessel traffic transits these waters during the brief open-water season, running from approximately June through September, to serve drilling platforms and to transfer supplies.

Beaufort Nearshore

The Beaufort Nearshore ecoregion is a component of the Beaufort-Chukchi Sea Barrier Island-Lagoon System ecoregion (Piatt and Springer 2007). This region spans roughly 5 nautical miles (9 km) from the mainland Alaska coastline, and is primarily under the jurisdiction of the State of Alaska (from the coast to 3 nautical miles [5.5 km]). This region is characterized by barrier islands and terrestrial (riverine) nutrient inputs. Barrier islands are known to periodically migrate as they erode and reform due to varying physical forces (Farquharson et al. 2018; Hequette and Ruz 1991; Jones et al. 2009a). In winter, landfast ice generally forms and extends from the shoreline out to depths up to 20 m (Mahoney et al. 2014). When prior wind patterns generate upwelling and river discharges are high, zooplankton are concentrated along a nearshore front, creating abundant foraging opportunities for higher trophic level species (Okkonen et al. 2016). Evidence suggests that this nearshore front is utilized by many taxa.

A number of drilling activities exist in the Beaufort Nearshore, including six gravel islands – artificially constructed drilling pads within 5 nautical miles (9 km) of the coast. These typically involve winter construction along ice roads and, upon completion, a pipeline connecting produced oil with lateral lines on the mainland.

Central Arctic Coastal Plain

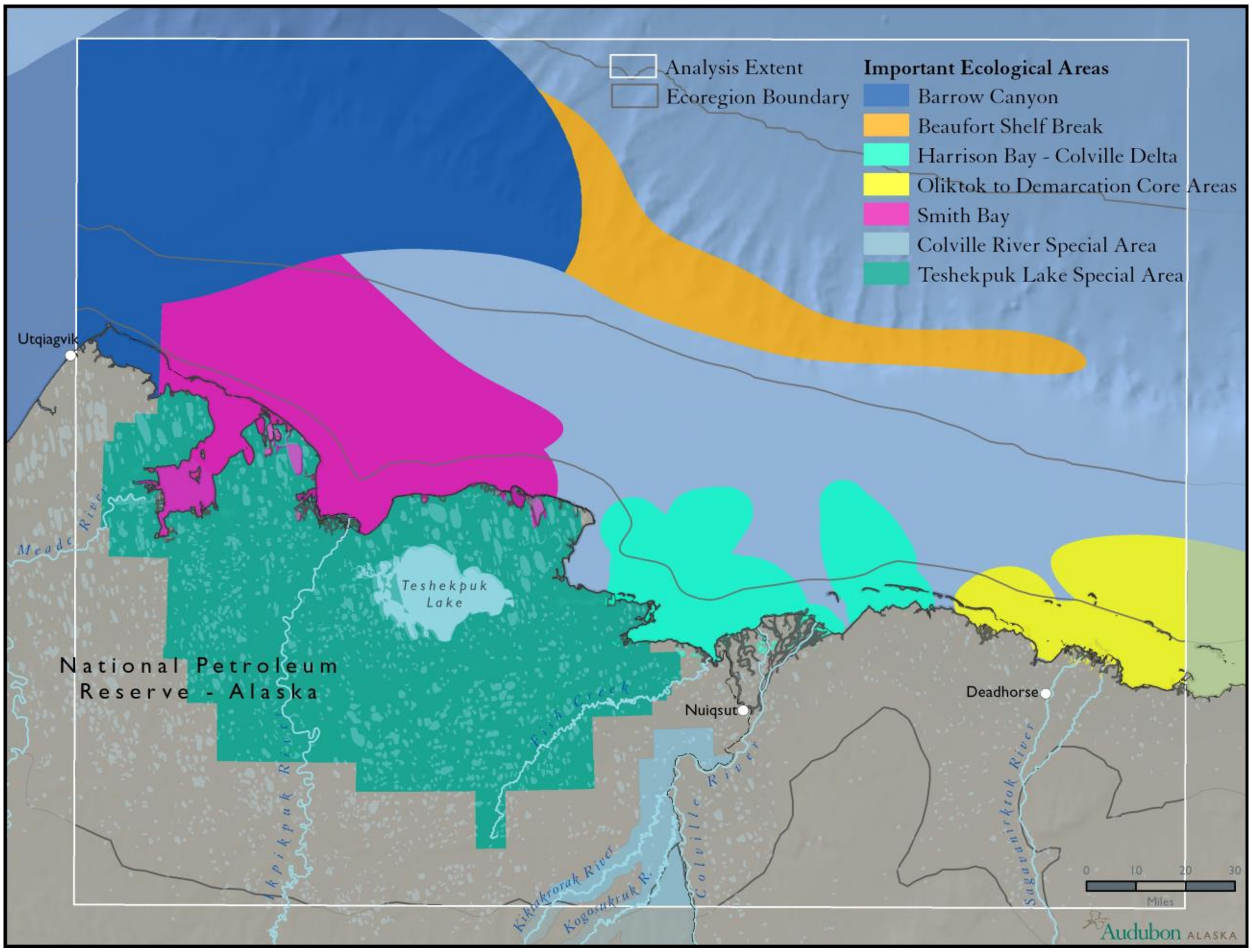
The Central Arctic Coastal Plain region is a component of the Arctic Coastal Plain ecoregion (Nowacki et al. 2001). This terrestrial region is characterized by tundra, permafrost, and extensive wetlands. About 75% of the Central Arctic Coastal Plain is within the National Petroleum Reserve–

Alaska (NPR–A), which is managed by the federal government. The remaining 25% of this region is owned and managed by the State of Alaska.

A large amount of oil drilling has occurred on the Central Arctic Coastal Plain since the 1980s. Development first focused on Prudhoe Bay oil fields, with subsequent development moving gradually north to the coast and westward along the edge of the NPR–A. Major oil finds such as Willow are concentrating industry interest within northeastern NPR–A, and other nearby prospects like Nanushuk may increase vessel traffic just offshore of the NPR–A. With the exception of Smith Bay (the development of which is currently on hold), announced finds and planned projects are close to the eastern edge of the NPRA, allowing them to connect to existing infrastructure.

II. Important Ecological Areas and Biological Values

The Beaufort Coastal Corridor is host to a high seasonal abundance and diversity of wildlife. Previous work (Audubon Alaska et al. 2016; Smith et al. 2011) has synthesized these values in order to identify Important Marine Areas in the Beaufort Sea and recommend Special Areas within the NPR–A. No similar analysis exists to identify such areas for the lands east of the Colville River. For convenience, this report will use the term Important Ecological Areas to refer to both Important Marine Areas and Special Areas. The table below summarizes the key biological features of these Important Ecological Areas (IEAs). Geophysical drivers of these features are discussed in further detail in the Regional Environmental Changes section.



Marine and terrestrial Important Ecological Areas.

Important Ecological Areas in the Beaufort Slope

Barrow Canyon

Barrow Canyon is a deep bathymetric feature spanning the boundary between the Chukchi and Beaufort Seas. Steep submarine cliffs and peaks tower about 1200 feet above a 150-mile long basin. Barrow Canyon has myriad biological values due to its geophysical characteristics and its location where the productive Bering Sea waters flow into the Canada Basin. The canyon's abrupt change in bathymetry creates complex upwelling, water mass mixing, and sea ice dynamics that lead to high levels of primary productivity and high concentrations of zooplankton, enhancing higher trophic levels. Crucially, prevailing current and wind patterns regularly produce a convergent front just northeast of Point Barrow, which concentrates prey organisms for higher trophic taxa such as bowhead whales, beluga whales, and ice seals (Okkonen et al. 2011).

Beaufort Shelf Break

The Beaufort Shelf Break provides perennial migration and feeding areas for beluga whales, likely due to upwelling as deeper waters encounter the Beaufort Shelf (Hauser et al. 2017). Beluga whales target primarily Arctic cod in this region (Hauser et al. 2015).

Important Ecological Areas in the Beaufort Shelf and Nearshore

Smith Bay

The Meade, Ikpikpuk, and other smaller, slow-moving rivers flow into the Smith Bay area, including Dease Inlet. Particularly in the western portion of this IEA, barrier islands bound brackish lagoons and, when wind conditions are favorable, collect and concentrate key forage organisms such as euphausiids, which may be later advected to sea when winds abate (Ashjian et al. 2010). Smith Bay provides important marine foraging habitat for a variety of seabirds and loons (Audubon Alaska et al. 2016) as well as feeding, reproduction, and migration areas for cetaceans (Clarke et al. 2015).

Harrison Bay – Colville Delta

The Colville River drains into Harrison Bay, transporting terrestrial-derived nutrients into nearshore waters. Barrier islands in the east provide sheltered lagoons that serve as fish nurseries. The Harrison Bay – Colville Delta complex supports large numbers of foraging and staging birds such as loons and ducks (Audubon Alaska et al. 2016) and, in recent years, has hosted as many as 600 feeding bowhead whales at once, an unprecedented density (DeMarban 2018).

Oliktok Point to Demarcation Bay

The network of barrier islands and productive nearshore lagoons between Oliktok Point and Demarcation Bay provide important habitat for a variety of taxa including polar bears, pinnipeds, cetaceans, and nesting seabirds (Audubon Alaska et al. 2016). The kelp forests of the Stefansson Sound Boulder Patch provide a unique, diverse ecosystem due to the presence of hard substrate, rather than the soft seafloor typical of the Beaufort Sea (Dunton et al. 1982; Wilce and Dunton 2014).

Important Ecological Areas in the Central Arctic Coastal Plain

Teshekpuk Lake

Teshekpuk Lake is the world's largest thermokarst lake, and surrounding wetlands harbor a high concentration of thaw-oriented lakes (lakes featuring specific and consistent elongation along one axis), particularly north of Teshekpuk Lake (Derksen et al. 1982). The drier landscape south of the lake is dominated by tussock tundra (Walker et al. 2005). This area's western shoreline includes barrier islands and the Ikpikpuk River Delta. A wide array of wildlife in significant aggregations – including shorebirds, loons, geese, polar bears, and caribou – utilize a variety of available habitats in this region (Andres et al. 2012; Liebezeit et al. 2011; Person et al. 2007).

Colville River

The Colville River is North America's largest Arctic river. Steep cliffs along the river offer some of the only suitable nest sites for raptors in the Arctic Coastal Plain, and they concentrate in spectacular numbers alongside the Colville and tributaries such as Kikiakrorak and Kogosukruk (Bruggeman et al. 2015).

Transboundary Important Ecological Area Connections

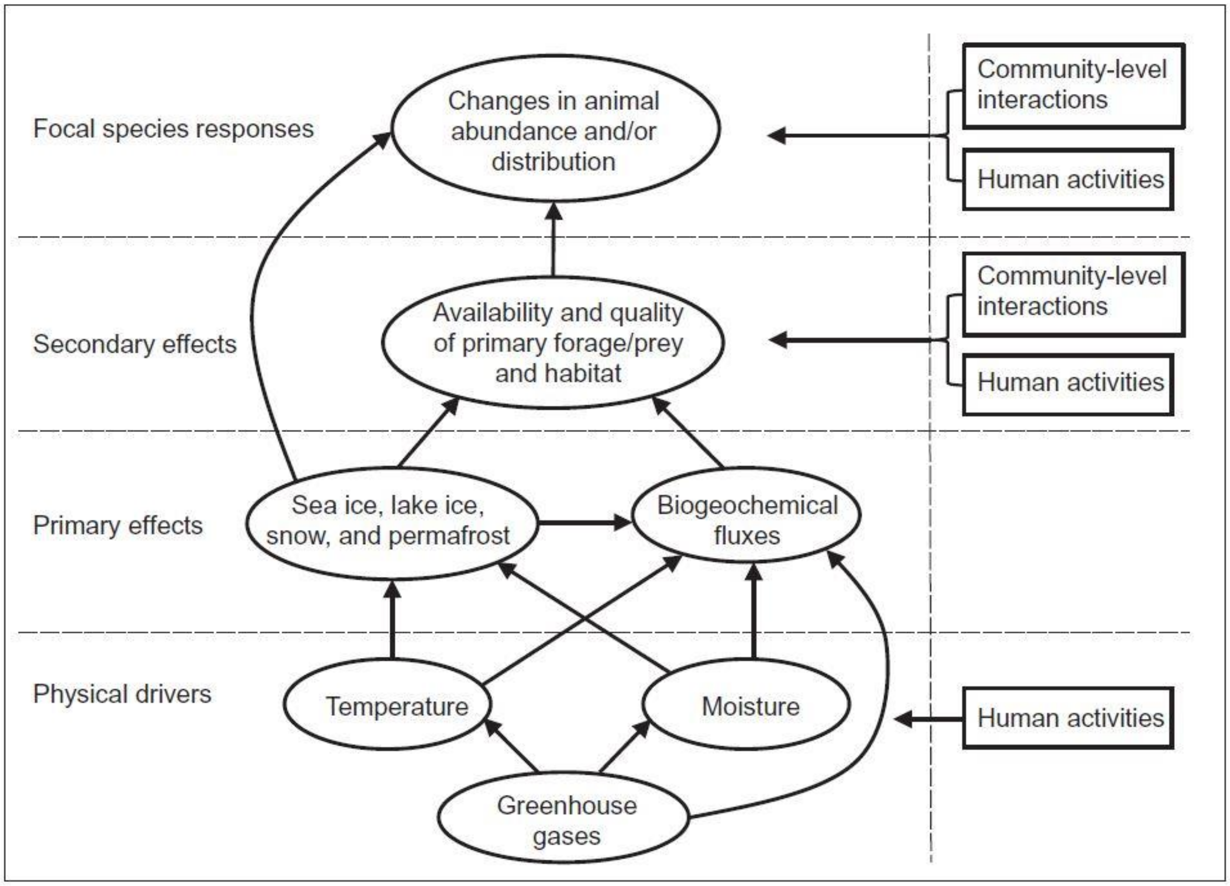
Although much marine productivity comes from advected nutrients and more productive waters elsewhere, recent research suggests that terrestrial carbon has an important role in Beaufort nearshore marine areas (Dunton et al. 2012; Dunton et al. 2006). As such, the Colville River delta adds significant inputs into Harrison Bay, coupling these two IEAs, and major rivers bring terrestrial-derived nutrients to the nearshore waters of Smith Bay (Ikpikpuk River) and Dease Inlet (Meade River), connecting the Teshekpuk Lake and Smith Bay IEAs.

Important Ecological Area	Ecoregion	Geophysical Features	Key Values	Mammal Species	Birds		
					Loons and Waterfowl	Shorebirds, Landbirds, and Raptors	Gulls, Terns, and Alcids
Barrow Canyon	Beaufort Slope	Submarine canyon, upwelling	Cetaceans: migration and feeding	Bowhead, Beluga, and Gray* Whale	Red-throated Loon, Yellow-billed Loon	Red Phalarope	Arctic Tern
			Birds: marine foraging	Polar Bear	King Eider, Spectacled Eider, Steller's Eider		Black-legged Kittiwake, Glaucous Gull, Sabine's Gull
				Walrus*, Bearded, Ringed, and Ribbon* Seal	Long-tailed Duck		
Beaufort Shelf Break	Beaufort Shelf	Shelf break, upwelling	Cetaceans: migration	Bowhead* and Beluga Whale			
Smith Bay	Beaufort Nearshore and Shelf	River inflow, barrier islands	Cetaceans: migration and feeding	Bowhead Whale	Pacific Loon*, Red-throated Loon, Yellow-billed Loon	Red Phalarope, other shorebirds	Arctic Tern
			Polar Bears: feeding and denning	Polar Bear	Common Eider*, King Eider, Spectacled Eider, Steller's Eider	Pomarine Jaeger	Black-legged Kittiwake, Glaucous Gull, Sabine's Gull
			Pinnipeds: pupping	Walrus*, Bearded, Ringed, and Spotted Seal	Brant, Long-tailed Duck		Thick-billed Murre
			Birds: marine foraging				
Harrison Bay-Colville Delta	Beaufort Nearshore and Shelf	River delta	Birds: marine foraging, migration staging, waterfowl nesting and molting	Bowhead Whale (recent)	Red-throated Loon, Yellow-billed Loon		Arctic Tern
			Polar Bears: feeding and denning	Polar Bear	Surf Scoter, King Eider, Spectacled Eider		Glaucous Gull
			Bowhead Whales: feeding (recent)	Spotted Seal	Brant, Long-tailed Duck		
Oliktok Point to Demarcation Bay	Beaufort Nearshore and Shelf	Barrier islands, lagoons	Cetaceans: migration and feeding	Bowhead Whale	Red-throated Loon, Yellow-billed Loon		Arctic Tern
			Pinnipeds: foraging and pupping	Polar Bear	Surf Scoter, Common Eider, King Eider, Spectacled Eider		Glaucous Gull
			Polar Bears: feeding and denning	Bearded and Ringed Seal	Brant, Long-tailed Duck		Black Guillemot, Kittlitz's Murrelet
			Birds: marine foraging, waterfowl nesting, seabird colonies				
Teshekpuk Lake	Central Arctic Coastal Plain	Barrier islands, thaw-oriented lakes, river delta, coastal	Caribou: calving, migration, and insect relief	Caribou	Pacific Loon, Red-throated Loon, Yellow-billed Loon	American Golden-Plover, Black-bellied Plover, Buff-breasted Sandpiper, Bar-tailed Godwit, Dunlin, Long-billed Dowitcher, Pectoral Sandpiper, Red Phalarope, Red-necked Phalarope, Ruddy Turnstone, Semipalmated Sandpiper, Stilt Sandpiper	Arctic Tern
			Birds: nesting, migration staging, and waterfowl molting	Polar Bear	Black Scoter, King Eider, Spectacled Eider, Steller's Eider		Sabine's Gull
			Polar Bears: denning		Brant, Cackling Goose, Emperor Goose, Greater White-fronted Goose, Long-tailed Duck, Northern Pintail, Snow Goose*, Tundra Swan		
Colville River	Central Arctic Coastal Plain	Cliffs, largest arctic river (winter riparian habitat)	Birds: raptor nesting			Golden Eagle, Gyrfalcon, Peregrine Falcon, Rough-legged Hawk	

*Description and comparison of previously identified Important Ecological Areas within the study region. *: occasional use, present nearby, or present only in portion of total area.*

III. Regional Environmental Changes

The Beaufort Coastal Corridor ecosystem is a dynamic environment, and scientists are only beginning to understand how different components of this system might shift going forward. It is entirely possible that novel and emerging conditions will not follow existing causal relationships (Van Hemert et al. 2015). However, describing and mapping known relationships may be useful in tracing connections between physical drivers, primary and second effects, and wildlife responses, as indicated in the diagram below.



Conceptual diagram of myriad climate, geophysical, and biological interactions (Van Hemert et al. 2015).

A number of factors influence the distribution of biological values across the landscape. Basic factors such as food abundance and availability are the most obvious direct drivers of biological values, but a number of other connected phenomena are at work within this environment. Here, these phenomena are roughly categorized into climate change or direct anthropogenic stressors. People also act as direct participants in the ecosystem (e.g. hunting); in this case, anthropogenic stressors refer to actions with broad-scale effects (e.g. extractive industry). This report presents three stressors – climate change, oil and gas development, and transportation – and highlights primary and secondary effects in addition to presumed wildlife responses.

Climate Change

There is significant uncertainty about what trajectory climate change will take. Tangible effects of climate change are readily apparent to both researchers and residents of Arctic communities, and additional and intensifying effects appear likely. Efforts to dramatically reduce emissions or accelerate efforts to sequester greenhouse gases may still avert far-reaching, catastrophic impacts (IPCC 2007). However, climate change has and will continue to influence extensive and intensive changes in the Arctic ecosystem in particular (Post et al. 2009).

Environmental Impacts of Marine Changes

The Arctic Ocean ecosystem is driven by seasonal pulses that link physical conditions and events to biological productivity (Moore et al. 2016). Climate change will alter the timing and magnitude of many of these seasonal pulses and may fundamentally rearrange relationships between regions and trophic levels (Moore et al. 2016). The implications for upper trophic level animals like cetaceans and pinnipeds remain unclear and research documenting effects to wildlife are difficult to summarize because the data remain highly species-specific (Laidre et al. 2008; Moore and Huntington 2008). Community composition may shift, as previous sub-Arctic species expand their ranges: in the past decade, humpback, fin, and minke whales have been observed in the Chukchi Sea, but it remains to be seen whether these cetaceans will extend their range further into the Beaufort (Brower et al. 2018). Regardless, there is an expansive and increasing body of knowledge about specific physical changes and wildlife responses that have become tangible.

An overall decline in sea ice is one such tangible change and has been widely chronicled— the Beaufort Sea is now typically open water in the summer, rather than ice-covered (Wood et al. 2013). In the 1980s, annual minimum sea-ice concentration in the Beaufort and northern Chukchi Seas was 60–87%; now the minimum is dramatically lower and has higher variability, ranging from 5–56% (Wood et al. 2015). Seasons have also dramatically shifted— both spring sea ice retreat and fall freeze-up have shifted by about 30 days compared to data from the early 1980s (Wood et al. 2015).

Another indicator of Arctic ice decline is landfast ice, which is ice that is grounded along the seafloor near the shoreline, thereby “land-fastened.” Landfast ice extent and formation date in the Beaufort have not significantly changed over the past 40 years (Mahoney et al. 2007). However, landfast ice is breaking up sooner in the spring; breakup date has advanced by about a week per decade (Mahoney et al. 2007).

Lower sea ice coverage can lead to increased primary productivity. In the Beaufort Sea, patterns of upwelling and associated surges in productivity are primarily driven by winds and seasonal storms, which are predicted to change in the future (Pickart et al. 2013). Upwelling events have typically occurred when ice cover exists, thereby preventing significant blooms from developing. However, as ice cover recedes in the spring, these upwelling events may no longer be dampened by ice, resulting in increased primary productivity (Pickart et al. 2013).

Changing wind patterns have three major impacts: altering nutrient inputs, reinforcing patterns of sea-ice decline, and shifting seasonality. Easterly winds from the Aleutian low pressure system periodically reverse the typical Beaufort shelfbreak jet, causing phytoplankton blooms in the central Chukchi (Spall et al. 2014). This enhanced primary productivity might process more fixed nitrogen, potentially reducing the amount of fixed nitrogen advected to the Beaufort (Spall et al.

2014). Recent trends suggest that these winds and resultant upwelling events might become more frequent in the future (Spall et al. 2014; Wood et al. 2013). These winds will transport discharge from the Mackenzie River, shifting these warmer waters into the central Beaufort and resulting in high rates of ice melt (Wood et al. 2013). Additionally, the timing of wind patterns has shifted in recent decades, with easterly winds peaking in June and October, rather than the long-term trends of peaks in May and later in the fall (Lin et al. 2016). Because these winds drive upwelling, as described above, seasonal productivity is predicted to shift as well (Lin et al. 2016).

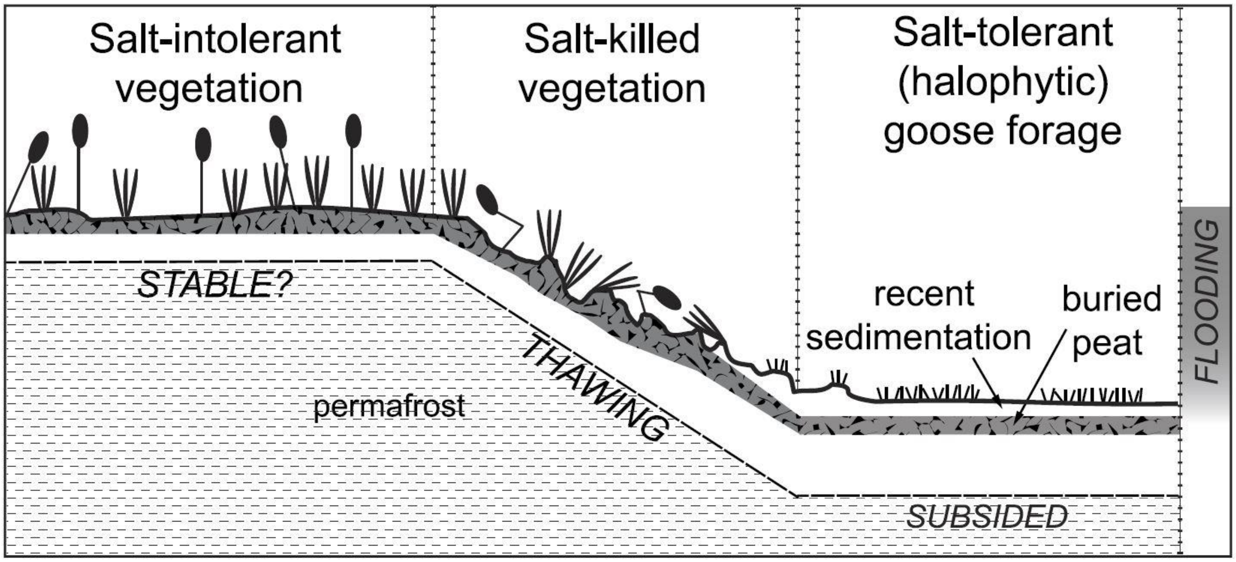
In the past decade, humpback, fin, and minke whales have been observed in the Chukchi Sea, possibly evidencing range expansion, but it remains to be seen whether these sub-Arctic cetaceans will extend their range further into the Beaufort (Brower et al. 2018).

The large circulation patterns that bring nutrients and lower-trophic organisms into the Beaufort system are demonstrating changes, as well. Evidence suggests that the all-important north Pacific water, carrying nutrients from the shallow Bering Sea shelf, is being drawn further north as it passes through Barrow Canyon, rather than following the Beaufort coastline as it has historically (Brugler et al. 2014). This is hypothesized to be related to reductions in sea ice in the interior Canada Basin (Brugler et al. 2014). Volumetric transport of the Alaskan Coastal Current, as measured just offshore of Cape Halkett, decreased by 80% from 2002 to 2011 (Brugler et al. 2014). Because most of the zooplankton in the Beaufort Sea is advected from the Chukchi Sea or northern Bering Sea (Elliott et al. 2017), currents have a key role in transporting zooplankton into typical cetacean migration corridors or typical seabird foraging areas. An evidently weakening Alaska Coastal Current may divert the usual supply of zooplankton further northward into the Chukchi rather than following the Beaufort shelf eastward be weakening in recent decades (Brugler et al. 2014).

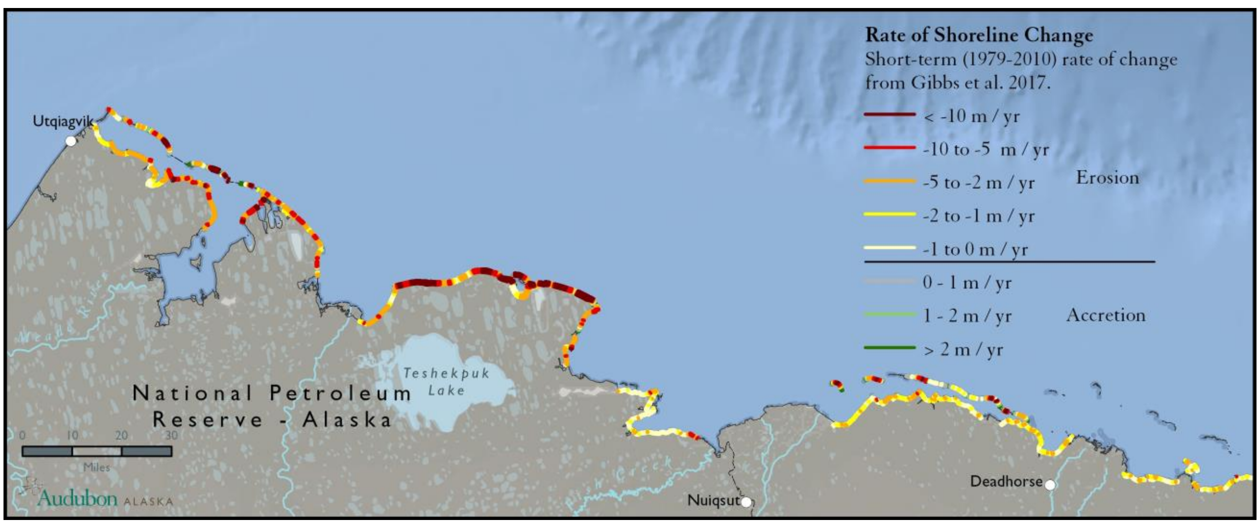
In addition to sea ice, wind, and circulation changes, ocean acidification— caused by the uptake of CO_2 in seawater— is also taking place in the Arctic. Ocean acidification reduces the concentration of carbonate ions (CO_3^{2-}), which are the core of the biogenic calcium carbonate ($CaCO_3$) (Orr et al. 2005). Benthic organisms such as bivalves and plankton that rely on calcium carbonate shells will be most affected (Fabry et al. 2009; Orr et al. 2005), with the most significant negative effects on Arctic benthic communities (Bates and Mathis 2009; Yamamoto-Kawai et al. 2009). Additional impacts such as benthic food limitation or warming water temperatures may exacerbate the impacts of acidification (Goethel et al. 2017). However, recent evidence suggests that Arctic bivalves' response to acidification is species-specific, with some species demonstrating resilience to simulated changes (Goethel et al. 2017).

Environmental Impacts of Coastal Changes

Coastal erosion is most dramatically— and literally— reshaping Arctic Alaska (Gibbs and Richmond 2017). Reduced sea ice leads to increased wave action and greater erosion (Overeem et al. 2011), most notably along the Beaufort coast. Some shorelines north of Teshekpuk Lake have receded by as much as 0.6 miles (0.9km) in the last 50 years (Mars and Houseknecht 2007), and, as seen in the map below, these areas have estimated erosion rates as high as 78 feet (24m) per year over the past three decades (Gibbs and Richmond 2017). Stronger storm surges and subsequent flooding compound the ecological impacts, as saltwater inundation and sedimentation have led to rapidly changing vegetation communities along the Arctic coast (Arp et al. 2010). The relatively warm saltwater increases permafrost melt and further favors salt-tolerant vegetation, altering habitat toward a subsided, halophytic-dominated tundra (Tape et al. 2013). Changes to habitats have implications for which species of birds and wildlife are able to survive and thrive, as discussed further in sections below.



Coastal vegetation changes along the Beaufort coast. Diagram from Tape et al. (2013).



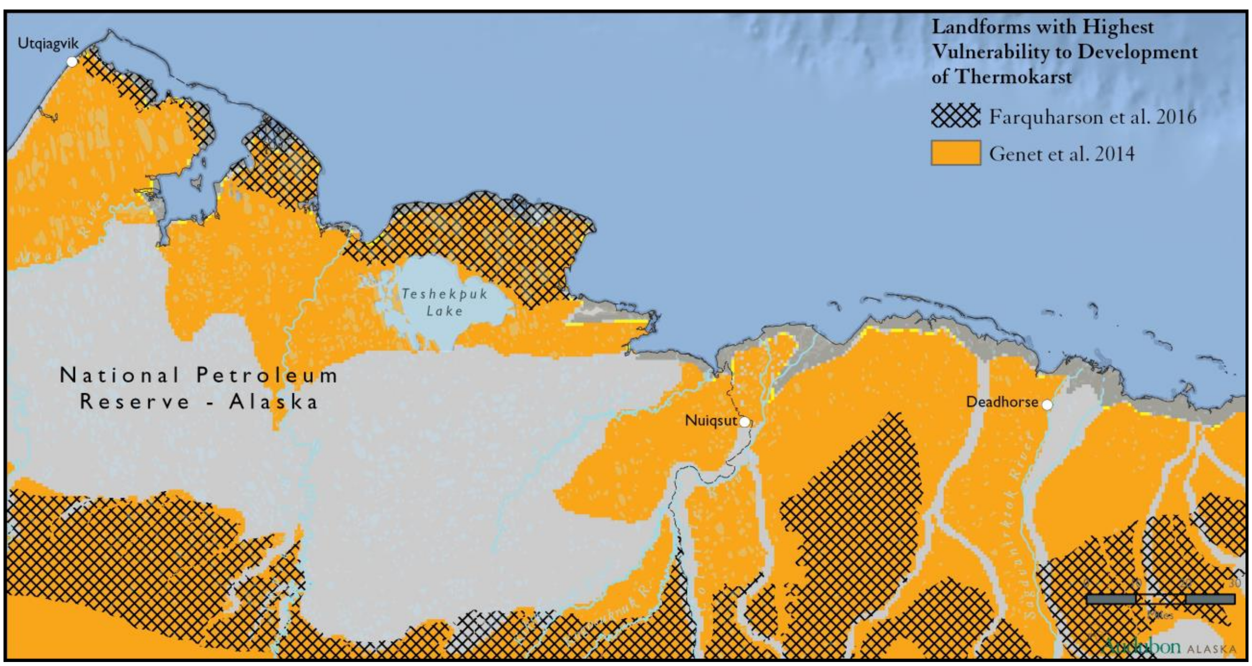
Modeled shoreline change rates, 1979-2010. Data from Gibbs and Richmond (2017).

Environmental Impacts of Terrestrial Changes

The entire terrestrial Arctic Coastal Plain is underlain by continuous permafrost with a generally shallow active layer (Jorgenson et al. 2008). Permafrost degrades in response both to localized disturbance (resulting in the creation of ice lenses, ice wedges, and thermokarst) and broad-scale temperature increases (Olefeldt et al. 2016). Geomorphology related to permafrost degradation, such as lake growth and shrinkage, is projected to be heterogeneous at a landscape scale (Jorgenson et al. 2014; White et al. 2007).

Thermokarst, a distinctive type of landform created by permafrost thaw, is a common feature across the Arctic. Within areas in the circumpolar Arctic underlain by continuous permafrost, 20% of the total area is dominated by thermokarst features such as lakes and pits (Olefeldt et al. 2016). The concentration is even higher in the Arctic Coastal Plain: in some areas, thermokarst covers as much as 60% of the landscape (Farquharson et al. 2016). Site-specific factors such as surface geology, topography, vegetation, and water intrusion mean that some areas may have more extensive thermokarst than others (Jorgenson et al. 2010b). Vegetation and soil properties can buffer permafrost from warm air temperatures, preventing degradation at ambient temperatures up to 2 degrees C, whereas impounded water has the opposite effect and can melt permafrost even when ambient temperatures are as low as -20 degrees Celsius (Jorgenson et al. 2010b).

Broadly, climate change is accelerating the rate of thermokarst development, raising average permafrost temperatures by as much as 1.5 degrees Celsius over the past decade (Farquharson et al. 2016). However, on a finer spatial scale, predicting susceptibility to thermokarst is complicated because of interacting disturbance regimes, ecological processes, and local features such as soil composition (Jorgenson et al. 2014). Some modeling work based on surface geology indicates that marine silt and Aeolian silt have the highest potential for severe thermokarst development in Arctic Alaska (Farquharson et al. 2016). Many regions (43% by surface area) of marine silt have already undergone thermokarst processes, so future geophysical changes will largely involve re-working the same areas that have already become dominated by thermokarst (Farquharson et al. 2016). A different modeling approach using inputs such as permafrost ice content, soil type, and physiography highlights similar areas as most vulnerable to thermokarst development (Genet et al. 2014). As indicated in the map below, both modeling frameworks highlight the areas north of Teshekpuk Lake as the landforms most susceptible to thermokarst.



Estimated areas with high vulnerability to thermokarst development. Data from Farquharson et al. (2016) and Genet et al. (2014).

Thermokarst has significant effects on vegetation communities in the Alaskan tundra by altering soil temperature, moisture, and nutrient availability. During thermokarst formation, significant amounts of carbon are lost from the tundra to the atmosphere and nearby freshwater systems, and the recovery of this soil organic matter can take centuries (Pearce et al. 2015). Depending on local site characteristics, major portions of existing nutrients could be diverted into the aquatic food web, rather than continue the existing tight cycles within the tundra (Pearce et al. 2015). If these nutrients are retained locally, surface soil carbon and nitrogen pools will naturally regenerate over a decadal timescale (Pizano et al. 2014) and local nutrient cycling may even be enhanced by the disturbance (Schuur et al. 2009), stimulating a functional vegetation recovery on a similar timescale (Pearce et al. 2015). However, post-disturbance vegetation is significantly different: for at least some period of time, post-thermokarst vegetation is dominated by tall (>1m) shrubs (Lantz et al. 2009; Pizano et al. 2014; Schuur et al. 2009). There is a widely noted general shift from graminoid-dominated to shrub-dominated communities (Pizano et al. 2014; Schuur et al. 2009), although intermediate stages might temporarily increase graminoid growth (Schuur et al. 2007). Disturbance by thermokarst may also provide a vector for novel colonization by species at the edge of their geographic range such as alders (Lantz et al. 2009).

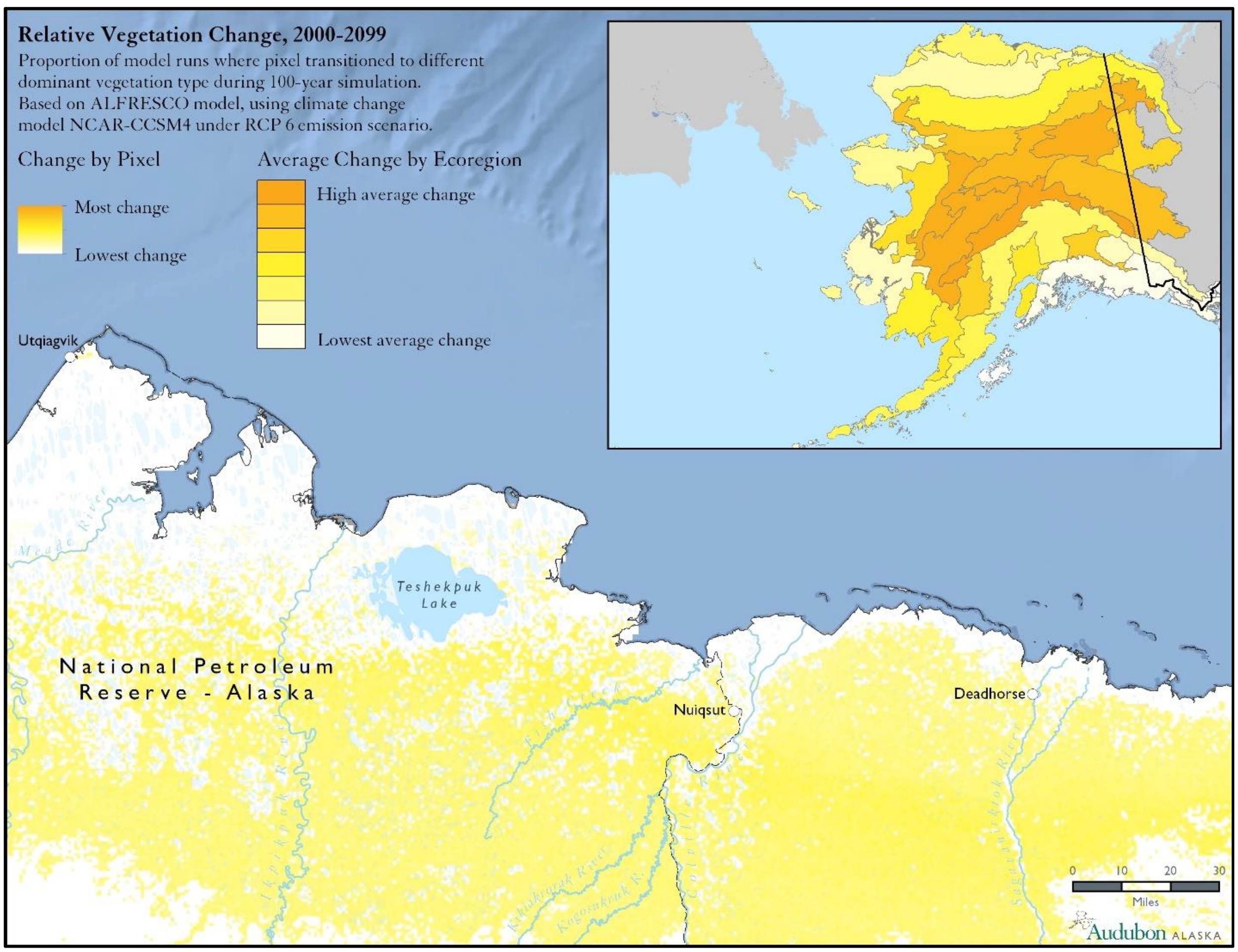
In addition to these vegetation changes, permafrost melting and thermokarst formation exacerbate global climate change in a positive feedback cycle, as stored carbon is released into the atmosphere (Schuur et al. 2008). Toxic compounds such as mercury that were previously contained by permafrost may be released and mobilized (Stern et al. 2012). Permafrost is the largest global pool of mercury, containing over twice as much mercury as exists in all other sources (Schuster et al. 2018), and evidence suggests that inorganic mercury is methylated in thermokarst ponds, allowing it to bioaccumulate across trophic levels to potentially acutely toxic concentrations (Calder et al. 2016; MacMillan et al. 2015; National Research Council 2000). Together, these lines of evidence suggest that Arctic wildlife, particularly higher-trophic taxa in freshwater and nearshore marine systems, will experience increasing levels of mercury exposure and potential related health hazards (Schartup et al. 2015).

Although Arctic wildfires have been exceedingly rare according to the historical record, wildfires are key drivers in boreal ecosystems and have the potential to become more frequent within Arctic Alaska tundra as the climate changes (Joly et al. 2012). The 2007 Anaktuvuk River fire burned more than 375 mi^2 (1,000 km^2)of tundra (Mack et al. 2011), with significant impacts to both vegetation (Jones et al. 2013) and subsurface thermal regimes (especially permafrost; Jones et al. 2015). Within the Alaskan Arctic, fires occur less frequently on wet tundra than other land cover types (Rocha et al. 2012), although recent analysis has identified at least three fires that have occurred on the Arctic Coastal Plain since 2010 (Jones et al. 2013). Two of these fires occurred on the wet sedge and moss communities that are predominant throughout the ecoregion (Raynolds et al. 2005; Walker et al. 2005). Given the myriad implications of reduced sea ice and elevated temperatures, climate change is predicted to increase the vulnerability of Alaskan Arctic tundra ecosystems to fires, so these events and consequent ecological restructuring will likely become more frequent (Hu et al. 2010).

Increased wildfire activity will likely have significant impacts on Arctic wildlife. Caribou rely on lichens in the winter, but lichen communities recover very slowly (50 years or more) after wildfire (Joly et al. 2009). Mostly as a result of changing fire regimes, high-quality winter habitat for the

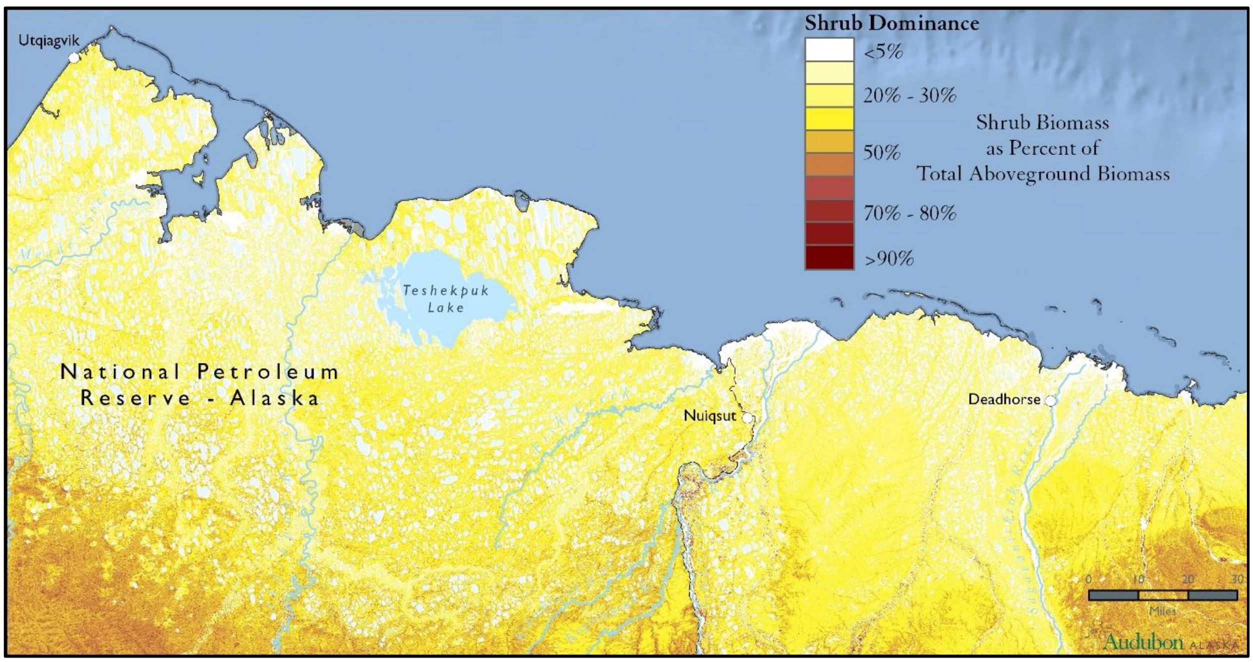
Western Arctic caribou herd is projected to decline by nearly 30% over the next 40 years (Joly et al. 2012). Conversely, moose habitat in these same areas is projected to increase by 19–64% over the next 40 years, possibly introducing competition and/or increasing predator density, both of which would apply additional pressures on caribou (Joly et al. 2012).

Although vegetation— and wildlife— will respond to climate change in spatially heterogeneous ways at a local scale (Gustine et al. 2017), many separate lines of evidence suggest that graminoid communities in the Arctic Coastal Plain will persist and likely expand in wet, coastal areas. Graminoids are already flourishing under new climate regimes, as wetland graminoid productivity has more than doubled over 20 years in some portions of the Arctic (Gauthier et al. 2013). Experimental warming across the Arctic suggests that graminoids and shrubs will increase coverage as air temperatures increase and lichen coverage diminishes (Walker et al. 2006). Herbivory may also bolster graminoid dominance: the predominant halophytic graminoinds on the Arctic Coastal Plain, *Carex subspathacea* and *Puccinellia phyragnodes*, expand in extent in response to grazing pressure (Person et al. 2003; Tape et al. 2013). As these preferred foraging habitats expand across the Coastal Plain, wildlife are likely to shift their distribution (Lewis et al. 2010; Tape et al. 2013) and even increase in population (Flint et al. 2014; Hupp et al. 2017).



Projected vegetation change. Data from McGuire et al. (2016).

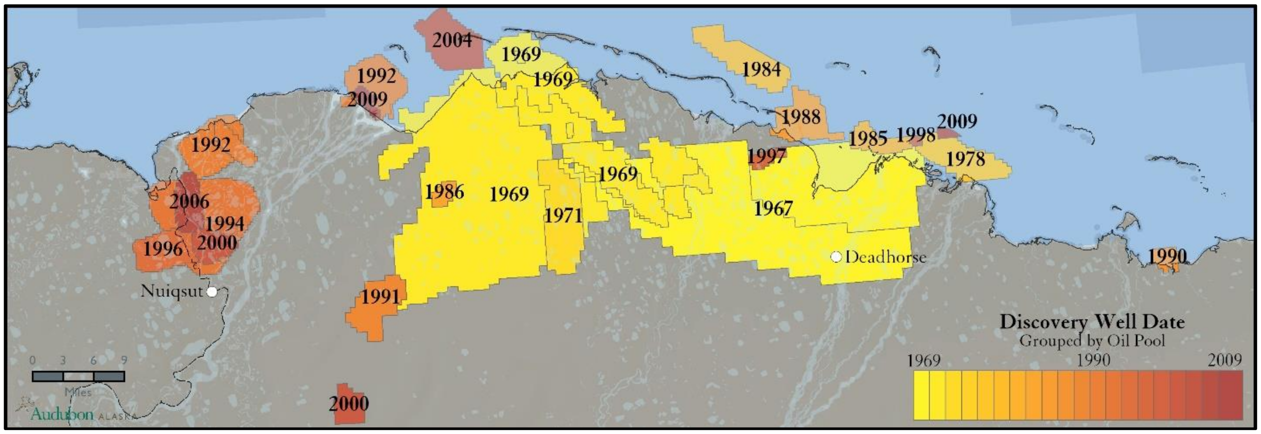
Arctic tundra is being colonized by shrubs, especially alder, dwarf birch, and willow (Tape et al. 2006), particularly in riparian systems and in inland areas further from saltwater instrusion and sedimentation (Tape et al. 2016a). Although Alaska-wide integrated ecosystem modeling suggests that the Arctic Coastal Plain will demonstrate a low degree of vegetation change (McGuire et al. 2016), this model is based primarily on fire dynamics, which may play less of a role in shaping Arctic tundra succession than other, more frequent disturbances such as thermokarst (Lantz et al. 2009). There is consensus that climate change will lead to increased shrub dominance throughout the Arctic Coastal Plain (Berner et al. 2018), and the interaction of thermokarst features and riparian floodplain communities provides a vector for future shrub colonization of areas closer to the coast (Lantz et al. 2009; Tape et al. 2016a). Shrub-associated species such as moose and showshoe hare are predicted to shift into the NPR-A (Cason et al. 2016), as increased shrub height provides access to winter foraging for moose (Tape et al. 2016a; Tape et al. 2016b).



Shrub dominance within the study region. Data from Berner et al. (2018).

Oil and Gas Development

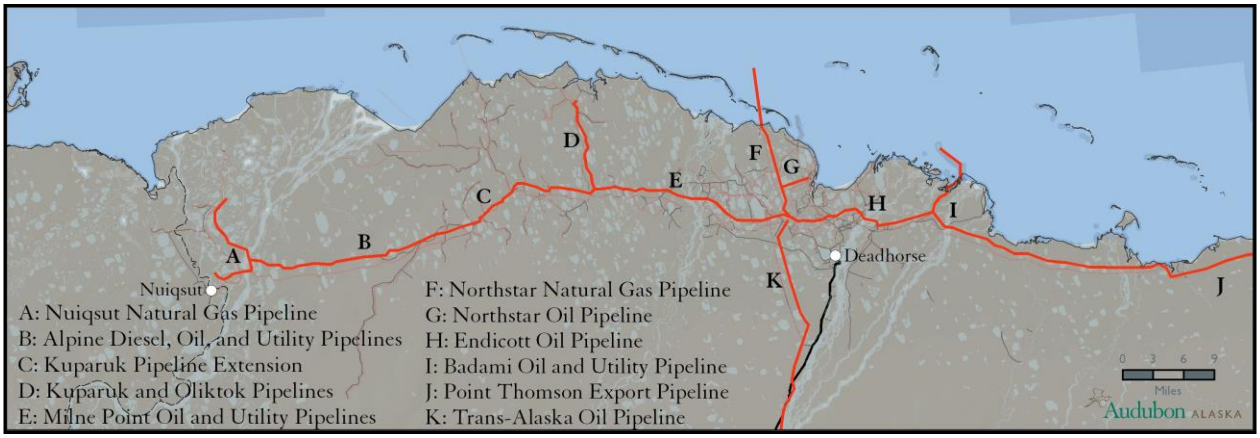
Petroleum products sourced from Arctic Alaska are broad drivers of anthropogenic climate change, but the extraction of these products also causes acute impacts to the marine, coastal, and terrestrial environments at the point of extraction. Alaska's North Slope has had oil and gas development for decades, beginning with exploration wells drilled in the Prudhoe Bay oil field in the 1960s (Hillmer-Pegram 2014). For a more in-depth description of oil and gas development, refer to Hillmer-Pegram (2014) and Sullender (2017). Broadly, oil and gas development has five phases: leasing, exploration, development, production, and decommissioning. Except for leasing, each phase has a variety of impacts. The majority of activity has been on land, although oil companies have drilled a number of exploration wells offshore and have developed a number of oil fields in the Beaufort nearshore as gravel islands.



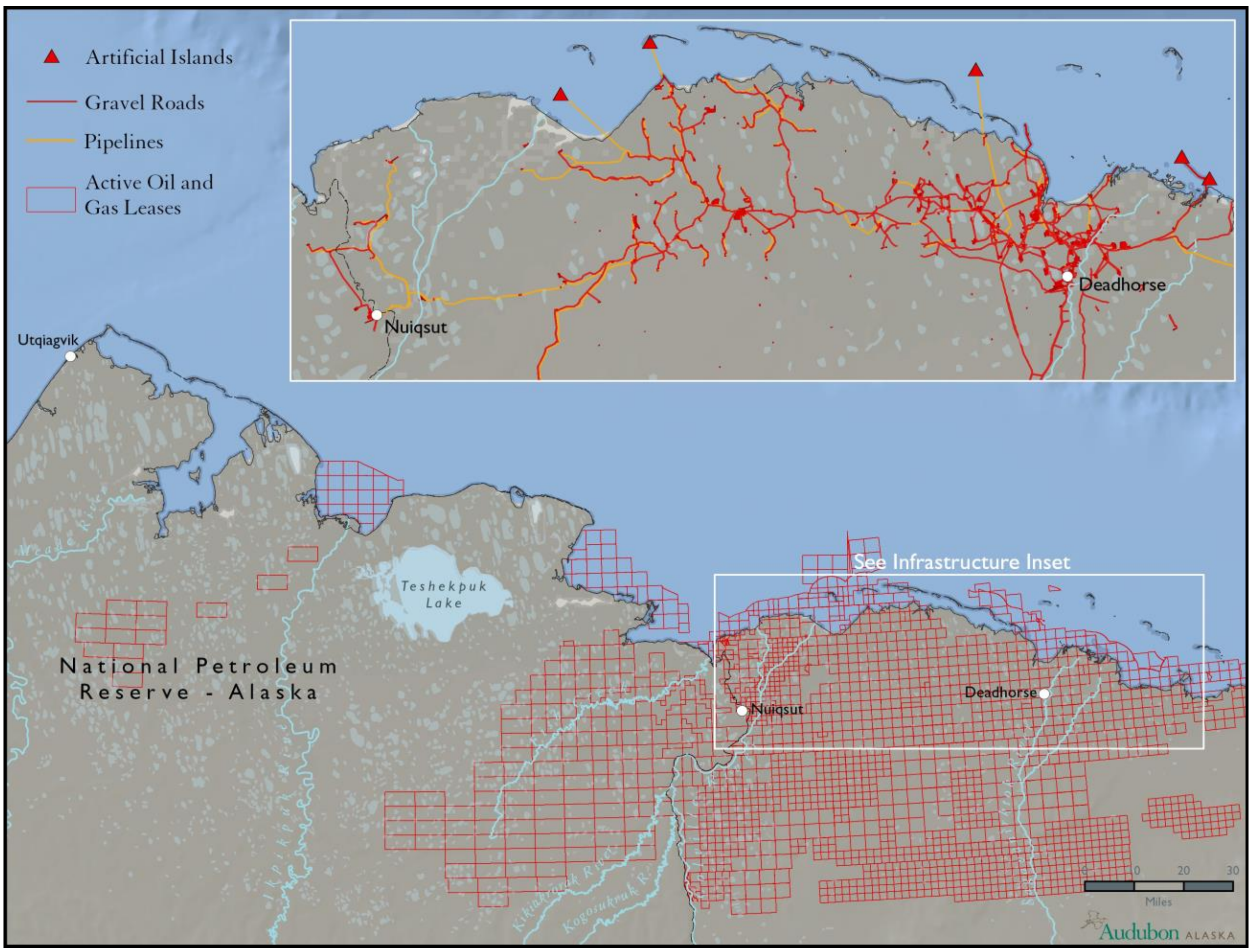
General timeline for major oil and gas producing areas, using date of discovery well. Data from Alaska Department of Administration – Alaska Oil and Gas Conservation Commission.

Gravel islands have been the preferred method of oil extraction from marine areas in the nearshore waters of the Beaufort Sea, with a total of four actively producing oil since 1989 and a fifth currently in permitting. Construction generally occurs during the winter months, when trucks haul gravel onto sea ice and deposit it through holes in the ice to build up artificial islands. These islands are then armored against ice scouring and storm damage and are used as platforms from which drilling occurs, sending oil back through pipelines. The Endicott oil field uses an aboveground causeway, allowing vehicular access to the drill site, while Oooguruk, Nikaitchuq, and Northstar use subsea pipelines and rely on aircraft or boat access in the ice-free seasons.

Oil produced on the North Slope, including from offshore wells, is transported south to a marine terminal via the 800-mile Trans-Alaska Pipeline System (TAPS). Because the economics of oil production depend on transporting extracted oil off site and moving materials and personnel on site, a sprawling network of gravel roads and pipelines connects almost all oil fields to the central Prudhoe Bay hub. Other hubs such as the Alpine Central Processing Facility have been constructed as additional oil fields have come online. As of 2007, a total of eight central processing units are in use on the North Slope: Prudhoe Bay, Kuparuk River, Lisburne, Milne Point, Endicott, Badami, Northstar, and Alpine (Attanasi and Freeman 2009). A network of major pipelines connect satellite fields to these hubs.



Major pipelines on the North Slope. Data from Alaska Department of Natural Resources – Division of Oil and Gas (2018).



Current leasing and infrastructure extent on Alaska's North Slope.

New and Potential Oil and Gas Development

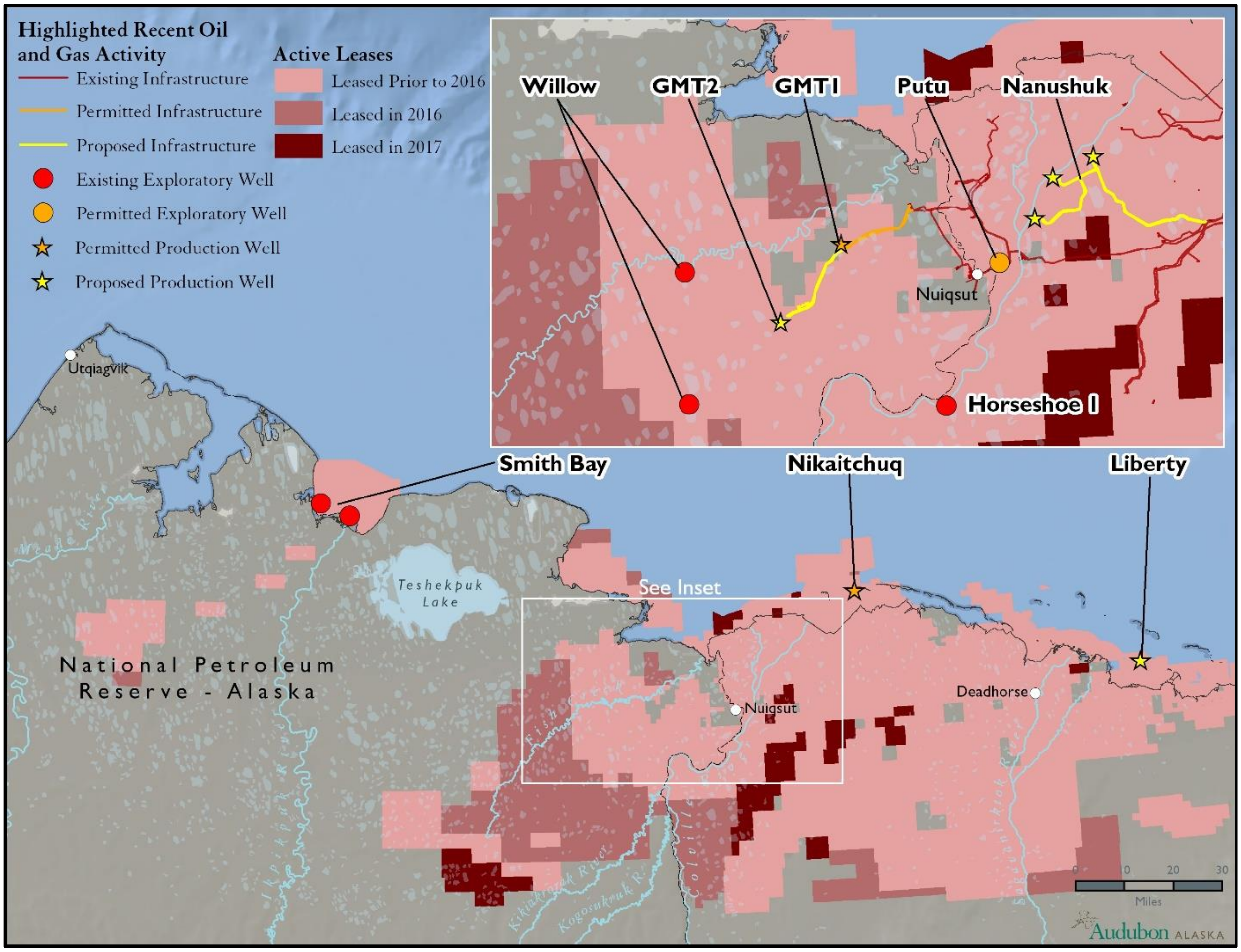
In the nearshore, Eni, an Italian petroleum company, has submitted plans to expand drilling operations in the Nikaitchuq oil field. Eni has constructed onshore facilities and currently drills from one onshore pad and one 11-acre offshore gravel island, called Spy Island. Currently, Spy Island actively produces oil from 32 wells. Eni has proposed to add four exploratory wells reaching over 5 miles north into adjacent federal waters. As of December 2017, Eni's plans were approved, initial safety inspections were passed, and drilling was expected to commence in winter 2017–2018. The two main wells would be drilled from December – April 2018 and from December 2018–April 2019 (Eni US Operating Co. Inc. 2017).

About 50 miles east, a new proposed gravel island called Liberty is currently in the permitting process. Hilcorp Alaska LLC is proposing constructing a new 9.3-acre island about five miles offshore. The Liberty project began in 1982 when Shell Oil Company drilled a series of exploration wells, before selling its stakes to BP Exploration (Alaska) in 1996. In 2014, BP sold a majority stake in the Liberty project to Hilcorp and Hilcorp took over the planning process. A final Environmental Impact Statement and Record of Decision are expected in fall 2018 (Bureau of Ocean Energy Management 2017b).

To the west, a reported discovery in Smith Bay remains unconfirmed. Caelus Energy Alaska originally purchased 26 leases in Smith Bay state waters from NordAq Energy (Anchorage, AK) in June 2015 and drilled two exploratory wells over the following winter. Caelus heralded the results as a "world-class discovery," with potential for 200,000 barrels of oil per day to be produced, but Caelus deferred additional exploration drilling until at least 2019 (DeMarban 2017a).

Nanushuk, a major new development prospect on state lands, is currently in the permitting process. A network of pipelines and roads would connect three drill sites with a new central processing facility located about 12 miles from Nuiqsut. Depending on how the infrastructure is configured, there would be about 21–26 miles of new gravel road, 81–86 acres of new gravel pads, and 36–48 miles of new pipelines (US Army Corps of Engineers 2017). In November 2017, Armstrong Energy and GMT Exploration LLC (based in Denver, CO) sold their operating stakes in Nanushuk to Oil Search Limited, a Papua New Guinea-based petroleum company. Armstrong, Repsol S.A. (Madrid, Spain), and GMT Exploration will retain partial ownership, although Oil Search will assume all operating duties and has the right to buy out all of Armstrong's and GMT Exploration's remaining shares in the future (Oil Search Limited 2017). In fall 2017, the Draft Environmental Impact Statement was issued and subsequent public meetings were held (US Army Corps of Engineers 2017). A Final Environmental Impact is expected in 2018.

ConocoPhillips Alaska Inc. has made significant investments in oil development in the NPR–A and has several projects at various stages in the region. Construction for the Greater Mooses Tooth 1 (GMT1) production well site began in winter 2017–2018, and the Record of Decision on a permit for GMT2 is expected in early fall 2018 (ConocoPhillips Alaska Inc. 2017a). ConocoPhillips also owns the controversial exploration site Putu 2, which lies within three miles of the community of Nuiqsut and which is also slated to be drilled during the 2018-2019 winter season. The Alaska Department of Natural Resources (DNR) transferred the Putu leases from Brooks Range Petroleum to ConocoPhillips. When ConocoPhillips requested a deferral due to strong public concern from Nuiqsut residents, DNR threatened to revoke the leases and forced ConocoPhillips to proceed (Brehmer 2018). ConocoPhillips' most recent announcement, the Willow project, resulted from exploration wells Tinmiaq 2 and Tinmiaq 6. ConocoPhillips estimates that the Willow prospect will be approximately two-thirds the size of the Alpine oil field (ConocoPhillips Alaska Inc. 2017a).

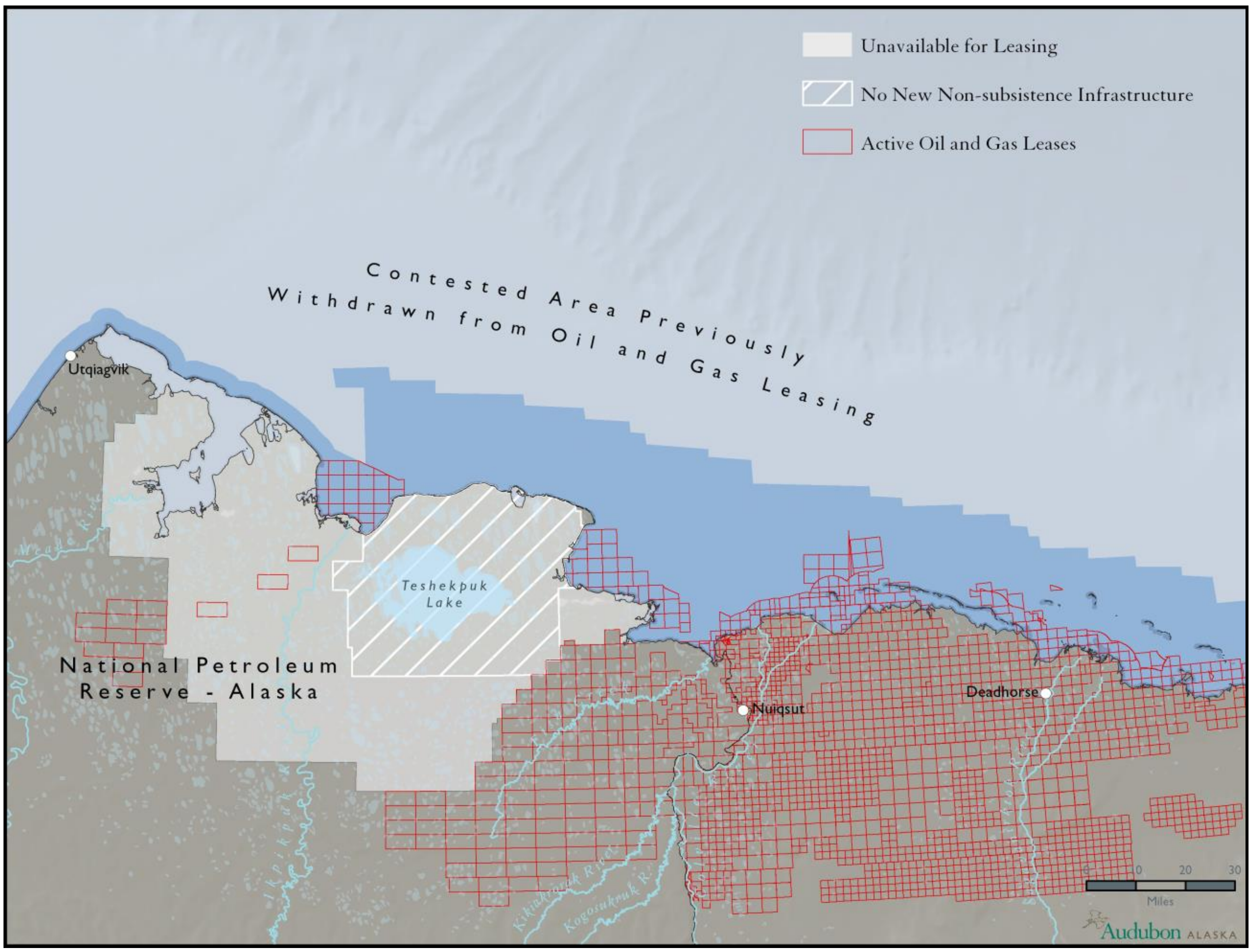


Oil and gas development trajectory and highlighted recent activity and proposals.

In addition to entirely new prospects such as those discussed above, oil and gas operators are continuing to develop older, mature fields, in some cases turning to emerging technologies to stimulate production and expanding existing facilities. ConocoPhillips completed a $400 million expansion to an existing drill site at 1H Northeast West Sak to add about 8,000 barrels per day in production from viscous oil (ConocoPhillips Alaska Inc. 2017b). Between 2016 and 2017, Hilcorp expanded its Milne Point mine site by 22 acres, extended drill pads by five acres, and constructed the 13-acre Moose Pad and three miles of associated access roads (Hilcorp Alaska 2017). Although oil producers have been increasing production through injection wells for years, the first tests of hydraulic fracturing (fracking) targeting shale rock is currently occurring south of Prudhoe Bay (DeMarban 2017b).

Oil and gas development in federal lands and waters is inherently uncertain with respect to economic factors, permitting outcomes, and land status and ownership. However, recent policy shifts and proposed administrative regulatory rollbacks have caused an even more unusually high level of certainty. The Obama administration withdrew federal waters in the Chukchi and Beaufort Seas from oil and gas leasing, with the exception of a 2.8-million-acre portion of the Beaufort nearshore. The Trump administration subquently issued an order that purpoted to overturn the withdrawal. The validity of these orders, and therefore the status of the withdrawn marine acreage, is now the subject of ongoing litigation. The Bureau of Ocean Energy Management (BOEM) is meanwhile proceeding with a planning process to write a new 2019–2024 Outer Continental Shelf Leasing Program, which will implicate areas that are currently the subject of this pending litigation.

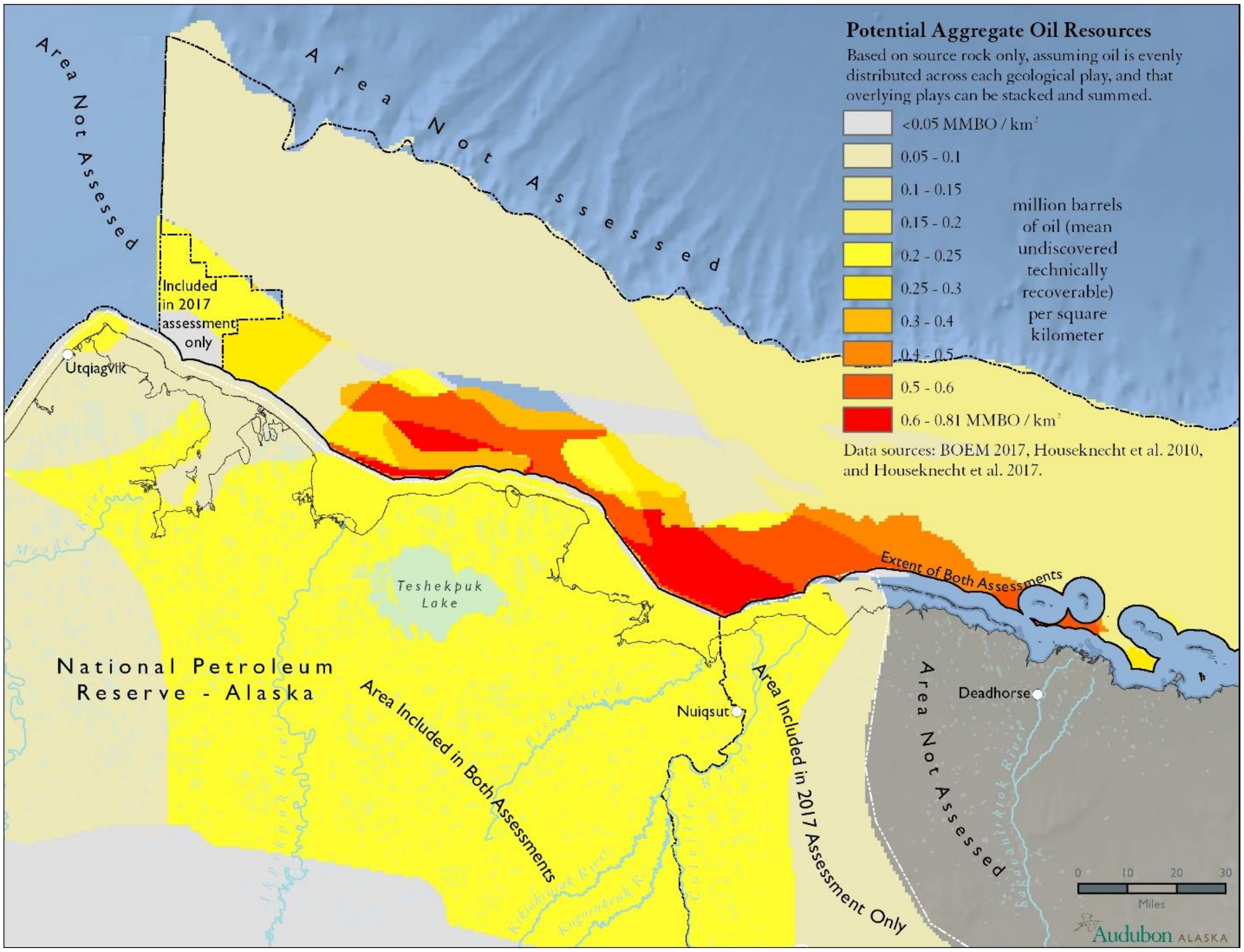
This regulatory uncertainty persists onshore as well. Within the NPRA, the 2013 Integrated Activity Plan (IAP) governs land management decisions. The IAP provides industry access to tracts in which oil and gas development may occur, while simultaneously meeting the Bureau of Land Management's congressional mandate to protect important surface values for wildlife, subsistence, recreation, and other values. The IAP delineated Special Areas, leasing stipulations, and Best Management Practices to help maintain the values required by BLM's statutory mandate.



Current management regimes with respect to oil and gas development.

Hydrocarbon Resource Potential

Knowing the location of oil and gas resources in the Arctic is of critical importance for understanding future development pressures and anticipated impacts on co-located biological values. However, data on the location, volume, and quality of hydrocarbon resources are inherently unpredictable, complex, and closely guarded. Oil and gas companies typically use their own proprietary data about potential hydrocarbon resources to make decisions about where to lease, explore, and ultimately develop. Government agencies also periodically release publicly accessible assessments of hydrocarbon resources. Agency and industry resource assessments can vary dramatically in terms of input data, interpretation and methodology, spatial resolution, and final results. Agency assessments are useful as a guideline at broader spatial scales to understand areas that may see intensifying industry interest. Based on industry findings, these assessments may change unexpectedly. For example, 2010 oil and gas assessments of the NPRA estimated a mean of 896 million undiscovered, technically recoverable barrels of oil (Houseknecht et al. 2010). The most recent report, based on a revision of six of 19 geological assessment units, estimated 8,813 million barrels of oil in a comparable area (Houseknecht et al. 2017). Similar updates were made for the Outer Continental Shelf waters: a 2017 assessment estimated a mean of 8,902 million barrels of oil in the Beaufort Sea (Bureau of Ocean Energy Management 2017a). Using the data from these two assessments, it is possible to conduct a very basic spatial analysis to show general areas of relatively higher hydrocarbon potential. This analysis is inherently unrealistic because it uses a series of simplifying assumptions that may confound geological reality, including the assumption that oil is evenly distributed across geological plays and that overlapping geological features can be aggregated. Notwithstanding these shortcomings, the analysis is presented below to show an interpretation of general oil potential.



General oil potential across the study area. Analysis uses geological play assessment data from Bureau of Ocean Energy Management (2017a) and Houseknecht et al. (2017). Note that state lands are not completely assessed. The abrupt change in resource potential in the nearshore marine areas is an artifact of publicly accessible data, rather than an actual geological transition.

When these simple assessments are combined with leasing data and management plans, about 11.7 billion barrels of oil (mean undiscovered, technically recoverable) are within the Beaufort Coastal Corridor area of interest. Of those 11.7 billion barrels, only 39% (4.6 billion barrels) are unavailable for leasing under current management plans. Approximately 22% (2.6 billion barrels) are already leased, leaving a total of 4.5 billion barrels of oil undiscovered, unleased, and available. Although all of these figures are abstracted from generalized data and should only be considered as estimates, current management would allow industry to access over 60% of available undiscovered, technically recoverable crude oil. Given technological advances such as extended-reach drilling, this proportion of available oil resources is likely even higher. Clearly, current management plans along the Beaufort Coastal Corridor are not preventing oil development and allow industry access to a large volume of hydrocarbons.

The same assessments can be combined with IEA boundaries and current leases to calculate a rough estimate of oil potential and leasing extent across IEAs. Together, these numbers approximate relative risk of oil development. These results are presented in the table below. Of these, Teshekpuk Lake and Smith Bay stand out as having high oil potential but with relatively lower percentages of their overall area leased. Note that this analysis is based on the same series of simplifying assumptions discussed above, and should be considered as a rough estimate rather than a precise figure.

Important Ecological Area	Total Area (acres)	Area within Beaufort Coastal Corridor AOI (acres)	Leased Area (acres)	Percent of Beaufort Coastal Corridor AOI Leased	Total Estimated Oil Potential (million barrels)
Barrow Canyon	3,937,414	3,105,740	-	0%	500
Beaufort Shelf Break	1,446,230	893,160	-	0%	100
Smith Bay	1,689,703	1,761,400	116,963	7%	1,500
Harrison Bay–Colville Delta	901,421	901,421	288,782	32%	1,400
Oliktok to Demarcation Bay	2,211,517	618,988	153,785	25%	200
Teshekpuk Lake	3,652,440	3,652,440	520,247	14%	3,300
Colville River	2,442,940	281,788	143,316	51%	300

Summary of oil and gas leasing and oil potential by Important Ecological Area (IEA). The threat summary analysis was performed only on the portion of the IEA within the study area boundary; data outside the IEA boundary was excluded. The total area is given as a reference only; all subsequent columns refer to the subset of the IEA within the Beaufort Coastal Corridor Area of Interest (AOI). Oil potential is based on a series of simplifying assumptions and on generalized data, and should be used as an approximate figure only.

Environmental Impacts of Oil and Gas Development

Environmental impacts from oil and gas activity throughout exploration, development, and production. The first physical steps in exploration typically involve seismic surveys, which can be damaging when conducted in both terrestrial and marine environments. Seismic surveying involves directing high-amplitude waves into the earth and recording how those waves return to near-surface sensors, using this information to delineate subterranean geology at a finer scale than other methods. In contrast to some other aspects of oil and gas activity, recent technological advancements have only increased the environmental impacts of terrestrial seismic exploration: the new, 3-D seismic surveys require a much denser survey grid, with individual lines spaced 650—1640 feet (0.2–0.5 km) apart, rather than the 3.1—12.4 mile (5–20 km) spacing for older 2–D surveys (Jorgenson et al. 2010a).

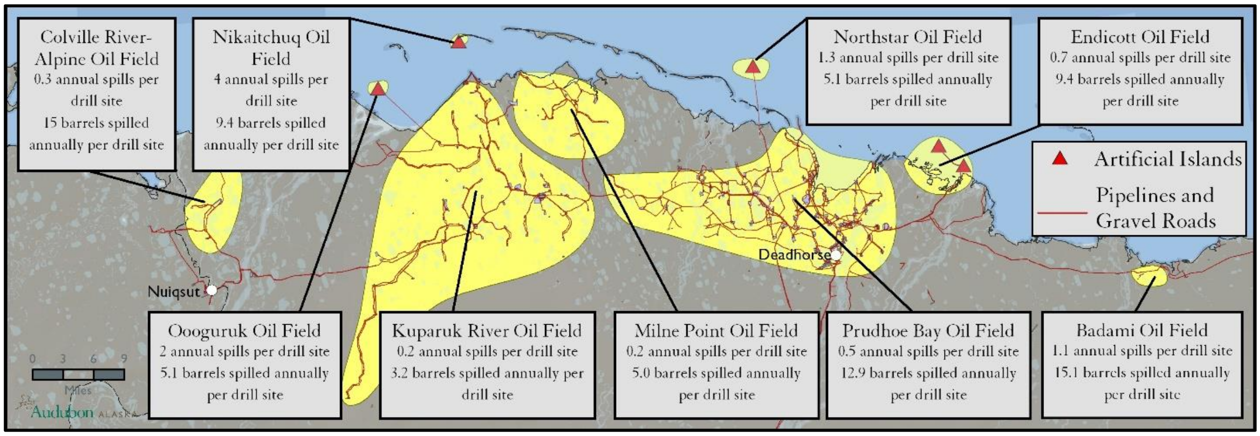
Seismic surveys have destructive and persistent impacts on tundra vegetation (Felix and Raynolds 1989; Jorgenson et al. 2010a), and marine surveys disturb a wide variety of marine organisms with acute, cumulative, and chronic effects ranging from disturbance to permanent physiological damage (Gordon et al. 2003; Nowacek et al. 2015). Although seismic exploration typically occurs during the winter, seismic trails on tundra have a lasting effect, especially in areas with low or no snow cover. Marine mammals use auditory cues to navigate, locate prey, and communicate, and anthropogenic sounds such as seismic surveys disrupt or reduce effective ranges of these key behaviors (Clark et al. 2009; Stafford 2013; Stafford et al. 2017). Within the Alaskan context, seismic surveys alter Beaufort Sea bowhead whale calling rates within 62 miles (100 km) and effectively cease all bowhead whale calling within 25 miles (40 km) of a seismic survey (Blackwell et al. 2015).

As a drill pad is developed, industry typically constructs ice roads during the winter season and uses a combination of vehicles traveling on these ice roads and aircraft to transport materials and people (Hillmer-Pegram 2014). Ice road impact on tundra vegetation varies based on landcover type, permafrost conditions, ice thickness, and volume of traffic, but is generally considered to be minimal (Adam and Hernandez 1977; Bureau of Land Management 2014). However, the impacts of ice roads on North Slope hydrology and lake dynamics can be significant, particularly in terms of water withdrawal eliminating or reducing overwintering fish habitat, blocking aquatic connectivity, and permanently altering permafrost thermal dynamics (Heim et al. 2015; Jones et al. 2009b; West et al. 1992).

After seismic surveys and ice road construction, gravel pads are typically used to develop a site for oil and gas production. A thorough review of the ecological impacts of gravel placement on the North Slope is provided by Sullender (2017) and will not be further discussed here.

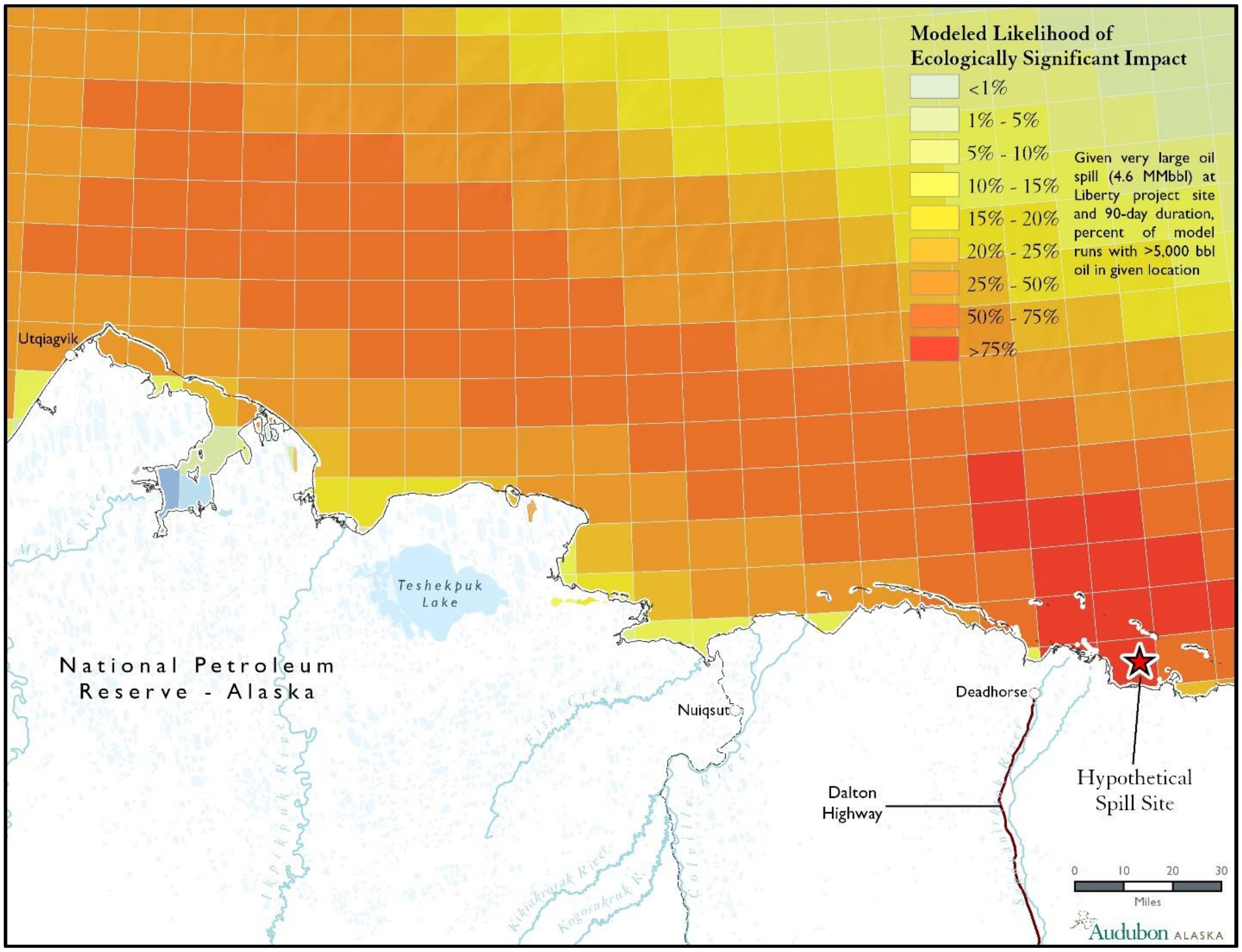
One of the most pernicious threats to Arctic wildlife from oil and gas development is an oil spill. Effects can be acute (e.g. mortality, injury) or chronic (e.g. population decline, community-level changes), depending on scale and location (National Research Council 2014). Broadly, there is a significant lack of preparation and lack of resources to respond to an oil spill in the Arctic (Pew Environment Group 2010) and, in the event of an Arctic marine emergency, the nearest U.S. Coast Guard response station is about a week away (US Army Corps of Engineers and Alaska Department of Transportation and Public Facilities 2013). Harsh conditions and the difficulty of organizing logistics and supporting response efforts in such a remote region further contribute to the risks of an oil spill (Pew Environment Group 2010).

Oil spills are more than a hypothetical threat: more than a thousand oil spills totaling over 30,000 barrels (1 barrel = 42 US gallons) have already occurred on the North Slope (Robertson et al. 2013). Annual spill rates depend on the amount of oil produced, with a long-term average of about 40 spills greater than one barrel per year. When accounting for number of years in production and number of drill sites, offshore oil fields on the North Slope have generally higher spill rates and result in greater spill volumes than onshore oil fields (Robertson et al. 2013). Furthermore, spill rates are the highest during the summer months (June and July), when wildlife have greater chances of exposure. Besides oil, there are many other types of toxic substances – waste muds, hydrostatic test fluid, tank-bottom sludge, gas dehydration wastes, “produced water”, and sewage, for example – produced in enormous quantities on a daily basis (National Research Council 2003). The production, transportation, storage, treatment, and disposal of these substances raises risks of accidental discharge and subsequent impact on the Arctic environment.



Oil spill rates for North Slope oil fields. Normalized by number of years in operation and by number of drill sites. Data from Robertson et al. (2013).

Recent advances in ocean current, meteorology, and chemical decomposition modeling have allowed stochastic simulations to predict location and magnitude of oil spills. The following map represents the very large oil spill scenario described in the Liberty EIS process (Bureau of Ocean Energy Management 2017c), modeled through the Arctic Trajectory Analysis Planner (ATAP) and using 5,000 barrels per cell as the ecological injury threshold per ATAP approximations (Ammann et al. 2017). The modeled spill location represents the proposed drill site of the Liberty oil development project (Bureau of Ocean Energy Management 2017c).



Hypothetical oil spill from drill site in Beaufort nearshore waters. Parameters as specified by Bureau of Ocean Energy Management (2017c) and modeling results from Ammann et al. (2017).

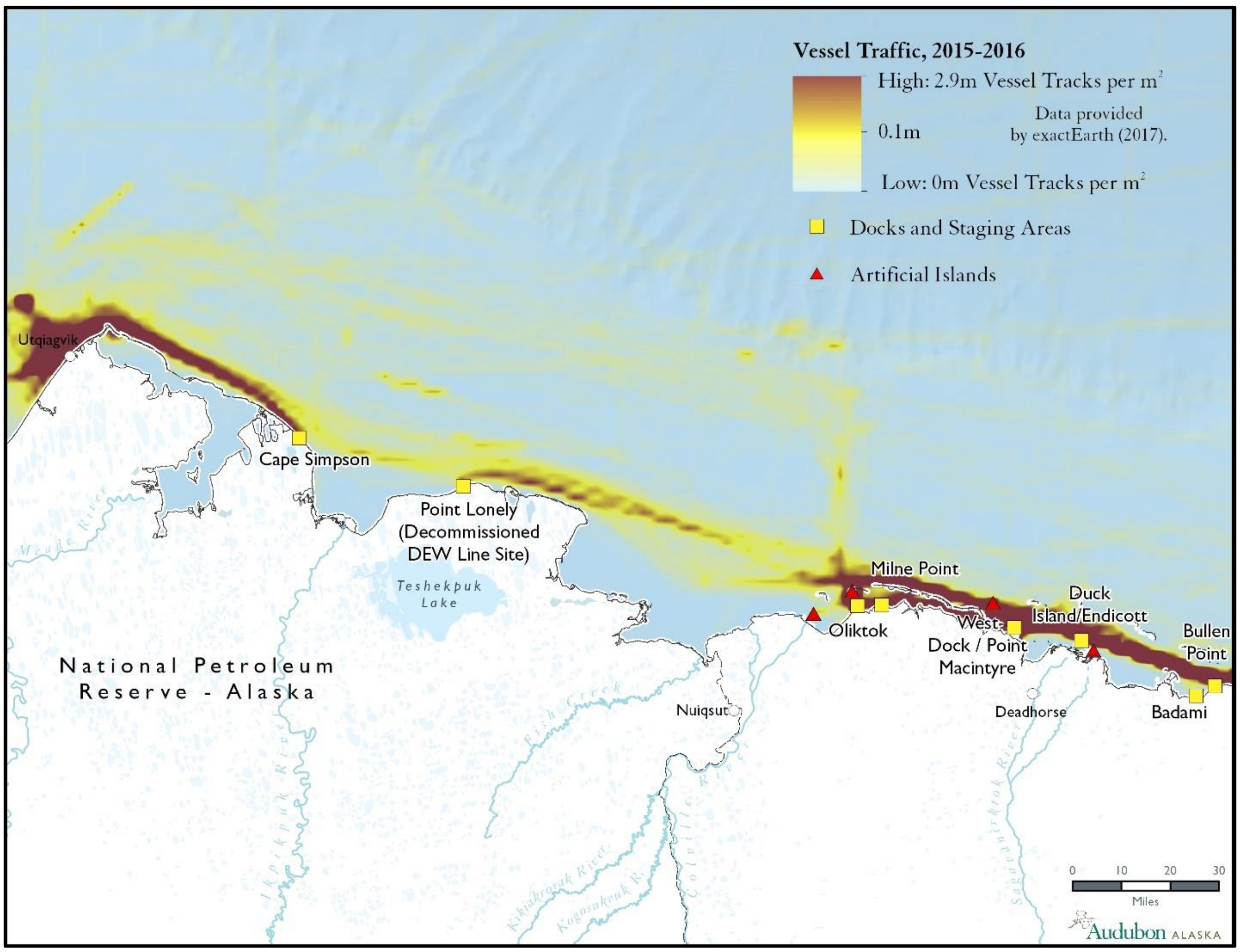
Transportation

Outside of the Dalton Highway, road networks around Utqiaġvik, and oil field-related gravel roads, there is limited year-round ground transportation in the study area. Long-distance movement of people, goods, and equipment generally relies on aircraft and seasonal modes of transit such as ice roads, informal snow trails, and, during the short open-water season, vessels serving sites along the coast. Sullender (2017) provides a more in-depth discussion of ground- or air-based transportation options, and this report focuses on vessel traffic.

The proposed Arctic Strategic Transportation and Resources (ASTAR) project, funded by the Alaska Department of Natural Resources, is in the early stages of planning a permanent road network connecting communities across the North Slope (Harball 2017). Although no definitive routes, timelines, or financial details have been developed, the permanent gravel roads proposed as part of this project would have significant implications for Arctic wildlife (Sullender 2017 and references therein). Due to the uncertainty surrounding this project, ASTAR is mentioned but not analyzed, as there are no defined components to analyze yet.

Environmental Impacts of Vessel Traffic

Vessel traffic has five major impacts on the environment: oil spills, ship strikes and noise, emissions, sewage and graywater, and invasive species (Ocean Conservancy 2017). Ocean Conservancy (2017) and Smith et al. (2017; section 7.5) provide a more in-depth analysis of these impacts. This report uses vessel traffic (number of vessels per unit time) to quantify overall environmental impact from vessel traffic in the focal area, enough thought other analyses may better estimate individual impact categories. For oil spill threat, for example, tankers have the potential to release more oil and would therefore be ranked of higher importance than fishing vessels. Similarly, vessels traveling faster or using higher-power engines would result in more acoustic disturbance than small skiffs. However, in order to broadly summarize the various impacts from vessels, this analysis considers the total density of all ships, regardless of type, speed, or cargo.



Vessel traffic patterns and major docks, staging areas, and gravel islands along the Beaufort Sea. Data from exactEarth (2017).

Vessel traffic volumes in the Beaufort Sea are currently small compared with other waters south of the Bering Strait (Audubon Alaska 2017). Existing vessel traffic densities for each IEA for 2015 and 2016 are presented in the table below. Vessel traffic is projected to increase, especially as receding sea ice opens Arctic routes (Arctic Council 2009).

Important Ecological Area	Total Area (acres)	Area within Beaufort Coastal Corridor AOI (acres)	Vessel Traffic (km/yr)	Vessel Traffic Density (km/sq km)
Barrow Canyon	3,937,414	3,105,740	13,000	1.03
Beaufort Shelf Break	1,446,230	893,160	2,000	0.55
Smith Bay	1,689,703	1,761,400	16,000	2.24
Harrison Bay–Colville Delta	901,421	901,421	14,000	3.84
Oliktok to Demarcation Bay	2,211,517	618,988	19,000	7.58
Teshekpuk Lake	3,652,440	3,652,440	N/A	N/A
Colville River	2,442,940	281,788	N/A	N/A

Summary of vessel traffic by Important Ecological Area (IEA). The vessel traffic calculation was performed only on the portion of the IEA within the study area boundary; data outside the IEA boundary was excluded. The total area is given as a reference only; all subsequent columns refer to the subset of the IEA within the Beaufort Coastal Corridor study area.

Oil and gas activities often increase vessel traffic, as ships transport personnel, equipment, and other materials. Vessel traffic along the Beaufort coast is routed through hubs, docks, and staging facilities. The table below shows the approximate number of voyages per site for all of 2015 and 2016. Official Environment Impact Statement documents estimate about 3,000 trips per year to offshore gravel islands, using a combination of hovercraft and passenger boats based on ice conditions, during active drilling, and about 1,500 trips per year during production and regular operations (Eni US Operating Co. Inc. 2017).

Name of Site	Type of Site	Approximate Number of Vessel Trips*, 2015–2016
West Dock / Point Macintyre	Oil and Gas - Dock	1200
Oliktok	Oil and Gas - Dock	425
Utqiaġvik (Both Docks Combined)	City	399
Point Thomson	Oil and Gas - Dock	286
Nikiatchuq	Oil and Gas - Offshore Production Island	206
Northstar	Oil and Gas - Offshore Production Island	88
Duck Island / Endicott	Oil and Gas - Offshore Production Island	45
Lonely (Decommissioned DEW Site)	Other	38
Milne Point	Oil and Gas - Dock	33
Cape Simpson	Oil and Gas - Dock	30
Oooguruk	Oil and Gas - Offshore Production Island	19
Bullen Point (Decommissioned DEW Site)	Other	17
Badami	Oil and Gas - Dock	12

*Beaufort nearshore marine traffic, by site, according to satellite AIS data 2015–2016. *: due to incomplete adoption of AIS technology and technical limitations, these numbers are under-estimates.*

The US Coast Guard is expected to initiate planning of the Arctic Port-Access Route Study (PARS), which will build from a similar process already completed in the Chukchi Sea, Bering Strait, and Bering Sea. Once developed, the Arctic PARS will serve as a guideline for vessels transiting Arctic waters, potentially including a recommended route, Areas to Be Avoided (ATBAs), and/or other vessel safety measures. If implemented, an Arctic PARS could concentrate vessel traffic into specific areas and leave other areas with minimal transits and significantly lessened impacts.

IV. Variability and Uncertainty

Spatial Heterogeneity

Arctic ecology depends on narrow margins. Although the Arctic Coastal Plain may appear flat and featureless, fine-scale topographic features provide remarkably different habitat conditions, and wildlife respond to these conditions. For example, one recent study found that six shorebird species select nest sites based on features within 10 feet (3 m) of a potential nest site (Cunningham et al. 2016). Terrain ruggedness significantly affects habitat selection at multiple spatial scales (Wilson et al. 2012) and travel time (Wilson et al. 2016) for caribou. Similarly, oceanographic and marine life responses to general climate change vary across a given region or ecosystem (Moore and Huntington 2008; Mueter and Litzow 2008), and wildlife distribution shifts from year to year based on interannual variation in environmental conditions (Elliott et al. 2017). Together, these lines of evidence suggest that it is inappropriate to make sweeping conclusions across an entire landscape; a more nuanced, spatially explicit understanding is required to understand ecological responses to factors such as climate change, oil and gas development, and transportation.

Population Trends

Major changes in population size directly change wildlife distribution. For some species such as Black Scoters and Steller's Eiders, declines may restrict distribution so that only a small portion of suitable habitat is occupied (Warnock 2017). The Audubon Alaska WatchList (Warnock 2017) highlights nearly a dozen imperiled species that utilize the Arctic Coastal Plain at some point in their annual life histories: Yellow-billed Loon, Spectacled Eider, Steller's Eider, Black Scoter, American Golden-Plover, Bar-tailed Godwit, Pectoral Sandpiper, Dunlin, Buff-breasted Sandpiper, Black-legged Kittiwake, and Snowy Owl. For these species, even a widely dispersed group of individuals could have biological significance although it may fail to meet density-based definitions of importance.

Conversely, other species such as Greater White-fronted Goose and Snow Goose have experienced dramatic population increases, potentially leading to interspecific competition and displacement into suboptimal nesting habitat (Flint et al. 2008). Particular care should be taken when identifying core habitat for booming populations such as these.

Long-distance Connections

Because many species of Arctic wildlife undertake long-distance migrations, teleconnections – causal links between phenomena in widely separated areas – are a key part of understanding local biological values. For example, there is the potential for caribou populations to be impacted by loss of preferred foraging resources in areas hundreds of kilometers away from calving grounds on the Arctic Coastal Plain. Access to and abundance of lichens are important for caribou during the winter (Joly et al. 2007; Joly et al. 2009), particularly for parturient females who must maintain body condition to supply initial lactation (Gustine et al. 2017). Decrease in lichen abundance was the primary factor implicated in the extirpation of caribou from St. Matthew Island (Klein and Shulski 2009), and a more intensive fire regime will reduce lichen abundance in the wintering ranges of Arctic caribou herds (Joly et al. 2009). The long-distance movements of caribou and the variable habitat quality across seasonal ranges are complicating factors that managers must consider.

Migratory birds also may face problems with finding suitable habitat outside this report's focal area. Conditions at overwintering or migratory stop-over sites might have more of an impact than conditions at breeding grounds (Weiser et al. 2018b), particularly for shorebirds such as Dunlin that use the East Asian-Australasian Flyway, where coastal development is increasing (Szabo et al. 2016). Changes to preferred seagrass communities in wintering habitats along the west coast of North America is changing reproductive performance in Brant regardless of sufficient summer habitat and foraging opportunities on the North Slope (Ward et al. 2005). Although Arctic nesting populations of Brant demonstrate faster growth rates and higher survival of goslings than those in the sub-Arctic, survival rates have declined range-wide, suggesting that conditions in wintering or migration areas are negatively impacting Brant populations (Leach et al. 2017).

In assessing stressors to Arctic wildlife, it is essential to account for long-distance connections such as these. Mitigating the inherent uncertainty surrounding the status and needs of Arctic migratory wildlife requires robust and efficient coordination between agencies, states, and nations to conserve habitat at each stage of an animal's annual life cycle. Mechanisms like the Migratory Bird Treaty Act, Flyway partnerships, and cooperation between federal and state agencies within Alaska are critical for overcoming the barriers that stand between Arctic migrants and their essential habitat.

Phenology

In many species, breeding and other resource-intensive life history events coincide with the period of highest resource availability, an adaptive strategy to synchronize resource demand and supply (Doiron et al. 2015; Durant et al. 2005). As climate change alters the timing of resource peaks, there is the potential for life history events to be mistimed relative to resource availability (Durant et al. 2005; Kerby and Post 2013). This phenomenon is widely called ecological mismatch, trophic mismatch, or phenological mismatch (Gustine et al. 2017; Senner et al. 2017).

Within the Arctic context, snow cover and ambient air temperature are two of the primary aspects limiting terrestrial primary productivity (Bokhorst et al. 2016), and, as these factors change, plant phenology will shift (Bjorkman et al. 2015; Khorsand Rosa et al. 2015). Already, spring snowmelt has advanced by 1 to 3 days per decade (Stone et al. 2002), and, although interannual variability partially dampens the trend, a subsequent lengthening of growing season has been observed across Arctic North America (Barichivich et al. 2013) and the timing of peak nutrient content in Arctic vegetation has shifted earlier (Doiron et al. 2015).

In the marine environment, the timing of spring ice melting in the Beaufort Sea is occurring 2.7 days earlier per decade while fall freeze-up is being delayed by 6.4 days per decade (Stroeve et al. 2014). Although a longer open-water season will lead to increased primary productivity (Babin et al. 2015), the potential ecological benefit of these increases may be offset by phenological mismatches (Hollowed et al. 2013). For example, the zooplankton *Calanus glacialis* synchronizes its initial reproduction with peak ice algae availability so that newborn zooplankton reach maturity just as sea ice recedes and the open-water phytoplankton bloom begins (Søreide et al. 2010). However, because spring sea ice melting is occurring earlier, *C. glacialis* are beginning to reach maturity after the peak pelagic phytoplankton bloom, resulting in a mismatch between resource demand and resource peak. Because *C. glacialis* comprise up to 80% of the total zooplankton biomass in some Arctic areas, this has cascading implications for a variety of trophic levels (Søreide et al. 2010).

The same mechanism has been demonstrated in the Bering Sea: in years with early ice retreat, euphausiids (small planktonic crustaceans) were 2.4 times less abundant, *C. glacialis* were 18.1 times less abundant, and neocalanus were 2.8 times less abundant (Renner et al. 2016). These dramatic decreases in zooplankton abundance likely resulted in a re-distribution or even decline of seabird populations, with 10 times fewer birds observed in years with early ice retreat (Renner et al. 2016). Similar phenological mismatches and impacts were recently observed in Svalbard, Norway, as Ramírez et al. (2017) implicated mismatches in sea-ice melt and pelagic phytoplankton bloom as principal causes in reduced breeding performance in marine birds.

For bowhead whales, which also rely on euphausiids, other factors may reduce the impact of apparent phenological mismatch among the plankton community. Climate change is projected to increase upwelling events (Pickart et al. 2013), which have been shown to drive seasonal bowhead whale distribution (Ashjian et al. 2010; Okkonen et al. 2016), and long-term physiological data from bowhead whales suggests that body condition is better in years with lower sea ice (and therefore more upwelling; George et al. 2015). Food abundance may not yet be a limiting factor, or the magnitude of marine phenological mismatch may be lower than that predicted.

As with whales, population-scale impacts from hypothesized phenological mismatch has not been conclusively observed in Alaska's Arctic caribou herds. Species that migrate long distances typically use photoperiod as an indicator for migration timing, and caribou migration is strongly linked to photic signals (Post and Forchhammer 2008). Caribou calving is remarkably consistent across years (Kerby and Post 2013), in contrast to vegetation phenology, creating the potential for phenological mismatch (Gustine et al. 2017). Although a study on caribou in Greenland found evidence of trophic mismatch through reduced calf production and increased calf mortality (Post and Forchhammer 2008), recent studies suggest that analogous impacts are not occurring within Alaskan caribou herds (Gustine et al. 2017) or within other *Rangifer tarandus* populations (Veiberg et al. 2017). One reason may be related to caribou life history: as capital breeders, parturient females utilize overwinter stores of nutrients and energy to provide sufficient resources to calves during lactation (Barboza et al. 2018; Mallory and Boyce 2017). As such, peak nutrient demand is offset from initial green-up, suggesting that a phenological mismatch for caribou would occur in the late summer or early fall, when forage quality has not significantly changed over 36 years (Gustine et al. 2017).

Arctic migratory breeding birds have demonstrated a response to shifting phenology. Avian annual migration and breeding cycles are primarily driven by photoperiod, although some species and some populations (especially short-distance migrants) demonstrate some plasticity in response to environmental conditions (Dawson 2008; Kumar et al. 2010). In contrast to caribou's consistent calving phenology, Arctic-breeding birds have in general shifted clutch initiation earlier in years with advanced snowmelt. Clutch initiation date among passerines has advanced by 0.4–0.8 days per year (Liebezeit et al. 2014), and, within Snow Geese, clutch initiation averaged a 3.8 day shift for a 10 day change in snowmelt over a 23-year period (Gauthier et al. 2013).

Although Arctic breeding birds show a shift in nesting variables, evidence for physiological and demographic impacts as a result of these changes has been inconsistent at best. Average gosling body mass declines when annual mismatches are greater than 7 days (Doiron et al. 2015), and longer mismatches have led to reductions in both clutch size and nest success for snow geese (Ross et al. 2017). However, these declines occurred during a period of overall population growth

(Ross et al. 2017), so population-scale effects are still to be determined. Contrary to observations from snow geese, phenological changes have resulted in neither reduced adult survival for six shorebirds species (Weiser et al. 2018b) nor reductions in breeding performance among 17 shorebird species (Weiser et al. 2018a). Despite the comprehensive approach, these two studies used data going back to only 2010 and pooled data across enormous distances. Geographic diversity might misrepresent the overall amount of variation analyzed: when the data are pooled, there is an apparent difference of 59 days in spring snowmelt, but individual site variation averages less than one week (Weiser et al. 2018b, Supplemental Figure 1a). Given that consequences of phenological mismatch are only apparent in snow geese at durations of more than seven days (Doiron et al. 2015), these two shorebird studies may not capture the range of variation necessary to cause broad-scale impacts. More research is needed to better understand how phenological mismatch may or may not be resulting in individual or population-level impacts of Arctic migratory birds.

Overall, local and regional heterogeneity have a tremendous influence on the potential for and the magnitude of impacts from phenological mismatch (Gustine et al. 2017; Ramírez et al. 2017). Separate populations of the same species might exhibit remarkably different responses to changing phenology, and local variation within a population's range may also be key (Senner et al. 2017). Counter to hypothesized impacts on marine planktivores, bowhead whales have demonstrated improved body condition in years with less sea ice, potentially due to regional increases in upwelling and consequent aggregation of prey items (George et al. 2015). Species may alter behavior to mitigate phenological mismatch: caribou select calving habitat based on vegetation green-up date, among other factors (Wilson et al. 2012), and Common Murre parents shift the balance between nest attendance and foraging time to compensate for a phenological mismatch between juvenile resource demand and capelin availability (Regular et al. 2014).

V. Persistence of Wildlife Distributions

As environmental conditions change, wildlife distributions often shift in response. However, some areas may harbor either a great enough variety of microhabitats or a high enough abundance of resources so that, even when conditions change, there is still sufficient suitable habitat for wildlife in the same general area. Identifying areas of continued high wildlife use – persistent biological value – highlights the role of important ecological areas throughout changing conditions. The two overarching goals of the following persistence analysis are to: 1) Downscale data to show gradients of biological values within existing IEA boundaries; 2) Determine which areas support recurring concentrations of wildlife species.

Because the persistence analysis is dependent on long-term, repeated surveys using a consistent protocol and timing, this report only analyses birds and marine mammals, a small subset of the Arctic wildlife that inhabit the study area. Important wildlife such as caribou, polar bears, and raptors were not included in this analysis due to lack of suitable data. Additionally, the methods and results from this analysis are preliminary and only intended as a first-cut approximation of trends. Future work will improve upon these analyses.

Data and Methods

Two major ongoing aerial surveys in Alaska's Arctic allow comparisons over time for different taxa to test for persistence of use of core habitat areas. The Aerial Survey of Arctic Marine Mammals (ASAMM) is a collaborative effort between BOEM, Department of the Interior, and National Oceanic and Atmospheric Administration's (NOAA) Alaska Fisheries Science Center. The ASAMM program combines the Bowhead Whale Aerial Survey Project (BWASP; run from 1979–2010), and the Chukchi Offshore Monitoring in Drilling Areas (COMIDA; began in 2008). For the ASAMM analysis, only beluga and bowhead whales were analyzed, using only the highest quality data which were from the months of September and October.

The US Fish & Wildlife Service Division of Migratory Bird Management conducts annual surveys of Alaska's Arctic coastal plain (ACP). The original ACP survey was run from 1986–2006, and the North Slope Eider survey, designed for a different goal, was conducted from 1992–2006. These two surveys were combined and redesigned in 2007. Importantly, only terrestrial observations were used in these analyses; many species of birds have essential marine areas they use for foraging, molting, or staging.

For the ACP Waterbird Survey, only species with more than 1,000 observations were used, restricting the 63 observed species to 18 species (see table below). Of these, 13 species were selected to analyze: Brant, Greater White-fronted Goose, King Eider, Long-tailed Duck, Northern Pintail, Pacific Loon, Red-throated Loon, scaup (undifferentiated; Greater or Lesser), shorebird (undifferentiated; several dozen species), Snow Goose, Spectacled Eider, Tundra Swan, Yellow-billed Loon. Although meeting the minimum observation threshold, five species (Arctic Tern, Glaucous Gull, Sabine's Gull, unidentified Jaeger, and Canada Goose) were not analyzed due to widespread, generalized distribution across the entire study area. The 13 analyzed species were grouped into five guilds: geese (Brant, Greater White-fronted Goose, and Snow Goose), sea ducks (King Eider, Spectacled Eider, and Long-tailed Duck), loons (Pacific Loon, Red-throated Loon, and Yellow-billed Loon), shorebirds (undifferentiated), and other waterfowl (Northern Pintail, undifferentiated scaup, and Tundra Swan).

Species	Guild	Count of Observations	Total Number Observed
Greater White-fronted Goose	Goose	35,932	111,564
Brant	Goose	2,410	9,112
Snow Goose	Goose	1,578	13,654
Long-tailed Duck	Sea Duck	14,409	23,421
King Eider	Sea Duck	4,625	7,669
Spectacled Eider	Sea Duck	1,477	2,095
Pacific Loon	Loon	13,406	20,185
Red-throated Loon	Loon	1,377	1,936
Yellow-billed Loon	Loon	1,304	1,708
Undifferentiated shorebird	Shorebird	19,794	40,931
Northern Pintail	Other Waterfowl	16,542	33,006
Tundra Swan	Other Waterfowl	5,655	8,648
Undifferentiated scaup	Other Waterfowl	4,854	10,163
Arctic Tern	*Not analyzed*	*8,046*	*14,062*
Glaucous Gull	*Not analyzed*	*7,905*	*13,535*
Sabine's Gull	*Not analyzed*	*4,329*	*9,268*
Undifferentiated jaeger	*Not analyzed*	*3,769*	*4,492*
Canada/Cackling Goose	*Not analyzed*	*2,011*	*9,763*

Most frequently observed bird species during the ACP Waterbird Survey, 1996-2015.

A summary of the methods is presented in the conceptual diagram below. All data were analyzed in four five-year time periods: 1996–2000 (t1), 2001–2005 (t2), 2006–2010 (t3), and 2011–2015 (t4). After initial filtering of data to remove poor-quality records and filtering by species to account for a minimum number of observations, observations were aggregated by five-year time period, in 15 km cells. Survey effort—recorded as flight length (km) for ASAMM and area surveyed (km^2) for the ACP Waterbird Survey—was also aggregated into a set of 15 km cells. Observations were weighted by the total survey effort to account for cells with different survey intensities. Any cells with fewer than 5% of the area surveyed per year (11.25 km^2 or 25 km of flight length) were removed from the analysis.

Conceptual diagram of persistence analysis methods.

The output—observations weighted by survey effort, for each species and each time period—was run through an isotropic kernel density function with a 45 km search radius (equivalent to a standard deviation of 15 km). This step both downscales the effort-weighted density rasters and allows data to be populated in cells not meeting sufficient survey thresholds but adjacent to known cells, removing edge artifacts that would otherwise be penalized.

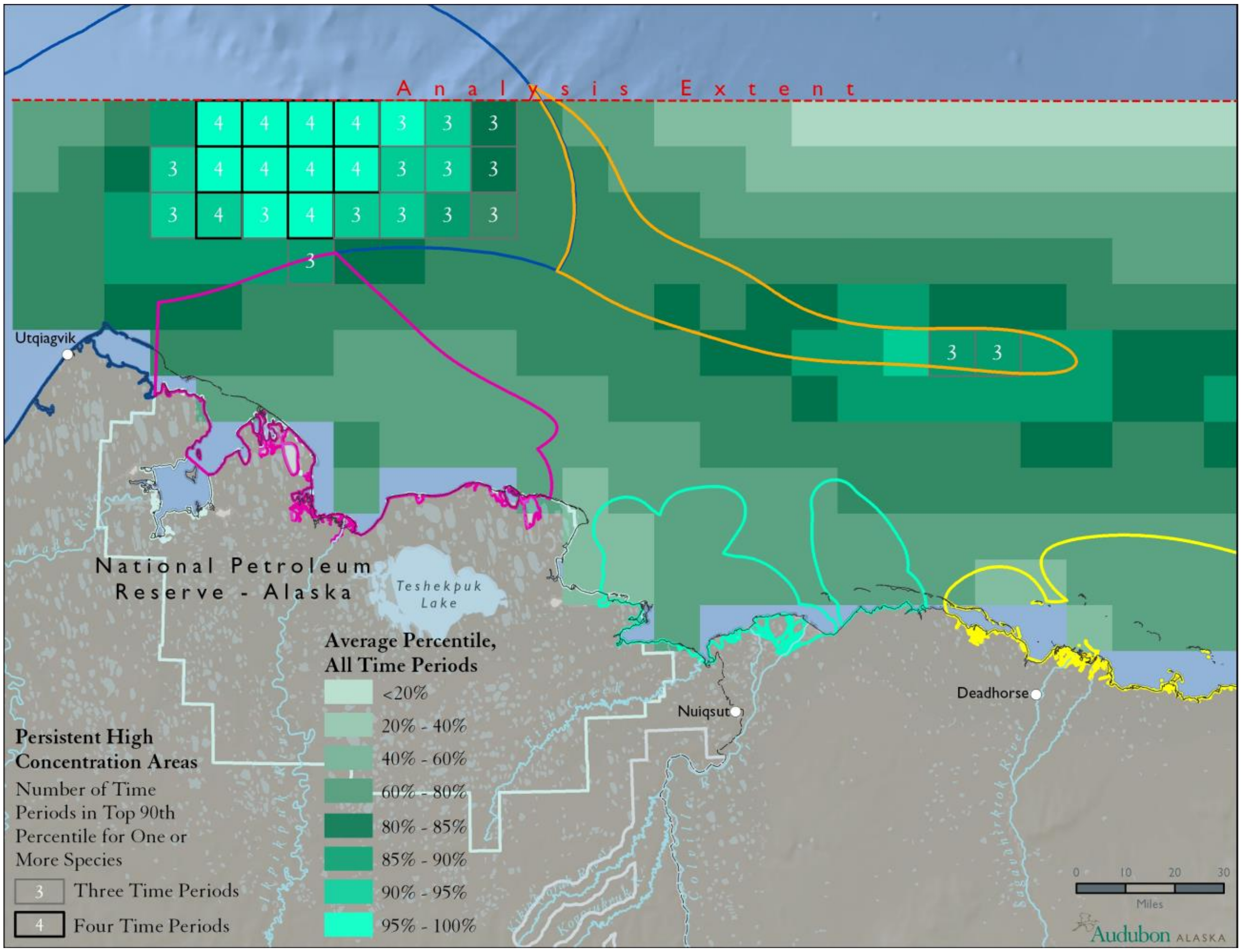
Next, the area-weighted average value was calculated for each species and for each time period, using zonal statistics with a 15km cell size. In order to compare results across years, all cells with values greater than zero were converted into a percentile value. Using percentiles helps track an area's importance regardless of population fluctuations. In other words, although a species' population might increase or decrease from one five-year time period to the next, the most important areas (as indicated by higher percentiles) would consistently stand out. For guild-based analysis, each species was weighted equally, and the percentile-based classification meant that species with lower abundances had the same statistical weight as species with higher abundances. All spatial analyses were performed in a combination of R and ArcMap.

Results

The output percentiles were split into two final products, both displayed in the maps below: 1) a 15km grid with the average percentile ranking for that species or group of species across all time steps; and 2) a series of 15km grid that represented cells in the top 90th percentile or higher (high concentration areas) for at least three of the four time periods for each species. The average percentile ranking is visualized using brighter colors for higher percentiles. Cells annotated with a "3" or "4" indicate that a species has consistently concentrated in that area for three or four of the time periods.

Results for Beluga Whales

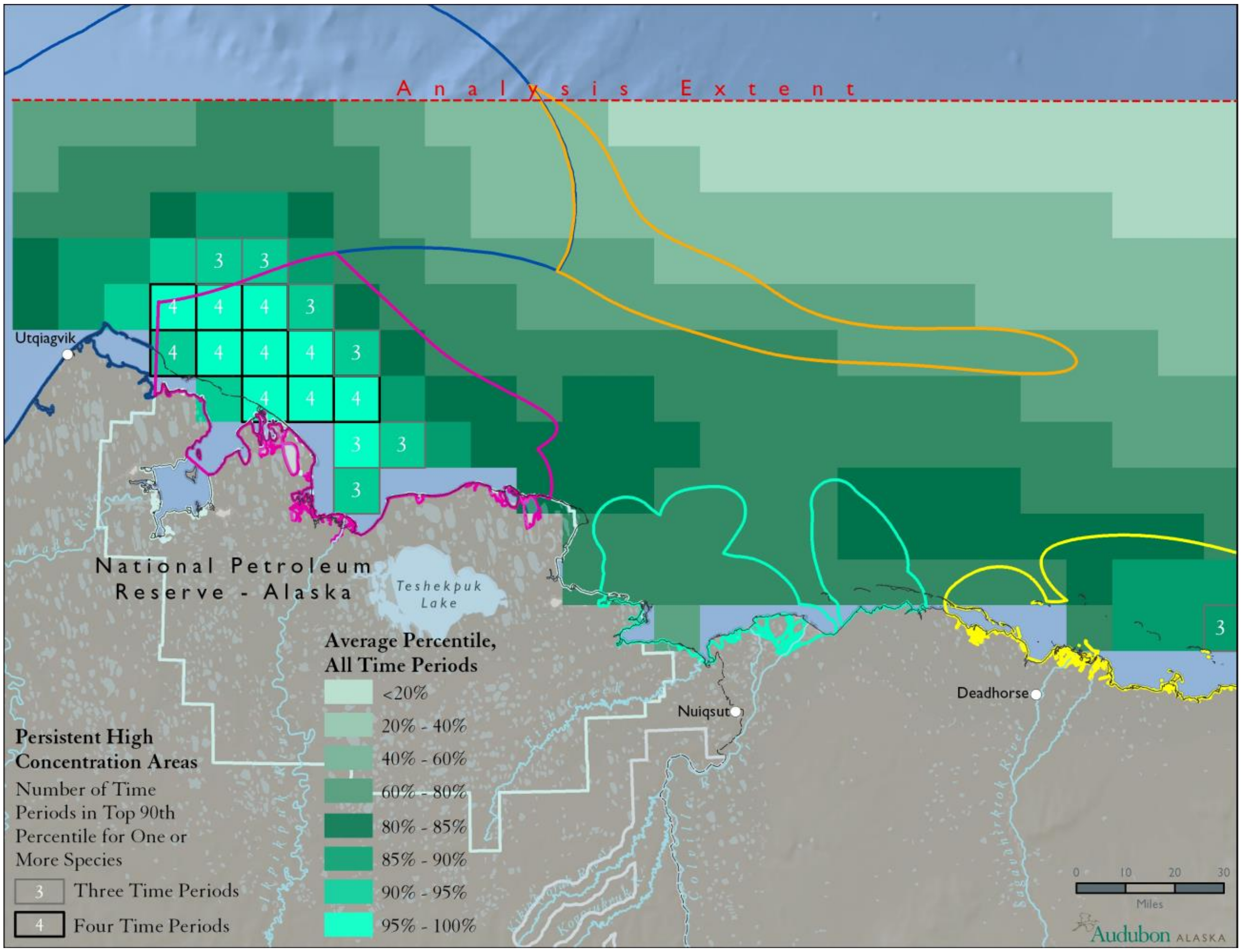
Areas along the central Beaufort shelf break have recurring high concentrations of beluga whales, as well as where the shelf break meets Barrow Canyon. Locations along the shelf break, where the seafloor rises from the Arctic Basin (approximately 6,500 feet [2000 m] deep) to the shallow continental shelf (approximately 160 feet [50 m] deep), have higher average density percentiles across all time periods than more deep or more shallow areas. Towards Barrow Canyon, belugas demonstrate persistent use of waters around 650 feet (200 m) deep.



Beluga whale persistence analysis. Recurring high concentration areas are in the deeper portions of Barrow Canyon and along the central Beaufort shelf break.

Results for Bowhead Whales

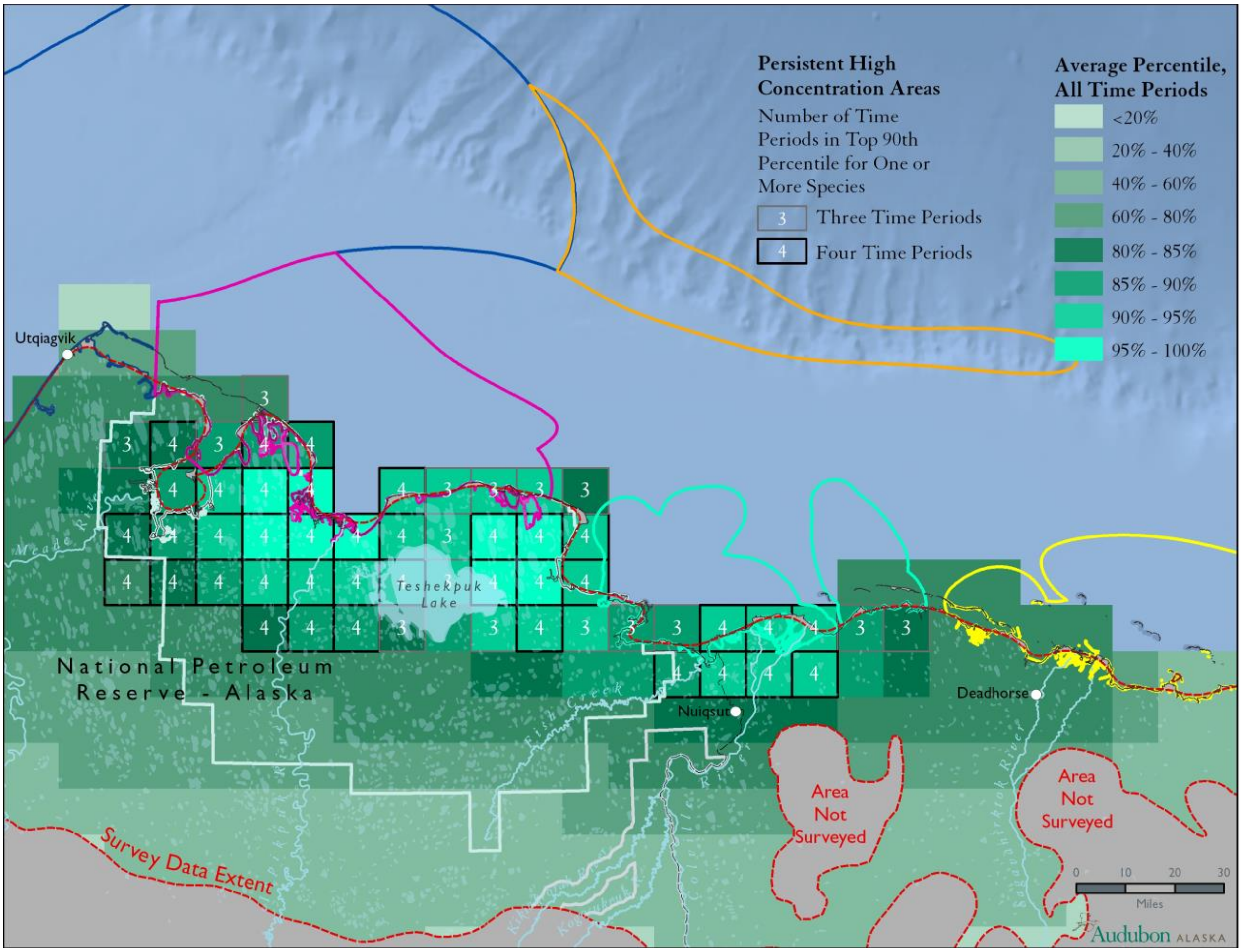
Bowhead whales are concentrated in shallower waters, compared with beluga whale distributions. The largest persistent high concentration area for bowhead whales is south and east of Barrow Canyon, near the 65 foot (20 m) depth contour (isobath). A localized persistent concentration area is located just north of Tigvariak Island, on the eastern edge of the study area. Other higher-than-average concentration areas are offshore of Cape Halkett and along the 65 foot (20 m) isobath north of the central Beaufort barrier island complexes.



Bowhead whale persistence analysis. The primary recurring high concentration area is close to and slightly southeast of Barrow Canyon, with a smaller persistent high concentration area near Tigvariak Island.

Results for Geese

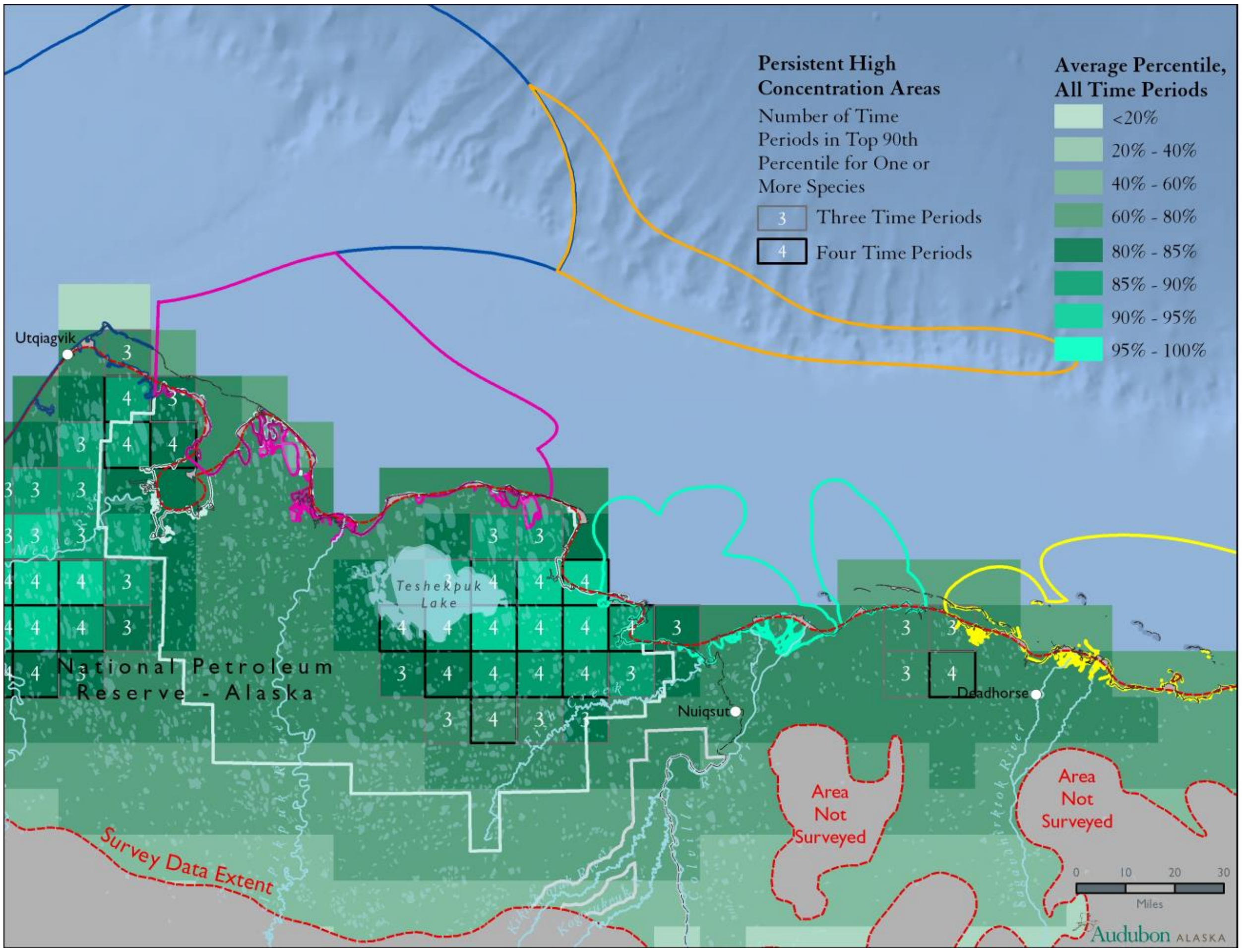
Geese–Brant, Greater White-fronted Goose, and Snow Goose–demonstrate consistent distribution patterns across all time periods. Key high concentration areas are located close to the coast: Ikpikpuk River delta, Kogru Inlet and north of Teshekpuk Lake, and the Colville River delta. Individual species show some geographic separation in high concentration areas, as indicated by the persistent importance but lower average percentile around Dease Inlet. This highlights the importance of using both persistent high concentration areas (derived for each species, showing individual variation across species and time period) and average percentile (averaged across all time periods and all species), as either of these results presented as a standalone visual would overlook key areas.



Goose guild persistence analysis. The goose guild aggregated Brant, Greater White-fronted Goose, and Snow Goose observations. Relative densities for each species were converted into percentiles for each time period and averaged across time periods and across species. Persistent high concentration areas represent one or more species.

Results for Sea Ducks

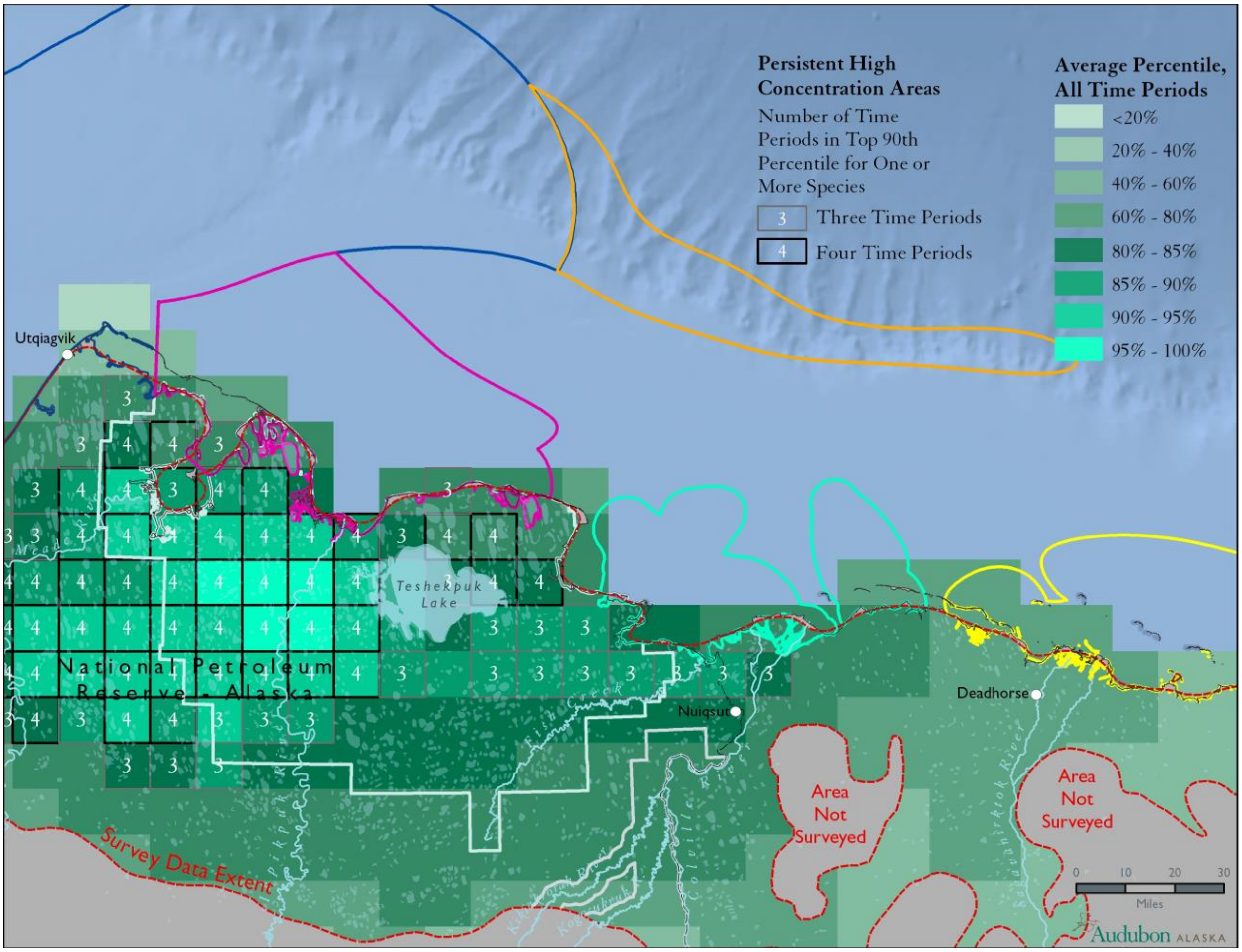
The sea duck guild, comprised of King Eider, Long-tailed Duck, and Spectacled Eider, have persistent high concentration areas slightly inland from those of geese: south of Utqiaġvik, along the Meade River, Kogru Inlet and south to Fish Creek, and just west of Deadhorse.



Sea duck guild persistence analysis. The sea duck guild aggregated King Eider, Long-tailed Duck, and Spectacled Eider observations. Relative densities for each species were converted into percentiles for each time period and averaged across time periods and across species. Persistent high concentration areas represent one or more species.

Results for Loons

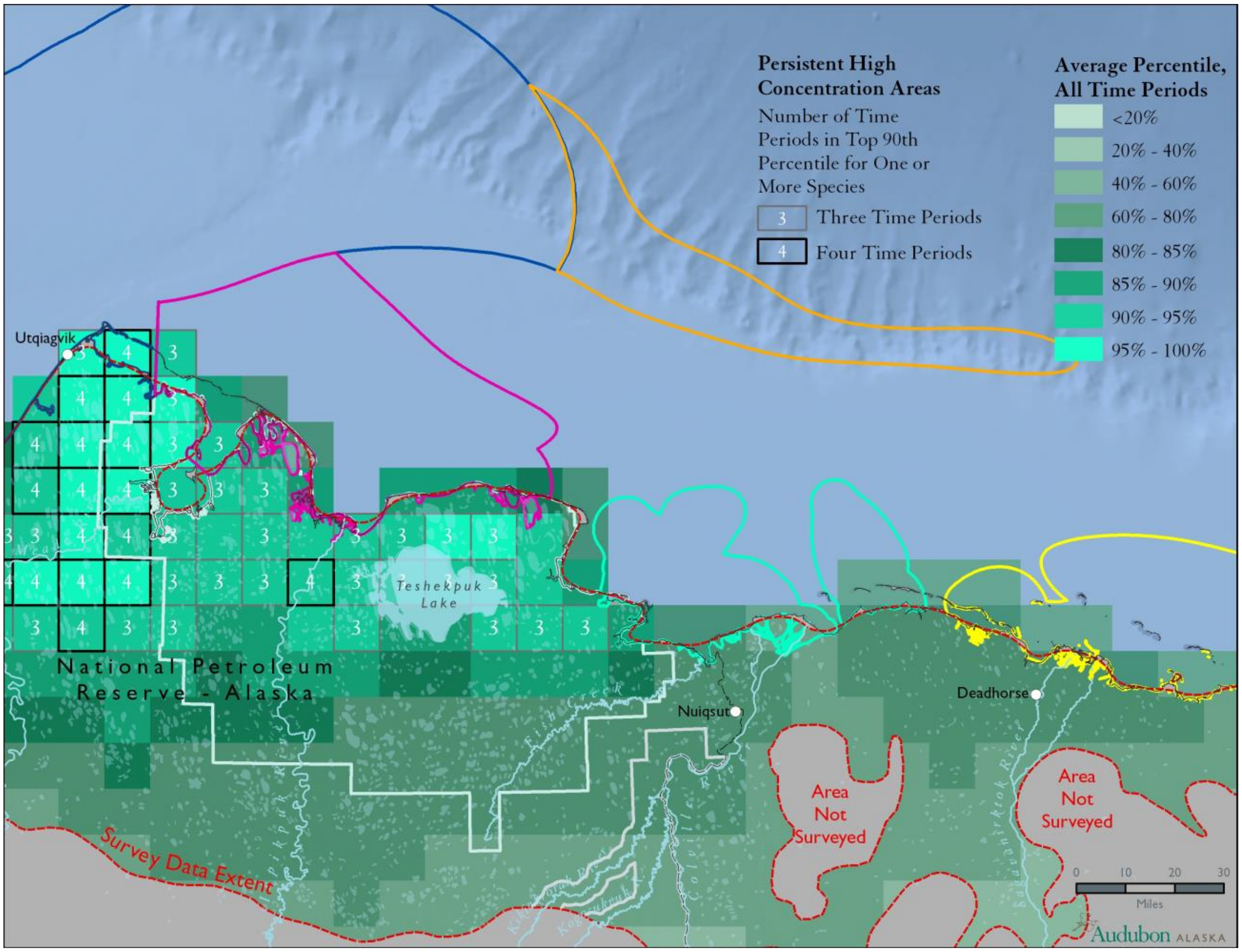
All three species of loons (Pacific Loon, Red-throated Loon, and Yellow-billed Loon) concentrate most in the coastal plain between the Meade River and the Ikpikpuk River, with other persistent high concentration areas north and southeast of Teshekpuk Lake. As with the goose guild, some persistent high concentration areas are not located within the highest average percentiles. These areas – primarily, northeast of Teshekpuk Lake and along the Dease Inlet shoreline – are consistently important for at least one species, but do not have the same high average value across all species and all time periods.



Loon guild persistence analysis. The loon guild aggregated Pacific Loon, Red-throated Loon, and Yellow-billed Loon observations. Relative densities for each species were converted into percentiles for each time period and averaged across time periods and across species. Persistent high concentration areas represent one or more species.

Results for Shorebirds

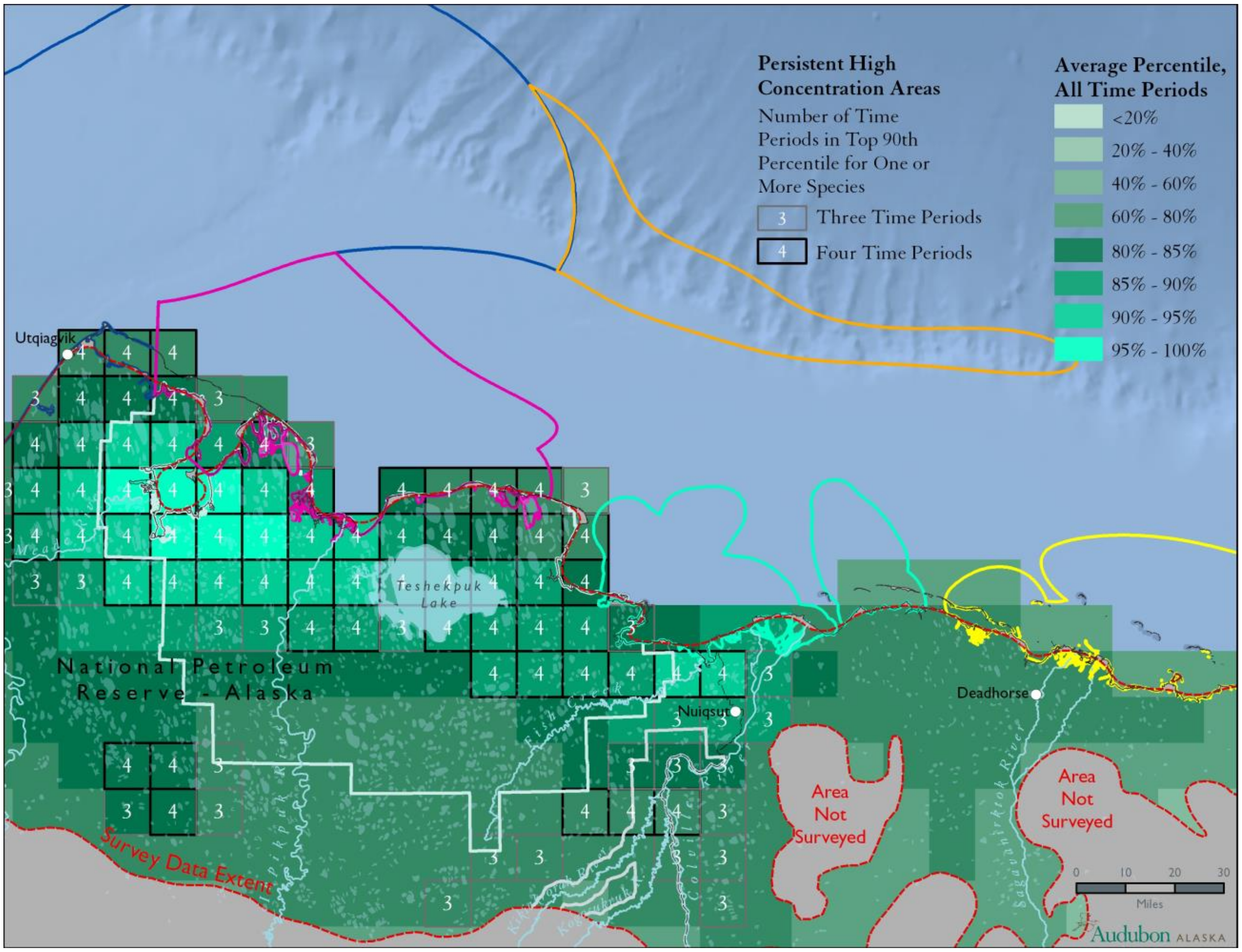
The persistence analysis aggregated many species of shorebirds representing different ecological niches and different preferred habitat types. However, there remains utility in this analysis which, on aggregate, shows that the highest concentration areas and the most persistent high concentration areas were in a connected area from Utqiaġvik south to the Meade River, across the lower Ikpukpuk River, along the northern shoreline of Teshekpuk Lake, and east to Kogru Inlet.



Shorebird guild persistence analysis. The shorebird guild aggregated all undifferentiated shorebird observations. Relative densities were converted into percentiles for each time period and averaged across time periods.

Results for Other Waterfowl

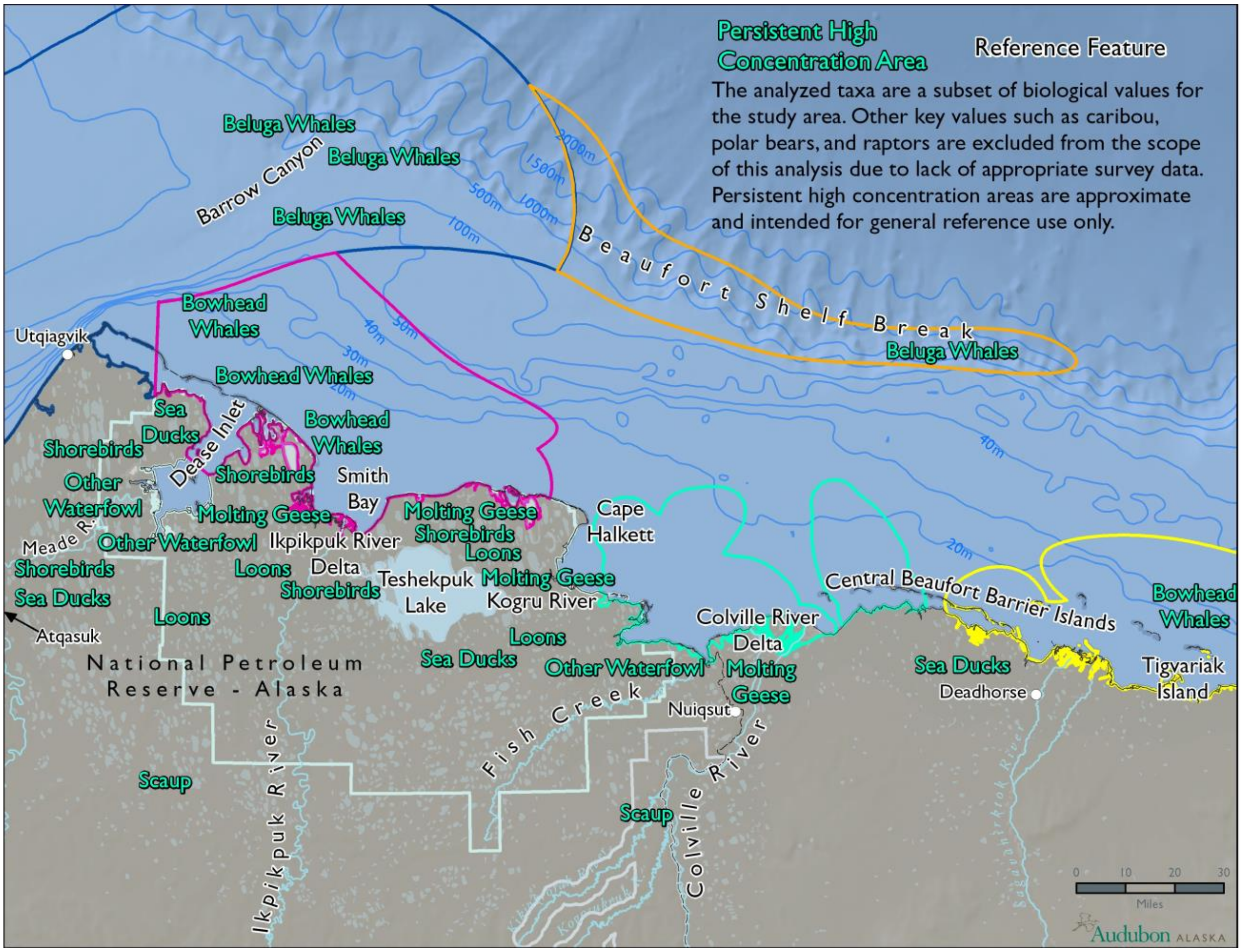
The remaining three bird species (Northern Pintail, Tundra Swan, and undifferentiated scaup) have more widely dispersed persistent high concentration areas, with all three species overlapping the most around Dease Inlet and towards the Fish Creek and Colville River deltas. Northern Pintails have persistent concentration areas around Teshekpuk Lake, and scaup are persistent near where the Kikiakrorak and Kogosukruk Rivers meet the Colville River and inland between the Ikpikpuk and Meade Rivers.



Other waterfowl guild persistence analysis. The other waterfowl guild aggregated Northern Pintail, Tundra Swan, and undifferentiated scaup observations. Relative densities for each species were converted into percentiles for each time period and averaged across time periods and across species. Persistent high concentration areas represent one or more species.

Summary of Results

These separate analyses can be aggregated geographically according to a few reference features (see figure below). Note that the persistence analysis selected species opportunistically, and corresponding survey data over long time horizons has not been acquired or analyzed for critical species such as caribou, polar bears, and raptors.



Qualitative summary of persistence analysis results. Names of guilds and species represent approximate location of persistent high concentration areas.

VI. Synthesis

The environmental changes, anthropogenic changes, and sources of uncertainty all have the potential to alter the biological values underlying Important Ecological Areas (IEAs) in the Beaufort Coastal Corridor region. These underlying biological factors have in large part remained consistent over time and merit strong ongoing conservation measures due to their key role in a functioning Arctic ecosystem. This section highlights major findings from this report using the spatial lens of IEAs.

Offshore

In the Arctic marine environment, productivity is dictated by upwelling, advection, discharge of terrestrial-derived nutrients, and other physical processes (Moore and Stabeno 2015; Moore et al. 2016). The marine IEAs in the Beaufort Sea are focused around geophysical features that influence these processes. Because climate change will likely not alter the underlying bathymetry or general geography, these features and their ecological importance will likely be resilient to climate change (Genin 2004). Barrow Canyon and the Beaufort Shelf Break are both sites where abrupt bathymetric changes trigger upwelling and subsequent productivity, and habitat selection for bowhead and beluga whales is driven by consistent bathymetric features such as these (Hauser et al. 2018; Hauser et al. 2017). The nearshore IEAs—Smith Bay, Harrison Bay–Colville Delta, and Oliktok Point to Demarcation Bay—are also ecologically important due to underlying physical factors: due to containment of brackish water rich in terrestrial nutrients, barrier islands create suitable habitat for a wide range of lower-trophic taxa dominated by the benthos (Dunton et al. 2012). Relatively consistent land-fast ice regimes result in consistent disturbance (ice scour) patterns (Mahoney et al. 2014), a key component of diversity, biomass, and overall abundance within Arctic benthic communities (Conlan and Kvitek 2005). However, these nearshore IEAs are more reliant on the Alaska Coastal Current and prevailing wind patterns to concentrate and periodically release primary production (Ashjian et al. 2010; Elliott et al. 2017), and with these two factors likely to shift in the future (Brugler et al. 2014), biological responses to climate change should be carefully monitored in these locations.

Oil and gas development is a leading regional threat in the Beaufort Coastal Corridor. Industrial activities such as seismic exploration or dense vessel-based transportation may disturb and displace Arctic cetaceans (Reeves et al. 2014). Both oil development and vessel traffic introduce the risk of oil spills, the consequences of which would be catastrophic in the Arctic marine environment (National Research Council 2014). Importantly, these two anthropogenic stressors–oil development and vessel traffic–are related, as oil and gas development leads to dramatically increased vessel traffic in marine areas.

Barrow Canyon

Although there have been observed or hypothesized shifts in lower-trophic phenology (Søreide et al. 2010), prevailing winds (Spall et al. 2014), and ocean current patterns (Brugler et al. 2014), cetacean use of the Barrow Canyon IEA has been persistent over the last 20 years. The drivers of Barrow Canyon's biological value are geophysical, as the submarine canyon promotes upwelling and triggers lower-trophic productivity, and these drivers are not likely to change (Genin 2004). Climate change may not have as significant an impact on recurring biological values in the Barrow Canyon IEA, provided zooplankton abundance does not decrease below a critical threshold for supporting upper trophic level taxa.

As vessel traffic increases in the Arctic, a large portion of those vessels will likely pass through or near this IEA. The Northwest Passage is a trans-Arctic maritime route from the Pacific to the Atlantic and is expected to increase in importance for international commerce, with a commensurate increase in vessel traffic, as sea ice recedes (Ocean Conservancy 2017). The Northwest Passage has five recognized variations, and all five routes travel past Point Barrow, in the Barrow Canyon IEA (Arctic Council 2009). This means that, under current management regimes, any increased traffic would go through the Barrow Canyon IEA. In addition to international commerce, vessels supporting oil and gas development along the Beaufort coast would pass through the Barrow Canyon IEA while traveling from transport hubs further south.

Proposed and existing oil and gas development on gravel islands would threaten Barrow Canyon in the event of a major oil spill. As indicated by results of the Arctic Trajectory Analysis Planner (ATAP), currents would sweep a hypothetical oil spill away from likely spill sites near Prudhoe Bay and towards Barrow Canyon. Given the difficulties of responding to an Arctic marine oil spill (National Research Council 2014) and the persistent high concentrations of cetaceans in this area (Citta et al. 2015), the consequences would be severe.

Beaufort Shelf Break

As with Barrow Canyon, the Beaufort Shelf Break IEA is similarly driven by bathymetric features that drive productivity, meaning that the geophysical basis of its biological values are unlikely to shift in the future (Genin 2004). This IEA supports persistent high concentration areas and, although sea ice conditions are changing rapidly, research indicates that beluga whale habitat selection has not significantly changed (Hauser et al. 2018).

Because of its location over 50 miles (80 km) offshore, the Beaufort Shelf Break is largely removed from major oil and gas vessel traffic routes and potential new international commerce. Additionally, the predominantly western currents along nearshore areas would drive potential oil spills away from the shelf, meaning that this IEA would be largely protected from the highest concentrations of discharged oil in the event of a major spill.

Smith Bay

The Smith Bay IEA may see change in the future and should be closely monitored. As indicated by the persistence analysis, bowhead whale distribution keys in on the areas offshore of Dease Inlet and near Barrow Canyon where a combination of currents, upwelling, and winds create favorable foraging conditions (Ashjian et al. 2010; Moore et al. 2010). Likely as a result of these factors, the Smith Bay IEA also has high value for other species not analyzed in this report (see Audubon Alaska et al. 2016). Major rivers (including the Meade and Ikpikpuk Rivers) transport terrestrial nutrients into nearshore areas, and the western portion of the Smith Bay IEA has barrier island complexes that harbor sheltered lagoons, all of which are important aspects of lower-trophic productivity.

However, with shifting winds and currents (Brugler et al. 2014; Spall et al. 2014), these hotspots of productivity may spatially or temporally shift so that they no longer align with cetacean migration. Recent aerial surveys have indicated unprecedented concentrations of bowhead whales in novel areas, east of the Smith Bay IEA (DeMarban 2018). Future research should investigate whether these observations represent a new normal or are unusual aberrations from otherwise consistent spatial aggregations.

In addition to climate change, Smith Bay may be subject to intensifying pressure from oil development. The Smith Bay IEA has high oil potential, and Caelus has heralded positive results from initial exploration. However, these results remain unconfirmed and Caelus' decision to postpone drilling delineation wells underlines the uncertainty in their claims (DeMarban 2017a). Relative to other emerging prospects, the Smith Bay drill sites are much further from existing infrastructure, and the consequent high transportation cost of getting produced oil to market may act as an additional barrier to development.

Harrison Bay – Colville Delta

Existing biological values of the Harrison Bay – Colville Delta IEA, including marine bird foraging and staging areas (Audubon Alaska et al. 2016), may expand in the future, as indicated by the novel aggregation of bowhead whales (DeMarban 2018). Physically, this IEA somewhat mirrors Smith Bay IEA: lagoons and protective barrier islands in the east, and riverine transport of terrestrial-derived nutrients into more open water in the west. Given that currents and winds are key factors in biological productivity in these nearshore areas (Elliott et al. 2017), climate change may spatially or temporally shift productivity and subsequent higher trophic concentrations, similar to Smith Bay.

The Harrison Bay – Colville Delta IEA also has significant oil potential, and may become the target of increased industry interest. Already, the expansions at Nikaitchuq and the eight new leases acquired in 2017 are perhaps an indication of future oil activities. Relatively high levels of vessel traffic, when compared with other areas in the region, are largely a result of existing oil development. Additional developments within the Harrison Bay – Colville Delta IEA further expose wildlife to the risks of oil spills, as well as intensifying disturbance from vessels serving oil fields.

Oliktok Point to Demarcation Bay

The Oliktok Point to Demarcation Bay IEA spans an extended network of barrier islands, lagoons, and riverine inflows. Although the biological values of this IEA were not included in the persistence analysis, this area supports a variety of wildlife, from polar bears to pinnipeds to seabirds (Audubon Alaska et al. 2016). Little is known about how this area will respond to climate change, aside from increased barrier island erosion and migration (Jones et al. 2009a).

Due to proximity to existing infrastructure at Prudhoe Bay, new oil development in the Oliktok Point to Demarcation Bay IEA would be relatively inexpensive to tying in to export pipelines. Lower transportation costs may increase industry interest in the future. Already, Liberty, a proposed gravel island-based drill site, is entering permitting phases, and other nearshore development may follow. Vessel traffic is relatively high within this region, due primarily to transportation logistics for oil developments. The risks of oil spills in this IEA are higher than in other marine IEAs due to elevated vessel and oil development activity.

Onshore

On a broad scale, the Arctic Coastal Plain provides a higher overall quantity and longer duration of digestible forage than in the nearby Brooks Range (Barboza et al. 2018), the cliffs along major rivers such as the Colville support prime raptor nesting sites (Ritchie et al. 2003), and the wetland mosaic of the Teshekpuk Lake Special Area provides high-density, high-quality habitat for shorebirds and waterfowl alike (Andres et al. 2012; Derksen et al. 1981). However, climate change is rapidly reshaping the Arctic terrestrial environment. Forces such as permafrost degradation, coastal erosion, intensifying fire regimes, and colonization by novel species are expected to result in major changes to wildlife distributions (Van Hemert et al. 2015). However, unexpected feedbacks and uncertainties such as the role of spatial heterogeneity make it difficult to accurately predict how, where, when, and even whether these changes will take place. These uncertainties limit the effectiveness of landscape-level conclusions, meaning that analyses at finer spatial scales may more accurately illustrate the biological impacts of a changing climate.

Oil and gas development is widespread across most of the North Slope, resulting in observed impacts to various wildlife species, some of which are summarized by Sullender (2017). Current wildlife values are most concentrated in areas with no existing permanent oil and gas infrastructure such the Teshekpuk Lake IEA. However, industry interest has intensified in recent years, and development plans are proceeding westward from the Colville River into the NPR–A.

Teshekpuk Lake

The Teshkepuk Lake IEA is in the process of undergoing significant ecological changes, particularly along the Beaufort coastline and in inland areas vulnerable to extensive thermokarst processes. Researchers are working to understand the nature of changes in this system, and initial conclusions suggest that the abundant waterfowl are acting as ecosystem engineers, creating and expanding suitable habitat through grazing activity (Flint et al. 2014; Person et al. 2003; Tape et al. 2013). The range expansions and population growth seen in Brant, Greater White-fronted Geese, and Snow Geese suggest that climate change may be complementing other density-dependent factors and creating more suitable habitat for geese (Flint et al. 2008; Tape et al. 2013). As indicated by the persistence analysis, the long-standing recurrence of high concentrations of geese around Teshekpuk Lake suggests that geophysical factors such as coastal erosion and thermokarst expansion are not disrupting existing goose distribution.

The vegetation changes in the Teshekpuk Lake IEA may have a larger bearing on caribou. Individuals from the Teshekpuk Caribou Herd (TCH) seasonally access the Beaufort coastline for insect relief (Person et al. 2007), but if suitable forage is unavailable due to waterbird-triggered vegetation shifts, caribou may be displaced to less suitable alternate habitats to satisfy their nutritional demands. Other impacts of climate change on caribou may be more neutral. Evidence suggests that trophic mismatch is not currently affecting Arctic caribou (Gustine et al. 2017), and because a large proportion (65%) of the herd overwinters in or near the Arctic Coastal Plain (Person et al. 2007), the TCH may be less vulnerable to the loss of lichen due to wildfire than herds that range further south (Joly et al. 2012). Furthermore, the TCH's range is further from areas susceptible to moose habitat and potential interspecific competition than among other herds (Tape et al. 2016b). Determining the trajectory of coastline caribou habitat suitability appears to be a key question for the biological values of the Teshekpuk Lake Special Area going forward.

The Teshekpuk Lake IEA has very high levels of industry interest and the highest oil potential within the study region. If pursued, ConocoPhillips' Willow prospect would be partially within this IEA— the Tinmiaq 6 exploration well is within the Special Area boundary. Because the eastern portion of the Teshekpuk Lake Special Area–near the Kogru River–is a key caribou migration corridor and (Person et al. 2007; Yokel et al. 2011) and much of the area serves as high-quality summer habitat (Wilson et al. 2012), there is significant potential for industrial-wildlife conflict if development proceeds.

Colville River

The Colville River is likely to remain important for nesting raptors, but expanding shrubs may change riparian vegetation communities. The Colville River Special Area is less susceptible to thermokarst than Teshekpuk Lake Special Area, but, as a major riparian corridor, is a likely vector for colonizing species such as alders and moose. However, given that the Colville River's key biological values are focused on nesting raptors, climate change may not have much impact on the raptor values within this area. Studies of similar Arctic raptor systems are equivocal, with earlier snowmelt and warmer summer temperatures hypothesized to improve raptor productivity (Bruggeman et al. 2015), but these gains may be offset by potential phenological mismatch and loss of existing nests due to geomorphological hazards such as landslides (Beardsell et al. 2017). Existing nests are particularly important because metrics of reproductive success are strongly linked with nest site and surrounding habitat characteristics (Bruggeman et al. 2015) and Arctic raptors that re-use nesting sites have higher productivity when compared with raptors that build a new nest (Beardsell et al. 2016).

Oil and gas activity may not substantially increase within the Colville River, but nearby developments and associated infrastructure may spill over. The Colville River Special Area has a high percentage of its acreage already leased (over 51% of the area within the Beaufort Coastal Corridor study extent), but recent assessments do not indicate as much oil potential as further north. Still, the GMT2 project would neighbor the Special Area— the proposed production well location is only few hundred meters (0.11 miles) north of the Colville River Special Area boundary. Most of the northern portion of this IEA is leased or adjacent to existing leases.

VII. Conclusions

Wildlife ranging from shorebirds to cetaceans have used the Important Ecological Areas (IEAs) described in this report for at least as long as records have been kept. Evidence indicates that these areas will remain important, even in a changing landscape, as there are key underlying geophysical features that drive productivity and influence the distribution of upper trophic taxa. The persistence analysis conducted here provides further support for this idea: a wide range of wildlife guilds and species demonstrated recurring high concentration areas across 20 years of surveys. Spatial protection of important habitats is therefore likely to be an effective strategy for conservation of key biological values, provided these protected areas are large enough to account for naturally occurring variability.

Across the Arctic, large changes are already occurring and are predicted to intensify in the future (Hinzman et al. 2005). Within the marine environment, research has noted recent changes in sea ice extent, sea ice seasonality, wind and ocean circulation patterns, the frequency of upwelling events, and even fundamental chemistry. On land and along the coast, erosion and saltwater inundation is increasing, permafrost degradation is accelerating, fire regimes are intensifying, halophytic vegetation is increasingly dominant, shrub extent is advancing, and novel species are expanding range northwards. Development, in the form of oil and gas extraction and transportation networks, is adding additional stressors to this ecosystem. Impacts from development may extend far beyond immediate project areas, as disrupted migration corridors, altered hydrology patterns, acute and chronic toxicity, and habitat loss.

However, variability and uncertainty make it difficult to define ecological responses to myriad changes. Finer-scale responses to environmental changes, fluctuations in populations, long-distance connections, and shifting phenology may drive wildlife to use novel areas outside existing IEAs boundaries. Management plans should incorporate an understanding that wildlife will spatially and temporally track suitable conditions as needed.

In this dynamic environment, the principles of Integrated Arctic Management, as laid out by Hartsig (2016) and Clement et al. (2013), are essential guidelines for successful planning. Among many other components, some key values include regional, rather than piecemeal, planning; inter-agency coordination across local, state, and federal levels; explicit assessment of cumulative effects; adaptive approach to integrating ongoing research; focus on ensuring continuity of ecosystem functions and services; and meaningful stakeholder engagement and consultation. By applying these principles, effective, sustainable, and robust management of Alaska’s Beaufort Coastal Corridor is possible, even in the face of a rapidly changing environment.

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Alaska's Beaufort Coastal Corridor

Photo: Gerrit Vyn

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