Government of Northwest Territories
Gouvernement des Territoires du Nord-Ouest

NWT Cumulative Impact Monitoring Program (NWT CIMP)
FINAL REPORT TEMPLATE 2023-2024

1. Project Information

NWT CIMP #	187		
Project Title	Vegetation productivity and phenology across the Bathurst caribou range		
Project Lead and Organization	Ryan Danby, Queen's University		
Date Submitted	May 24, 2024	**Project Length:** *years of NWT CIMP funding*	7
Type of Research	☒ Science ☐ Traditional Knowledge		
Valued Component *Check all that apply. If 'other' please specify.*	☒ Caribou ☐ Fish ☐ Water ☐ Other:____________		
NWT Area/Region and Closest Community	☐ North/South Slave ☐ Dehcho ☐ Sahtú ☐ Gwich'in ☐ ISR ☒ Wek'èezhii Closest NWT Community(s): Wekweètì		
Project Location *(Provide specific coordinates; or if regional, provide 4 coordinates for the bounding box.)*	North: 67.256 South: 61.599 East: -106.433 West: -121.593 Please use DD.MMMMM format		
Project Keywords *(at least four)*	Bathurst caribou, remote sensing, dendrochronology, vegetation, climate change		
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2. Consent

I acknowledge and permit the completed report, including photos to be posted for public access on the NWT Discovery Portal.	☒ I agree

3. Key Messages

- Satellite image analysis reveals significant changes in the seasonality and peak annual production of vegetation across portions of the Bathurst caribou herd's range between 2000-2021. Changes on the herd's winter range are driven by forest fire history. Changes in portions of the range beyond treeline are moderate and weakly linked to variation in timing of snowmelt and the type of vegetation present at a site.

- Field validation of the satellite image analysis on the late summer range indicates that the “greening” signal is a result of higher survival, increased growth, and greater leaf production on preexisting shrub stems, rather than widespread establishment of new shrubs.

- An updated analysis of caribou telemetry locations confirms significant reduction in the extent of the Bathurst caribou herd’s annual and seasonal ranges during the population decline and indicates that the timing of spring migration and calving are changing. The herd’s summer range has contracted significantly to an area surrounding Contwoyto Lake.

- The widespread, though moderate, level of greening on the Bathurst caribou herd’s summer range is attributable partly to increased growth of tall deciduous shrubs. However, the specific influence of this change as a contributing factor in the herd’s decline is unclear.

4. Abstract

Vegetation change in response to climate change is one hypothesis for the rapid decline of the Bathurst caribou herd. We explored this through range-wide monitoring of vegetation on an annual basis in conjunction with an updated analysis of herd distribution and range use. A time-series of images from NASA’s MODIS satellite sensor was generated to determine how annual productivity and phenology of vegetation changed from 2000 to 2021. Maximum annual enhanced vegetation index (EVI), annual growing season length, and annual time-integrated EVI increased significantly on approximately 40%, 30%, and 50% of the herd’s core annual range, respectively. Declines were minimal (often 1% or less), meaning that there was an overall directional increase in annual total production over the study period. Trends toward longer growing seasons were driven more heavily by earlier spring green-up than by later onset of senescence. Trends in wooded regions, which correspond primarily with the herd’s winter range, were overwhelmingly related to the influence of forest fires, which have burned more than half of the area below forest line since mapping began in 1965.

Nearly 2000 tall shrubs (mostly *Betula glandulosa*) were measured and sampled from sites in central portions of the herd’s range where significant increases in productivity were observed as well as from sites where no changes were observed. Annual rings were counted and measured to generate age distributions and ring-width chronologies. There was no significant difference in the age of shrubs between Greening and No Change sites, indicating that the differences in productivity trends detected between the two site types were not due to differences in tall shrub establishment. However, there was a significantly greater tall shrub canopy at Greening sites and a significantly greater proportion of dead stems at No Change sites. Shrubs at greening sites also had significantly wider annual growth rings during the period of satellite observation. Together, these results suggest that increases in satellite-observed productivity are partly attributable to increases in the growth of preexisting erect deciduous shrubs that have allowed them to support greater leaf area.

Finally, available caribou location data was used to conduct seasonal range mapping for the herd. The maps indicate that the extent of the herd’s range shrunk substantially since the late 1990s, and that most seasonal ranges also declined in area. Centres of seasonal range tended to move northwards during the period of analysis. The timing of some annual life history periods also changed; the calving period trended toward an earlier start and the late summer period trended toward a later start. Analysis of annual habitat use between the period after calving and the return to winter range supports the observation that the herd has contracted to an area surrounding Contwoyto Lake. However, preliminary modeling results do not indicate a strong relationship between this range contraction and the changes in range productivity and phenology measured remotely.

5. Introduction

Northern ecosystems are expected to change significantly as climate warming continues, with serious implications for biodiversity and earth-system processes, and there is evidence that this is already occurring in many regions. Results from satellite remote sensing studies show that productivity of many tundra and boreal ecosystems have increased and decreased, respectively, over the past 40 years. These trends are commonly referred to as "Arctic greening" and "boreal browning" (Guay et al. 2014). Field measurements in tundra ecosystems have linked Arctic greening in many regions to a proliferation of shrubs and other woody vegetation (Myers-Smith et al. 2011). Causes of boreal browning are less definitive, but they may be the result of climate-induced moisture stress, increased plant mortality, or changes in plant carbon allocation (Lapenis et al. 2013).

The range of the Bathurst caribou herd encompasses large areas both north and south of the forest-tundra transition and is potentially affected by both greening and browning trends. The herd declined drastically from more than 180,000 individuals in 2003 to less than 10,000 in 2022. Herbivores are closely tied to vegetation condition on their range, and changes in the structure, composition, and/or productivity of their range in response to climate change may be partly responsible for the Bathurst herd's decline. Monitoring these changes across the entire range, and understanding how climate drives these changes, is critical for implementing a sustainable long-term management plan for the herd.

The purpose of this project is to map and analyze changes in ecosystem productivity and phenology across the entire range of the Bathurst caribou herd, and to identify linkages between these changes and shifts in herd distribution and habitat use during the same period. The project is rooted in three research/monitoring questions and objectives:

Question 1: How has vegetation productivity and phenology changed across the Bathurst caribou herd's range over the last two decades? **Objectives**: (**1a**) Map changes in vegetation productivity and phenology on an annual basis across the entire range of the Bathurst caribou herd using remotely sensed imagery obtained from the NASA MODIS sensor (available since 2000), and (**1b**) analyze these data to identify where the most significant changes have occurred and the environmental and climate variables most associated with the changes.

Question 2: To what extent have increases or decreases in woody plant growth and abundance contributed to greening and browning trends in undisturbed portions of the herd's range? **Objectives**: (**2a**) Determine changes in the growth, establishment, and mortality of trees and shrubs in the recent past by conducting tree/shrub ring sampling at significant locations of mapped change, and (**2b**) establish monitoring plots in different vegetation types to examine differences in plant community composition relative to mapped changes.

Question 3: How has annual and seasonal distribution of the Bathurst caribou herd changed during the monitoring period and what is the relationship between these changes and the mapped changes in range condition? **Objectives**: (**3a**) Use available caribou collar data to update seasonal range mapping of the herd to analyze changes in timing and extent of range use, and (**3b**) determine if/how seasonal habitat use of the Bathurst caribou herd has changed in relation to the observed vegetation change.

This report provides details on the methods and results for each of these three project components. A report was submitted in 2020 detailing progress from the first three years of the project (2017-2020). Funding was then renewed for another cycle (2021-2024). This document reports on the entire length of the project. However, we refer the reader to key project deliverables in instances where additional details may be useful. Each of these are available on the NWT Discovery Portal.

6. Methods

6.1 Methods – Remote Sensing

6.1.1 Data Acquisition

There are dozens of Earth-observing satellite sensors currently in operation, each of which have advantages and disadvantages for vegetation change detection. Although other satellite sensors have higher spatial resolution, the Moderate Resolution Imaging Spectroradiometer (MODIS) acquires images of the entire planet at a much higher frequency, making its data extremely useful for examining vegetation change throughout the course of a year. As such, we used MODIS data to examine changes in both productivity and phenology within each of the seasonal components of the Bathurst range.

As detailed in our 2020 report, we opted to use NASA's Collection 6 data, which are provided in 16-day composites at 250-m resolution (MOD13Q). Though this composite period is longer than that of other MODIS products, we considered it to be the best option, since longer composite periods have a lower proportion of poor quality pixels (Ji et al. 2010; Verbyla 2015). NASA offers both normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI) products derived from MODIS v6 data. NDVI is more commonly used in monitoring vegetation dynamics, but we chose to use EVI because it has been shown to be more sensitive to phenological change (Xiao et al. 2005), and because minimizes the influence of bare soil backscatter which is important in tundra landscapes (Huete et al. 2002).

Our analysis was first conducted for years 2000-2017, and then subsequently updated to 2021. We downloaded the corresponding years of 16-day composite EVI data, but composite images can still contain some poor quality pixels so we also downloaded the accompanying pixel quality data provided by NASA. We then mosaiced the imagery and reprojected it from its original global Sinusoidal projection to the Lambert Conformal Conic projection used by the Government of the Northwest Territories.

6.1.2 Data Processing

Time series of vegetation indices are frequently noisy due to differences in view angle, illumination patterns, aerosol content in the atmosphere, and cloud cover between composite periods. We minimized this noise by fitting a curve to measured EVI values (Cai et al. 2017). Specifically, we fit a double logistic function to measured values, as it generally performs better than other functions when there are no ground-based phenology calibration data available (Beck et al. 2006; Cai et al. 2017). We reduced the influence of poor quality pixels on fitted curves by weighting them in accordance with the pixel quality information provided by NASA. Curve fitting was carried out in Timesat, version 3.3 (http://web.nateko.lu.se/timesat/timesat.asp) (Jönsson and Eklundh 2004). This process is described in detail in our 2020 report as well as in Dearborn and Danby (2022).

We then used modelled EVI values to extract annual productivity and phenology metrics for each pixel **(Figure 1)**. We derived annual maximum EVI, start and end of season dates, season length (the difference in days between end and start of season dates), and time integrated EVI (area under the modelled EVI curve). Start and end of season dates were identified as the day in each year when modelled EVI values rose above and fell below a threshold of 0.72 of the amplitude of the annual curve as the start and end of season dates, respectively (Cai et al. 2017). Length of season was calculated as the number days between the two.

We performed pixel-wise linear regressions to determine the direction and magnitude of trends in productivity and phenology metrics between 2000 and 2017 (n = 18 years for each pixel), as well as the statistical significance of these trends. For the follow up 2000-2021 trend analysis we instead opted for a Thiel-Sen analysis. This is a nonparametric alternative to linear regression which is insensitive to outliers and better suited for dealing with the autocorrelation inherent in spatial data.

6.1.3 Geospatial Data Analysis

We used ArcGIS to calculate percentages of significant positive and negative trends in each seasonal component of the range of the Bathurst herd (spring migration, calving grounds, summer range, fall/breeding range, and winter range), as well as throughout the annual range **(Figure 2)**. Seasonal range maps were provided by the Government of the Northwest Territories and were based on caribou GPS collar data obtained between 1996 and 2015. We also calculated percentages of significant trends within the broader range planning area of the herd (which includes areas that have historically supported the herd) after segmenting it into areas north of treeline, between treeline and forest line, and south of forest line (based on Timoney et al. 1992). We conducted this analysis twice: once with all pixels in the dataset, and a second time after masking masking out pixels in which fire had occurred within the last 60 years (based on the Canadian National Fire Database polygons). Given that vegetation indices have been shown to return to pre-fire values in less than 50 years following fire in northern forests (Tan et al. 2013), we considered the trends from the second analysis to be more highly reflective of climate-induced vegetation change. All waterbodies (as identified in the MODIS land-water map) were masked from the analysis such that percentages of significant trends in each range component were calculated per total land area (rather than total area).

Additional geospatial layers were acquired from a variety of sources to develop a geospatial atlas of the entire Bathurst Herd's range (**Table 1**). These data were derived for the purpose of developing a suite of models for exploring the environmental variables related to the changes in productivity we observed from 2000-2021. We conducted this analysis using random forest modeling, using the trend in MaxEVI as the dependent variable. We used 1% of all pixels for modeling and a 70/30 split for training/validation. We used %IncMSE (the increase in mean squared error when a variable is omitted) and IncNodePurity (a measure of how much the model error increases when a variable is randomly permuted or shuffled) to rank variable importance, and we generated a series of partial dependence plots to examine the nature of the relationship between MaxEVI and each independent variable.

6.2 Methods - Vegetation Ecology

6.2.1 Study Area

CIMP project 187 focussed on the range planning area for the Bathurst caribou herd as defined by the GNWT, which is based partly on the herd's annual range as defined by satellite telemetry data from radio-collared cows. However, sampling for field validation across this entire region was not logistically feasible. We instead targeted the forest-tundra transition zone immediately north of treeline for sampling. This transition zone has experienced the most climate-driven vegetation change on the herd's range (Bonney et al. 2018). Furthermore, two characteristics of the transition, (i) position of treeline, and (ii) trends in shrub cover beyond treeline, have been identified as indicators for NWT State of the Environment Reporting https://www.gov.nt.ca/ecc/en/services/nwt-state-environment-report). The southern parts of this zone consist of open spruce woodlands sheltered on slopes and in valley bottoms, with open tundra on the exposed ridges of Precambrian bedrock outcrops and extensive wetlands in low areas (Ecosystem Classification Group 2008). Further north is a treeless landscape dominated by dwarf and low erect shrub uplands, interspersed with sedge fen lowlands, and underlain by continuous permafrost (Ecosystem Classification Group 2012). Dwarf birch and various species of willow are the most abundant erect deciduous shrubs in the study area (Porsild and Cody 1980).

6.2.2 Shrub Establishment and Growth

Field Methods Sampling sites for our examination of shrub establishment and growth were identified *a priori*. From the results of our 2000-2017 MODIS-based remote sensing analysis, we selected areas from the herd's late summer range that encompassed sites that experienced significant greening (hereafter referred to as "Greening" sites) for comparison with sites where vegetation productivity had not significantly changed ("No Change") during the monitoring period. Greening sites included areas with positive trends for maximum Enhanced Vegetation Index (EVI) and, as much as possible, positive trends for time-integrated EVI. Greening sites were chosen from among significantly greening pixels having maximum EVI slopes of 0.0025 or greater, while No Change sites were chosen from among relatively neutral pixels having slopes between -0.001 and 0.001.

Field investigation was timed to coincide with the period of annual peak productivity from mid-July to mid-August. Sampling was conducted at 20 sites in summer 2018 in the MacKay Lake area and at nine sites in summer 2019 in the Daring Lake/Yamba Lake area of the NWT (**Figure 3**). A total of 15 Greening sites and 14 No Change sites were visited. Sampling was accomplished by travelling the landscape by canoe and accessing each site by foot from campsites established along the routes (see Danby et al. 2016).

A comprehensive description of field sampling protocols is provided in the PhD thesis of C. Bonta (2024). In summary, we established sampling plots within areas of homogenous cover at each site. Each plot comprised four parallel 100 m transects spaced 50 m apart, and shrub stems were sampled at 10 m intervals along each transect (**Figure 4**). At each sampling point, the nearest shrub stem was measured and two cross-section samples were obtained: one from the base of the stem at ground level and the second halfway along the length of the stem. Growth ring analysis from the basal sample was used to reveal the approximate year of stem establishment, thus providing an estimate of the age distribution of stems on the landscape, while the year in which the stem reached half its current height was used to determine its vertical growth rate. To quantify the degree of stem mortality in live shrubs, we counted the number of living and dead stems associated with the individual or clump of ramets from which a stem was sampled.

In addition to this systematic sampling, shrubs were also sampled opportunistically at each site for dendroclimatological analysis. For this, we sought out old shrubs most likely to have grown from seed. At each site, we collected sections of the dominant erect shrub species as close as possible to the root collar. Fifteen shrub root collars were collected from each site. When present, we also opportunistically sampled black spruce. Standard measurements including tree height, diameter at base, and diameter at breast height were obtained for each of the trees from which cores or sections were collected.

Laboratory Methods A total of 1276 shrub stem sample pairs were collected (n = 660 Greening and n = 616 No Change) for age distribution analysis. Stems were thin-sectioned to 20-30 μm using a sledge microtome. Thin sections were then placed on glass slides and examined under compound microscope and annual rings were counted. A total of 462 root collar sections (n = 236 Greening and n = 226 No Change; 91% dwarf birch) and 126 black spruce samples were collected for dendroclimatological analysis. All samples were air dried in the laboratory, and tree cores were mounted. Tree samples were sanded to a polish using progressively finer sandpaper up to 320-grit. Annual rings were counted, measured, and cross-dated using a Velmex sliding stage under a stereomicroscope. Shrub root collars were thin sectioned and growth rings were counted, measured, and cross-dated using digital image analysis. Methodological details are provided in Bonta (2024).

Data Analysis Age structures of shrub stems were constructed for each site by categorizing individuals into 5-year age-class frequency distributions (e.g. Danby and Hik 2007). Histograms were used to visually display shrub age distributions as the number of live individuals by year of establishment, for each of Greening and No Change sites. Data was also pooled to examine a collective age distribution for all Greening sites against all No Change sites and compared using a Kolmogorov-Smirnoff text.

The average age, height, diameter, and vertical growth rate of shrub stems, as well as their number of living and dead stems, was compared between Greening and No Change sites using a series of t-tests and Mann-Whitney tests. These tests were also used to compare the mean abundance and canopy cover of shrubs between the two site types (see Bonta et al. 2023 for details).

Bonta's thesis (2024) provides a comprehensive description of the process of shrub and tree ring width chronology development and analysis. In summary, a single ring width chronology was developed for shrubs at Greening sites in the MacKay Lake area and a corresponding chronology was developed for shrubs at No Change sites. A single spruce chronology was developed for the entire sampling area. Annual ring width indices were statistically related to several climatic variables using a series of Pearson's correlation analyses for the period of 1950-2017. Precipitation and temperature data were derived from the gridded Climatic Research Unit (CRU) time series (version 4.06; Harris et al. 2020) and values for the Arctic Oscillation index were obtained from the US National Oceanic and Atmospheric Administration (NOAA Climate Prediction Centre 2023).

6.2.3 Plant Community Composition

Study Approach Two separate investigations were conducted to assess differences in plant community composition. The first investigation was conducted for sites sampled in July 2019 near the Tundra Ecosystem Research Station (TERS) at Daring Lake (**Figure 5**). Potential sampling sites were targeted *a priori.* From an existing Landsat dataset of NDVI trends from 1984-2012 (Ju and Masek 2016), we selected pixels that experienced significant greening ($P<0.0001$; hereafter referred to as "Greening" sites) for comparison with sites where vegetation productivity had not significantly changed ("No Change"). Landsat pixel resolution is 30 m x 30 m, and provides a fine scale of resolution appropriate for investigating productivity trends at the plant community level. We attempted to further stratify sampling by predominant land cover type, selecting a mix of graminoid-dominated, shrub-dominated, and wetland communities based on a landcover classification by Olthof et. al. (2009).

The second investigation was conducted in July and August 2023 at sites in the Daring Lake area as well as further north along Fry Inlet on Contwoyto Lake. Potential sampling sites were also targeted *a priori* but sites were selected to incorporate areas where relative caribou use has either increased or decreased since the late 1990s (based on analyses described in 6.3, below). We further stratified site selection using the MODIS productivity trend mapping described above, such that sites with a wide range of greening values were sampled. Data from this 2023 investigation is still being analyzed and is not presented or discussed here. However, field methods and analysis are similar to the first investigation. We plan on completing this in 2025.

Field and Laboratory Methods C. Bonta (2024) describes methods of plant community sampling and data analysis in detail in her PhD thesis. In summary, plant communities were sampled from within a 30 m x 30 m area, corresponding with the spatial resolution of a Landsat pixel, within each of 15 Greening and 15 No Change sites. Each sampling area contained five replicate 1 m^2 plots (**Figure 6**). Percent cover of each of dwarf birch, tall willow, prostrate shrubs, graminoids, herbaceous plants, non-crustose lichens, moss, and unvegetated substrate was visually estimated from each plot. Prostrate shrubs were identified and categorized to species level, while all other cover estimates encompassed the functional type. Aboveground biomass was clipped and harvested from the centre plot. Plant materials were then returned to our laboratory in Kingston and sorted, dried, and weighed.

Data Analysis Measures of total dry weight biomass harvested from a single plot at each site, mean percent cover, and percent frequency of occurrence of a species or functional group across the five plots within a site were relativized by dividing the species-level measure at a site by the total of that measure across all species within that site. Importance values were calculated for each species or plant functional group at each site and served to integrate measures of cover, biomass, and frequency across plots within a site into a single metric (e.g., Danby et al. 2011; Zerbo et al. 2016).

Non-metric multidimensional scaling (NMDS) is an ordination technique for graphically representing the structure of ecological communities (McCune and Grace 2002), and was used to assess differences in plant community assemblages between Greening and No Change sites based on the calculated importance values for each species group. We also incorporated several environmental variables in the analysis that were presumed to influence species composition at our plots, including elevation, aspect, Topographic Wetness Index (TWI), and distance to nearest lake (derived from topographic maps), and a site-level moisture index informed by field observations and plot photographs. The final response matrix was thus comprised of importance values for a total of 12 individual species, Salix spp., and three functional types that occurred within the remaining 28 sites. Two wetland sites were removed from analysis because their unique plant communities dominated the outcome of the results over the more common shrub- and graminoid-dominated vegetation types.

6.3 Methods – Caribou Distribution Analysis

6.3.1 Data Acquisition and Processing

The Government of Northwest Territories has conducted telemetry monitoring for the Bathurst herd since January 1996. We acquired these data under terms of a data release agreement with GNWT ENR. Data were provided in geographic coordinates and were converted to metres in the Lambert Conformal Conic projection. The data contained information for both male and female caribou, but we removed data for males for two reasons. Firstly, our study focuses on the group movements of caribou and therefore adopts a herd-based perspective. Female caribou are more likely to move as a herd, and although the male's life history is important to herd survival, males are more likely to move independently from the herd (Calef 1981). Secondly, male caribou do not take part in concentrated *spring migration* or *calving* activities which are critical life history events for the herd (Calef 1981; GNWT 2019). Retention of male observations in the data would skew our movement analysis, and we would not be as confident in the timing of seasonal range-use. The final database remained robust after data filtering, with an average of 21 individuals per year (**Figure 7**).

6.3.2 Range Phenology Analysis

Barren-ground caribou move at different speeds and tortuosity (measure of turn rate) during different parts of the year (Calef 1981; Fancy et al. 1989; Bergman et al. 2000). We conducted *Residence Time* analysis (Barraquand and Benhamou 2008) on the processed telemetry data to characterize these movements (e.g. Wolfson et al. 2020) and identifed seven different periods within the herd's annual life cycle: (1) wintering, (2) spring migration, (3) calving, (4) post calving movement, (5) summer range use, (6) rutting season, and (7) fall migration. We used the *Lavielle* segmentation method to objectively separate these seven movement bouts and assign start and end dates to each (Lavielle 2005; Barraquand and Benhamou 2008). The *AdeHabitat* package (Calenge 2006) in R (R Development Core Team 2011) was used to conduct our *Residence Time* analysis. We fit linear models to the annual start and end dates of the seven seasonal periods, as well as to their total annual duration, to determine if significant trends in the timing of these events (phenology) occurred during the study period. Complete details on the process are described in the MSc thesis of R. Mennell (2021).

6.3.3 Home Range Analysis

A home range is the total areal extent an animal or population of animals utilize during a relevant time period (Alfred et al. 2012). Home range analyses are a common way to identify preferential or important areas for herding animals (Alfred et al., 2012; Howery et al., 1996; DeIongh et al., 1998). To this end, we examined three temporal scales of home ranges: (1) the area encompassing all observations across all years of the study period, (2) an area encompassing all observations on an annual basis, and (3) the area corresponding to observations during each of the seven seasonal ranges on an annual basis. The latter two approaches allowed us to examine how ranges have changed geographically through time and had never been implemented for the Bathurst caribou herd.

We used Brownian Bridge models (Horne et al. 2007) to map home ranges at these three temporal scales. This technique accounts for the issue of temporal autocorrelation in telemetered collars by incorporating an animal's directional trajectory when generating a home range probability surface; unlike other methods which consider probabilities to be omnidirectional around each point (Downs 2010; Benhamou and Cornélis 2010). Probabilities are the likelihood of finding an animal at any one place at any given time and are high around a point observation but also directly between successive points (i.e. the "bridge" between points).

We separated our telemetry data into periods based on the annual timing of range use identified in our Residence Time analysis and Lavielle segmentation (described above). We then conducted the Brownian Bridge modeling on these separated location data using the package *AdehabitatHR* (Calenge 2006). Model parameters varied slightly among years to account for differences in collar models and locational frequencies. The initial outputs of the *Brownian Bridge* modeling were raw raster probability maps for each individual caribou. We overlaid these raster maps and obtained an average of the probability values for the three time periods (i.e. the entire study period, on a yearly basis, and on a seasonal basis). This process yielded 185 unique maps: 1 for the cumulative study period, 23 yearly maps, and 161 seasonal range maps (i.e. 7 seasonal events x 23 study years).

We calculated the total range area occupied during each seasonal period as well as the total range area occupied on an annual basis. Calculations were based on the 95% use probability contour. We fit linear and exponential models to these data to determine if significant trends in the area of these ranges had occurred. In addition to total area, we determined the geographical spread of these ranges using the directional distribution function within ArcGIS v.10.5 (ESRI 2016). This function determines how each range is spread across a region by generating an ellipse whose two axes correspond to the standard deviation of x and y coordinates in two directions (see Wang et al. 2015). We calculated the area of these ellipses in each year and fit a linear model to the data to determine if there has been a trend toward either increasing or decreasing spread in the ranges.

6.3.4 Summer Range and Habitat Change

A second range delineation was conducted on the processed telemetry data to map annual summer range from 1997 to 2017. Location data from June 17th to October 16th of each year were used as input for Kernel Density Estimation using the *AdehabitatHR* package for R (Calenge 2006). A single map was output for each year, but we modified values so that each pixel was equal to a percent value within a contour (Calenge, 2006). This was undertaken to allow for comparison among years, since the number of animals that were collared increased over the course of the study period and the frequency of locations collected from each collar significantly increased with changing technology. In the modified data, pixels with a value of 0.95 connect together to form a contour(s) that captures 95% of the probability in that distribution. Contours with lower percentage (e.g. 75%) will be nested within contours of larger percentages (e.g. 95%) and represent smaller areas that capture a disproportionate amount of the total probability. This method is consistent with home-range mapping implemented for a variety of species (e.g. Benhamou and Cornélis 2010; Rayment et al. 2009).

We used Thiel-Sen analysis to determine the direction and magnitude of trends in relative use on the summer range between 1997 and 2017 (n = 21 years). We then mapped these trends to illustrate areas of the summer range that have experienced an increase in relative use, areas that experienced a decrease, and the statistical significance of these changes. It is important to note, however, that these changes are expressed in relative terms on an annual basis. Because the herd declined so substantially during the period (from an estimated 300,000 to 10,000 animals in two decades) the absolute use (e.g. number of animals or density) likely declined everywhere.

We are currently implementing random forest analysis to model the relationship between the changes in relative summer range use with a set of explanatory environmental variables, including the phenology and productivity metrics mapped as part of Question #1. This analysis is still in process as part of MSc student L. Cross's thesis, but some preliminary results are available and we include these in the following Results section.

7. Results

7.1 Remote Sensing Phenology and Productivity Trends

Vegetation productivity and phenology both underwent significant change within the range of the Bathurst caribou herd between 2000 and 2021. The length of the growing season increased significantly at rates between one and three days per year (**Figures 8, 9, 10**). This increase was heavily influenced by earlier growing season start dates (i.e. earlier green-up) rather than later growing season end dates (i.e. later senescence) (**Figures 11, 12**). Significant trends were most prevalent in the spring, calving, and summer portions of the range, which are predominantly above treeline. Significant reductions in growing season length (i.e. negative trends) were negligible, occurring in less than 1% of the annual range.

Productivity, as measured by annual maximum EVI values, increased at rates between 0.001 and 0.004 EVI per year across approximately 40% of the annual range (**Figure 13**). These trends were more or less evenly distributed throughout the range, though they were most common in the summer and fall components, the latter of which spans the tundra and forest-tundra ecotone. Negative trends in vegetation productivity were rare, occurring in only 1% of the annual range.

Time integrated EVI, which reflects trends in both growing season length and annual maximum EVI, increased in nearly half of the annual range (**Figure 14**). Significant increases in time integrated EVI were significantly lower in the forested portions of the range. Total area experiencing a decline in EVI was very small (i.e. less than 1%).

Trends differed somewhat when burned areas were excluded. In general, exclusion of burned regions reduced the total area that had experienced significant increases in MaxEVI, TIE, or LOS by approximately 10% in forested parts of the range and in herd's winter range.

Modeling of changes in MaxEVI indicate that time since fire had the largest influence on the nature of remotely-observed trends (**Figure 15**). However, the relationship was not linear. Partial dependence plots (**Figure 16**) illustrate that the trends were highly dependent on time since the most recent fire. Areas that burned during the period of observation (i.e. 2000-2021) typically underwent significant browning, while areas that experienced fire in the 30 years prior typically underwent significant greening. Thirteen other variables improved node purity better than random, but only time since burn, MaxEVI in 2001, trend in snowmelt timing, and standard deviation of snowmelt timing had a substantive effect on model performance (%IncMSE in **Figure 15**).

7.2 Changes in Vegetation Growth and Composition

All results related to Question 2 and Objectives 2a and 2b are presented in detail in the PhD thesis of C. Bonta (2024) and the publication by Bonta et al. (2023). These results are summarized here but the reader is directed to those references for a more comprehensive presentation.

7.2.1 Tree and Shrub Growth

There was no apparent difference in the pattern of ring width index (RWI) between shrubs sampled at Greening sites and those sampled at No Change sites over the 67-year chronology ($r = 0.555$, $p < 0.001$; **Figure 16**). Birch series were therefore pooled across all sites for the analyses of ring widths and climate data. However, there was a difference in the magnitude of birch RWI between Greening and No Change sites, particularly in recent decades (**Figure 17**) as RWI of shrubs at Greening sites increased at a greater rate than RWI of shrubs at No Change sites over the 2000-2017 period that aligned with our MODIS-based characterization of site type.

Annual variation in ring width was greater in dwarf birch than it was in spruce (**Figure 18**). The correlation in ring width between the two species was not significant (r = -0.134, p = 0.275) in the common period from 1950 to 2017. However, there was a significant positive correlation between birch and spruce RWI when birch ring-widths were shifted two years ahead (r = 0.264, p = 0.032), suggesting a slight offset of growth trends between the two species.

Radial growth of black spruce increased since the late 1800s, with linear slopes of 4.05 mm2/year (r = 0.691) for basal area increment (BAI) and 0.003 mm/year (r = 0.603) for raw ring width (rRW), nearly a tripling of annual growth rate over the period of the chronology (**Figure 20**). Raw ring width of dwarf birch increased by <0.01 mm/year (r = 0.076) and basal area increment (BAI) increased by 12.43 mm/year (r = 0.596) over the timeframe of the full chronology (**Figure 21**). However, as with spruce, growth rates for birch rose rapidly over a decadal period from 1993 to 2002 in which BAI increased by 1.07 mm2/year (r = 0.973) and rRW by 0.02 mm/year (r = 0.955).

Spruce growth did not respond to seasonal temperature or precipitation in either the current or previous growing season but did demonstrate a significant positive correlation with summer temperature two years earlier (r = 0.310, p = 0.010) (**Figure 22**). Birch ring-width demonstrated several significant correlations with regional climate, including being positively correlated with summer temperature (r = 0.274, p = 0.024) and negatively correlated with spring precipitation (r = –0.350, p = 0.003) in the current year of growth; fall temperatures in the previous year also had a positive relationship with birch ring-width (r = 0.246, p = 0.043) while summer precipitation two years prior was negatively correlated with ring-width (**Figure 22**).

7.2.2 Tundra Shrub Characteristics and Establishment

Overall, Greening and No Change sites were found to be similar in shrub species composition and structure. Both types of sites were dominated by birch, which was roughly nine times as abundant as willow (**Table 2**). There was no significant difference in mean shrub stem age, the mean age of the youngest shrub stems, or the mean age of the oldest shrub stems between Greening and No Change sites (**Table 3, Figure 23**). However, shrub cover was significantly greater at Greening sites than at No Change sites by nearly 13% but stem length was similar, with stems averaging 48.5 cm long at both site types (**Table 2**).

Shrubs were found to have an overall average of 7.46 live stems, with no significant difference between site types. However, after controlling for the number of living stems on a shrub, there was a significant effect of site type on percentage of persisting dead stems (ANCOVA, F1,17 = 14.42, p = 0.001). Shrubs at No Change sites had a significantly greater proportion (9%) of persisting dead stems than did shrubs at Greening sites (**Table 2**) and, as indicated by the parallel slopes evident in **Figure 24**, this difference held constant regardless of the total number of living stems on a shrub.

Growth rates were not significantly different between Greening and No Change sites. Stems at both site types averaged slower vertical growth (2.72 cm/year) in the upper half of the stem than in the lower half of the stem (3.88 cm/year; **Table 2**). Stems with larger basal diameters tended to be older than those with smaller basal diameters, a relationship that was best described as linear for stems at both Greening and No Change sites. However, the relationship between stem age and basal diameter did not differ between site types (t = 1.252, p = 0.227), with stems averaging 0.09 mm of radial growth annually.

7.2.3 Plant Community Characteristics

Nonmetric multidimensional scaling (NMS) Axis 1 explained 54.5% of the total variance in plant community composition and was associated strongly with the amount of standing water and of unvegetated substrate at a site (**Figure 25**). Axes 2 and 3 explained 22% and 8.7% of the total variance, respectively. All three axes showed weak association with the MODIS and Landsat productivity trends (“M_EVI” and “L_NDVI”, respectively) and with elevation (“Elevation”) (**Figure 25**). Variance along Axis 2 suggested slight differences between plant communities at Greening sites compared with those at No Change sites. However, there was no overall difference in current plant community composition between the two site types ($A = 0.011$, $p = 0.183$).

We used the Overlay Second Matrix function in PC-ORD to further explore the relationship between an individual species' importance within a community relative to its influence on the ordination scores. This view of the ordination highlights the contribution of an individual species' degree of importance within a site's plant community relative to that site's position along an ordination axis, but also permits a better assessment of the influence of zero values on species-axis correlations. The strongest patterns were observed in *Betula glandulosa*, graminoid, and lichen and very much emphasize the strong positive relationship between graminoid and standing water and the positive relationship between lichen and unvegetated substrate along Axis 1, as well as the strong contrast between lichen's importance within unvegetated No Change sites and *Betula glandulosa*'s importance within Greening sites along Axis 2 (see Figures 4-6, 4-7 and 4-8 in Bonta, 2024).

7.3 Caribou Range Phenology and Change

The timing and duration of annual range periods varied from 1997-2019 (**Figure 26**), and some significant temporal trends evident in the data (**Table 4**). The calving period trended toward a significantly earlier start date in the year, at a rate of 0.35 days per year over the monitoring period (**Table 4**). Spring migration had an earlier end date but also became significantly shorter in duration at a linear rate of 0.38 days per year. The start of the late summer period trended toward a significantly later date at a rate of 0.58 days per year. Similarly, the post-calving period had a later finish date and also became significantly longer by 17 days over the course of the study period (0.75 days per year; **Table 4**).

In the beginning of the study period (1997-2000) the yearly ranges extended as far south as northern Saskatchewan but have subsequently decreased in areal extent and have shifted north during the monitoring period. For example, the yearly range was 142,794 km^2 in 1997, 60,326 km^2 in 2002, 5,717km^2 in 2008, and 14,320km^2 in 2019; representing a 90% decrease in areal extent over the study period (95% probability level; **Figure 27**).

Seasonal range maps showed a general reduction in the size of all seasonal ranges during the monitoring period (**Figure 28**). Linear models were chosen to describe trends in area for the spring migration, calving, post-calving, late summer, fall rut, and fall migration ranges. However exponential models were chosen instead of linear models for the winter range and annual range as inspection of the data indicated a rapid decline in their area between 1997 and 2007, followed by little or no decline since. Based on the 95% Brownian Bridge contour, the spring migration range decreased by 90.2% over the study period, the calving range decreased by 35.2%, the post-calving range by 75.9%, the late summer range by 83%, the fall rut range by 87%, the fall migration range by 77%, and the winter range by 87.5%. The Winter range, spring migration, and the fall rut ranges experienced the largest decreases, while the calving range experienced the least.

Seasonal directional distribution ellipses indicated a significant reduction in the geographic extent of the herd's total annual range as well as most of its seasonal ranges (**Figure 29**). However, unlike annual and seasonal area occupied, the directional distributions decreased at a more consistent rate over the course of the study period and did not appear to plateau after 2008 (**Figure 29**). The results show shifts in the geographical center of distribution in the winter range, fall migration range, fall rut range, spring migration range, and total annual range all which have all progressively shifted northwest during the monitoring period (**Figure 30**).

Trend analysis of the herd's summer range extent based on kernel density estimation indicates a zone of significant increase in relative caribou use that is focussed around the Contwoyto Lake region along the Northwest Territories – Nunavut border (**Figure 31**). Significant decreases in relative caribou use occur in a zone surrounding this region of increase, and the most peripheral zones exhibited little change at all. Modeling of the drivers of this change is still in progress. However, preliminary results indicate that changes in summer temperature, snowmelt timing, length of growing season, and MaxEVI, each influence where these increases and decreases in relative use are occurring **(Figure 32)**.

8. Discussion

The results of each of our remote sensing investigations (Question 1) are discussed in depth in Dearborn and Danby (2022). Results of the field validations of these trends (Question 2) are discussed in depth in Bonta et al. (2023) and Bonta (2024). Results of caribou range phenology and change are discussed in depth in Mennell (2021). Readers should refer to those supporting documents for an in depth technical analysis and interpretation of the results. In the subsequent sections here, we provide an overarching summary of these discussions and emphasize their implications for understanding causes and consequences of change for the Bathurst caribou herd.

8.1 Remote Observation of Vegetation Productivity and Phenology

Maximum annual EVI, annual growing season length, and annual time-integrated EVI increased significantly on approximately 40%, 30%, and 50% of the herd's core annual range, respectively. Declines were minimal (often 1% or less), meaning that there was an overall directional increase in annual total production over the study period. Trends toward longer growing seasons were driven more heavily by earlier spring green-up than by later onset of senescence. All of these trends were similar between the core annual range and the larger range planning area. However, we observed substantial variability in the pattern and magnitude of change across the range. Increases in growing season and time-integrated EVI were most prevalent in tundra regions, which correspond primarily with the calving and summer ranges of the herd. Trends in wooded regions, which correspond primarily with the herd's winter range, were overwhelmingly related to the influence of forest fires, which have burned more than half of the area below forest line since mapping began in 1965.

The magnitude of greening we observed in the tundra and forest-tundra ecotone was less than what has been observed elsewhere in North America, but the pattern is generally similar (e.g. Pouliot et al. 2009; Ju and Masek 2016). For example, using Landsat, Bonney et al. (2018) found that 33% of the tundra portion of their study area underwent significant greening at rates of approximately 0.003 NDVI per year between 1984 and 2016, and Ju and Masek (2016) detected greening of a similar magnitude over the same period. There is some evidence that rates of tundra greening world- wide were greater in magnitude prior to the early 2000s than they have been since (Bhatt et al. 2013, 2017; Raynolds and Walker 2016). Combined with the shorter time frame of our study, this may explain why the magnitude of greening we observed was less than it was in these other studies.

Results of our modeling to date suggests that trends in productivity change were driven heavily by forest fire pattern and timing, at least in regions below treeline. Time since fire was the most important variable in both importance metrics and inspection of maps along with partial dependence plots confirmed that areas that burned prior to the start of the satellite record expressed positive (greening) trends, while those that burned during the period of record generally expressed negative (browning) trends. The importance of baseline EVI values in explaining the magnitude of change is intriguing as the relationship indicates that less heavily vegetated areas – such as tundra ecosystems – tended to experience higher levels of greening. Perhaps just as informative is the relative lack of importance of temperature and precipitation variables in explaining variation in greening. Many of these variables were no better than random in explaining greening trends. This does not mean that climate is unimportant, but that is is less important than the other variables we examined. We are continuing to refine these models and will be writing a paper for publication in the coming year.

8.2 Field Validation of Vegetation Trends

In contrast to our initial expectations, we found no difference in the age of shrubs between Greening and No Change sites. This indicates that the differences in EVI trends detected between the two site types were not due to differences in tall shrub establishment. If the greening signal was due to new shrub establishment, then Greening sites would have had a higher proportion of young shrubs than No Change sites; but this was not the case. Instead, the two main differences between the site types were a significantly greater tall shrub canopy at Greening sites and a significantly greater proportion of dead stems at No Change sites. This indicates that shrubs at Greening sites support a wider canopy spread, possibly due to increased growth of lateral stems or initiation of new branches, in turn supporting greater leaf area. It also indicates that Greening sites are supporting healthier shrubs and this vitality may be further reflected in larger, more abundant, or more productive leaves.

The differences in radial growth of dwarf birch that were observed between Greening and No Change sites supports this interpretation. There was little difference in ring width indices between the two site types prior to the mid 1990s. However, from the late 1990s to mid 2010s the rate of radial growth at Greening sites outpaced that measured at No Change sites. Climatological analysis of ring width trends indicated that annual ring width variation was positively related to summer temperatures and thermal sum (measured as growing degree days). This suggests that ongoing warming in the region will continue to lead to increased growth of shrubs.

There was no significant difference in plant community composition between Greening and No Change sites based on Landsat NDVI trends from 1984 to 2012. However, dwarf birch was more important at Greening sites and No Change sites supported a greater importance of lichen. While it is difficult to infer change from a single point in time, the higher importance of birch at Greening sites does support the hypothesis that increased productivity of tall deciduous shrubs is partly responsible for remotely observed trends. Nonetheless, we suspect that some of the dwarf shrub species may also be responsible and we anticipate that the follow-up study of plant community composition currently underway will further elucidate these trends.

8.3 Changes in Caribou Range and Phenology

The results of our caribou location analysis indicate that the areal extent of yearly and seasonal ranges declined dramatically over the study period. Our mapping and analysis show a 90% decrease in the core area being used by the Bathurst herd over the twenty-three-year period. This range contraction coincided with the population collapse; with an estimated 350,000 animals at the start of the study period (1997) and 8,200 at the end (2019), representing a 97% population decrease (GNWT, 2019). Range contraction (or expansion) as a result of changes in population size is not a phenomenon that necessarily occurs in all species. Some animals may capitalize on lower population densities by spreading themselves out. However, caribou are gregarious animals that prefer dense aggregations. As such, it has been hypothesized that when caribou populations decline, so too does the area they occupy, and our analysis clearly supports this.

Our results also indicate major geographic changes in seasonal range-use including a shift in location of the spring migration, late summer, and winter ranges during the period of population collapse. As mentioned above, decline in all these ranges is an expected outcome of population decline, however, it important to note that there are differences in the way each range declined. Unlike most seasonal ranges, which decreased linearly, the annual and winter range decreased exponentially in area during the study period, mirroring the exponential decline in caribou numbers during that period. Our data also showed that the geographic center of these ranges also changed, with spring migration, fall migration, and winter range moving considerable distances in the northwest direction. The calving range, which declined in area the least, also moved in position the least.

Our residence time analysis indicates that the timing of some of the herd's annual life history has changed since the late 1990s. In particular, the calving period has trended toward an earlier start and the late summer period trended toward a later start. These trends may be related to the changes in vegetation phenology and productivity that we identified, and this will be examined as we continue working with data from our results.

Our analysis of summer home range change indicates that the herd has retracted to a much smaller core region of use centred heavily on the areas around Contwoyto Lake. Our modeling of correlative relationships for this change in relative use is still preliminary. However, it does not indicate strong relationships with trends in productivity (expressed as annual rate of change in maximum EVI) or growing season length. We are continuing to work with these data to yield more definitive model results.

9. Community Engagement, Communication, and Capacity-building

Our project emerged from discussions with Tłı̨chǫ communities and government who expressed an interest in understanding caribou habitat change across the forest-tundra ecotone. At the same time, staff at GNWT ENR expressed an interest in using geospatial analysis to understand changes in the distribution of caribou across their range. The intersection of these two interests instigated our project and we have continued to develop linkages with these groups.

Our team undertook a number of communication and outreach activities throughout the duration of the project. Many of these were individual meetings with northerners during periods of summer fieldwork for the express purpose of developing new relationships and communicating research objectives and preliminary results. We also visited Yellowknife and Behchokǫ̀ during winter on five occasions for the express purpose of meeting with northerners in person to discuss our project progress.

Our 2020 report provided a detailed list of meetings with NWT decision-makers and community members, as well as northern outreach presentations. Unfortunately, as a result of the COVID-19 pandemic, these activities were significantly reduced in the second half of the project. Nonetheless, we were able to provide virtual presentations to groups in September 2020, and April and May of 2022 before our return to in-person meetings and presentations. In addition, PhD student C. Bonta collaborated with a graduate student on another CIMP-funded project to produce a joint video about their research which was deceminated to a variety of NWT communities and First Nations.

In March 2023, PI Danby spent one week in Yellowknife and Behchokǫ̀ with the express intent of connecting with communities. The timing of the visit was arranged when he was in Behchoko in December 2022 for the CIMP community results workshop. He was able to attend a Tłı̨chǫ Government caribou workshop March 28-30 at which time we were invited to visit the Boots on the Ground Monitoring camp during the summer. Timing was subsequently arranged for July 31-August 4. Danby and three students arrived by canoe at the end of their field season and spent the time interacting with and learning from the Boots on the Ground Team, as well as showing them the field sampling techniques we were using for our monitoring.

10. Key Information Needed by NWT CIMP

Check all boxes that apply for the project and provide a brief explanation.

This project ...		Briefly explain/describe
Directly impacted a current decision-making process	☐	Not directly, but see 'Other' below.
Could contribute to a future decision-making process	☒	The Bathurst Range Management Plan was released by the Department of Environment and Natural Resources in 2019. The

		intent of the plan is to provide "a guide for decision-makers, companies and communities to help manage activities on the land in a way that supports the recovery of the Bathurst herd". Our satellite image analysis is particularly useful for informing the plan. Our results pinpoint geographic areas that have changed the most since year 2000 due to factors other than fire or human disturbance and land development. Accordingly, these are the areas most likely to be experiencing significant impacts due to ongoing climate change. These areas should be explicitly considered in land use decisions on the herd's range given the potential for climate change to interact with other stressors in unforeseen and cumulative ways. The Conservation Planning and Implementation Unit at the Government of NWT contacted us in 2023 to discuss ways in which the data could be used for their projects.
Responded to a community concern	☒	This project grew from a scientific expedition in 2016 during which members of our team spent 4 days in Wekweètì and met with the Wekweètì Community Council. Council was particularly interested in understanding caribou habitat change and urged us to pursue work on that topic, which led to the establishment of this project. As such, the genesis of this project was in response to a community concern. Community input gained at two CIMP results workshops in 2018 and 2022 also helped refine the project and ensure we were addressing community concerns. Most useful was a meeting with community members in Behchoko at the Tlicho caribou workshop in March 2023. Discussions we had at that meeting confirmed the usefulness of the Contwoyto Lake area as a focus for the 2023 sampling campaign, as community members and members from the Boots on the Ground team commented on the increasing concentration of the remaining caribou in that region in summer.
Led to new or enhanced knowledge of cumulative impacts	☒	Different definitions of 'cumulative effects' exist and are being used by organizations in the NWT. For purposes here, we define cumulative effects using the definition of the Canadian Environmental Assessment Agency as "changes to the environment that are caused by an action in combination with other past, present and future human actions". The predominant single driver of change this project examines is climate. However, our analyses have highlighted the importance of two other largescale changes on the landscape: fire and caribou population reduction. As such, our results have contributed to enhanced knowledge of cumulative effects. The effects of fire on the Bathurst herd's range or its population are the focus of several other CIMP projects past and present. As such, we did not focus exclusively on fire. But it is impossible to conduct a range-wide analysis of habitat change and not see its effects. From our analysis it is has been obvious that fire is the primary driver of vegetation change in areas below treeline. Areas that have burned in the last half century are also the areas where the most significant trends in vegetation change were observed. However, there is a cumulative effect here in that climate change is altering the intensity and frequency of these fires. Moreover, regeneration patterns after fire are likely to be

		altered by climate change. This was not initially a focus of our project, but the cumulative effects of this interaction are stark. The second cumulative effect is a potential two-way interaction between habitat change and caribou population decline. From the outset of this project we hypothesized that vegetation change due to climate warming was one of the factors responsible for the Bathurst herd's population reduction. Our investigations have made us consider the reverse as an alternative hypothesis. In this sense, a positive feedback may be occurring in areas above treeline whereby climate change alters habitat enough to affect population size, but then a reduction in population size means a reduction in grazing and browsing, which leads to further changes in habitat. It is challenging to examine this beyond a correlative effect and so this remains a hypothesis at this stage. However, our modelling results do suggest an interaction between the two agents of change and therefore a cumulative effect.
Developed or used of a standardized monitoring protocol(s)	☒	Objective 1: The MODIS satellite image archive is freely available for download, making it a valuable open-access data source for monitoring environmental change. The frequency of image acquisition makes it especially useful for monitoring change within the year. The steps we have taken in processing the data were carried out with open-source software (MODIS Reprojection Tool and TIMESAT), and the final steps in analyzing the data were conducted with industry standard ArcMap GIS software. Our results provide a benchmark against which data from future years can be compared to implement an ongoing monitoring of ecosystem productivity. There is some requirement for operator expertise, but the steps we have identified allow for this monitoring to occur on an ongoing basis. Objective 2: The field protocol we developed for sampling shrub stems and characterizing vegetation characteristics is a refinement of approaches used previously elsewhere. However, it represents an improvement on other protocols in that it is capable of easily being adjusted to be compatible with metrics derived from freely available remotely sensed imagery available at multiple scales (e.g. MODIS, Landsat, Sentinel). We believe it has potential to be widely adopted as a standardized framework for characterizing subarctic and arctic vegetation. In addition, because all of our sites are georeferenced, any of our plot locations could be revisited in the future to assess change that occurred in the intervening years. Objective 3: We implemented two techniques used widely elsewhere for mapping range extent from animal location data and measuring its change over time. MSc student R. Mennell used the Brownian Bridge technique combined with least squares regression analysis. MSc student L. Cross used the Kernel Density technique combined with Thiel-Sen analysis. Both approaches yielded similar results, showing a substantial reduction of range size and a contraction of its core around Contwoyto Lake. Both approaches could be used in

		future analysis of the herd, although the Kernel Density approach may be better suited as it requires less data processing.
New or enhanced community capacity	☐	
Led to new or enhanced analytical tools, modeling capacity, or other	☒	This use of shrub rings as an indicator of vegetation change is relatively new, despite longstanding use of tree rings in this capacity. The work we have conducted for this project contributes to the ongoing enhancement of methods and techniques for using shrubs as a record of environmental change in northern environments. Our experience working with these samples has confirmed that accurate ring counts can be obtained from cross sections sampled aboveground for the purpose of aging plant stems. Our experience also indicates that rates of vertical growth can be estimated when multiple sections are obtained from the same stem. This is particularly important given the widespread proliferation of shrub species in treeline and tundra environments of northern Canada. This supports the method as a new or enhanced analytical tool. Remote sensing is now used regularly for monitoring productivity and phenological trends of northern ecosystems. However, because of its coarse resolution it is challenging to infer mechanisms of change. Field monitoring at specific locations is the oldest and most common technique for monitoring vegetation trends. But because of the detailed measurements required it is impossible to implement this monitoring at more than a handful of sites. By integrating these two techniques we were able to provide a widespread picture of vegetation change across the Bathurst caribou's range that was informed by a mechanistic understanding of the processes responsible for the change. In this sense, the approach we used was a substantially enhanced tool for monitoring habitat change. We are using these results to model their relationship to changes in the distribution of caribou, which greatly enhances the capacity for understanding the role of vegetation change on caribou population dynamics.
Presented to a community audience	☒	We delivered a presentation at the 2022 CIMP regional workshop, held in Behchoko. The audience for this workshop was comprised primarily of people from the four Tlicho communities. The presentation provided an overarching summary of our results and was followed by a lengthy question period. In 2021, PhD student C. Bonta delivered an invited presentation to the Hotıì ts'eeda Ełèts'ehdèe (annual gathering). This was held online due to COVID restrictions at the time, but the audience was primarily members from NWT First Nations. Finally, in summer 2023 our field team spent five days at the Ekwǫ̀ Nàxoèhdee K'è (Boots on the Ground) field camp. While this was not a formal presentation, and while there were just eight others at the camp, we feel that the two-way transfer of knowledge during this time far-surpassed any of the prior community presentations during this or the previous funding period.

Other:	☒	In May 2022 we were invited to present the results of our herd distribution and phenology analysis to the NWT Barren Ground Caribou Technical Working Group (comprised of staff from the Wekeezhii Renewable Resources Board, the Tlicho Government, and the GNWT). This group meets regularly to discuss information relevant to management of the Bathurst, Bluenose-East, and Beverly caribou herds. Of particular interest to the group was whether our method of mapping the herd's range could be adapted for identifying mobile core management zones. Actual decisions about management are not made by this group, so this does not qualify as directly impacting a current decision-making process, but the technical group was very interested in our results and their potential application.

11. Deliverables

Deliverables identified in proposal	Fiscal Year	Who was it provided to?	Sent to NWT CIMP? Yes/No (*if no, state reason*)	I acknowledge and permit posting for public access on the NWT Discovery Portal
Student Thesis (PhD) – Carolyn Bonta. (Analysis of vegetation growth and composition.)	2023-24	GNWT ECC, WRRB	Yes	☒ I agree
Student Thesis (MSc) – Robin Mennell. (Analysis of caribou range dynamics, 1996-2019.)	2021-22	GNWT ECC, WRRB	Yes	☒ I agree
Student Thesis (MSc) – Lauren Cross. (Analysis of changes in caribou habitat use, 1996-2019.)	In progress		No. Thesis is in progress. Anticipated completion Fall 2024.	☐ I agree
Scientific Paper – Dearborn & Danby. (Remote sensing analysis. Published in Arctic Science.)	2021-22	GNWT ECC, WRRB, Tłı̨chǫ Gov.	Yes	☒ I agree
Scientific Paper – Bonta et al. (Analysis of shrub growth and population dynamics. Published in Arctic Science.)	2023-24	GNWT ECC, WRRB, Tłı̨chǫ Gov.	Yes	☒ I agree
Scientific Paper – Mennell et al. (Analysis of caribou range dynamics, 1996-2019.)	In progress		No. The final results are completely detailed in the Mennell thesis. A peer-reviewed publication remains a goal.	☐ I agree
Scientific Paper – Bonta et al. (Analysis of tree and shrub growth in relation to climate.)	In progress		No. The final results are completely detailed in the Bonta thesis. A peer reviewed publication is nearly ready for peer review.	☐ I agree

Scientific Paper – Danby et al. (Synthesis of caribou-vegetation-climate connections.)	In progress		No. This will be completed once all other scientific papers have been published.	☐ I agree
NWT Environmental Research Bulletins (2)	2022-23, 2023-24	GNWT ECC, WRRB	Yes	☒ I agree
Plain Language Project Posters	2020-21	GNWT ECC, WRRB, Tlicho Gov. YKDFN Gov., NWT Metis, North Slave Metis	Yes	☒ I agree
GIS Data – phenology metrics	2023-24		Yes (doi:10.5683/SP3/UFAIES; link to permanent data archive for 2000-2017 analysis. URL for 2001-2021 analysis to be provided when Danby et al. paper is published. Note that these data are comprised of over 700 files and over 20GB. The Borealis repository is a permanent archive and a link to this archive may be a more practical alternative.	☒ I agree
GIS Data – environmental correlates	In progress		No. These data are still being analyzed but will be available when the Danby et al. scientific paper is submitted for publication.	☐ I agree
GIS Data – caribou analyses	2021-22	GNWT ECC, WRRB	Yes, but only in summary form to date as contained in the Mennell MSc thesis due to sensitivity of caribou collar data.	☐ I agree
Shrub age data	2023-24		Yes. (https://doi.org/10.5683/SP3/FJCGCG; this is a link to a permanent data archive)	☒ I agree
Tree ring width data	In progress		No. These data are currently being reformatted for open-access and will be available once the Bonta et al. scientific paper is submitted for publication.	☐ I agree

Vegetation plot data	In progress		No. These data are still being generated but will be available when the Danby et al. scientific paper is submitted for publication.	☐ I agree
Conference, meeting, and public information presentations and posters (15 in total since 2020).	All	Various	Yes	☒ I agree

Additional Deliverables	**Fiscal Year**	**Who was it provided to?**	**Sent to NWT CIMP?** Yes/No (*if no, state reason*)	**I acknowledge and permit posting for public access on the NWT Discovery Portal**
Project Video (Climate-Plants-People-Caribou: Exploring Cumulative Effects on a Changing Landscape. Available at: https://youtu.be/42NVSLG59Aw. Length: 9 mins 3 secs.)	2022-23	First Nations, GNWT ECC, WRRB	Yes	☒ I agree
Project Video (Vegetation Change on the Range of the Bathurst Caribou Herd. Available at: https://www.youtube.com/watch?v=-2QCuc040kQ&t=7s. Length: 14 mins 22 secs)	2023-24		Yes (but awaiting translation before wide distribution).	☒ I agree
Student Thesis (MSc) – Emily McKnight (Analysis of Bathurst caribou calving range, 1982-2016.)	In progress		No. Thesis is in progress. Anticipated completion Fall 2024.	☐ I agree
Scientific Paper – Andruko et al. (Analysis of shrub dynamics, 2006-2016. Published in Ecosystems.)	2020-21	GNWT ECC, WRRB	Yes	☒ I agree

12. References

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Thank you for your submission!

Table 1. Geospatial environmental variables generated for the entirety of the Bathurst caribou herd's range and used in explanatory modeling of annual productivity trends, 2000-2021.

Name	**Description**	**Values**
Temperature Trends	Trends in minimum, maximum, and mean temperatures during the 1981-2010 normal period, measured seasonally and annually.	Anomaly linear trend, Celsius
Growing-Degree Day Trends	Trends in growing degree days (base zero) during the 1981-2010 normal period, measured seasonally and annually.	Anomaly linear trend, GDD 0
Growing Temperature Frequency Trends	Trends in the number of days with mean air temperature above zero degrees during the 1981-2010 normal period, measured seasonally and annually.	Anomaly linear trend, tally
Precipitation Trends	Trends in total precipitation during the 1981-2010 normal period, determined seasonally and annually.	Anomaly linear trend, millimetres
Water Amount	Percentage of pixel comprised of surface water	0-100%
Baseline Productivity	Maximum annual EVI value as measured in 2001	-1 to 1
Years Since Forest Fire	Number of years since the most recent forest fire	0-100 years (100 is outside of recording period, similar to N/A)
Elevation	Digital surface elevation based on the ArcticDEM & Canadian 30m DEM	approx. 0-3000 masl
Slope	Local slope (based on 4 neighbours)	0-90 degrees
Aspect	Local aspect (based on 4 neighbours)	0-360 degrees
Terrain Roughness	The range of values for a pixel and its 8 neighbours (max - min)	approx. 0-1100 m
Terrain Wetness Index (TWI)	Upslope area & local slope	approx. -1-75
Distance to Treeline	Euclidean distance to the Forest Tundra/Tundra boundary	approx. -700 to +650 km
Distance to Ocean	Euclidean distance to to the Arctic Ocean	approx. +-136- -96 decimal degrees
Snowmelt timing - trend	Linear trend of change in the date of snowmelt, 2001-2015	approx. -8 to +7 days/year
Snowmelt timing - standard deviation	Standard deviation in the date of snowmelt, 2001-2015	approx. 2 to 70
Noise - Integer Percent	A randomly assigned value between 1 and 100	1-100

Table 2. Metrics of stem distribution (density, proportion birch) and growth (cover, length, growth rate, basal diameter, number of live stems per shrub, proportion dead stems per shrub) compared between Greening and No Change sites. From Bonta et al. (2023).

	Greening	No Change	Test Statistic (*df*)	*P*
Stem Density (stems/m^2)	35.17 ± 30.48 (*n* = 15)	38.97 ± 37.63 (*n* = 14)	*U* = 94.0	0.652
Proportion Birch (%)	95.45 ± 4.63 (*n* = 15)	90.89 ± 9.44 (*n* = 14)	*U* = 75	0.201
Shrub Cover (%)	**55.45 ± 0.65** **(*n* = 10)**	**42.73 ± 2.79** **(*n* = 10)**	***t* = 2.15 (18)**	**0.048**
Stem Length (cm)	47.87 ± 5.06 (*n* = 15)	49.15 ± 7.24 (*n* = 14)	*t* = 0.553 (27)	0.585
Number of Live Stems	7.69 ± 3.12 (*n* = 10)	7.22 ± 2.07 (*n* = 10)	*t* = 0.395 (18)	0.698
Proportion Dead Stems (%)	**14.29 ± 5.71** **(*n* = 10)**	**23.50 ± 6.16** **(*n* = 10)**	***t* = 3.469 (18)**	**0.003**
Growth Rate (cm/yr) – Lower Stem	4.00 ± 1.11 (*n* = 11)	3.76 ± 0.74 (*n* = 10)	*t* = 0.583 (19)	0.567
Growth Rate (cm/yr) – Upper Stem	2.91 ± 0.58 (*n* = 11)	2.54 ± 0.45 (*n* = 10)	*U* = 43.5	0.426
Basal Diameter (mm)	6.22 ± 0.91 (*n* = 15)	6.47 ± 0.97 (*n* = 14)	*t* = 0.737 (27)	0.467

Note: All values are means ± SD. Bolded rows indicate significant differences at $p \leq 0.05$. Sampling protocol differed slightly between 2018 and 2019, and not all metrics of growth were measured each year. As a result, there is some discrepancy in sample size across the different metrics analyzed.

Table 3. Comparisons of age metrics for stems at Greening (*n* = 12) and No Change (*n* = 12) sites. From Bonta et al. (2023).

Age Comparison (years)	Greening	No Change	Test Statistic $_{(df)}$	*p*
Average stem	22.61 ± 3.11	23.96 ± 2.62	t = 0. 553 $_{(22)}$	0.585
Youngest stems	6.92 ± 1.73	7.08 ± 1.88	t = 0.226 $_{(22)}$	0.823
Absolute oldest stems	51.42 ± 7.91	56.50 ± 10.94	U = 97.00	0.160
Mean of the three oldest stems	46.67 ± 7.24	49.33 ± 9.23	t = 0.788 $_{(22)}$	0.439
Mean of the five oldest stems	43.00 ± 6.82	45.08 ± 7.48	t = 0.713 $_{(22)}$	0.483

Note: All values are means ± *SD*.

Table 4. Trends in the timing and duration of annual range occupancy for the Bathurst caribou herd from 1997-2019. Trends are summarized and accompanied by linear equations, regression coefficients, and p-values. From Mennell (2021).

Season	**Start**	**Finish**	**Duration**
Spring Migration	No significant change Y=111+ 0.028x, R^2_{adj} =-0.047, P=0.8913	****Significantly Earlier** Y=154 - 0.35x, R^2_{adj} =0.2, P=0.017	****Significantly Shorter** Y=43- 0.38x, R^2_{adj} = 0.098, P=0.0799
Calving	****Significantly Earlier** Y=154 - 0.35x, R^2_{adj} =0.2, P=0.017	No significant change Y=173 - 0.17x, R^2_{adj} =8.4 e -5, P=0.3283	No significant change Y=19 + 0.18x, R^2_{adj} = 0.0026, P=0.3153
Post-calving	No significant change Y=173 - 0.17x, R^2_{adj} =8.4 e -5, P=0.3283	****Significantly Later** Y=209 + 0.58x, R^2_{adj} =0.22, P=0.013	****Significantly Longer** Y=35 + 0.75x, R^2_{adj} = 0.28, P=0.006
Late Summer	****Significantly Later** Y= 209 + 0.58x, R^2_{adj} =0.22, P=0.013	No significant change Y=270 + 0.049x, R^2_{adj} =-0.046, P=0.85	No significant change Y=62 - 0.54x, R^2_{adj} = 0.079, P=0.1036
Fall rut	No significant change Y=270 + 0.049x, R^2_{adj} =-0.046, P=0.85	No significant change Y=730 - 0.22x, R^2_{adj} =-0.0069, P=0.37	No significant change Y=22 - 0.27x, R^2_{adj} = 0.028, P=0.2144
Fall Migration	No significant change Y=293 - 0.22x, R^2_{adj} =-0.0069 P=0.37	No significant change Y=336 - 0.12x, R^2_{adj} =-0.043 P=0.77	No significant change Y=43- 0.1x, R^2_{adj} = -0.046 P=0.846
Winter	No significant change Y=336 - 0.12x, R^2_{adj} =-0.043, P=0.77	No significant change Y=111 - 0.069x, R^2_{adj} =-0.044, P=0.75	No significant change Y= 142- 0.13x, R^2_{adj} = -0.045, P=0.75

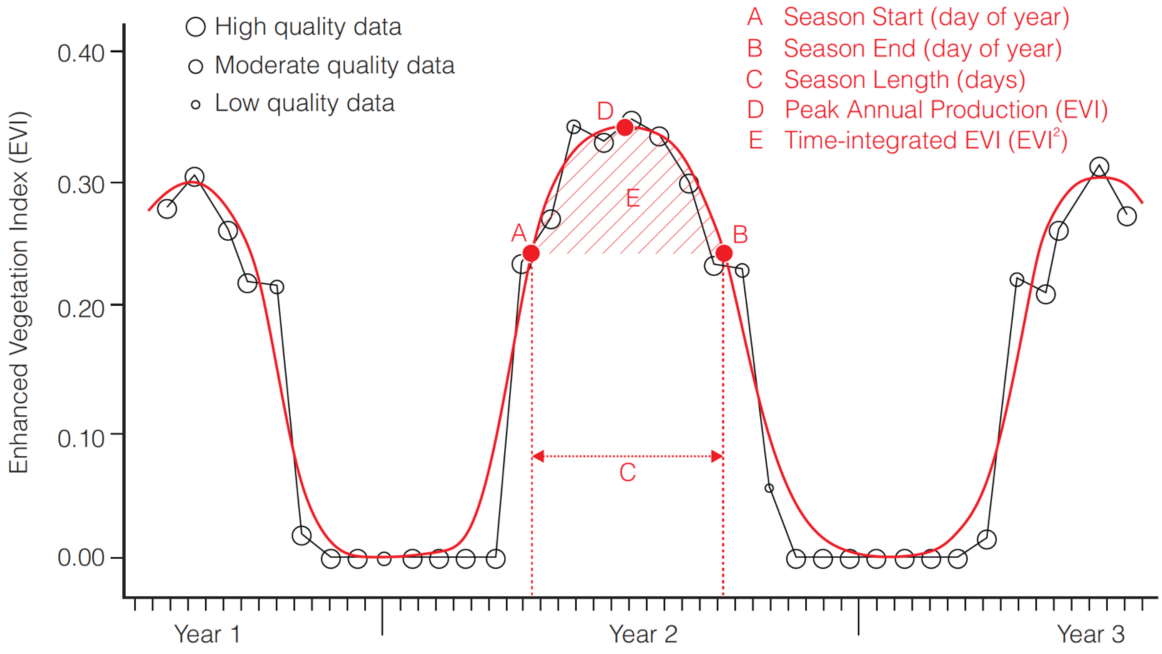

Figure 1. Illustrative example of curve fitting and derivation of productivity and phenology metrics for a single pixel. Open black circles represent EVI values extracted from the Moderate Resolution Imaging Spectroradiometer (MODIS) composite data. The red curve represents values modelled using a double logistic function. The size of the open black circles is indicative of the quality of the MODIS data; high-quality data was weighted 1.0 in modelling, moderate-quality data was weighted 0.5, and low-quality data was weighted 0.1. Letters indicate the values of the phenological metrics derived from the modelled data and used in the multiannual trend analysis. From Dearborn & Danby (2022).

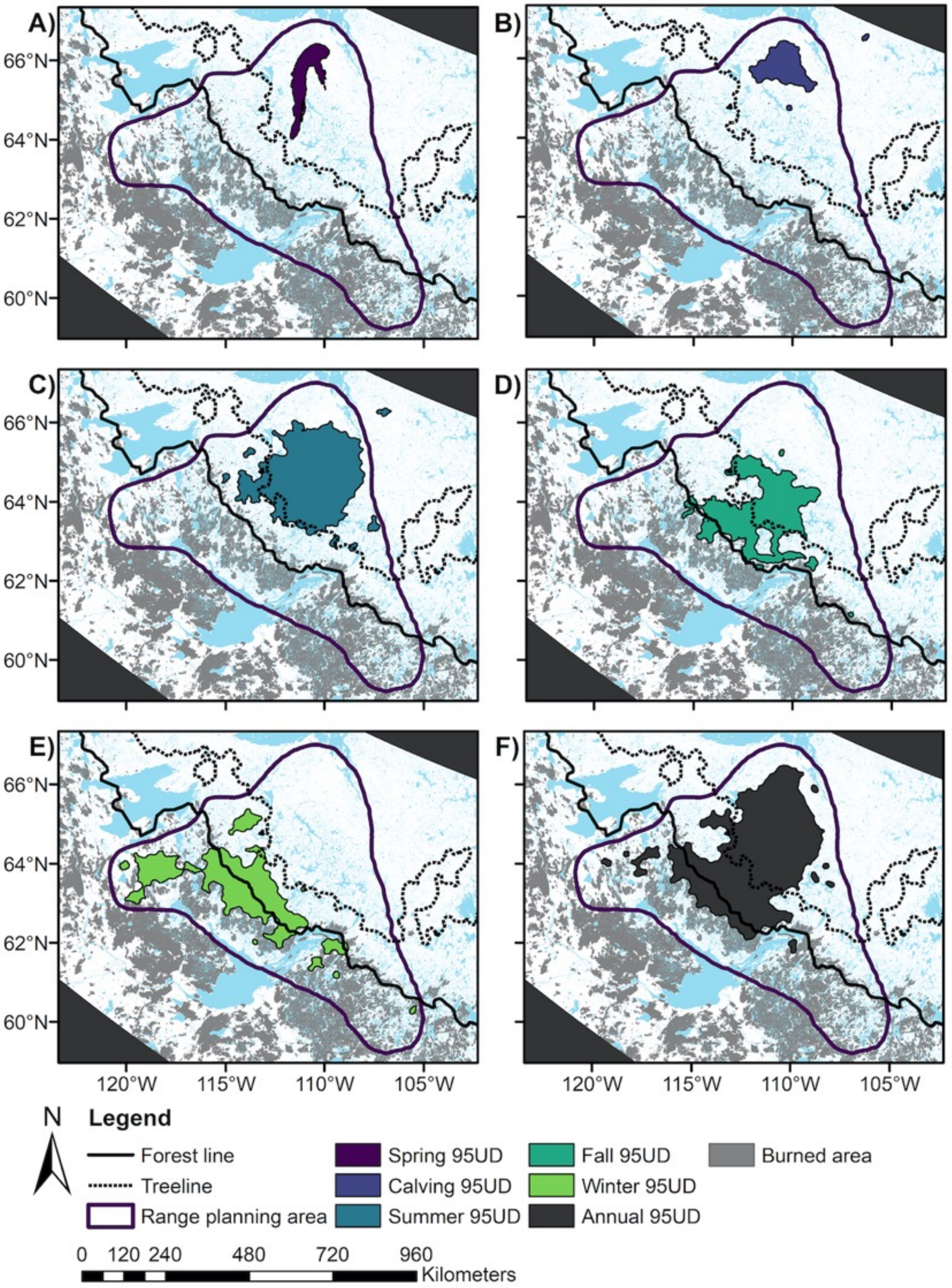

Figure 2. Seasonal ranges of the Bathurst caribou herd based on 95% utilization distributions (95UD) derived from GPS collar data obtained between 1996 and 2015 by the Government of the Northwest Territories. “Spring” includes movements from 20 April to 1 June (A), “Calving” from 2 June to 28 June (B), “Summer” from 29 June to 6 September (C), “Fall” from 7 September to 30 November (D), and “Winter” from 1 December to 19 April (E). “Annual” includes year-round movements (F). From Dearborn & Danby (2022).

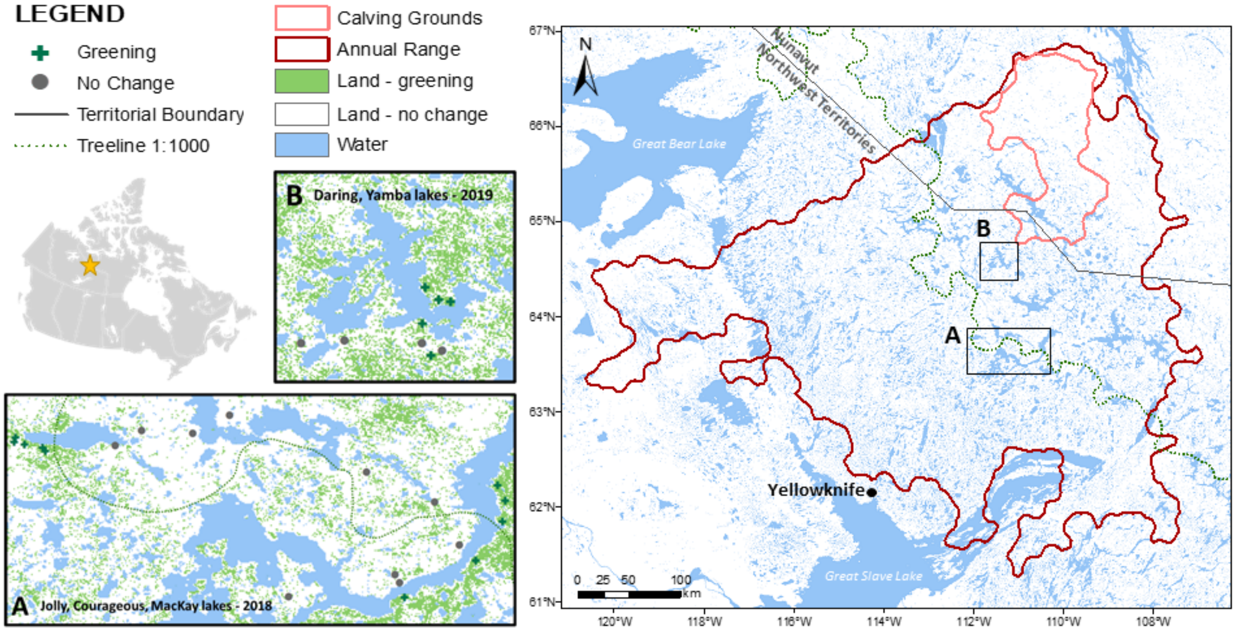

Figure 3. Annual range of the Bathurst caribou herd based on 99% utilization distributions derived from GPS collar data obtained between 1996 and 2015 by the Government of Northwest Territories. Field investigations targeted the MacKay Lake area (A) in 2018 and the Daring Lake/Yamba Lake area (B) in 2019 for comparison of shrub establishment, composition, and growth between areas that have significantly greened and areas where vegetation productivity did not significantly change, 2000-2017. Significantly "greening" pixels are shown in green; white pixels are either non-significant or demonstrate a significant trend that is neutral or negative. Locations of shrub sampling plots are indicated by green crosses for Greening sites and grey circles for No Change sites. From Bonta (2024).

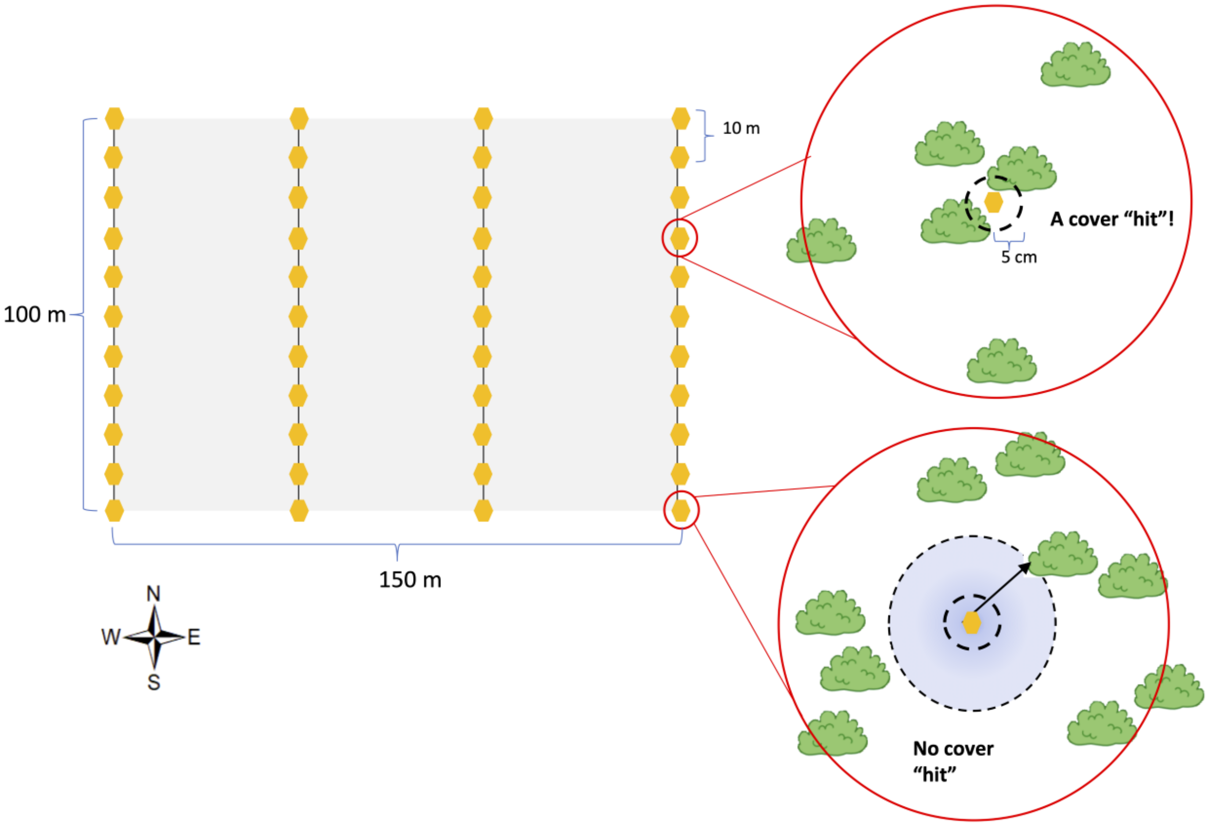

Figure 4. Configuration of plots for shrub stem sampling. Plots were comprised of four 100 m transects spaced 50 m apart, with 11 equally spaced sampling stations ("points") per transect. At each station, overlap of one or more shrubs within a 5 cm radius of a point was considered a "hit" for the purpose of estimating canopy cover. Distance to the nearest shrub stem was measured for estimating shrub density (one shrub per unit area) and two samples were obtained: one from the base of the stem and another from halfway along the length of the stem. From Bonta (2024).

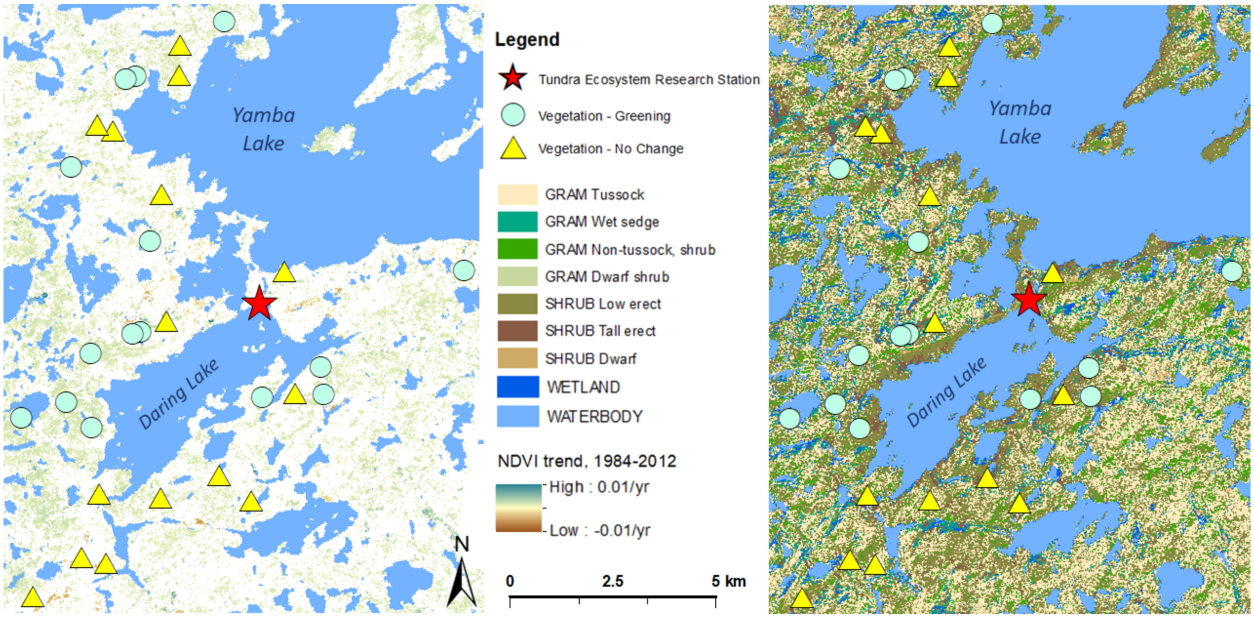

Figure 5. Plant community sampling sites in the Daring/Yamba lakes area of the Northwest Territories relative to significant Landsat NDVI trends, 1984-2012 (left) and circa 2000 land cover class (right). Blue circles indicate Greening sites and yellow triangles indicate No Change sites. Maps created in ESRI ArcMap v.10.7.1. Greening trend data from Ju and Masek (2016). Significantly greening pixels are in shades of green and pixels with significantly decreasing trends are in shades of brown; all other pixels are either non-significant and/or have neutral trends. Land cover is based on Landsat imagery from 1999 to 2002, as per Olthof et al. (2009). From Bonta (2024).

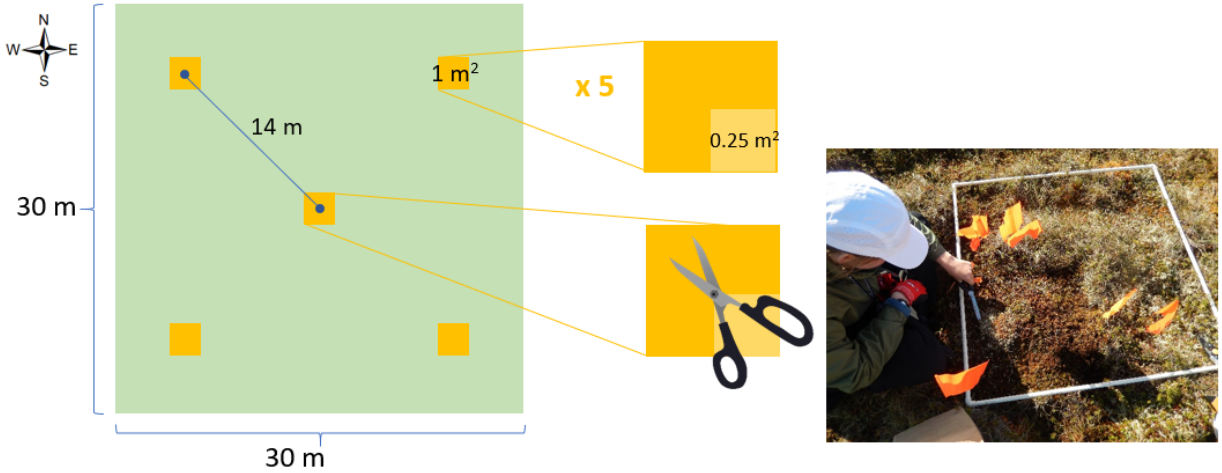

Figure 6. Configuration of plots for cover estimation and biomass sampling. Plant community sampling comprised five replicate 1 m x 1 m plots within a 30 m x 30 m area (sampling site), each of which included a 0.25 m^2 subplot in the southeast corner. Four corner plots were positioned with centres 14 m from the centre plot. Percent cover of vegetation was visually estimated from each of the five plots, and above-ground biomass was harvested from the centre plot. Erect shrubs were assessed from the full 1 m^2 area of each plot, while all other shrub species and plant functional types were assessed from the 0.25 m^2 subplot. From Bonta (2024).

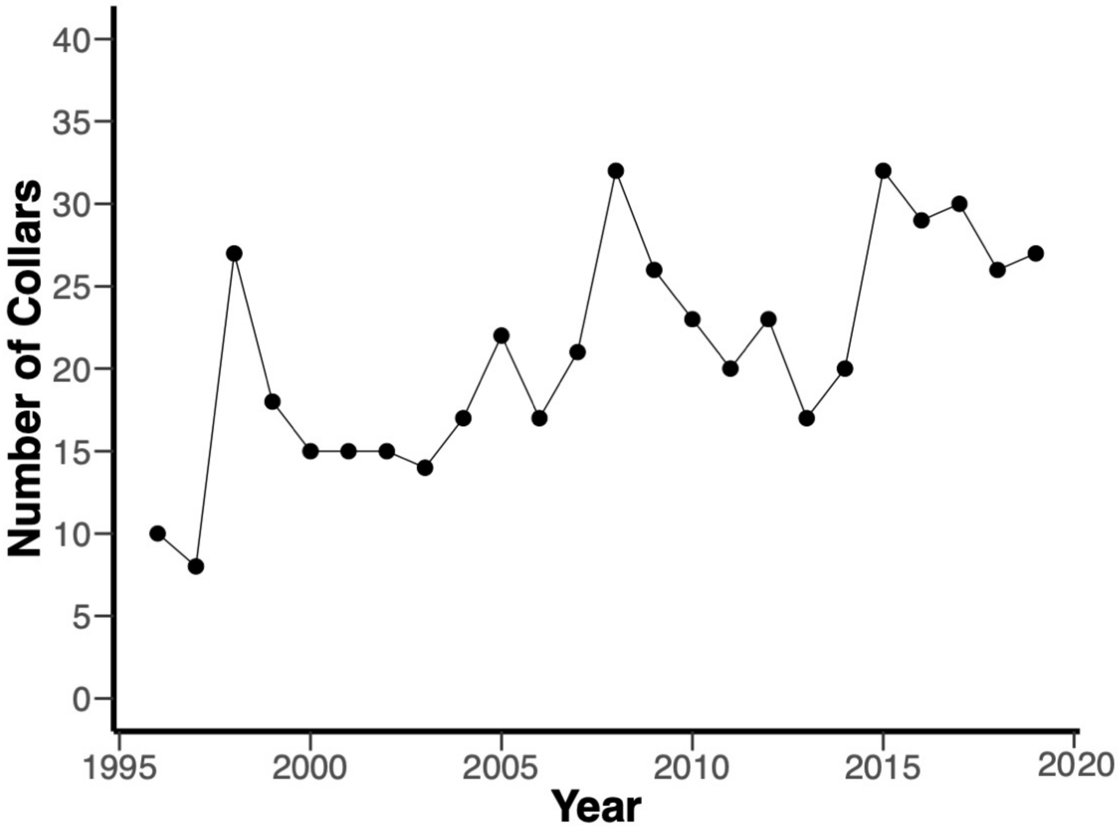

Figure 7. Annual number of individual caribou used in our data after filtering out males and duplicate data. The average number of collared caribou was 21 per year (min = 8, max = 31). From Mennell (2021).

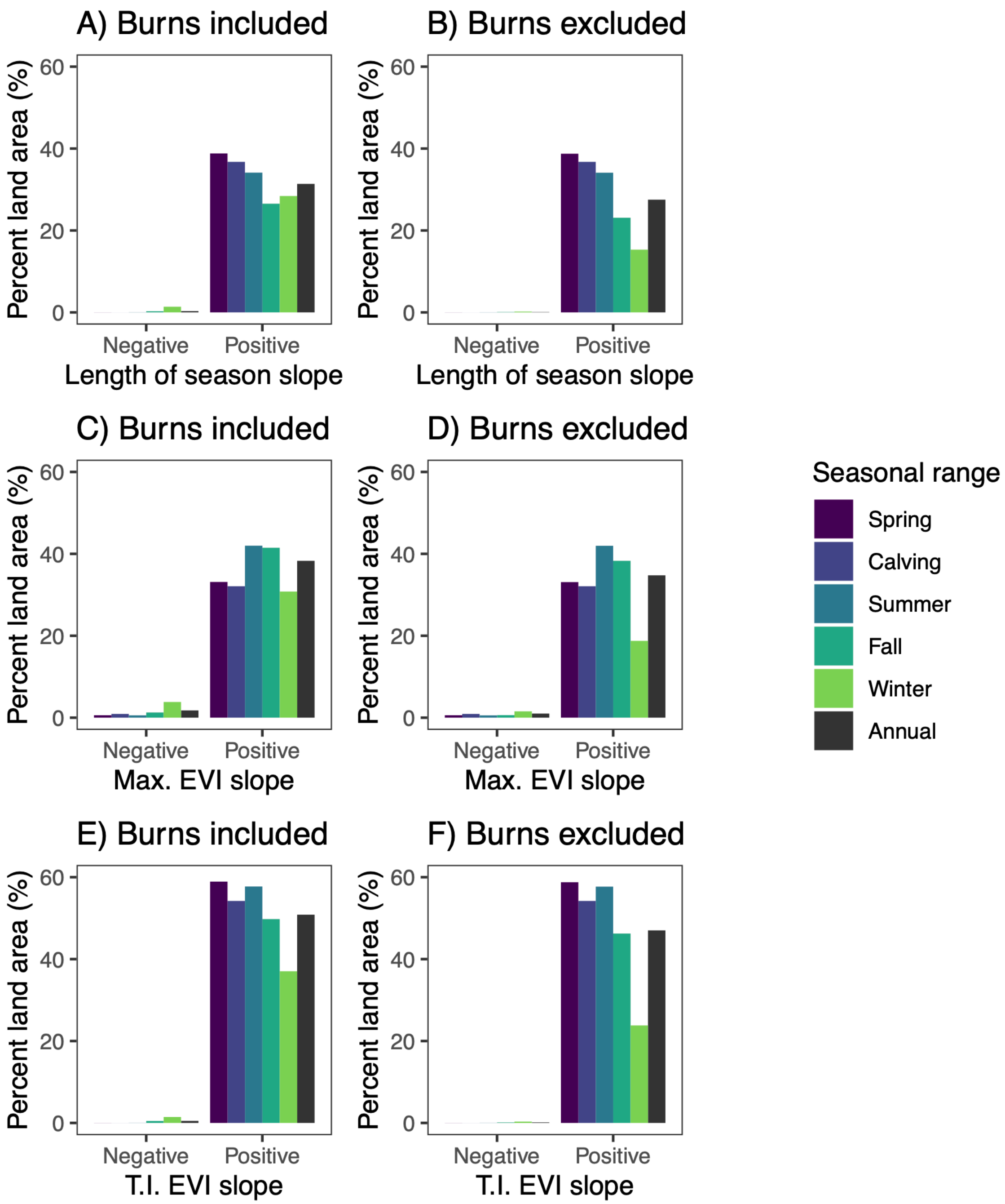

Figure 8. Percent of annual and seasonal core use areas of the Bathurst caribou range that exhibited statistically significant trends in the length of growing season (A and B), maximum (Max.) enhanced vegetation index (EVI) (C and D), and time-integrated (T.I.) EVI (E and F) from 2000 to 2021. Breakdown is presented for all areas (left column) and for areas with burned areas excluded (right column). All values exclude areas classified as water. Note that there is some spatial overlap among the different seasonal components of the range.

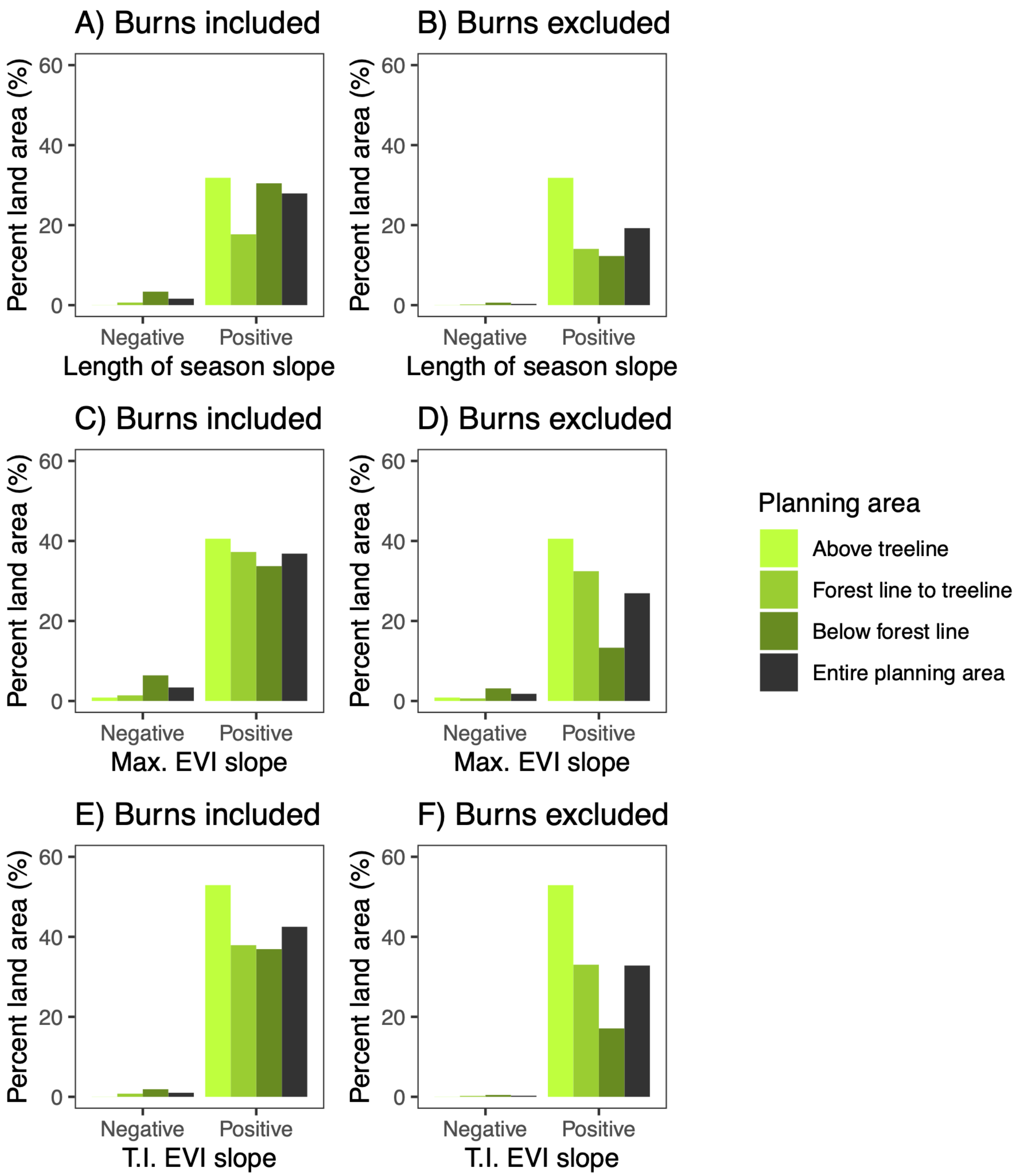

Figure 9. Percent of regions within the Bathurst caribou. Range plan that exhibited statistically significant trends in the length of growing season (A and B), maximum (Max.) enhanced vegetation index (EVI) (C and D), and time- integrated (T.I.) EVI (E and F) from 2000 to 2017. Breakdown is presented for all areas (left column) and for areas with burned areas excluded (right column). All values exclude areas classified as water. The three ecological zones (treeline, forest–tundra, and forest) within the range planning area correspond to Timoney et al. 1992.

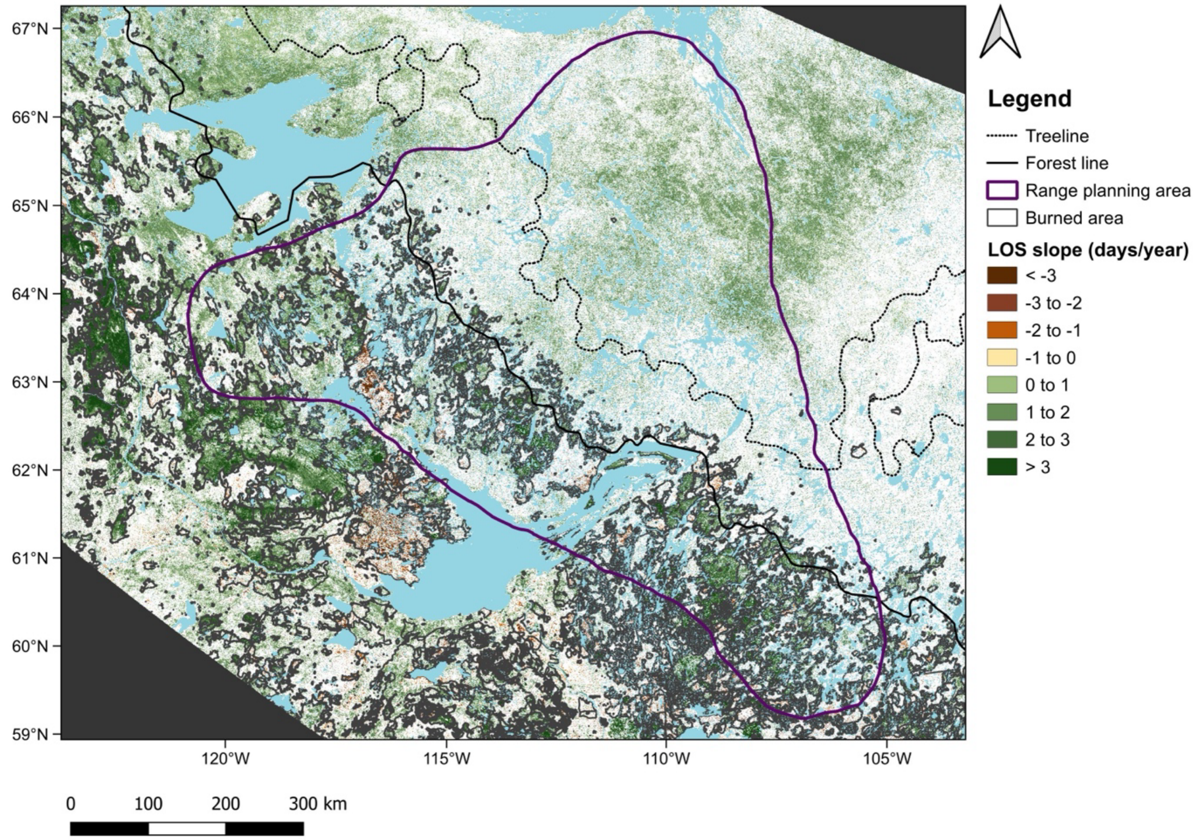

Figure 10. Statistically significant trends ($p \leq 0.05$) in growing season length (LOS) across the Bathurst caribou range, 2000–2021. Negative values indicate a significant linear trend over time toward shorter growing seasons; positive values indicate a significant linear trend toward longer growing seasons. Areas in white did not exhibit significant trends. Burned areas are outlined by grey polygons.

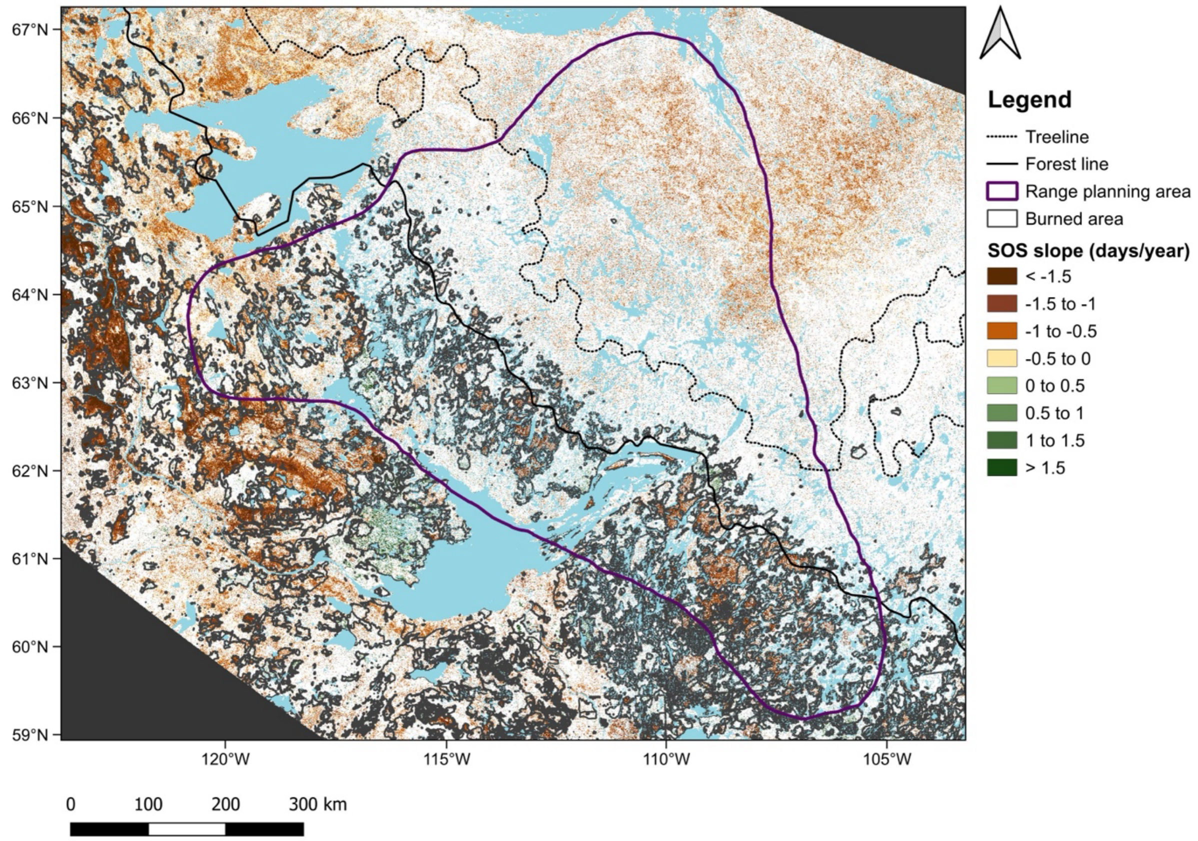

Figure 11. Statistically significant trends ($p \leq 0.05$) in the start of growing season (SOS) date across the Bathurst caribou range, 2000–2021. Negative values indicate a linear trend toward an earlier date; positive values indicate a linear trend toward a later date. Areas in white did not exhibit statistically significant trends. Burned areas are outlined by grey polygons.

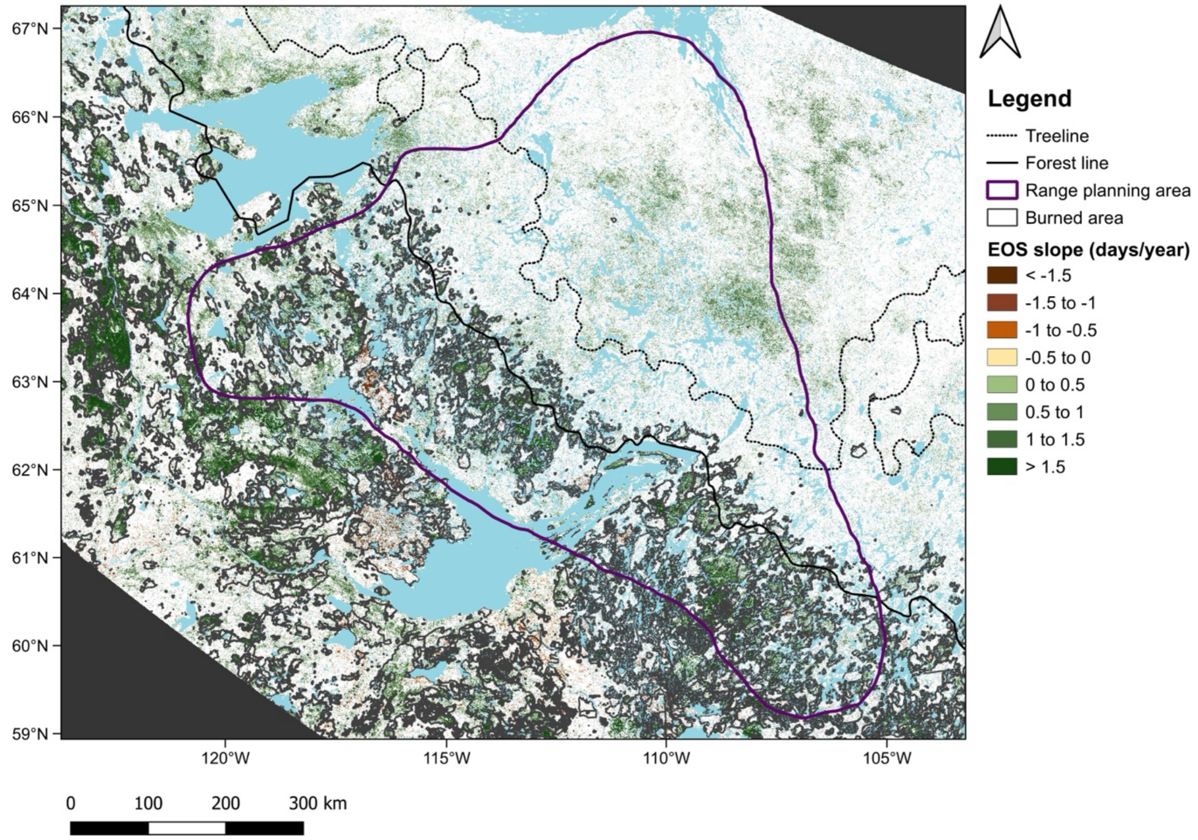

Figure 12. Statistically significant trends (p ≤ 0.05) in the end of growing season (EOS) date across the Bathurst caribou range, 2000–2021. Negative values indicate a linear trend toward an earlier date; positive values indicate a linear trend toward a later date. Areas in white did not exhibit statistically significant trends. Burned areas are outlined by grey polygons.

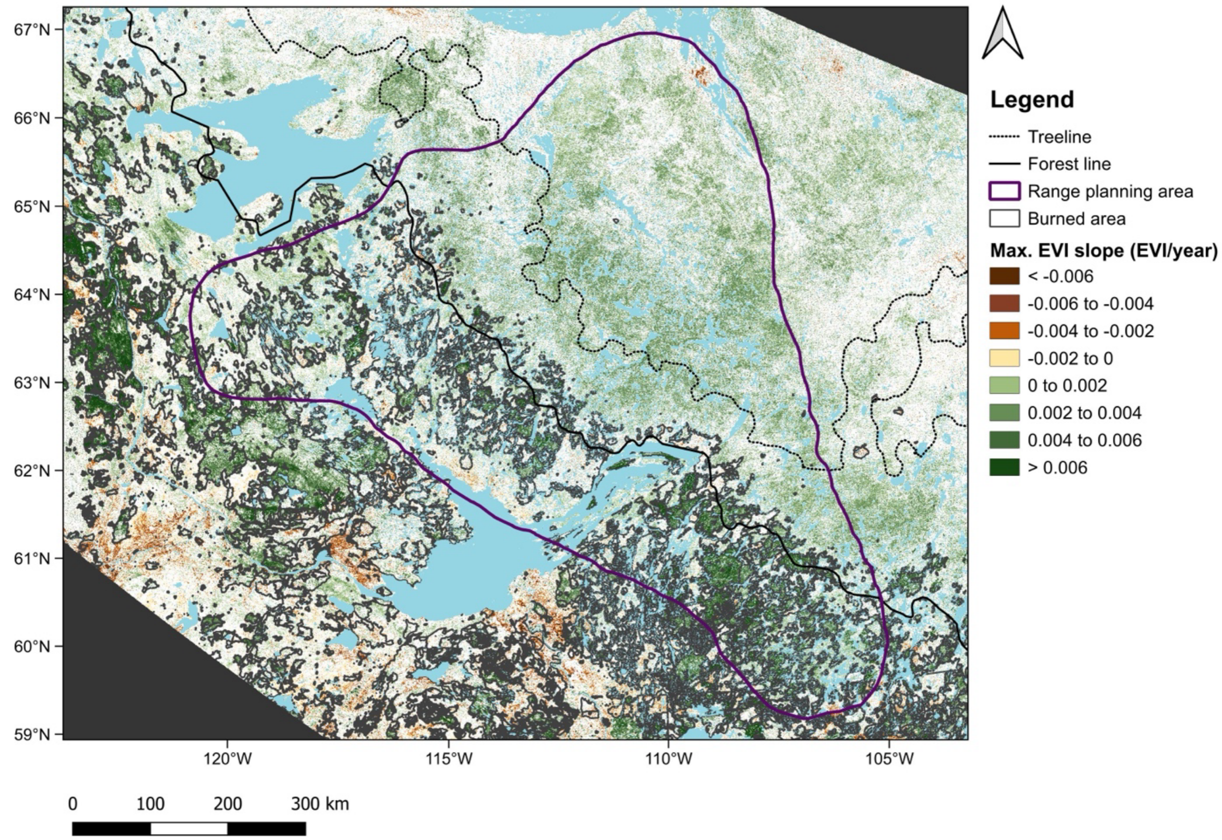

Figure 13. Statistically significant trends (p ≤ 0.05) in maximum annual enhanced vegetation index (Max EVI) across the Bathurst caribou range, 2000–2021. Negative values indicate a significant linear trend over time toward lower values; positive values indicate a significant trend toward higher values. Areas in white did not exhibit significant trends. Burned areas are outlined by grey polygons.

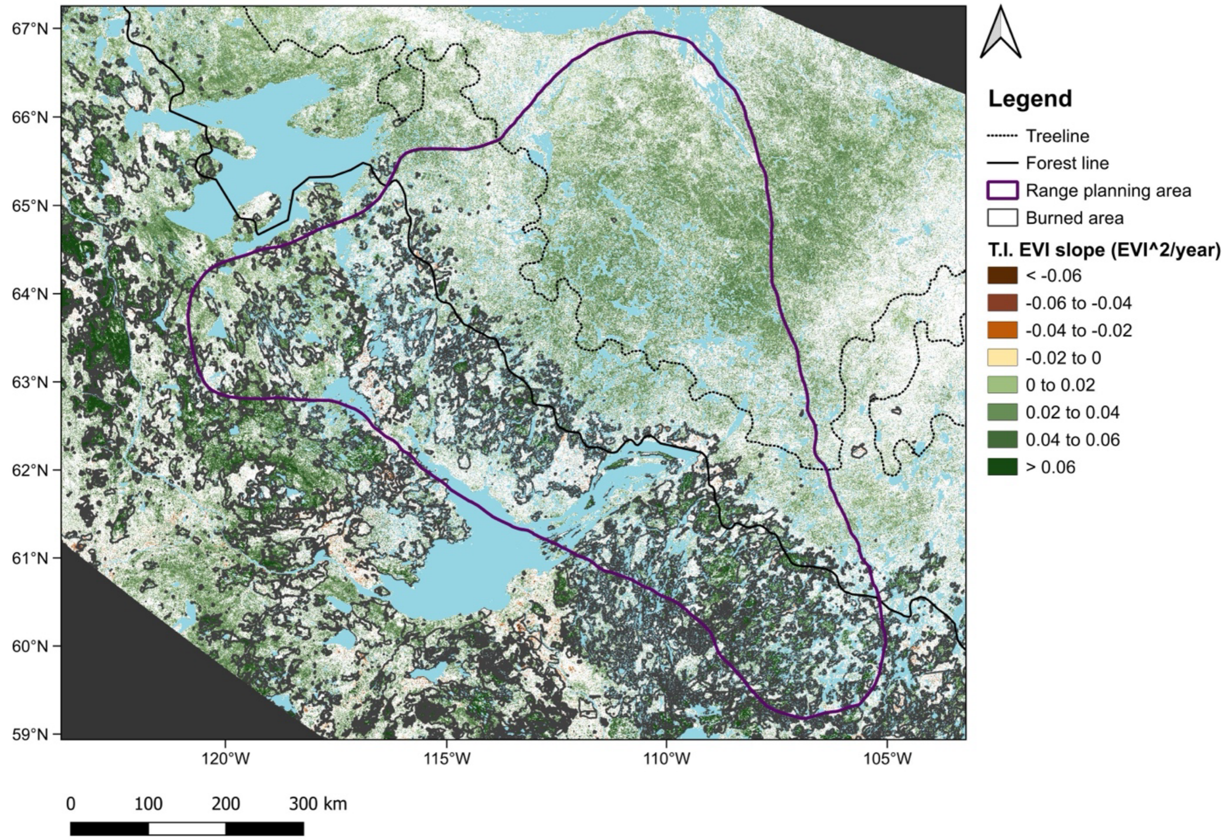

Figure 14. Statistically significant trends ($p \leq 0.05$) in time-integrated enhanced vegetation index (TIE) across the Bathurst caribou range, 2000–2021. Negative values indicate a significant linear trend toward lower total annual ecosystem production; positive values indicate a significant linear trend toward higher total annual ecosystem production. Areas in white did not exhibit significant trends. Burned areas are outlined by grey polygons.

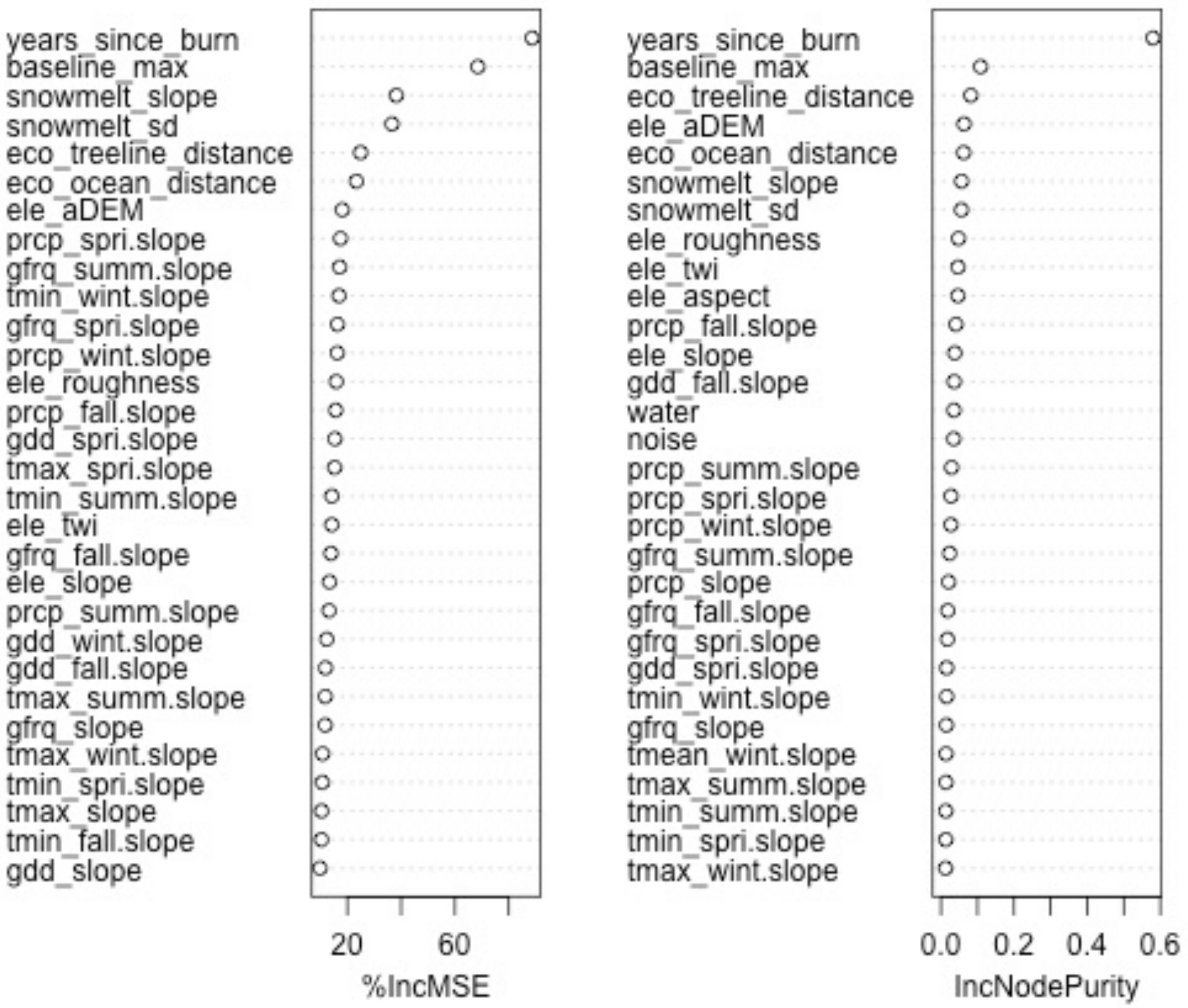

Figure 15. Variable importance plots for random forest modeling of trends in Max_EVI ("vegetation greenness"). The plot on the left (%IncMSE) indicates the increase in mean squared error when a variable is omitted and the plot on the right (IncNodePurity) indicates how much the model error increases when a variable is randomly permuted or shuffled. Variables are listed in order of importance as indicated by each metric.

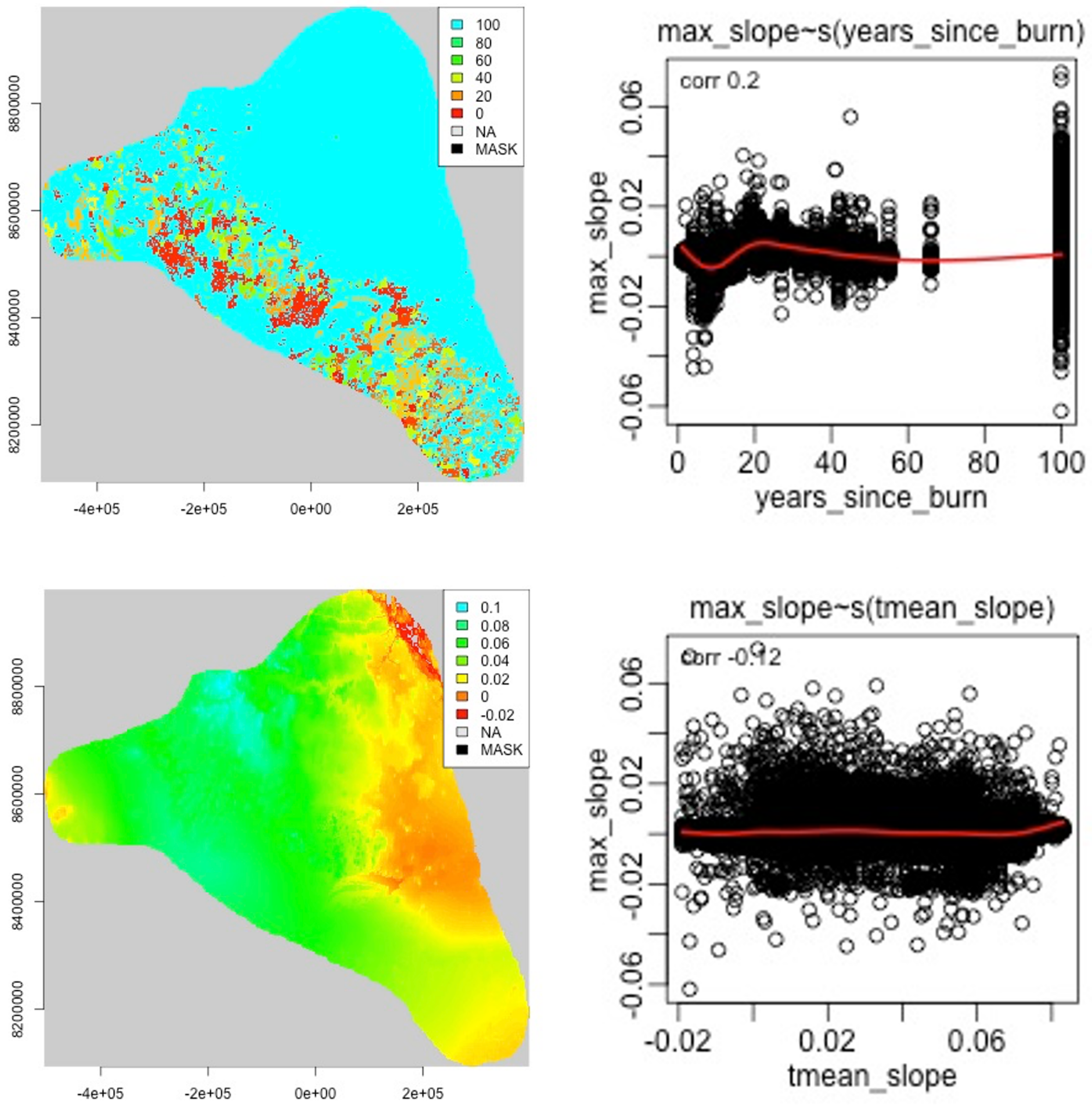

Figure 16. A set of analytical outputs for two of the variables used in random forest modeling of trends in annual maximum EVI. **Top**: Number of years since the last recorded forest fire (years_since_burn). **Bottom**: Trend in annual mean temperature (tmean_slope). Figures on the left are maps of each variable clipped to the Bathurst Range Planning Area. Figures on the right are partial dependence plots of the data used in training the model.

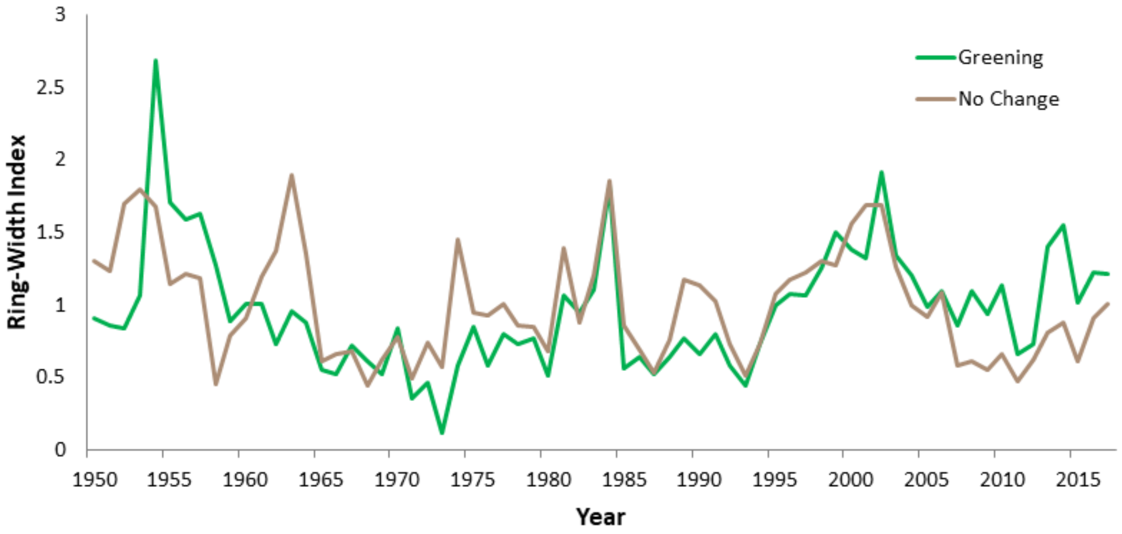

Figure 17. Time series of average ring-width index (RWI) based on detrended standard chronologies for dwarf birch. Growth is compared between shrubs at Greening sites and those at No Change sites for the 1950-2017 period. From Bonta (2024).

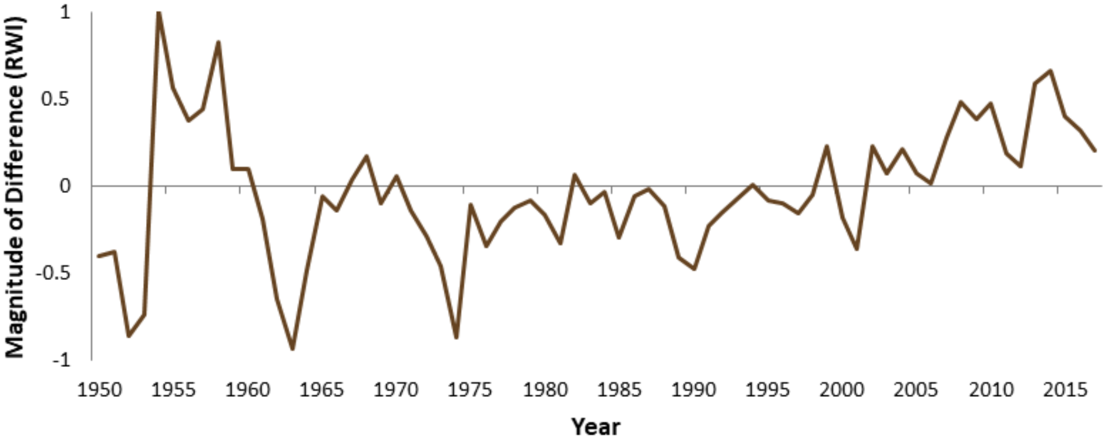

Figure 18. Magnitude of difference in mean ring-width index (RWI) based on detrended standard chronologies between birch at Greening sites compared with those at No Change sites (where Magnitude = [Greening RWI] – [No Change RWI]) for the 1950-2017 period. Sampling sites were defined as “Greening” or “No Change” based on EVI trends from 2000 to 2017. From Bonta (2024).

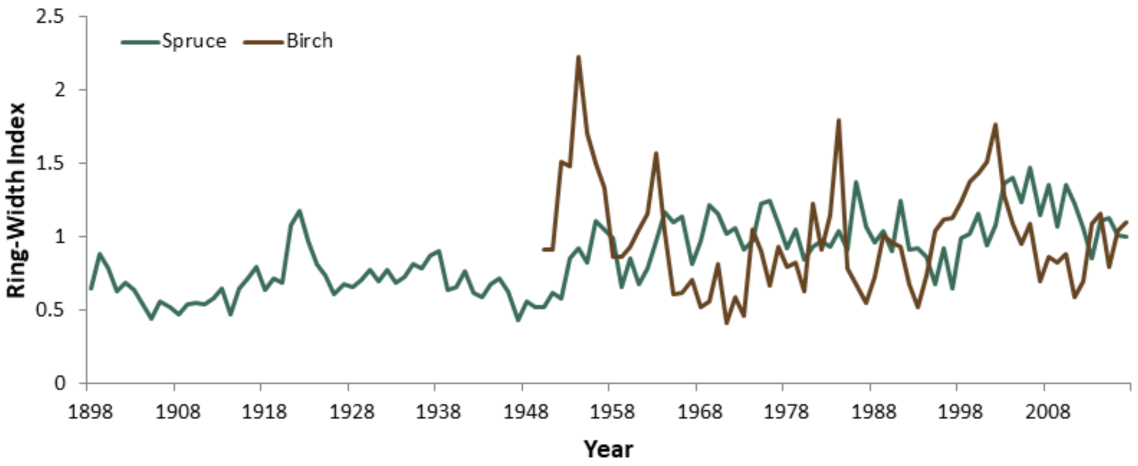

Figure 19. Detrended standard chronologies of ring-width index for black spruce and dwarf birch, with a comparison of growth over the common period of 1950 to 2017. From Bonta (2024).

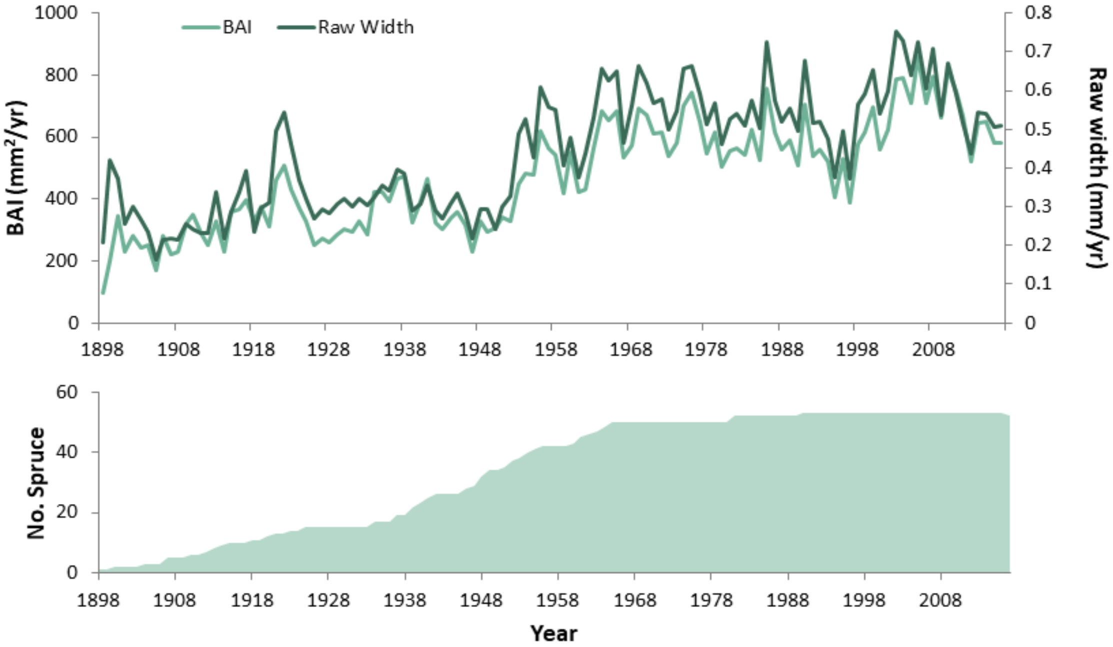

Figure 20. Average annual secondary growth of black spruce at treeline sites 1898-2017, as described by basal area increment (BAI; mm^2/year) and raw ring-width (mm/year). Sample depth, shown at bottom, corresponds to the number of individual trees that contributed to the mean. From Bonta (2024).

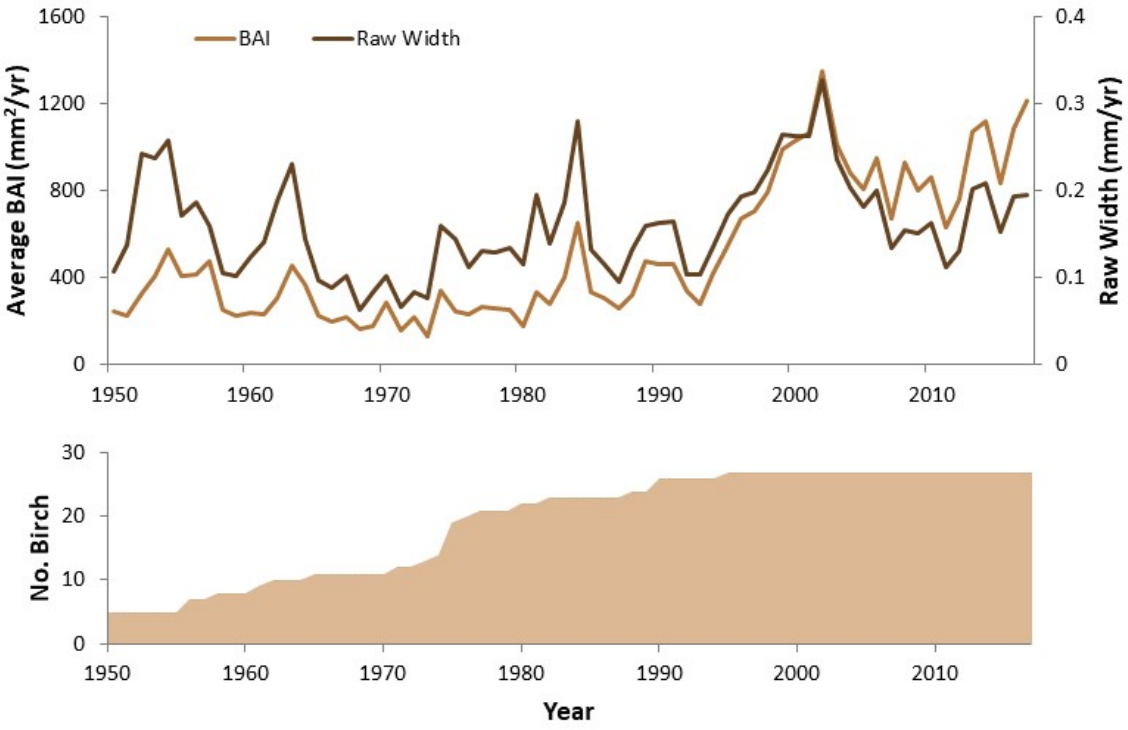

Figure 21. Average annual secondary growth of dwarf birch at treeline sites in central mainland Canada, 1950-2017, as described by basal area increment (BAI; mm^2/year) and raw ring-width (mm/year). Sample depth, shown at bottom, corresponds to the number of individual shrubs that contributed to the mean. From Bonta (2024).

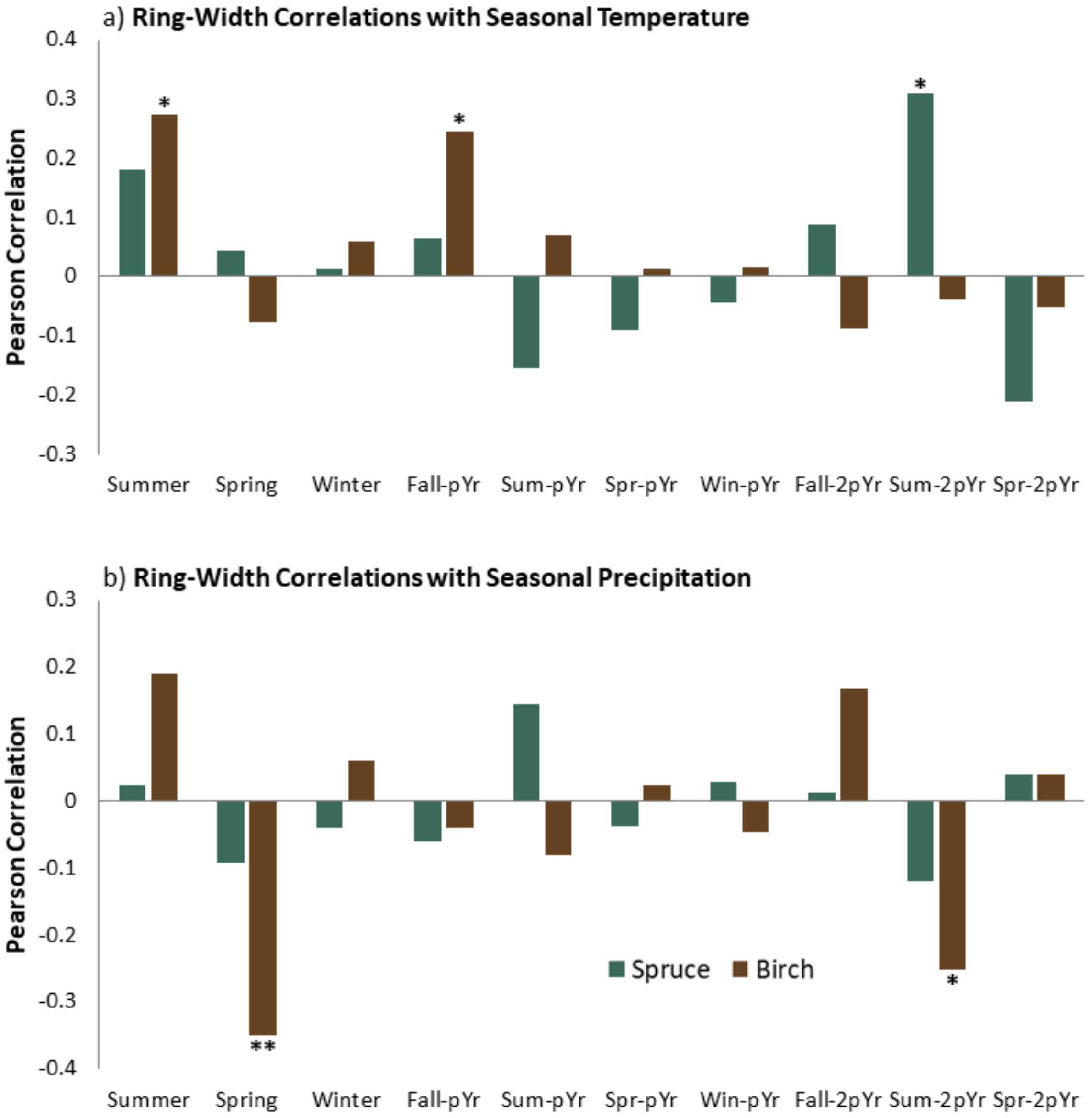

Figure 22. Pearson correlations between annual residual ring-width index of black spruce (green) and dwarf birch (brown) and a) seasonal temperature and b) seasonal precipitation. Climate-growth relationships were explored from the current growth year back to the beginning of growth two years prior. Asterisks indicate significant correlations at the $p < 0.05$ (*) or $p < 0.01$ (**) levels. From Bonta (2024).

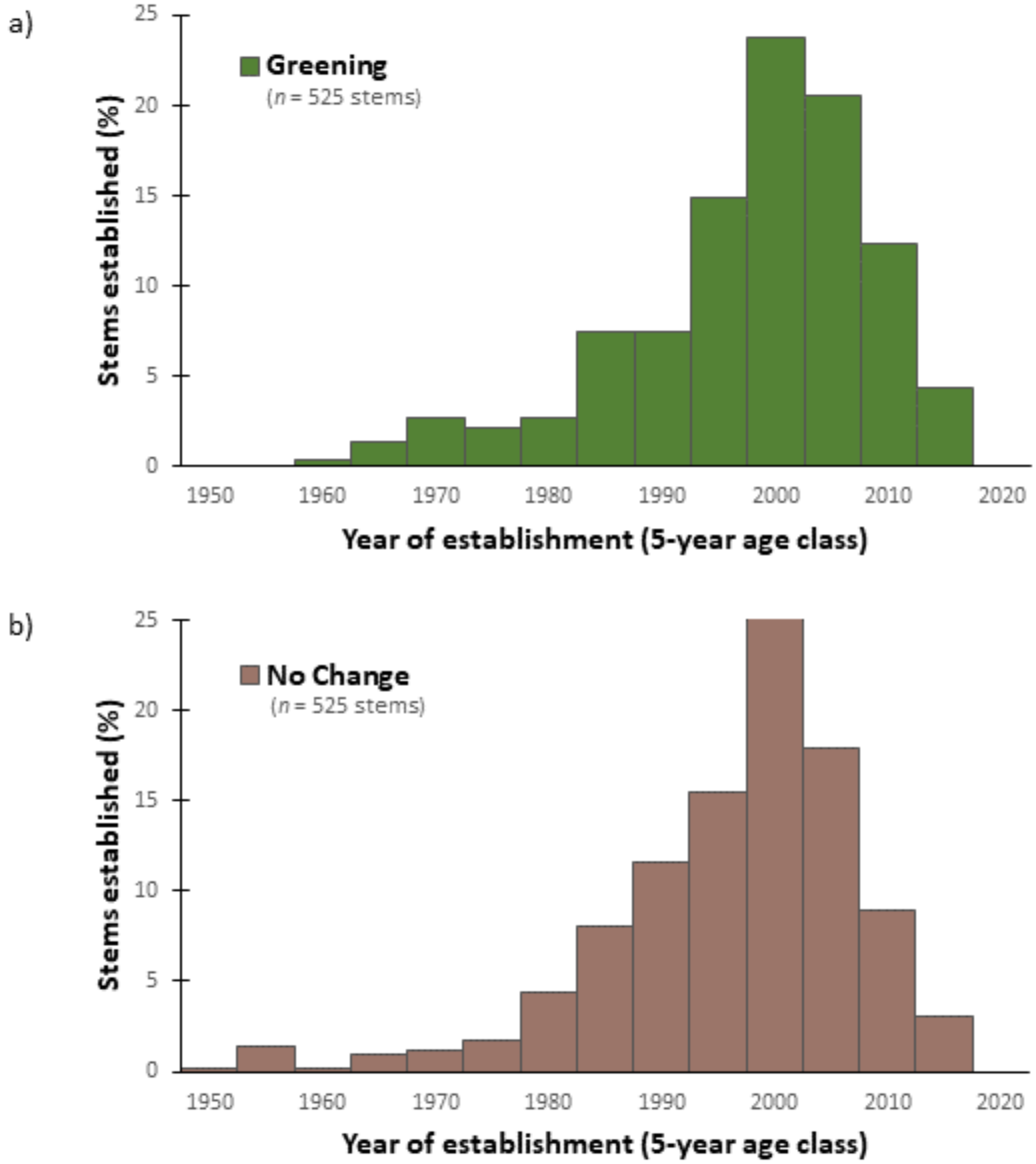

Figure 23. Frequency distributions of stem establishment (%) per year for a) stems at Greening sites and b) stems at No Change sites. Data are categorized into 5-year age classes where the year indicates the uppermost limit of the bin. From Bonta (2024).

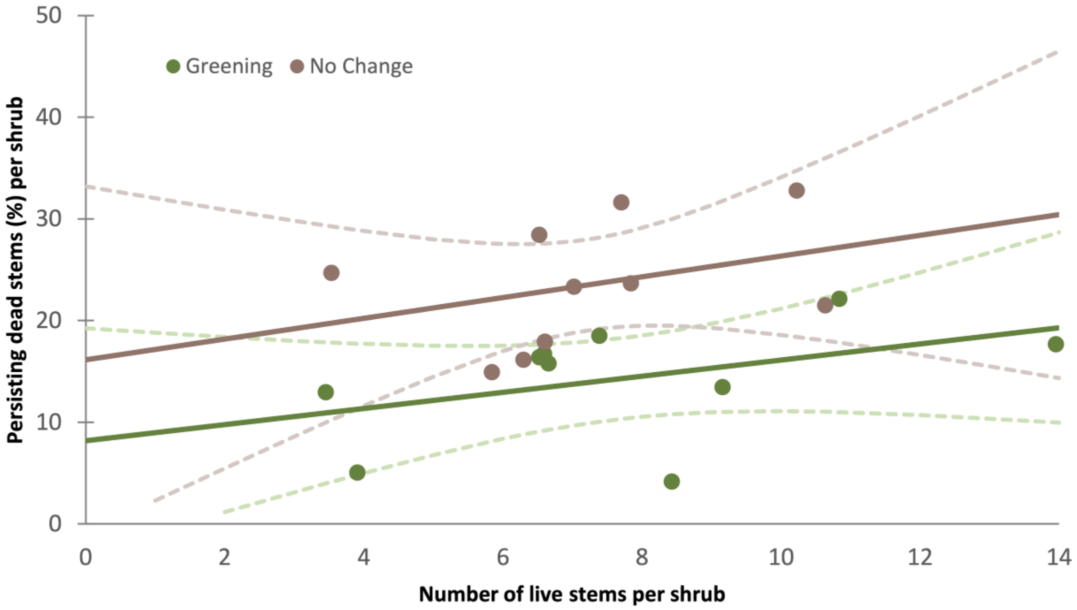

Figure 24. Persisting dead stems (%) in relation to the total number of live stems for shrubs at Greening sites ($y = 0.80x + 8.17$; $R^2 = 0.189$) compared with shrubs at No Change sites ($y = 1.02x + 16.13$; $R^2 = 0.118$). Pale dashed lines indicate 95% confidence intervals around the dark trendline for each site type. From Bonta (2024).

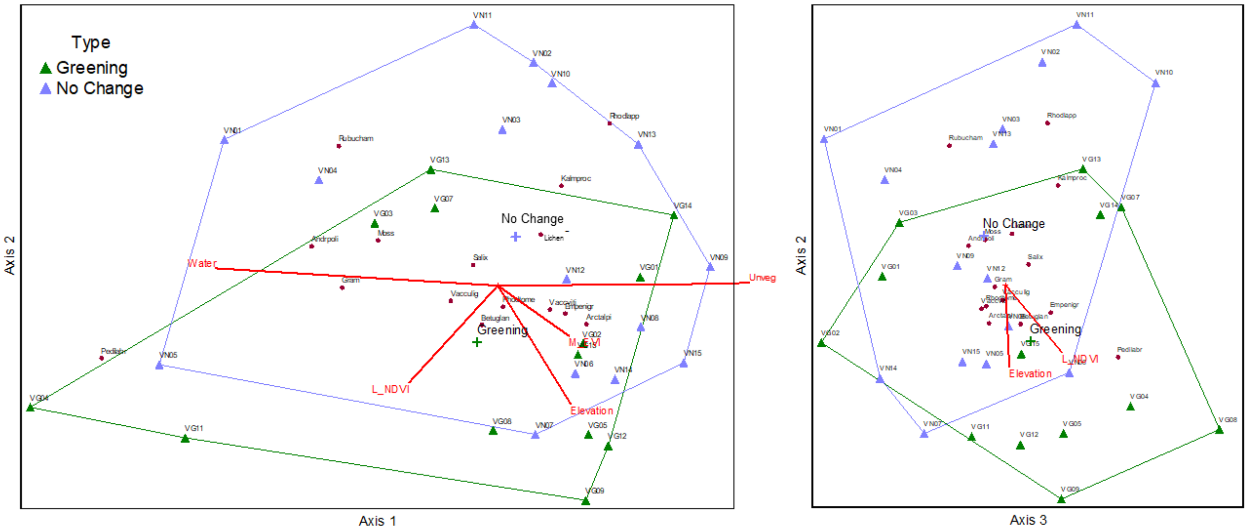

Figure 25. Non-metric multidimensional scaling (NMS) ordination bi-plots showing the relationship of tundra plant communities to moisture, pixel productivity trends, and elevation between pre-defined Greening sites (green symbols) and No Change sites (blue symbols). Centroids of each site type are indicated by crosshairs, +. Species importance within the ordination space is indicated by points. Vectors show direction and strength (magnitude increases with vector length) of linear correlations between ordination axes and environmental variables. Axis 1 explains 54.5%, Axis 2 explains 22.0%, and Axis 3 explains 8.7% of the total variance, respectively. The three-dimensional ordination solution is shown in two dimensions as Axis 2 against Axis 1 (top) and Axis 2 against Axis 3 (bottom). The two-dimensional view of Axis 1 against Axis 3 did not add any additional relevant information. From Bonta (2024).

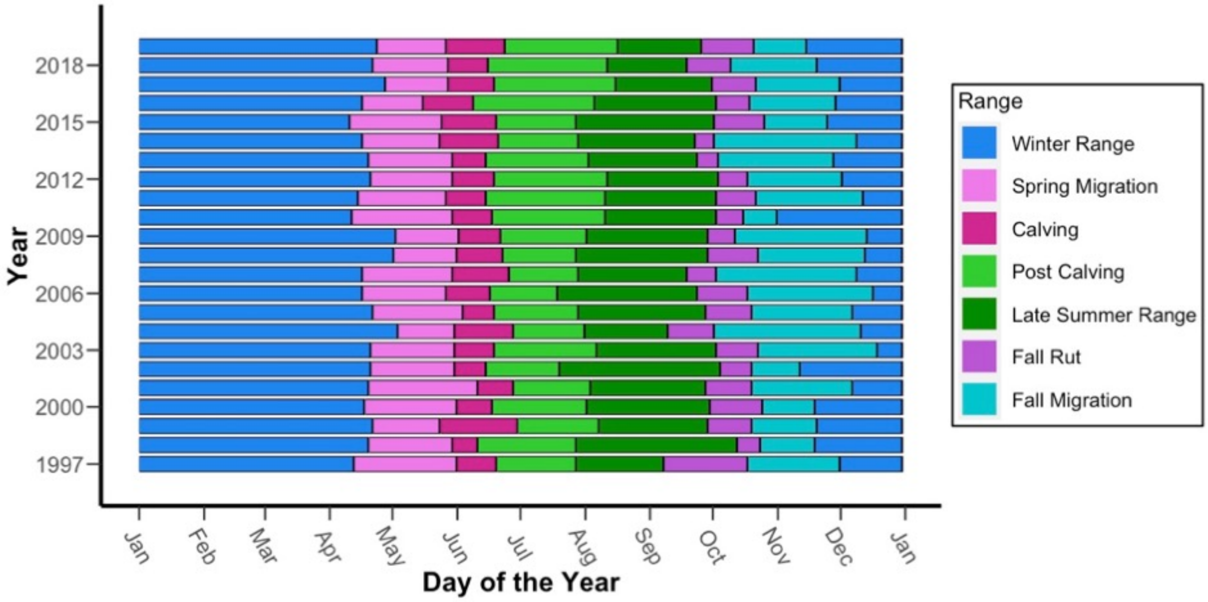

Figure 26. Timelines of seasonal ranges for each year of study. Timelines indicate the start, end, and duration of each seasonal range as derived using Residence Time analysis and Lavielle segmentation. From Mennell (2021).

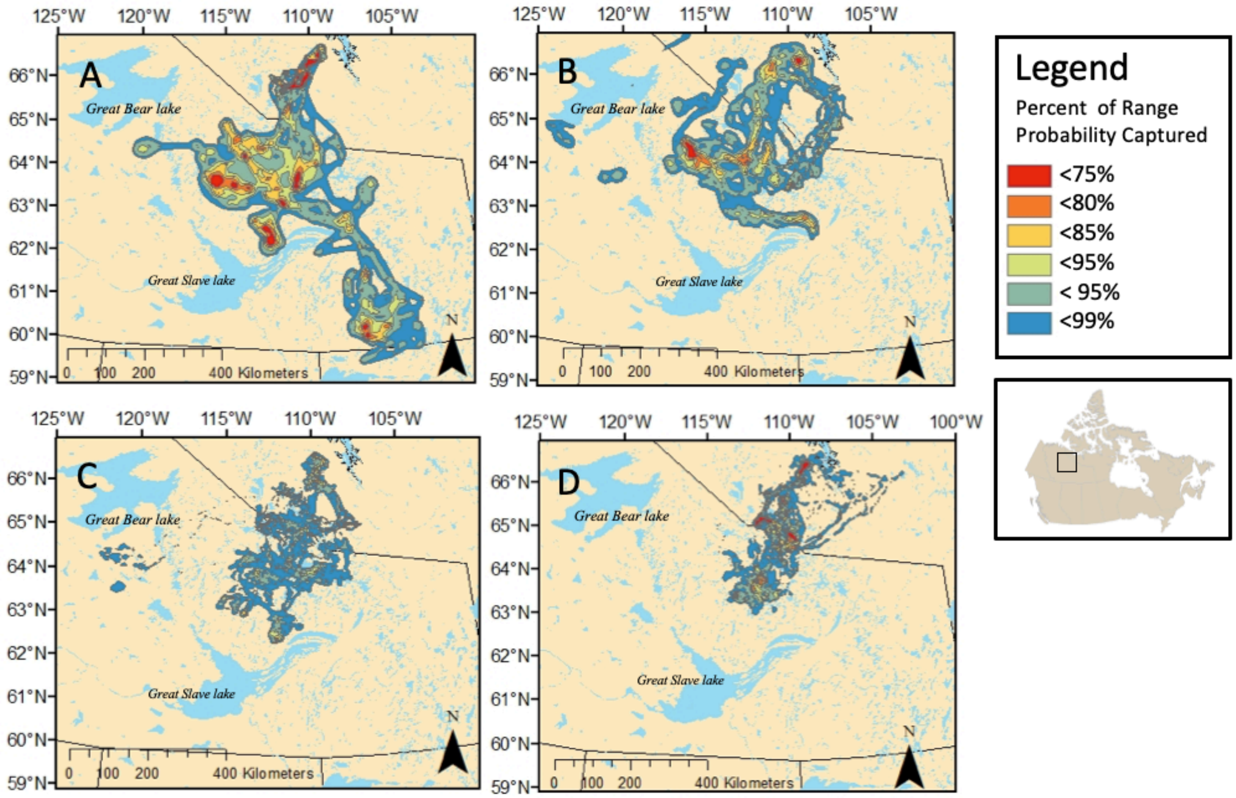

Figure 27. Yearly Brownian Bridge distribution maps of the Bathurst caribou herd for four distinct years. A is range-use in 1997, B is range-use in 2002, C is range-use in 2008, and D is range-use in 2019. This figure illustrates how the yearly range is shrinking and moving increasingly north. From Mennell (2021).

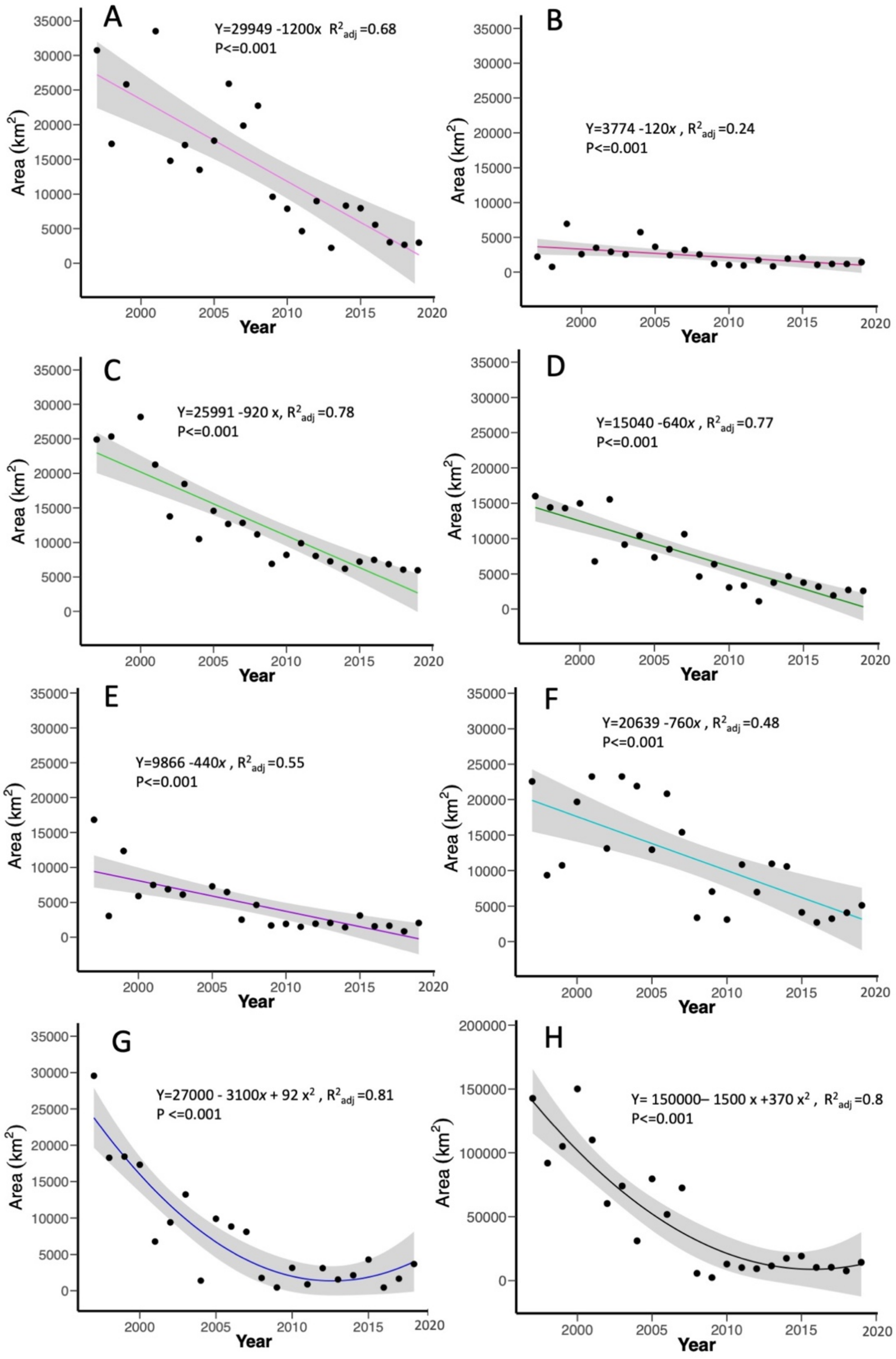

Figure 28. Changing area of the Bathurst caribou herd's annual and seasonal home ranges from 1997-2019. A: spring migration, B: calving, C: post-calving, D: late summer, E: fall rut, F: fall migration, G: winter, H: annual range. Areas are based on the 95% use probability obtained from Brownian Bridge analysis. Linear models and standard errors are illustrated for relationships A-H. Winter range (G) and annual range (H) were better represented using exponential relationships. Each graph includes regression equations, adjusted R^2, and p-values. From Mennell (2021).

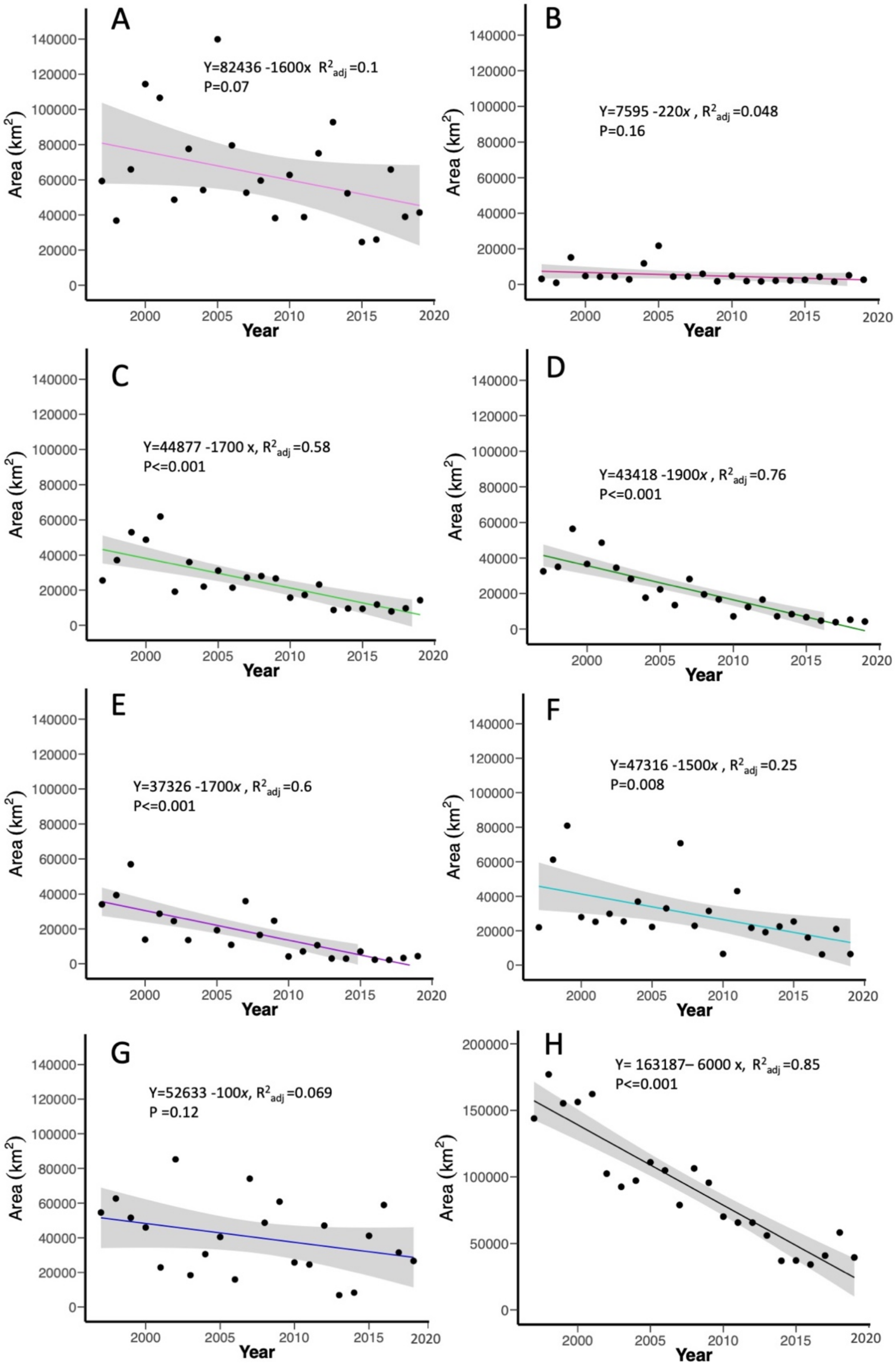

Figure 29. Changes in the area of directional distribution ellipses for the Bathurst caribou herd's annual and seasonal home ranges from 1997-2019. A: spring migration, B: calving, C: post-calving, D: late summer, E: fall rut, F: fall migration, G: winter, H: annual range. Linear models and standard errors are illustrated for each relationship. Regression equations, adjusted R^2, and p-values are also included. From Mennell (2021).

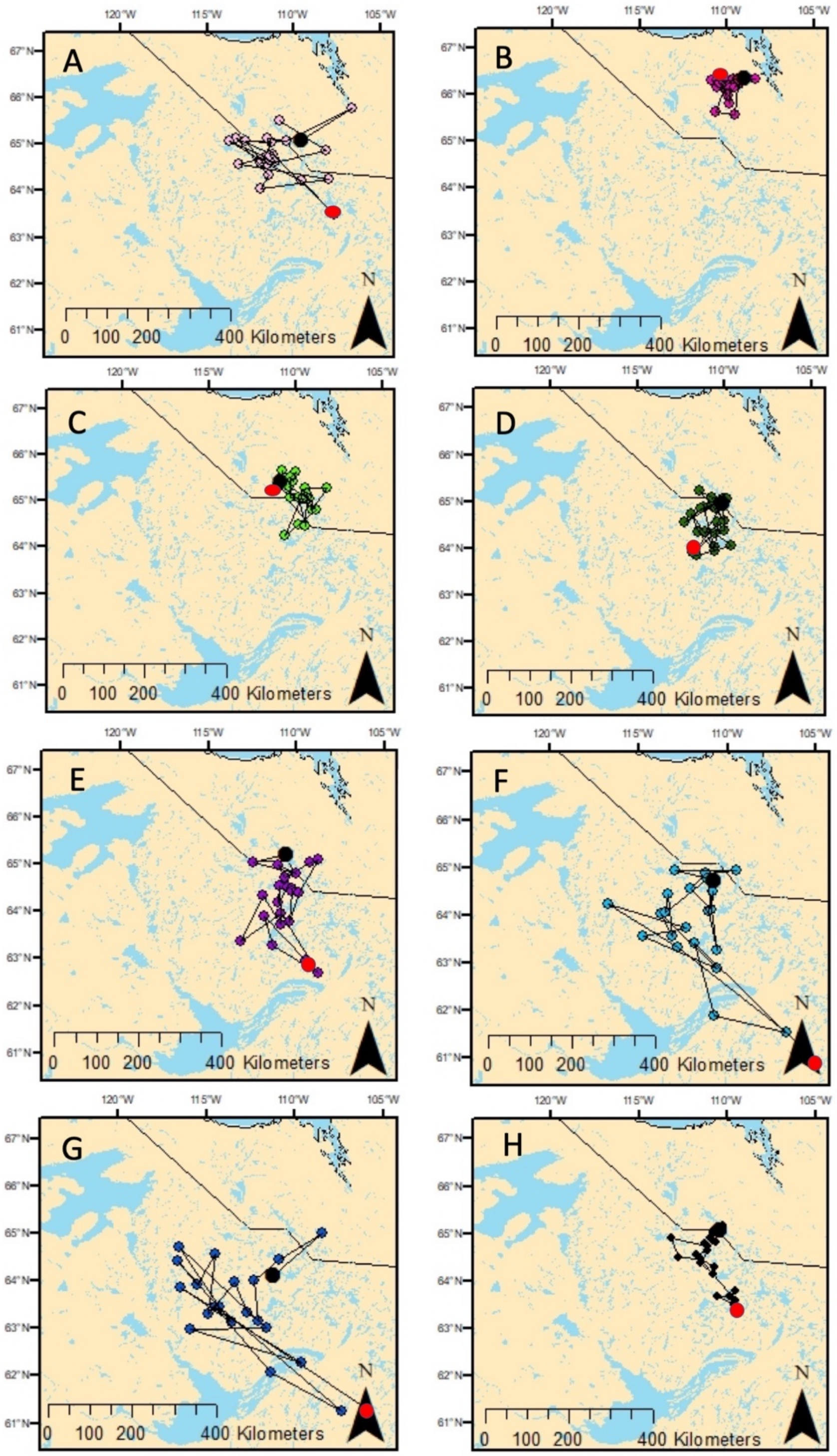

Figure 30. Changes in the centre of each seasonal range based on directional distribution ellipses for the Bathurst caribou herd's annual and seasonal home ranges from 1997-2019. A: spring migration, B: calving, C: post-calving, D: late summer, E: fall rut, F: fall migration, G: winter, H: annual range. The red dot indicates the centre of each range in 1997 and the largest black dot represents the centre of the range in 2019. From Mennell (2021).

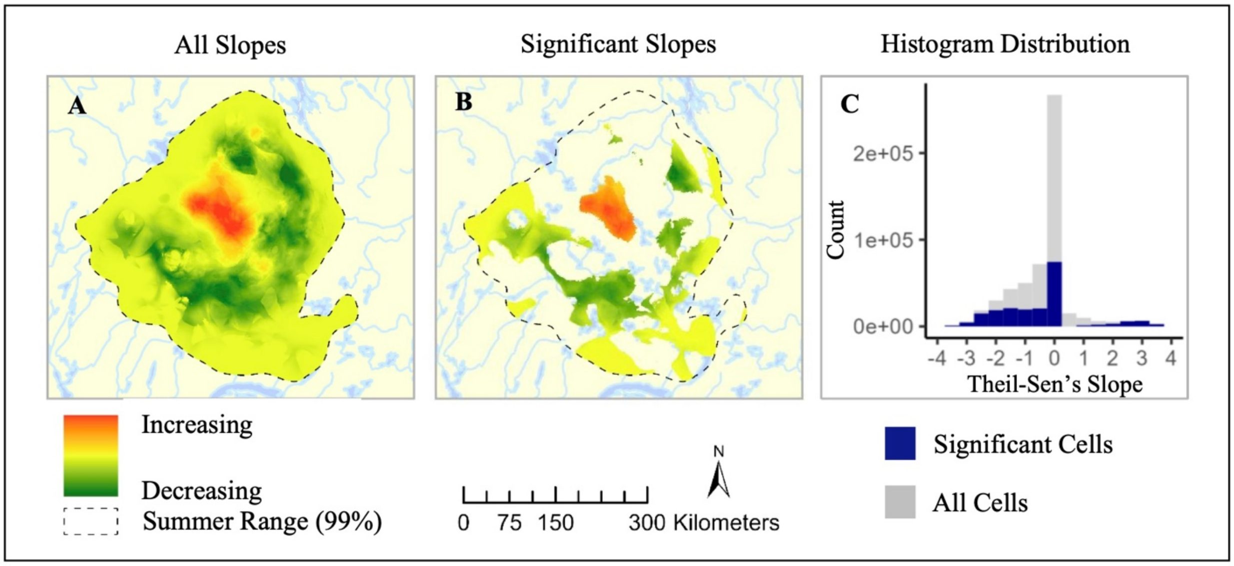

Figure 31. Results of pixel-wise Thiel-Sen regression analysis conducted on the summer Kernel Density range maps from 1997-2017. (A) shows the relative change in caribou use for all pixels. (B) shows only statistically significant trends ($P < 0.05$). In both maps, red regions represent areas that have experienced an increase in relative annual caribou use and green regions represent areas where a decrease was observed. Yellow represents areas that have experienced no changed. (C) presents a histogram of all values. The summer range was determined by implementing a minimum convex polygon from all caribou locations across all years.

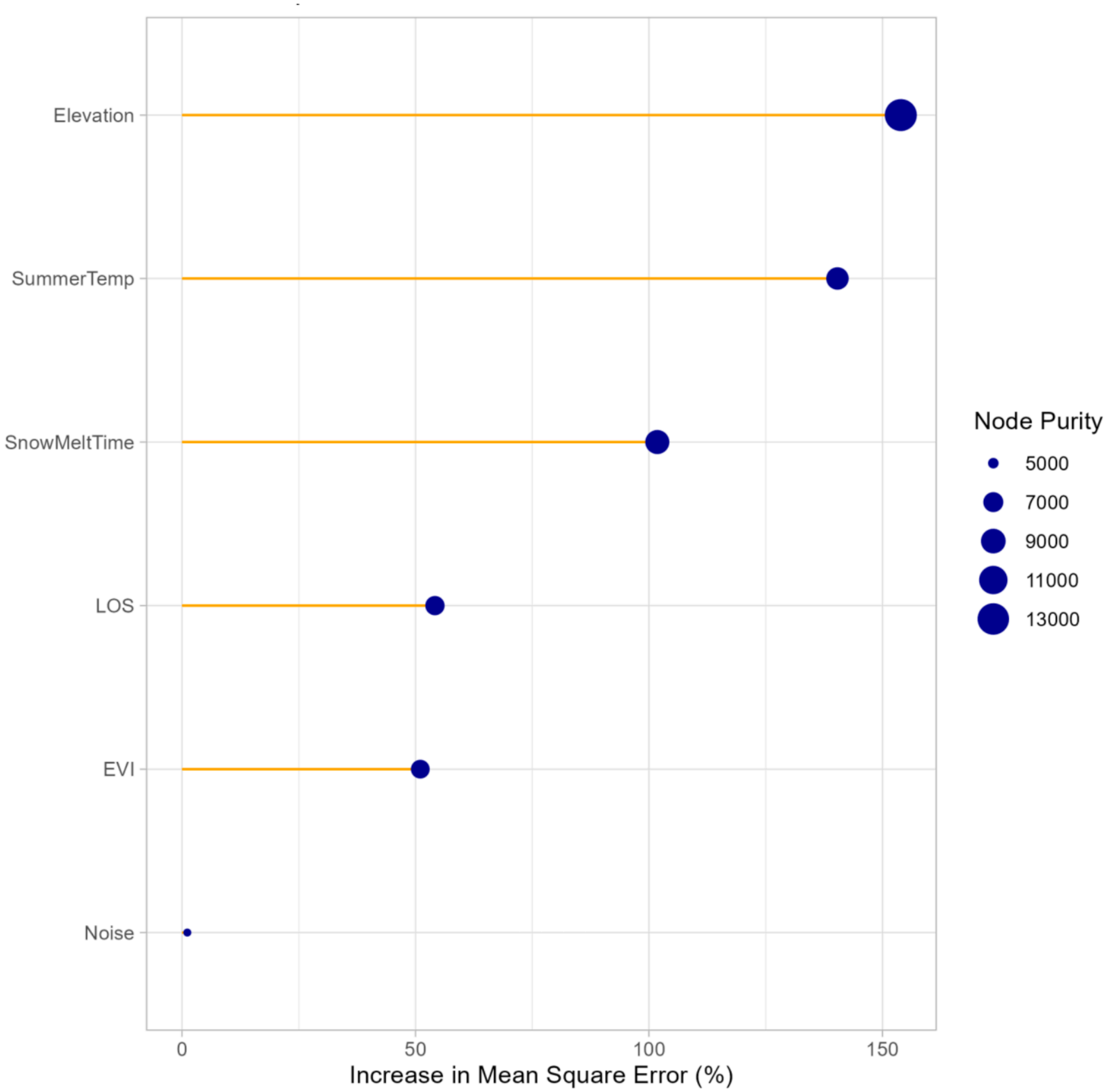

Figure 32. Variable importance of independent variables in the preliminary random forest model developed to explain variation in trends in caribou habitat use over time. Variables whose importance values were ranked lower than random noise were removed from the model. The greater the Increase in Mean Square Error, the greater the influence a variable has on model outcome. The node purity circles refer to how well the model splits the data at each node and in this case, the larger the circle the better the model is at splitting variables at each node.