**Shrubification in the Western Arctic   
and its Effects on the Porcupine Caribou Herd Habitat**

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# **Introduction**

**Arctic Amplification**

The **Arctic is warming more than twice as fast** as the global average (Post et al., 2019). Since the late 19th century, the Earth has warmed by approximately 0.8°C, while the Arctic has warmed by 2-3°C (Post et al., 2019; IPCC, 2013). This phenomenon is known as the **Arctic amplification (AA)** (Serreze & Barry, 2011) and is driven by complex and intertwined anthropogenic and natural processes (Cohen et al., 2020). Notably, rising greenhouse gas (GHG) concentrations in the atmosphere increase radiative forcing in the Arctic region (Stroeve et al., 2012; Gillett et al., 2008). This leads to a positive feedback, as decreased surface albedo due to sea ice loss replacing highly-reflective ice sheets with dark, poorly-reflective sea water, exacerbating warming (Winton, 2006). The **surface albedo feedback** is considered one of the major contributors of AA (Serreze & Barry, 2011). Other drivers of AA include increased cloud cover exacerbating the greenhouse effect (Graversen & Wang, 2009), the reduced longwave emissions per unit warming from the Arctic compared to the tropics (Pithan & Mauritsen, 2014), and deposits of black carbon on surfaces (Shindell & Faluvegi, 2009). Arctic temperatures are also sensitive to atmospheric currents driving warm and moist air from the tropics northward (Graversen et al., 2008).

**The Arctic is expected to reach 4°C mean annual warming under the +2°C global warming scenario** (Post et al., 2019). This would exacerbate and accelerate the ongoing loss of land and sea ice, with the potential development of an ice-free Arctic ocean in the summer (Wang & Overland, 2009), increasing global sea level rise (Post et al., 2019). The amplification of warming in the Arctic has been linked to extreme weather events such as floods, droughts and heat waves in mid-latitudes (Post et al., 2019). However, divergence between observational and model studies obfuscate our clarity of understanding of the influence of AA on midlatitudes weather (Cohen et al., 2020). Arctic warming is also likely to increase net methane emissions from wetlands and permafrost thawing, leading to a positive feedback in the global climate system (Arctic Monitoring and Assessment Programme (AMAP), 2017).

**Warming temperatures are influencing growing season length, soil hydrology and nutrient levels – which are affecting vegetation in complex ways**, including changes in vegetation composition, productivity, structure and phenology (Stow et al., 2004). Some of the most devastating consequences of pronounced Arctic warming would be suffered by the wildlife feeding on tundra vegetation and the human livelihoods depending on these for nutritional, economic and cultural reasons (Post et al., 2019).

**Warming-induced *Shrubification***

Concurrent with Arctic warming, **aboveground biomass of tundra vegetation has been increasing** since the 20th century (Epstein et al., 2012; Ju & Masek, 2016). This has been shown by field (Elmendorf et al., 2012c) and remote-sensing (Jia, Epstein & Walker, 2003) studies, as well as repeat photography (Fraser et al., 2014; Sturm, Racine & Tape, 2001) in high-latitude and Arctic ecosystems. Indeed, remote sensing detected an increase by 16.4% in peak NDVI - indicating green vegetation - between 1981-2001 in northern Alaska (Jia, Epstein & Walker, 2003), with greening (increasing vegetation productivity). Plot-based warming studies such as the **International Tundra Experiment (ITEX)** have consistently shown increases in vegetation height (Walker et al., 2006). In particular, **deciduous shrubs including willow, alder and birch, have expanded in relative abundance and cover** with variability across the Arctic region (Fraser et al., 2014; Elmendorf et al., 2012a; García Criado et al., 2020; Elmendorf et al., 2012b; Myers-Smith et al., 2011).

“Shrubs are woody plants with diverse growth forms including tall multi-stemmed shrubs (0.4–4.0 m), erect dwarf shrubs (0.1–0.4 m) and prostrate dwarf shrubs ( < 0.1m) that grow laterally along the ground surface.” (Myers-Smith et al., 2011)

The phenomenon of shrub expansion as a response to climate change is known as Arctic *shrubification,* and itoccurs in the form of infilling of existing patches through lateral growth, increased canopy height, and advancing of shrublines (Myers-Smith et al., 2011). Indeed, some species of shrubsuch as *Betula nana* are favoured by the increasing air temperatures (Myers-Smith et al., 2011).***Shrubification* on the North slope of Alaska has been found to occur mainly in valley bottoms and hillsides (Tape, Sturm & Racine, 2006), wet and warm sites, favouring microbial activities in the soil** (Myers-Smith et al., 2011). In Alaska and the Yukon Territory, willow and alder species are advancing upslope(Dial et al., 2007). Woody species such as *Betula*, *Alnus*, *Salix spp.* arestarting to dominate the Arctic landscape (Mekonnen et al., 2021). Shrub expansion may result in the outshading of understory shade-intolerant vegetation species, reducing overall species richness (Pajunen, Oksanen & Virtanen, 2011) and impacting food webs (Myers-Smith et al., 2011). Notably, lichen – an important forage species for many herbivores - has been found to decrease as shrub cover increases (Dawes et al., 2011; Joly, Jandt & Klein, 2009; Cornelissen et al., 2001). Moreover, shrubs may outcompete moss species, impacting their soil insulation function(Myers-Smith et al., 2011; Blok et al., 2011). Shrub expansion thus modifies ecosystem processes such as snowpack depth, nutrient exchange, and surface albedo. Continued *shrubification* is expected to alter carbon sequestration, fire dynamics and productivity in the Arctic regions (Myers-Smith et al., 2011). Overall, *shrubification* of tundra vegetation has the potential to mitigate and aggravate warming (Wookey et al., 2009).

Although coarse-scale satellite imagery indicates widespread arctic greening (Raynolds et al., 2012), site-level studies indicate that primary productivity in the tundra is highly heterogeneous (Kremers, Hollister & Oberbauer, 2015). Indeed, the spatial resolution of coarse satellite imagery is 250 m–8 km, whereas the spatial distribution of shrubs in the tundra is heterogenous (1-100m)(Myers-Smith et al., 2011). Validation via *in-situ* studies is therefore crucial to confirm low-resolution satellite information(Myers-Smith et al., 2011). However, bias from site-based research in the Arctic being highly clustered must be taken into account when making generalisations about vegetation trends (Metcalfe et al., 2018).

**Warming-induced Phenological Shifts**

**Arctic warming has been influencing phenology** – the timing of lifecycle events related to climate (Collins et al., 2021). Increasing temperatures have in fact altered snow regimes, accelerated decomposition rates, shortened flowering seasons (Prevéy et al., 2019) and extended growing seasons (Ernakovich et al., 2014). Periodic seasonal phenomena have been altered by increasing temperatures, with plant spring phenology events such as flowering and seed maturation advancing in time (Bjorkman et al., 2015) and with leaves senescence happening later in time (Bjorkman et al., 2019). Phenological responses of plants to warming affect trophic webs, with the **potential of developing mismatches in the synchrony of interacting species**, in particular consumer and resource species (Post et al., 2019). Adaptation and plasticity to changing environmental conditions may hit a threshold, hampering food web stability (Iler et al., 2013).

**Arctic Warming affects Large Herbivores**

**Large herbivores are crucial determinants of ecosystem dynamics in the Arctic** (Post et al., 2019), as well as having irreplaceable resource and socioeconomic value for indigenous communities livelihoods. The **complex feedbacks between herbivores and ecosystem function** in the Arctic are still being investigated, with recent findings linking herbivores to climate mitigation by affecting carbon uptake (Cahoon et al., 2012), land surface albedo (te Beest et al., 2016), and plant diversity (Post, 2013). **Herbivores play a vital role in preserving Arctic biodiversity** by hindering plant growth and favouring low-growing plants, avoiding their competitive exclusion (Kaarlejärvi, Eskelinen & Olofsson, 2017). Changes in vegetation community composition and phenology influence the abundance and distribution of Arctic herbivores (Mallory & Boyce, 2018).

Caribou (*Rangifer tarandus*) are among the most abundant long-range migratory herbivores in the Northern Hemisphere (Mallory & Boyce, 2018). Due to an observed 40% decline over three generations across the Arctic, caribou was classified as **vulnerable** by the IUCN red list in 2015 (Gunn, 2015). Migratory tundra caribou population abundance undergoes seasonal cycles and quasi-cyclic fluctuations over 40-90 year timescales (Ferguson, Williamson & Messier, 1998; Zalatan, Gunn & Henry, 2006). This means the influence of migratory herbivores on shrub populations is likely to change across time and space (Post et al., 2009). Fluctuations are thought to be related to climate oscillations (Joly et al., 2011), interactions with forage plants (Messier et al., 1988; Manseau, Huot & Crete, 1996) and predators (Bergerud, 1996). However, rapid climate-driven vegetation changes in the Arctic may alter this typical seasonality (Gunn, 2015). Indeed, despite **warming temperatures increasing plant biomass, the nutritional value of vegetation is declining and insect harassment is increasing**, counteracting the positive effects on caribou abundance (Gunn, 2015). Seasonal migration is the ecological strategy that caribou adopt to track emergent forage and avoid predation and parasitism from insects (Gunn, 2015).

The **causes of caribou decline remain uncertain**, but likely include habitat change and *shrubification*, associated with loss of sea ice (Fauchald et al., 2017). Caribou **population size responds negatively to vegetation change since caribou require late successional habitats** (Apps et al., 2001) and tend to browse in areas containing abundant lichen cover (Joly et al., 2003). Caribou are **generalists** (with diets including sedges, forbs, lichens, and shrubs) and **seasonally selective**: in the winter, caribou prefer to forage on slow-growing lichens (Russell, Martell & Nixon, 1993). Being migratory, caribou populations are highly susceptible to landscape change and seasonal habitat degradation, disrupting migration routes. Some known mechanisms causing disruption include anthropogenic barriers, unregulated hunting, and habitat fragmentation. The possible interactions of climate change with caribou population dynamics are highly complex and still under-studied. It is likely that warming temperatures will increase effects of disease and parasite loads (Gunn, 2015), but how migratory behaviour may be affected still remains unclear.

**The Porcupine Caribou Herd (PCH)**

Distributing across the U.S-Canadian border, the **Porcupine Caribou Herd (PCH)** is one of the largest herds in North America (Severson et al., 2021). The PCH plays a key role in the ecosystem by supporting predator populations such as bears and wolves (Musiani et al., 2007) and via grazing effects on vegetation (Wal, 2006). The PCH also has irreplaceable economic and cultural value, being crucial for the livelihoods of Indigenous peoples such as the Inuit and Tlicho (Kerber, 2015). **Arctic shrubification could deteriorate the herd’s pasture quality**, **with shrubs outcompeting lichen and mosses - caribou’s preferred diet** in winter and spring - resulting in potential declines in PCH populations (Fauchald et al., 2017).

Like most caribou populations, the **PCH undertakes annual long-distance migration between summer and winter ranges**, to **track emergent vegetation** and to **decrease predation risk** during the calving season (Mallory & Boyce, 2018). Migration is an ecologically fundamental behaviour, ultimately determining herd abundance (Gunn et al., 2009). The herd migrates in spring from the Yukon and Northwest Territories to its calving grounds in Alaska (Kerber, 2015). In particular, high-quality summer forage is critical for female (cow) body condition during lactation, with females having a window of 2 months over the summer to restore their fat reserves and gain enough fat to reproduce the following year (Barboza et al., 2018). The PCH enters its winter range with relatively low fat reserves, but manages to survive thanks to low snow and high lichen cover (Gunn et al., 2009). North of the tree line, in spring, the main dietary elements become evergreen shrubs and mosses, until the green-up of vegetation after snowmelt (Gunn et al., 2009). The timing of the green-up is crucial in determining the fate of new-born calves after the first month, with evidence of warmer springs favouring calf survival (Gunn et al., 2009). Indeed, nitrogen-rich emerging forage is crucial for milk production (Gunn et al., 2009).

Increased summer temperatures have however been found to **decrease nitrogen concentration in plant species due to increased net carbon production and dilution effects (Turunen et al., 2009)**, endangering caribou’s nutritional health and reproductive success. It is important to note that the PCH has had the lowest capacity for growth among Alaska barren-ground herds, indicating it has the lowest tolerance to anthropogenic and climate-change driven stressors (Douglas et al., 2002). Changes in plant phenology have been found to affect PCH spatial distribution, with caribou tracking protein-rich vegetation in early growth stages and **predominantly using Alaskan habitat in years of accelerated phenology** ((Severson et al., 2021); Fig.1). These phenological shifts could affect the present PCH migrationroute. Since herds are a prey base for large carnivores, the consequences of changes in PCH migratory behaviour could have cascading effects across food webs (Musiani et al., 2007).

Map

Description automatically generated

Fig. 1. Predicted probabilities of PCH calving habitat use during years of early **phenology (2015) and late phenology (2018)** (Severson et al., 2021).

Conservation Implications

While human-driven threats to caribou such as land-use change and energy production are well documented (Gunn, 2015), the impacts of climate change on caribou population dynamics are still unclear. Understanding how the PCH distribution may respond to shrubification is therefore crucial to inform habitat conservation commitments across the Alaska-Yukon border. The effectiveness of protected areas in landscape management is contentious since such conservation actions havenot slowed down caribou decline (Johnson, Ehlers & Seip, 2015). Given the migratory nature of caribou, conservation efforts should aim to provide a network of protection for annual ranges, across international borders.  Warming temperatures and improved access to resources in the northern Arctic are likely to increase industrial activity and development (Severson et al., 2021), increasing disturbance within the PCH habitat. It is therefore crucial to **understand how suitable habitat may be distributed in the future in order to protect the PCH habitat and to support its role in the ecosystem and ensure the subsistence of Indigenous communities** (Severson et al., 2021).

## **Objectives and Rationale**

The overarching aim of this research is to investigate vegetation change in the PCH Alaskan summer range habitat over the timescale 2007-2016.

## **Research Questions and Hypotheses**

I will answer the following research questions (RQ), focusing on the PCH Alaskan summer range:

**RQ1: How much of the PCH summer range is shrub covered?**

**RQ2: Are shrubs found in warmer and wetter range areas?**

**H2:** More shrubs found in wetter and warmer areas of the range due to enhanced soil microbial activity facilitating shrub growth (Myers-Smith et al., 2011)

H20:

H2a:

**RQ3: Is there more shrub cover in early or late phenology years?**

**H3:** Greater shrub cover in early phenology years: more growing time (Collins et al., 2021)

H30: no relationship

H3a: alternate hypothesis

**RQ4: How has vegetation cover changed over time?**

**H4**: Shrub cover increasing over time outcompeting other plant functional types (Myers-Smith et al., 2011)

H40:

H4a:

**RQ5: Do plot-based and landscape estimates of vegetation trends match?**

**H5**: NDVI vegetation trend correlating with plot-based estimates (Myers-Smith et al., 2019)

H50:

H5a:

**Predictions**

# Methods

## Study Site

\*\*Map\*\*

## Study Species

\*\*about the PCH\*\*

## Data Collection

I gathered data from different open-access sources. I used the following datasets:

**a. Climate data**

CHELSA dataset

**b. Shrub cover data**:

from Berner et al

**c. PCH core range data**

**d. ITEX data**

**e. Phenology data**

**f. NDVI data**

\*\*diagram on data wrangling\*\*

## Data Analysis

* 1. **RQ1: Shrub percentage cover in the PCH summer range**

I overlaid a shrub cover map of the Alaskan North Slope from 2007-2016 (Russell, Martell & Nixon, 1993) with a caribou summer range map from 2016. I cropped the shrub map to the summer range map and I estimated shrub percentage cover.

* 1. **RQ2: Shrub presence-absence in climatic regions**

I point-extracted climate data (summer temperature and precipitation) and shrub presence-absence from polygons within the map. I used ANOVA to compare shrub dominance VS climate data.

* 1. **RQ3. Shrub cover in early VS late phenology years**

I plotted shrub cover over time using hierarchical linear models. I plotted a shrub phenology variable (Prevéy et al., 2021) over time, and determined late/early phenology years using an arbitrary tthreshold. I used ANOVA to compare late or early phenology year VS shrub cover.

* 1. **RQ4. Vegetation trends over time**

I plotted percentage cover of various plant functional types (shrubs, mosses, lichens, forbs) over time using hierarchical linear models.

* 1. **RQ5. Vegetation trends across scales**

I fond NDVI trends (browning, greening, no change) in the region. I correlated plot-based estimated of vegetation cover with NDVI estimates of vegetation cover trends.

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