



Vegetation and Snow Phenology Monitoring in the Arctic Network through 2020

Results from Satellites and Land-based Cameras

Natural Resource Report NPS/ARCN/NRR—2021/2337



ON THE COVER

An example of a remote automated camera photograph from the Mt. Noak climate monitoring station on June 6, 2019. The abundant white flowers in the foreground are *Dryas integrifolia*, a plant that is a useful spring plant phenology indicator.
NPS

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Natural Resource Report NPS/ARC/NRR—2021/2337

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Abstract

The Arctic Inventory and Monitoring Network of the National Park Service in Alaska monitors the length of the snow season and the growing season in the five northernmost US National Park units. Monitoring includes on-the-ground cameras at one location in each park (with data beginning in 2013), and satellite observations that cover all the parks using the MODIS sensor (with data beginning in the year 2000). Comparison of the on-the-ground camera observations with satellite determinations of start and end of the continuous snow season and start and end of the green vegetation season generally show good agreement, with the weakest correspondence between ground observations and end of the green season. The satellite data suggest significant lengthening of both the snow-free and green season over the 21-year period of observations. Application of our methods to data from the VIIRS satellite, which began recording data in 2012 and is expected to outlive MODIS, produced similar results for the start and end of the green season.

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List of Terms

ARCN: The National Park Service Arctic Inventory and Monitoring Network, which includes five NPS units in northern Alaska.

EOCSS: End of the continuous snow season. The date at the end of the longest period of continuous snow cover.

EOG: End of greenness. The end of the green vegetation season as defined by image characteristics.

MODIS: Moderate Resolution Imaging Spectroradiometer, an instrument gathering data from the Aqua and Terra satellites.

NDVI: Normalized difference vegetation index ($NDVI = (NIR - R) / (NIR + R)$), where NIR is near infrared reflectance and R is red reflectance. NDVI is closely related to vegetation greenness.

SOCSS: Start of the continuous snow season. The date at the start of the longest period of continuous snow cover.

SOG: Start of greenness. The start of the green vegetation season as defined by image characteristics.

VIIRS: Visible Infrared Imaging Radiometer Suite, an instrument on the Suomi National Polar-Orbiting Partnership (Suomi NPP) satellite.

Introduction

The climate of the Arctic has been warming since the 1970s, and the timing of spring snow loss has become significantly earlier over the same time period (Box et al. 2019). Greenness of the Arctic land surface, based on normalized difference vegetation index (NDVI) calculated from the Global Inventory Modeling and Mapping Studies (GIMMS) dataset (8-km resolution) has increased over much of the Arctic since the 1980s (A. Beamish et al. 2020). In view of the fundamental importance of snow cover and terrestrial plant productivity to ecosystems in the National Parks of northern Alaska, the National Park Service monitors vegetation and snow phenology as a part of its long-term monitoring program (Lawler et al. 2009; Swanson 2017a). The MODIS (Moderate Resolution Imaging Spectroradiometer (MODIS Land Science Team 2021) instruments on the Aqua and Terra satellites have been providing satellite images with 250 m resolution on a daily basis since the year 2000. We use these images to study the timing of snow cover and vegetation green-up and senescence.

Ground-based cameras can also provide valuable information about vegetation phenology (Richardson, Hufkens, Milliman, Aubrecht, et al. 2018), and these data can be used to verify results obtained from satellite images (Richardson, Hufkens, Milliman, and Froking 2018). The National Park Service (NPS) maintains one automated ground camera in each of the NPS units that make up the Arctic Inventory and Monitoring Network (ARCN, Fig. 1). These cameras are co-located with climate monitoring stations. Our original camera monitoring protocol (Swanson 2017b) was based on quantitative analysis of rectangular regions in the photos after (Richardson et al. 2007) and (Sonnentag et al. 2012). Application of this protocol since our initial report (Swanson 2015) has shown it to be quite labor-intensive, and difficult to apply due to the lack of suitable analysis regions at some sites and frequent camera movements due to wildlife and weather damage. In response I developed a simpler set of visual phenology indicators that can be quickly identified by simply filing manually through the photos. These are reported here along with a reduced set of quantitative photo analyses.

The purpose of this report is to evaluate the visual and quantitative phenology indicators from the ground cameras in relation to one another and to degree-day sums at the stations, and to compare these observations with the satellite phenological indicators. After verifying the usefulness of the satellite phenological data, I then use them to analyze trends in the timing of snow-on and snow-off, green-up, and senescence for ARCN as a whole. My results show that spring snow-off and green-up have become earlier since the year 2000, in continuation of the long-term trend. Peak greenness has increased slightly also. Fall vegetation senescence and establishment of the snow cover became later over the study time interval, but these trends are more difficult to quantify due to cloudiness and the low sun angles of the study area during that time of year.

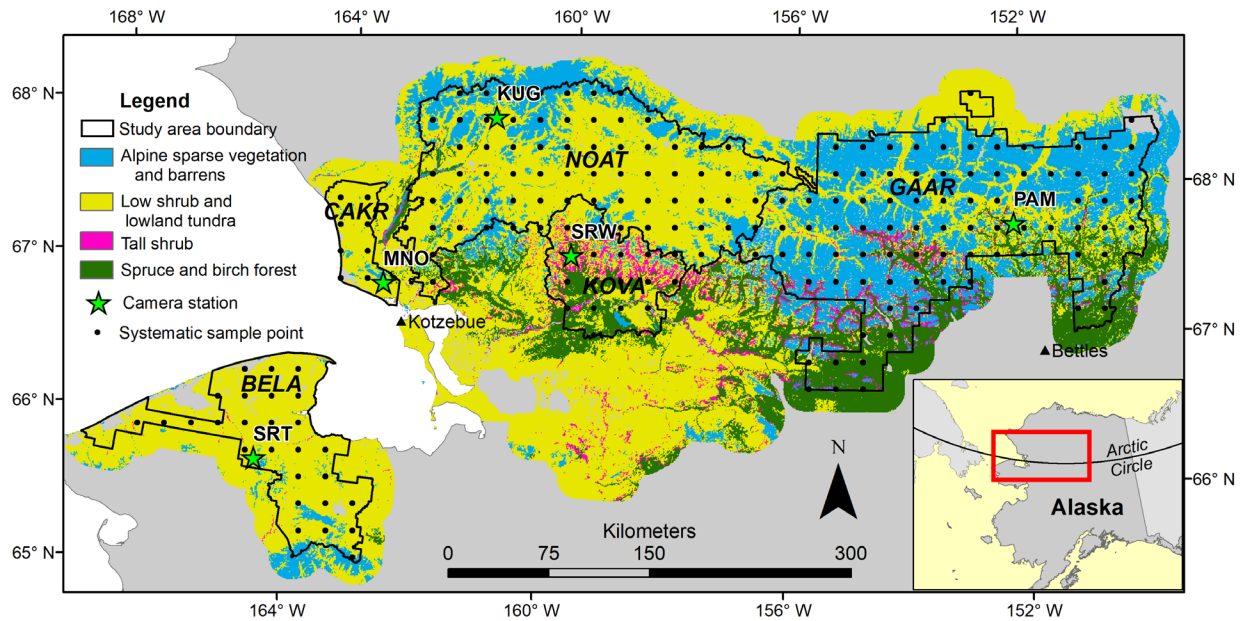


Figure 1. Location and general vegetation of the five National Park Service (NPS) units that form the Arctic Inventory and Monitoring Network (ARCIN). Vegetation is generalized from Jorgenson et al. (2009). The park abbreviations are: Bering Land Bridge National Preserve (BELA), Cape Krusenstern National Monument (CAKR), Gates of the Arctic National Park and Preserve (GAAR), Kobuk Valley National Park (KOVA), Noatak National Preserve (NOAT). Shown also are the five remote automated camera locations Kugururok (KUG), Mt. Noak (MNO), Pamichtuk (PAM), Serpentine (SRT), and Salmon River (SRW) and the locations of the 210 systematic sample points.

Study Area

The study area is ARCN, the five NPS units in northern Alaska (Fig. 1). These parks cover approximately 82,000 km², including lowlands near sea level and rugged mountainous terrain with elevations that reach over 2000 m above sea level. The climate is arctic and subarctic, with long-term mean annual air temperatures ranging from about −5 °C at low elevations in the south and west to about −10 °C in the northern mountains. Mean January temperatures range from about −19 °C in the maritime west and at mid-elevations in the southern mountains, to about −24 °C in the interior lowlands of NOAT and GAAR (for NPS unit abbreviations, see Fig. 1). July mean temperatures range from 14–15 °C at low elevations in southern inland locations, to about 10 °C near the coast and less than 5 °C in the highest mountains; temperatures are modeled 1981–2010 means by (PRISM Climate Group 2020). Long-term National Weather Service records from Kotzebue and Bettles show a generally increasing annual sum of thaw degree-days (a general index of growing season warmth; Barrett et al. 2015) since consistent records began in the late 1940s and 1950s (Fig. 2). Most of the study area is arctic tundra or alpine barrens, with boreal forests of spruce (*Picea mariana* and *P. glauca*) and birch (*Betula neoalaskana*) or aspen and poplar (*P. tremuloides*, *Populus balsamifera*) present at low elevations in southern inland locations (Fig. 1). The study area encompasses about one-fourth of all NPS-administered lands in the United States.

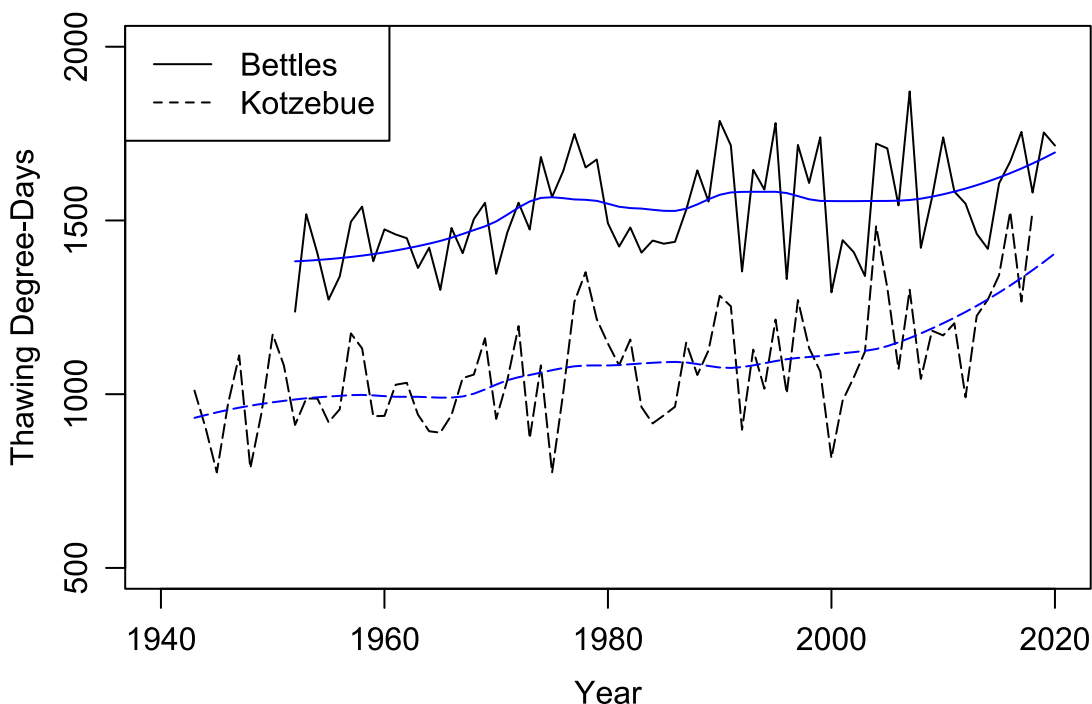


Figure 2. Annual sum of thaw degree-days for Bettles and Kotzebue. Estimated from monthly means, using National Weather Service data from NOAA Regional Climate Centers (2020). The blue curves were smoothed by the “loess” method (R Core Team 2017) with order = 2 and span = 0.5.

Methods

Satellite Snow Cover

The MODIS Terra Snow Cover Daily L3 Global 500m Grid data (MOD10A1, collection 6; (G. A. Riggs, Hall, and Román 2016) from the National Snow and Ice Data center (NSIDC) were used to determine the snow season. The MODIS Terra satellite gathers multispectral data daily at 10:30 AM local solar time (NASA 2021). In cloud-free pixels, snow albedo (the percentage of solar radiation reflected) and fractional snow cover (estimated snow cover in percent) were mapped by the NSIDC using a snow mapping algorithm based on the Normalized Difference Snow Index (NDSI) and other criteria (G. A. Riggs, Hall, and Román 2016).

Determination of the start and end of the snow season are complicated by clouds and by the fact that snow cover in a season may be interrupted by snow-free periods. Additional processing of the daily NSIDC snow product, to interpolate across cloudy periods and detect the start and end of snow cover periods of different lengths, was performed by the Geographic Information Network of Alaska (GINA) at the University of Alaska, Fairbanks (Lindsay et al. 2015). This snow metrics algorithm locates the very first and last snow days in the snow year, along with the start and end of the longest of the continuous snow periods (defined as periods of continuous snow cover more than 2 weeks long with 2 or fewer days of no-snow). At the time of this report, data were available to determine snow-on dates from the fall of 2000 through the fall of 2019 and snow-off dates from the spring of 2001 through the spring of 2020.

In this report I analyze trends in the start of continuous snow season (SOCSS) and end of continuous snow season (EOCSS). Temporal trends across the years of available data for this metric were analyzed on a pixel-by-pixel basis using the Mann-Kendall test. A pixel-by-pixel analysis can reveal location-specific trends. The Mann-Kendall test is a non-parametric test for the significance of a monotonic trend. It is based on the direction of change over time between all pairs of observations and does not assume normality or linearity of trend (Helsel and Hirsch 2002). I implemented the Mann-Kendall test in the "Kendall" package in R (McLeod 2011) using the "raster" package (Hijmans 2015). Additional details and the R scripts are available in (Swanson 2017b).

In addition, I extracted the time series of EOCSS and SOCSS at 210 systematically arrayed sample points spaced 20 km apart across ARCN. These points have been used in other studies of ecological change in my study area (Swanson 2013; Pastick et al. 2018) and, as described below, were also used here to analyze satellite greenness. I used these 210 points to summarize ARCN-wide year-to-year variability and trend in EOCSS and SOCSS. To estimate the ARCN-wide trend I ran a linear mixed model of date vs. year with the point identifier as a random effect, fitting a random effect intercept but not slope. This analysis is appropriate for diagnosing any region-wide trends, while the random-effect intercept allows there to be local variation (due to factors like elevation) in the absolute timing of snow-off and snow-on.

I also extracted the SOCSS and EOCSS for the pixels at locations where our ground observation stations were located (Fig. 1), to allow comparison with the weather data and camera phenological characteristics described below.

Satellite Greenness

Satellite greenness was also derived from MODIS satellite data. I used the AppEARS point extraction tool (AppEARS Team 2020) to extract all of the daily measurements of red and near infrared surface reflectance for the MODIS record up to the end of 2020. The MODIS products were MOD09GQ and MYD09GQ, version 6 (Vermote and Wolfe 2015b; Vermote and Wolfe 2015a) for the Aqua (2003–2020) and Terra (2000–2020) satellites, respectively. These products contain daily observations at 250 m resolution, corrected for atmospheric conditions such as gasses, aerosols, and Rayleigh scattering. I made point extractions for the 210 systematically arrayed points (20 km spacing) across ARCN described above, and also for the five on-the-ground camera station locations (Fig. 1).

I computed normalized difference vegetation index ($NDVI = (NIR - R)/(NIR + R)$), where NIR is near infrared reflectance (MODIS band 2) and R is red reflectance (MODIS band 1). EVI (enhanced vegetation index) is an alternative to NDVI that was not utilized here because it has a complex and ambiguous relationship with snow cover and in wet tundra environments is not as strongly linked to green biomass as NDVI (Zhang et al. 2020). EVI also requires the lower-resolution (500 m) blue MODIS band that is more prone to atmospheric scattering, especially at low sun angles typical of my study area. Greenness computed from optical bands (red, green, and blue) alone has proven successful in tracking phenology with on-the-ground cameras (e.g. see below and A. L. Beamish et al. 2016). However, optical greenness from satellite data has not been widely used as a vegetation index, and was not even mentioned in a recent review of satellite indices (Zeng et al. 2020). My experimentation confirmed the inferior quality of RGB greenness indices computed from satellite data: they clearly were noisier and showed weaker seasonal variation than NDVI.

Cloud cover results in low NDVI readings throughout the year. To approximate the yearly cycle of cloud-free NDVI, I plotted NDVI vs. ordinal date and ran a 90% quantile spline (Koenker, Ng, and Portnoy 1994) using the R package “quantreg” (Koenker 2021), the “rqss” function with a “lambda” smoothing parameter of 10. This traces a curve through the year near the upper limit observed NDVI values, i.e., the cloud-free observations.

As will be described in the Results, comparison of the MODIS NDVI data with our camera observations revealed that snow had NDVI near zero as expected, while the NDVI of the snow-free surface before green-up or after vegetation senescence was significantly higher than zero. To locate the true start of vegetation green-up (SOG, start of greenness) and fall vegetation senescence (EOG, end of greenness) on the annual curve of NDVI values thus requires an estimate the NDVI level of snow-free but leaf-off conditions. As will be illustrated further in the Results, the 90% quantile spline curves of NDVI show a flat region in the fall that represents senesced vegetation prior to the seasonal snowpack establishment. This fall “plateau” region was most apparent on a multi-year plot of NDVI vs. date, because in any single year it could be obscured by clouds or snow. The NDVI of senesced vegetation at each point (climate station or 20-km systematic grid point) was approximated by fitting a 90% quantile spline to all years of available data and searching the resulting curve for the flattest slope in the fall, after the summer peak but prior to the winter low NDVI produced by snow. To accomplish this, I computed a 2-week running regression of the 90% quantile spline-fitted values vs.

date, and corresponding 2-week running means of the fitted spline values. I then defined the “senesced vegetation” NDVI as the 2-week mean of the splined (90th quantile) NDVI values for the date with the flattest regression slope after day 240 (August 28) and before the NDVI dropped below 0.1 (i.e., snow-covered).

This “senesced vegetation” NDVI level from multi-year data was intersected with 90% quantile curves fitted to annual data to find the SOG. To find EOG, I computed the NDVI level that was 0.1 of the distance between the multi-year “senesced” level and each year's summer maximum NDVI. The 0.1 factor was needed to ensure that the intersection occurred on the downward leg of the curve. I also subjected the fall data to stronger smoothing (“lambda” smoothing parameter of 50) because greater cloudiness in the fall resulted in periods of low NDVI that could be otherwise interpreted as senescence.

Summary statistics for the time series of SOG and EOG were similar to SOCSS and EOCSS, described above.

When the MODIS sensors age beyond usefulness, they will probably be replaced by the VIIRS sensor for vegetation and snow monitoring (Skakun et al. 2018; G. Riggs and Hall 2020; Benedict et al. 2021). The VIIRS sensor has slightly lower resolution (375 m) but is otherwise comparable to MODIS and has been returning data since 2012 (Cao et al. 2017). It is available using the AppEEARS point extraction tool by the same process as we used to obtain MODIS data in this study. The VIIRS product is VNP09GA.001, Daily Surface Reflectance 500/1000 m. The bands used to compute NDVI are bands I1 (red) and I2 (near infra-red), which are available in this product at a resampled resolution of 500 m. I extracted data for the entire VIIRS period of record for the ARCN camera stations and the 20-km grid points and subjected them to the same analysis as the MODIS data.

Ground Camera Data

Ground verification of satellite phenology observations was obtained from automated cameras at five NPS climate monitoring stations (Fig. 1, Table 1, (Swanson 2015). Campbell Scientific CC5MPX cameras were mounted in the summer of 2013 on the tripods used for climate instruments at four climate monitoring sites, and an addition installation at station KUG was made in 2015. Photographs were taken at the full resolution available on the cameras (2592 by 1944 pixels), five photos per day at hourly intervals centered at solar noon. The cameras face generally north to minimize glare from direct sunlight. Photos were saved in jpg format on an internal SD card and collected annually. Most of the data began in 2014 or 2015 when power-supply issues were solved. Periods of missing data are present at some cameras due to wind or wildlife damage.

A set of visual phenology indicators at each station was chosen (Table 2; Fig. 3). These phenology indicators were observed in a consistently defined portion of the cameras view at each location as described in the monitoring protocol (Swanson 2017b). The protocol also provides additional guidelines for recognizing the dates of these events.

Table 1. Remote Camera Stations.

Station Name	Symbol	National Park Unit	Latitude (deg)	Longitude (deg)	Elevation (m)	Vegetation
Kugururok	KUG	Noatak National Preserve	68.317	-161.492	335	Open low shrub tundra (<i>Betula</i> , <i>Salix</i> , <i>Ledum</i> , <i>Vaccinium</i>)
Mt. Noak	MNO	Cape Krusenstern National Monument	67.141	-162.995	257	Dwarf shrub tundra (<i>Dryas</i>)
Pamichtuk Lake	PAM	Gates of the Arctic National Park and Preserve	67.766	-152.164	1019	Dwarf shrub tundra (<i>Dryas</i> , <i>Salix</i>)
Salmon River	SRW	Kobuk Valley National Park	67.460	-159.841	381	Mosaic of open low and tall scrub (<i>Betula</i> , <i>Salix</i> , <i>Alnus</i>)
Serpentine	SRT	Bering Land Bridge National Preserve	65.852	-164.708	143	Open low shrub tundra (<i>Betula</i>)

Table 2. Camera Phenological Events.

Season	Event	Stations	Explanation
spring	snow_off50	All	Spring snow cover first less than or equal to 50%
spring	snow_off_all	All	Spring first complete loss of winter snowpack
spring	dryas_first	MNO, PAM, SRW	First appearance of <i>Dryas</i> flowers
spring	dryas_peak	MNO, PAM, SRW	Peak of <i>Dryas</i> flowering
spring	alder_half_leafout	SRW	Alders (<i>Alnus</i>) at half leaf-out
spring	birch_first	KUG, SRT	First greening of <i>Betula nana</i>
spring	birch_full	KUG, SRT	Full leaf-out of <i>Betula nana</i>
spring	gr25_spl	MNO, PAM, SRT	On the spring (rising) spline-smoothed Gcc greenness curve, 25% of the distance from minimum to maximum
spring	gr50_spl	MNO, PAM, SRT	On the spring (rising) spline-smoothed Gcc greenness curve, 50% of the distance from minimum to maximum

Table 2 (continued). Camera Phenological Events.

Season	Event	Stations	Explanation
fall	se50_spl	MNO, PAM, SRT	On the fall (descending) spline-smoothed G_{cc} greenness curve, 50% of the distance from minimum to maximum
fall	se25_spl	MNO, PAM, SRT	On the fall (descending) spline-smoothed G_{cc} greenness curve, 25% of the distance from minimum to maximum
fall	birch_max_red	KUG, SRT, SRW	Maximum redness of <i>Betula nana</i>
fall	salix_yellow	PAM, SRW	Willows (<i>Salix</i>) at maximum fall colors
fall	snow_on	All	First snow cover (>50 % cover) established for at least 2 weeks



Figure 3. An example phenology camera photograph, from station MNO on 6 June 2019. This was the date recorded as the peak of *Dryas integrifolia* flowering (the abundant white flowers in the foreground).

For the three stations with suitable rectangular areas of uniform vegetation in the photo foreground, (MNO, PAM, and SRT), I computed greenness metrics from the phenology cameras as outlined by (Richardson, Hufkens, Milliman, Aubrecht, et al. 2018). I defined an analysis window and computed its mean green chromic coordinate (G_{cc}) on each image.

$$G_{cc} = G_{DN}/(R_{DN} + G_{DN} + B_{DN})$$

where R_{DN} , G_{DN} , and B_{DN} are the digital numbers of the red, green, and blue bands, respectively. I computed the median G_{cc} of the five daily observations, and fit a smoothed curve through these points by median spline (Koenker, Ng, and Portnoy 1994) using the R package “quantile” (Koenker 2021), the “rqss” function with a “lambda” smoothing parameter of 10. I computed the pre-greenness minimum of this curve from the date range April 10 through June 1, and summer maximum June 1 through Aug 1. I computed the G_{cc} values that were 0.25 and 0.5 of the distance between these minima and maxima and found the dates on spring (rising) and fall (descending) legs of the curve corresponding to these greenness levels. The analysis window at station SRT was dominated by birch (*Betula nana*) shrubs, and the shape of the falling curve of G_{cc} there was dominated by a well-defined fall minimum corresponding closely to the visually chosen date of maximum redness of leaves (Table 3). The visual estimates of the redness maximum were used in further analysis because they could also be recorded for dispersed or irregularly-shaped patches of birches at stations KUG and SRW that were not suitable for the quantitative analysis by G_{cc} .

Table 3. Comparison of date of G_{cc} fall minimum and visual estimates of maximum birch fall redness at station SRT^A.

Year	G_{cc} fall minimum (ordinal date)	Visual maximum redness (ordinal date)
2013	250	248
2014	250	253
2015	247	248
2016	249	248
2017	250	249

^A Root mean square difference 1.8 days, mean difference 0.0 days.

Running sums of degree-days (0°C base temperature) were computed from the air temperature data at each ARCN climate station. I computed the running sums of degree-days for both the daily mean temperatures (mean of hourly values) and the daily maximum temperatures. I dealt with positive temperatures during the time in the spring when temperatures fluctuate above and below freezing as follows: along with the running sum of positive degree-days (from the daily mean or maximum), a running count was kept of the number of days with positive temperatures that had occurred to date. Each day with a sub-freezing (mean or maximum) temperature was subtracted from the running total of “positive” days. If this running total fell back to zero, the running thaw degree-day sum was reset to zero. Thus, for example, if a thaw of 3 days duration was followed by a subfreezing period 3 or

more days long, the positive degree-days accumulated during the 3-day thaw were not added to the cumulative annual total.

I averaged the degree-day sums for each spring phenological event at each station, then used this amount to predict the date when the event would be expected to occur. The success of these predictions was quantified by computing the mean square deviation and mean difference in days of the predicted date of the event from the observed date.

The camera-based phenology metrics were compared with the satellite-derived dates for the same years by extracting the MODIS-derived pixel values for analogous metrics at the camera locations. Only approximate correspondence between the two measurements was expected, because of the different areas sampled by the two methods: a small obliquely viewed area close to the ground by the camera (e.g., Fig. 3) versus a 250 m (greenness) or 500 m (snow) pixel by MODIS. Also, the ground phenology indicators are conspicuous events (e.g., *Dryas* flowering) that do not necessarily coincide with the start of mass leaf-out that drives satellite NDVI. The G_{cc} metrics are in principle similar to satellite NDVI metrics, though G_{cc} is based on visual wavelengths (red, green and blue) while the satellite sensors incorporate near-infrared reflectance into NDVI.

Solar Radiation

Solar Radiation was measured by a Li-Cor LI-200X Pyranometer 3 m above ground level. Hourly averages in $W\ m^{-2}$ were summed by day and converted into daily light increment in $mol\ m^{-2}\ day^{-1}$ (a unit often used in plant physiology studies and horticulture) by the factor $0.007265\ mol\ Wh^{-1}$ (Faust and Logan 2018).

Results and Discussion

Camera and Satellite Phenology Events

Spring Snow-off

The MODIS EOCSS date at the stations generally fell between the camera observation of 50% and full snow-off, resulting in positive mean differences between MODIS EOCSS and camera 50% snow-off, and negative differences between MODIS EOCSS and camera full snow-off (Fig. 4, Table 4). The exception was at SRT, where MODIS EOCSS preceded both the camera full snow-off and 50% snow-off; it preceded the latter by 5 days on average, presumably because the MODIS pixels incorporated rock outcrops or more windswept areas than the camera view. In general, however, this cross-check between remotely sensed snow-off date and the ground cameras suggests that MODIS EOCSS represents the date when snow covered distinctly less than half of the landscape, but not zero snow cover.

The satellite and camera snow phenology events were also consistently related to the sum of thaw degree-days. The 50% snow off, MODIS EOCSS, and full snow-off dates nearly always occurred between degree-day sums of 0 and 100 °C-days at KUG, MNO, and PAM. At windswept SRT the camera 50% snow-off and full snow-off were typically separated by just a few days very near the first date of average temperatures above 0°C, and the MODIS EOCSS actually preceded the first date of average temperatures above 0°C. At SRW, where deep drifts were present, complete snow-off required more than 300 °C-days in some years.

Table 4. Difference between MODIS End of Continuous Snow Season and Camera Snow-off Events.

Station	Camera Event ^A	MODIS – Camera Root Mean Square Difference (days)	MODIS – Camera Mean Difference (days) ^B	Years of Data
KUG	snow_off_50%	7.3	7.0	4
KUG	snow_off_all	2.8	-1.3	4
MNO	snow_off_50%	6.6	3.0	3
MNO	snow_off_all	4.7	-2.7	3
PAM	snow_off_50%	9.8	8.2	5
PAM	snow_off_all	10.4	-10.0	5
SRT	snow_off_50%	9.3	-5.2	5
SRT	snow_off_all	12.8	-11.6	5
SRW	snow_off_50%	10.3	8.8	5
SRW	snow_off_all	23.7	-23.5	4

^A For event definitions, see Table 2

^B Negative sign indicates earlier date of the MODIS observation than the camera.

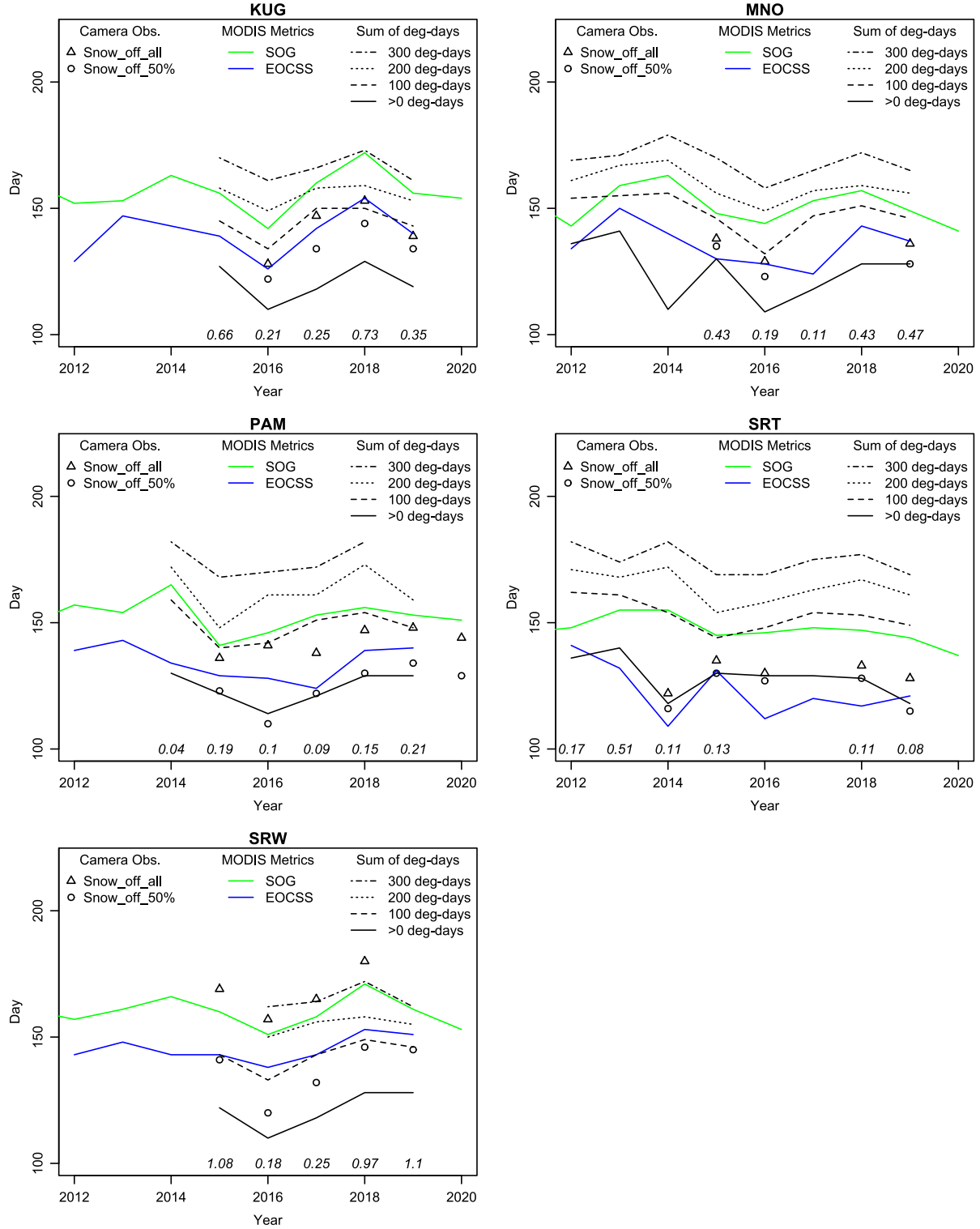


Figure 4. Timing of snow-off events by MODIS satellite and on-the-ground camera observations. For explanations of the “Camera Obs.” (camera observations of phenology events), see Table 2. The numbers in italics along the bottom of the plot are the maximum snow depth (m) measured by ultrasonic sensor at one location near the camera.

Spring Green-up

The MODIS SOG dates fell reliably among the early spring indicators of plant activity visible on the ground photos (Fig. 5). At KUG, the MODIS average SOG fell between shrub birch first leaves and full leaf-out (Table 5), but examination of the individual years (Fig. 5) showed MODIS SOG to fall before birch first leaf-out and after full leaf-out in some years. Note that at this site, birch is not the dominant species (and thus did not drive the overall greenness), but it was conspicuous enough to record in the camera view. At SRT, where shrub birch is a dominant species, MODIS SOG came well after snow-off and a few days before birch first leaves. First flowering of *Dryas* matched MODIS SOG quite closely at PAM (Table 5), while a small sample at MNO show MODIS SOG was between snow-off and *Dryas* first flowering. At SRW, MODIS SOG usually fell between first and peak flowering of *Dryas*, and a few days before alder_half_leafout. The various visual spring phenology events, degree-days sums, and the MODIS SOG also showed similar patterns in their year-to-year variations (Fig. 5).

Table 5. Difference between MODIS Start of Greenness and Selected Spring Camera Events.

Station	Event ^A	MODIS – Camera Root Mean Square Difference (days)	MODIS – Camera Mean Difference (days) ^B	Years of Data
KUG	birch_first	8.7	2.2	5
KUG	birch_full	8.4	-2.4	5
MNO	snow_off_all	12.8	12.7	3
MNO	dryas_first	11.0	-9.7	3
MNO	gr25_spl	13.9	5.0	2
PAM	dryas_first	3.8	-2.1	8
PAM	gr25_spl	9.0	8.0	5
SRT	snow_off_all	19.5	17.8	5
SRT	birch_first	5.9	-5.2	5
SRT	gr25_spl	1.4	0.7	3
SRW	dryas_first	6.4	4.8	5
SRW	dryas_peak	5.3	-3.3	4
SRW	alder_half_leafout	6.5	-5.25	4

^A For event definitions, see Table 2.

^B Negative sign indicates earlier date in the MODIS observation than the camera.

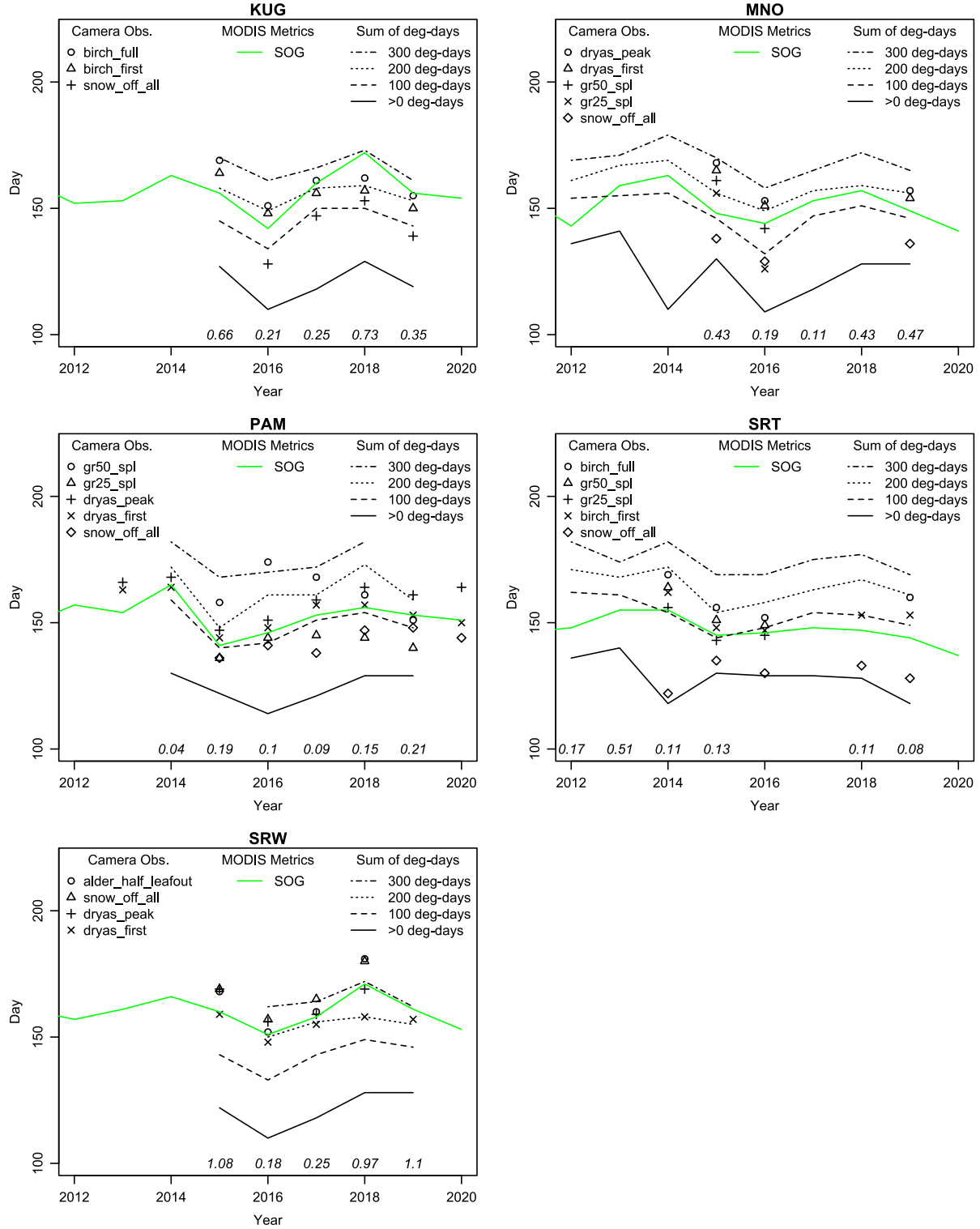


Figure 5. Timing of spring phenology events and degree-day sums at five observations stations in ARCN. For explanations of the “Camera Obs.” (camera observations of phenology events), see Table 2. The numbers in italics along the bottom of the plot are the maximum snow depth (m) measured by ultrasonic sensor at one location near the camera.

The match between spring greenness metrics taken from the smoothed curves of G_{cc} and other phenology events varied greatly between stations (Fig. 5; Tables 5, and 6). Suitable homogenous areas for computing G_{cc} were not present at KUG and SRW. At PAM, the G_{cc} curve metrics varied erratically; 25% greenness was nearest to snow-off and 50% greenness nearest to *Dryas* flowering peak, but with a poor fit (root mean square error of 13 days; Table 6). The signal to noise ratio at the PAM station was distinctly lower (i.e., worse) than the other two stations, owing to its very sparse vegetation (Table 7). The small sample ($n = 2$) at MNO suggests a rather poor relationship of G_{cc} metrics with other phenology measures, the best being between 50% greenness and “dryas_first” (root mean square error of 7 days). In contrast, at the more densely vegetated site SRT, 50% greenness from G_{cc} was reliably between the visual events “birch_first” and “birch_full”, with its best fit to the former (root mean square error 2.4 days), albeit with only 3 years of data. At SRT, 25% greenness by camera G_{cc} also closely matched MODIS start of green season (Table 6).

Table 6. Difference between phenology camera curve fit dates and selected spring camera events.

Station	Camera Curve Metric ^A	Visual Phenology Event ^A	Root Mean Square Error (days)	Mean error (days)	Year of Data
MNO	gr50_spl	dryas_first	7.0	-6.5	2
PAM	gr50_spl	dryas_peak	13.0	6.0	5
SRT	gr25_spl	birch first	4.7	-4.3	3
SRT	gr50_spl	birch first	2.4	2.3	3

^A For event definitions, see Table 2.

Table 7. Signal to noise ratio of median spline curves fit to G_{cc} data.

Station	Year	Signal-to-Noise Ratio ^A
MNO	2015	4.5
MNO	2016	5.4
PAM	2015	2.5
PAM	2016	2.0
PAM	2017	2.5
PAM	2018	1.8
PAM	2019	2.5
SRT	2014	5.0
SRT	2015	4.9
SRT	2016	4.6

^A The amplitude of the smoothed curve divided by the root mean square of the residuals (Richardson et al. 2018)

Many of the spring phenology camera events had a close relationship with thaw degree-days (Fig. 5, Table 8). The year-to-year variation in snow-off dates as determined visually from the cameras generally followed the year-to-year variation in degree-day sums (Fig. 5). The strength of the relationship between spring phenology events and thaw degree-days is illustrated by Table 8, which gives the error (in days) that would result from using the average thaw degree-day sum (computed using the daily mean or the daily maximum temperature) for the event to predict its date each year. For many events the root mean square error was less than 3 days. The worst match between events and degree-day sums is for G_{cc} greenness 25% and 50% at MNO (where it is inconclusive due to only two year of data) and PAM (whereas mentioned above there is a poor signal-to-noise ratio in the G_{cc} curves due to very sparse vegetation).

Table 8. Mean dates and degree-day sums of spring phenological events, and date prediction errors.

Station	Event ^A	Date		TDD from Daily Mean ^D		TDD from Daily Maximum ^E		N (years)
		Mean ^B (days)	Error ^C (days)	Mean ^F (°C-days)	Error ^G (days)	Mean ^F (°C-days)	Error ^G (days)	
KUG	snow_off50	133.5	7.8	43.8	3	111.2	2.2	4
KUG	snow_off_all	141.8	9.4	88.5	3.4	191.1	3.9	4
KUG	birch_first	155	5.7	188	4.1	340.9	4.1	5
KUG	mod_sog	158.2	9.6	223.5	6.6	390	6.1	5
KUG	birch_full	159.6	6.2	247.5	3.3	425.2	3.4	5
MNO	snow_off50	128.7	4.9	30.4	5	81.5	5.5	3
MNO	snow_off_all	134.3	3.9	55.8	4.5	123.4	4.5	3
MNO	gr25_spl	141	15	137.1	10.2	244.8	9.2	2
MNO	gr50_spl	151.5	9.5	190.9	7.1	335.5	5	2
MNO	mod_sog	152.3	6.8	131	5.4	230.3	6.5	8
MNO	dryas_first	156.7	6	226	3.2	379.4	4	3
MNO	dryas_peak	159.3	6.4	250.5	2.8	414.9	4	3
PAM	snow_off50	123.8	8.2	3.4	2.7	11.6	2.4	5
PAM	gr25_spl	141.8	3.4	66.7	6.4	120.6	6.8	5

^A For event definitions, see Table 2

^B Date, Mean: the mean ordinal day number for the event.

^C Date, Error: the root mean square error in days using the mean date as a predictor of the day of the event.

^D TDD from Daily Mean: sum of thaw degree-days computed using daily mean temperatures

^E TDD Daily by Maximum: sum of thaw degree-days as computed using daily maximum temperatures,

^F Mean: mean sum of thaw degree-days at the time of the event.

^G Error: the root mean square error in days using the mean sum of TDD as a predictor of the day of the event.

Table 8 (continued). Mean dates and degree-day sums of spring phenological events, and date prediction errors.

Station	Event ^A	Date		TDD from Daily Mean ^D		TDD from Daily Maximum ^E		N (years)
		Mean ^B (days)	Error ^C (days)	Mean ^F (°C-days)	Error ^G (days)	Mean ^F (°C-days)	Error ^G (days)	
PAM	snow_off_all	142	4.8	75.7	4.4	129.5	4.1	5
PAM	mod_sog	153.1	7.6	127.4	1.2	214.9	2.7	6
PAM	dryas_first	155.1	6.6	143.7	1.4	237.1	2	6
PAM	dryas_peak	159.4	7.3	172.4	3.8	290.7	2.9	6
PAM	gr50_spl	162.4	7	222.2	9.6	351.3	10.2	4
SRT	snow_off50	123.2	6.4	1.3	1.4	8.7	6.9	5
SRT	snow_off_all	129.6	4.5	22	4.4	47.5	3.4	5
SRT	gr25_spl	148	5.7	98.1	2.1	188.8	4.5	3
SRT	mod_sog	148.2	4	76.4	4.7	183.9	6.1	8
SRT	birch_first	152.6	5.3	120.7	2.3	243.8	3.6	5
SRT	gr50_spl	154.7	6.7	154	1.4	276.2	3.1	3
SRT	birch_full	159.2	6.3	188	2.8	344.2	3.7	4
SRW	snow_off50	136.8	9.7	70	4.3	137.8	3.9	5
SRW	dryas_first	155.4	3.9	204.9	1.7	329.3	1.4	4
SRW	mod_sog	161.1	7.2	264	3.2	411.9	1.9	4
SRW	dryas_peak	163.2	5.8	262.2	1.3	418.8	0.8	3
SRW	alder_half_leafout	165.2	12.2	311.4	8.1	479	6.9	3
SRW	snow_off_all	167.8	9.6	336.5	5.4	516.2	3.7	3

^A For event definitions, see Table 2

^B Date, Mean: the mean ordinal day number for the event.

^C Date, Error: the root mean square error in days using the mean date as a predictor of the day of the event.

^D TDD from Daily Mean: sum of thaw degree-days computed using daily mean temperatures

^E TDD Daily by Maximum: sum of thaw degree-days as computed using daily maximum temperatures,

^F Mean: mean sum of thaw degree-days at the time of the event.

^G Error: the root mean square error in days using the mean sum of TDD as a predictor of the day of the event.

Fall Senescence

Fall senescence dates of shrubs visible on the photos varied little between years at a given station (Table 9). This was especially true for birch maximum redness, which varied within narrow limits: at KUG day 237 to 240 ($n = 4$), at SRT day 248 to 253 ($n = 4$), at SRW day 248 to 255 ($n = 6$). The MODIS EOG dates varied more, and the pattern of variation did not match the shrub senescence events (Fig. 6, Table 10). For example, at KUG the range in MODIS EOG was days 244 to 265 during the 4 years with maximum birch redness at days 237 to 240. Note that at KUG birch does not dominate the vegetation. At SRT, where birch is more dominant, variation in MODIS EOG was still weakly related to birch redness, varying from 257 to 275 during the 6 years where maximum birch redness date varied from day 248 to 253 (Fig. 6). At the more herb-dominated station MNO, MODIS EOG was fairly close to the 25% green point on the camera greenness curve, but only two years were available. The best match of MODIS EOG with camera observations was at sparsely vegetated PAM, where MODIS EOG was consistently about 2 days earlier than both the 50% greenness point on the camera greenness curve, and visual *Salix* maximum yellow color point. Recall however that the signal-to-noise ratio for G_{cc} at PAM was poor, and spring G_{cc} metric were judged unreliable. At SRW MODIS EOG occurred consistently after the visual shrub senescence events.

Table 9. Timing of fall phenological events.

Station	Event ^A	Mean (days)	Standard deviation (days)	N (years)
KUG	birch_max_red	238.2	1.3	4
KUG	snow_on	282.0	11.2	4
MNO	se50	239.0	2.8	2
MNO	se25	256.5	4.9	2
MNO	snow_on	292.4	19.0	5
PAM	salix_yellow	248.7	3.9	6
PAM	se50	249.0	5.4	4
PAM	se25	258.5	12.2	4
PAM	snow_on	265.0	9.3	7
SRT	birch_max_red	249.0	2.0	6
SRT	birch_max_red_spl	249.2	1.3	5
SRT	snow_on	294.2	11.5	4
SRW	birch_max_red	251.0	2.6	6
SRW	salix_yellow	251.3	3.3	6
SRW	snow_on	276.5	12.3	6

^A For event definitions, see Table 2

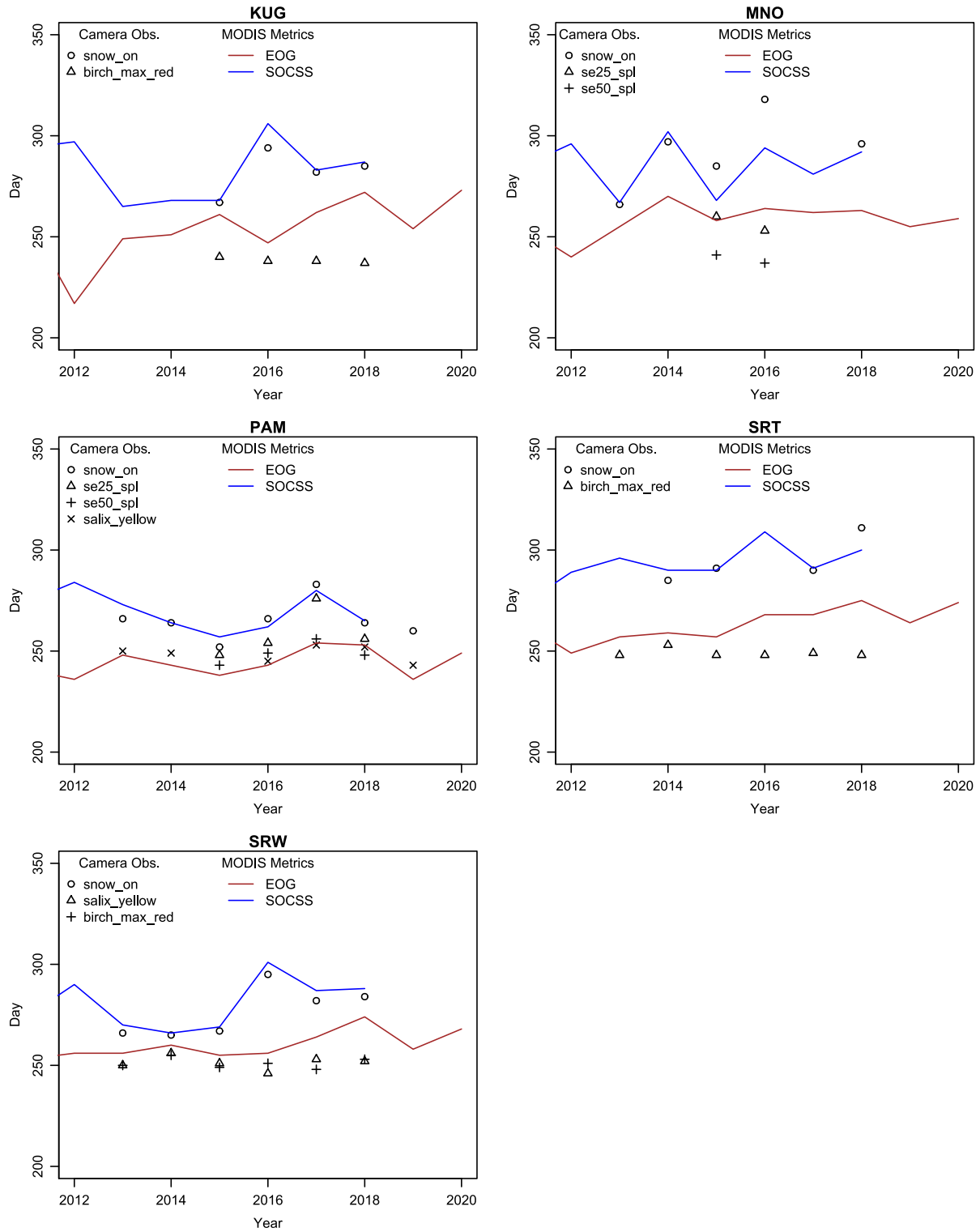


Figure 6. Timing of fall phenology events by MODIS satellite and on-the-ground camera observations. For explanations of the “Camera Obs.” (camera observations of phenology events), see Table 2.

Table 10. Difference between MODIS end of green season and camera observations of fall events.

Station	Event ^A	Root Mean Square Difference (days)	Mean Difference (days) ^B	N (years)
KUG	birch_max_red	14.2	12.0	4
MNO	se25_spl	7.9	4.5	2
PAM	se50_spl	4.7	-2.0	4
PAM	salix_yellow	4.0	-2.5	6
SRT	birch_max_red	16.8	15.0	6
SRW	birch_max_red	11.7	9.8	6
SRW	salix_yellow	11.4	9.5	6

^A For event definitions, see Table 2

^B Negative sign indicates earlier date in the MODIS observation than the camera.

Fall Snow-on

Fall snow-on varied greatly between years, with standard deviations of 9 to 19 days for the camera start of continuous snow season. Snow on as observed on the phenocams matched MODIS SOCSS quite closely (Fig. 6, Table 11). The largest mismatches (MNO in 2015–2016, SRT in 2018) were cases where an early season snowfall persisted less than 2 weeks before briefly melting enough to fall below the 50% threshold used for the camera observations. The MODIS method flagged the earlier date as SOCSS while the camera observation recorded a later snow event as “snow on”.

Table 11. Difference between MODIS and camera observations of SOCSS.

Station	Root Mean Square Difference (days)	Mean Difference (days) ^A	N (years)
KUG	6.1	4.0	4
MNO	13.5	-7.8	5
PAM	4.1	1.0	6
SRT	6.1	-1.5	4
SRW	4.0	3.7	6

^A Negative sign indicates earlier date in the MODIS observation than the camera.

Summary Comparison of Camera and MODIS Phenology

MODIS EOCSS was consistently between the observed spring 50% and full snow-off at the stations, giving us confidence in the former as an index of change in length of the snow season over time. The various spring plant-derived visual phenology events generally show a consistent relationship to one another, to degree-day sums, and to MODIS SOG. This lends confidence to our use of MODIS SOG as an indicator of growing season length, and our use of these simple camera observations as indicators of seasons. The MODIS SOG aligns with different on-the-ground events in different locations, not surprising given that different plants are responsible for green-up in different locations. Where vegetation is sparse, quantitative curve-fitting to greenness values from the phenocams appears to be less reliable indicator of green-up than conspicuous visual features such as *Dryas* flowering.

Shrub senescence was the conspicuous fall phenology event visible on photos, and this varied little from year-to-year. The EOG based on MODIS and photo G_{cc} showed more year-to-year variation than the shrub colors. It is difficult to determine how much of the year-to-year variation in the MODIS EOG was due to non-shrub plants that have greater weather-dependent plasticity in fall greenness than shrubs, and how much was due to snow or clouds affecting the shape of the smoothed NDVI curves. As will be discussed further below, it is also more difficult to extract EOG from the NDVI curves than SOG, because of the seasonal shape of the NDVI cycle.

The good correspondence between MODIS SOCSS and camera snow observations gives us reason to trust our MODIS SOCSS as a long-term indicator of snow season.

Satellite Snow Cover Trends

The mean start and end of the continuous snow season at the 210 systematic sample points shows large year-to-year variations but nonetheless significant trends over time (Figs. 7 and 8). The 90% confidence interval for residuals from the linear model fit to EOCSS at each location was -15.1 to +14.2 days; in other words, we can expect a range of about 29 days in EOCSS in any 10 years at any location. For SOCSS the 90% interval was even wider, -19.0 to +17.8, or about 37 days in any 10 years at a single location. For SOCSS the 90% interval was even wider, -19.0 to +17.9, or about 37 days in any 10 years at a single location. The overall trend across the 20 years was toward earlier EOCSS and later SOCSS. The slopes of the linear models in Fig. 7 and 8 suggest that on average EOCSS has become 7.7 days earlier (± 0.5 days standard error) and SOCSS 4.6 days later (± 0.7 days) across the 20 years of observations. The great variability in both SOCSS and EOCSS is demonstrated by the fact that the ARCN-wide average earliest EOCSS was near the beginning of our records (2004; though it was less than one day earlier than 2016), while the SOCSS in the recent year 2015 nearly matched the earliest (2000). The pattern of ARCN-wide year-to-year variation in EOCSS here matches closely that obtained from MODIS product MOD10AZ 8-day snow cover composites for the years 2001–2015 in NOAT (Potter and Alexander 2019). Maps of snow seasons with example early and late years are given in Appendix A.

Pixels with significant negative trends (toward earlier EOCSS) in the 20-year MODIS record are concentrated in BELA and the upper Noatak River valley, while large areas have non-significant negative trends (Fig. 9). The largest concentration of pixels with negative trend is just north of our

study area. Most of ARCN had non-significant trends in SOCSS on individual pixels. Significant trends were mostly toward later SOCSS and concentrated in CAKR (Fig. 10).

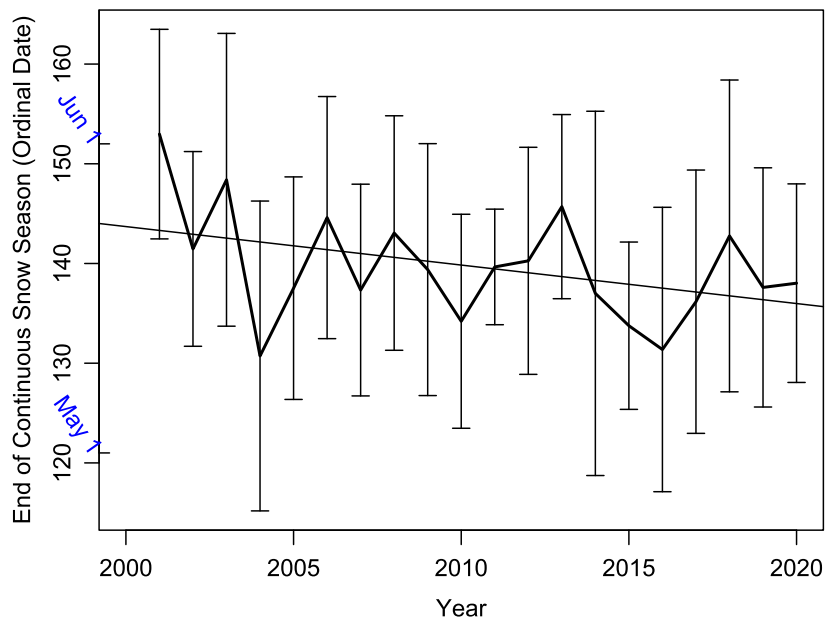


Figure 7. Mean date of the end of the continuous snow season for 210 systematic sample points across ARCN. Error bars give the standard deviation. The trendline is a linear mixed effect model of EOCSS vs. Year with the sample point intercept as a random effect, $y = 915.62 - 0.38596x$, standard error of the intercept 50.99, slope 0.02536.

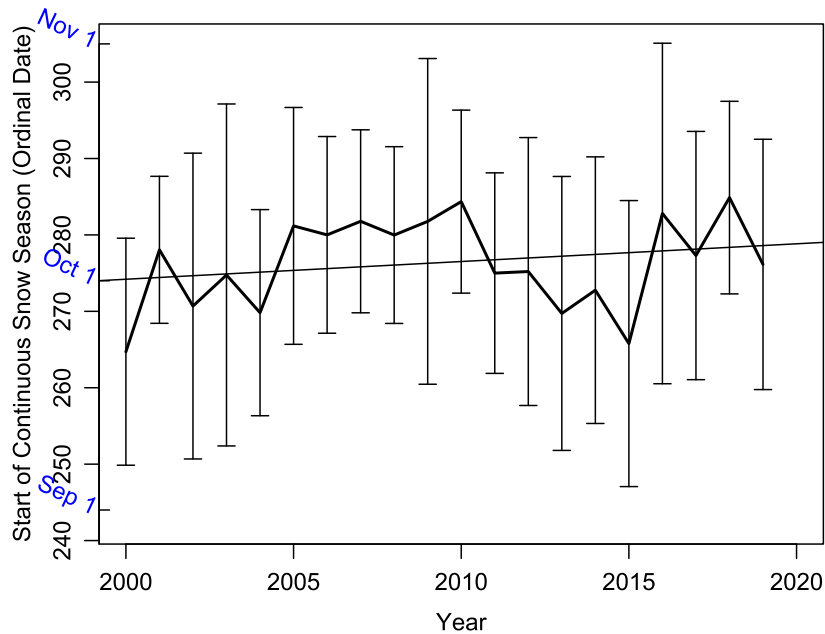


Figure 8. Mean date of the start of the continuous snow season for 210 systematic sample points across ARC-N. Error bars give the standard deviation. The trendline is a linear mixed effect model of SOCSS vs. Year with the sample point intercept as a random effect, $y = -189.80 + 0.23200x$, intercept standard error 66.37, slope 0.03303.

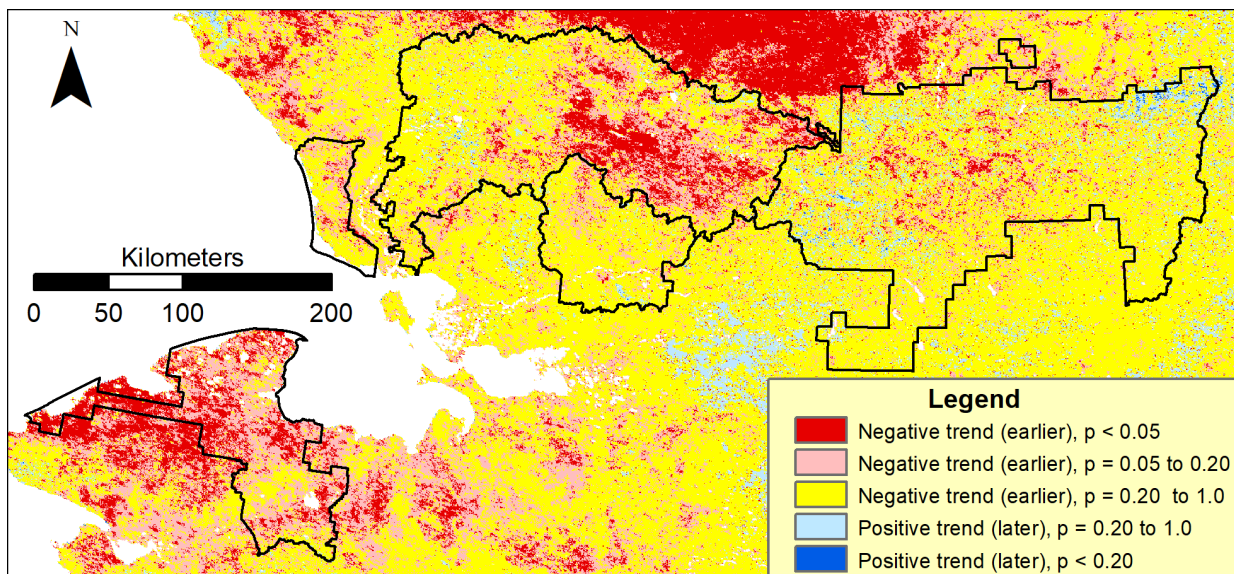


Figure 9. Mann-Kendall trend tests probabilities for spring end of continuous snow season 2001–2020.

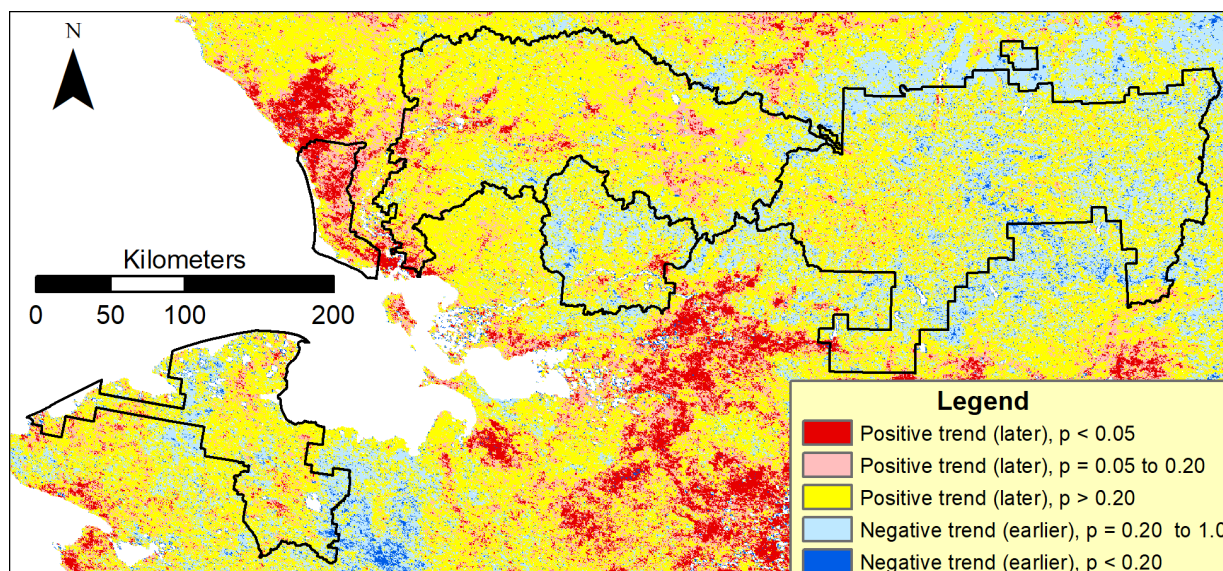


Figure 10. Mann-Kendall trend tests probabilities for fall start of continuous snow season 2000–2019.

In a previous report I presented a figure illustrating the average sum of degree-days at the median date of EOCSS (Swanson 2015). Here I update this figure with more years of MODIS EOCSS data to compute the median snow-off date and updated mean monthly temperatures (PRISM Climate Group 2020) to estimate the sum of thaw degree-days at the time of snow-off (Fig. 11). Results are substantially the same as the previous map and reveal extensive areas where snow-off typically occurs with few accumulated thaw degree-days (less than 10 °C-days), indicating very thin snowpacks. Areas with high degree-days sums at the time of snow-off indicate deeper snowpacks, possibly combined with low radiation exposure in north-facing slopes. Most areas of snow requiring more than 30 degree-days to ablate are found in the foothills on the south side of the Brooks Range in KOVA and southern GAAR. This persistent snow is widespread on various aspects and in level areas, indicating deeper initial snowpacks. The narrow east-west bands of deep snow in northeastern GAAR are at high elevations on north-facing slopes and probably represent both relatively deep snow and aspect-related effects on incoming solar energy.

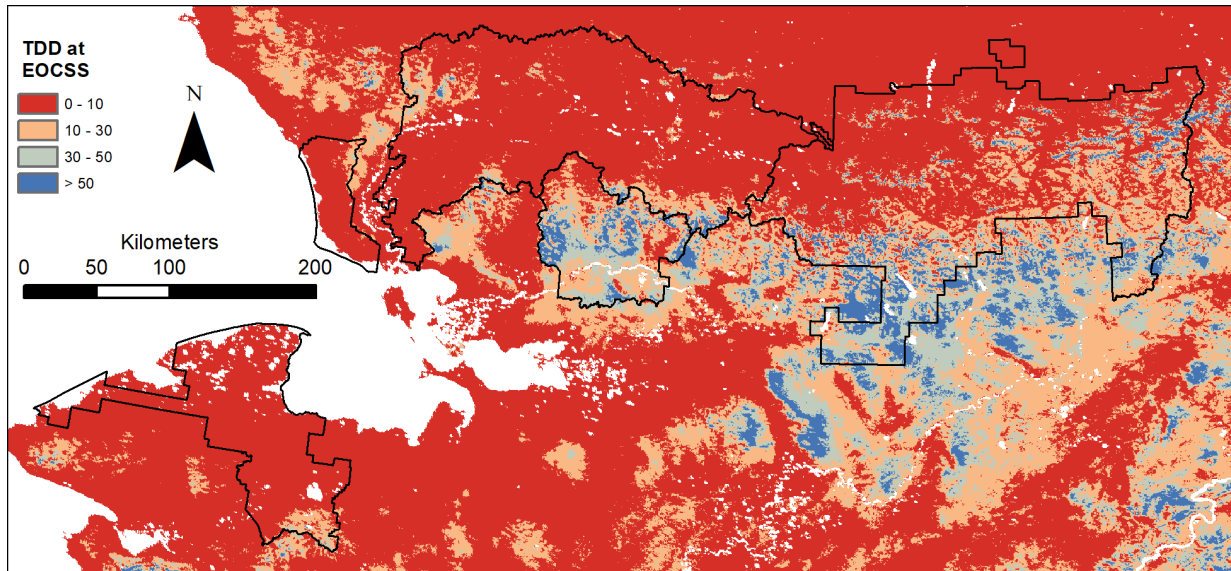


Figure 11. Long-term mean thaw degree-day sum on the median day at the end of continuous snow cover. The median EOCSS was computed from 2001–2020 MODIS data in this study and intersected with mean running thaw-degree-day sums computed by interpolation of modeled monthly mean temperatures for 1981–2010 by PRISM Climate Group (2020).

Satellite Greenness

Greenness as measured by NDVI from satellite showed the expected summer peak at all the ARCN climate monitoring stations, but comparison of satellite NDVI readings with on-the-ground camera observations clearly showed that the seasonal rise and fall of NDVI was not due exclusively to vegetation green-up and senescence. In fact, as shown with the typical example of the Kugururok Station in 2016 (Fig. 12), over half of the annual amplitude in NDVI change was due to the transition from the snow-covered landscape with NDVI near zero, to an NDVI near 0.5 representing litter, soil, and leafless vegetation in the fall or spring. The contribution of green vegetation in this example was to raise the NDVI from 0.5 to the midsummer green peak of about 0.8. Soil and leaf litter are known to have a non-zero NDVI (Nagler, Daughtry, and Goward 2000; Boelman et al. 2011). To use NDVI to determine the timing of start or end of the green season, we must therefore identify the NDVI level at a location that represents snow-free but pre-green-up or post-senescence vegetation.

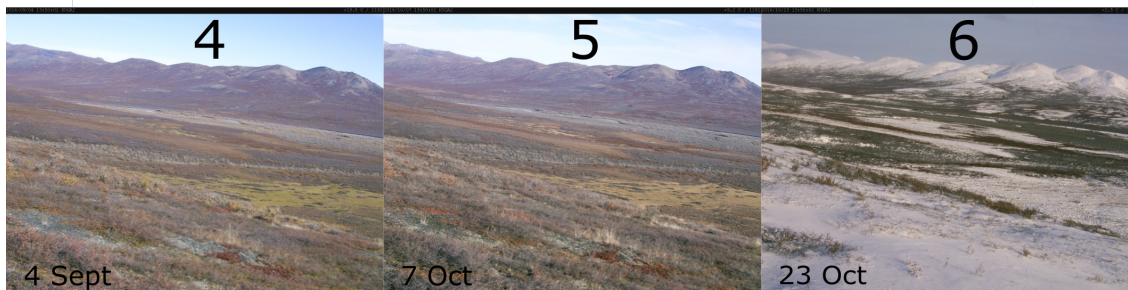
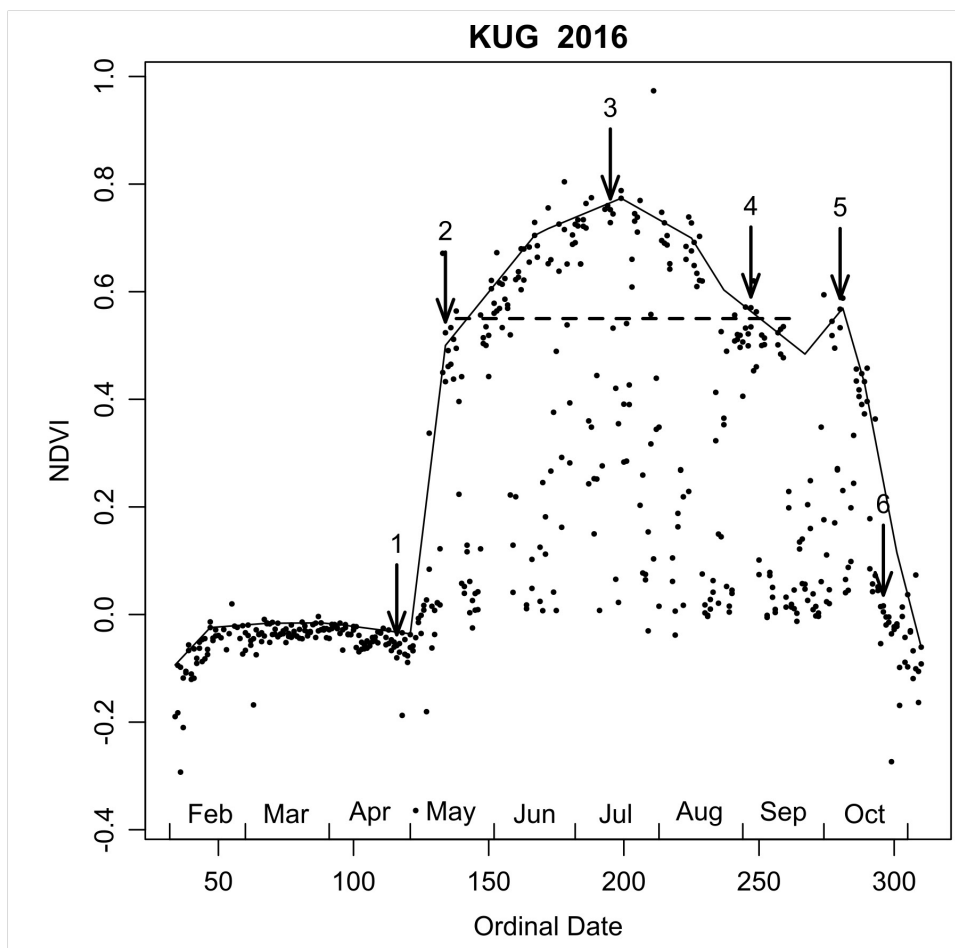
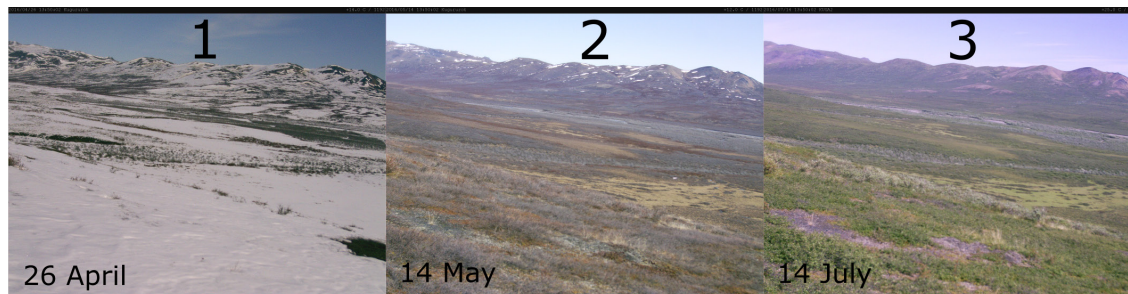


Figure 12. MODIS NDVI vs. day at the Kugururok climate monitoring station (KUG) in 2016, with example photos illustrating conditions on 6 dates. The horizontal dashed line approximates the NDVI level of senesced vegetation, as determined by multi-year observations of fall NDVI as described in the text. The red circled point has intermediate NDVI of 0.34 and is discussed in the text.

The shape of the NDVI cycle in Fig. 12 is typical for our region: a rapid rise attributable to snow loss (points 1 to 2), followed immediately by a slower rise due to vegetation green-up (points 2 to 3). After peak green-up, NDVI falls again to the intermediate level corresponding to senesced vegetation (point 4), after which it usually fluctuates for a time between zero and the “senesced” level due to clouds and intermittent snow cover, before falling to consistent level near zero when permanent winter snow cover is established (point 6). If all years of data are plotted together (Fig. 13) the level of senesced fall vegetation is visible on the NDVI curves as a distinct flat region beginning near day 250 (7 September). The NDVI value of the fall senesced vegetation can be approximated by fitting a 90th quantile spline curve to the data and searching for the flattest slope after the summer peak. This level was intersected with the curve fitted to annual data to find the date of start and end of the green season at the camera locations.

The rapid rise in NDVI during snow loss is attributable at least in part to the specific behavior of NDVI in pixels with partial snow cover. To illustrate, Fig. 14 presents the relationship between NDVI and snow cover, using a mixing model that assumes typical values for red and near infrared reflectances of snow and litter from the Kugururok climate station. NDVI remains quite low until the snow is nearly gone.

Comparison of camera observations for first dates of 50% and 0% snow cover with NDVI curves (Fig. 15) generally support the idea that snow-off controls the early rise in spring NDVI, as mediated by the snow cover-NDVI relationship. However, comparison of camera and satellite data is complicated by the fact that camera snow observations are for a small foreground area near the camera that usually becomes snow-free while drifts linger on the larger landscape captured by the 250 m MODIS pixel; the exception in our data is station SRW, where a large snowdrift lingers late in the camera view in the lee of a rock outcrop. Thus, in nearly all cases displayed in Fig. 15, 50% snow as observed by the camera coincides with the very end of winter NDVI levels; this agrees with the mixing model relationship displayed in Fig. 13, where 50% snow results in NDVI near 0. The satellite NDVI value at first camera observation of 0% snow cover is generally on the steeply rising portion of the curve but varies with year and locality. The coincidence of the first 0% snow cover in the camera foreground with the steeply rising portion of the NDVI curve is reasonably explained as due to the presence of a small amount of snow outside the camera view in the MODIS pixel that is disappearing. For example, as the last 10% of snow disappears, we would expect the NDVI to rise about 0.25 units (Fig. 14). The exception is station SRW, where a drift directly in the camera view results in snow lingering past the start of green-up, as shown by leaf-out (Fig. 4) and NDVI (Fig. 15).

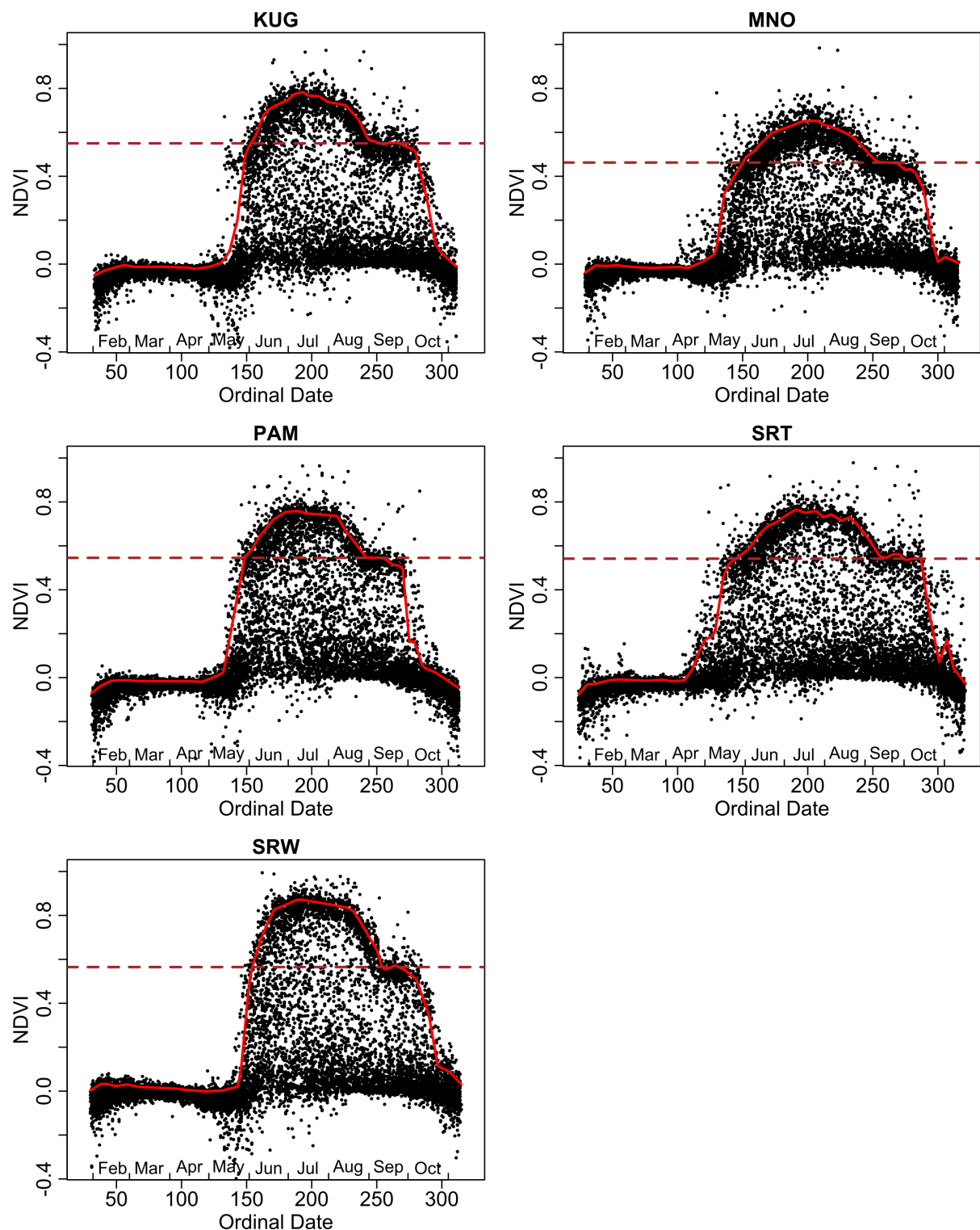


Figure 13. MODIS NDVI vs. date for all years of data (2000–2020) for the ARC camera climate stations. The red curves are quantile splines fit to the 90th percentile value (Koenker 2021); the horizontal dashed lines give the NDVI level of senesced fall vegetation as determined by the flattest portion of the fall “plateau” region.

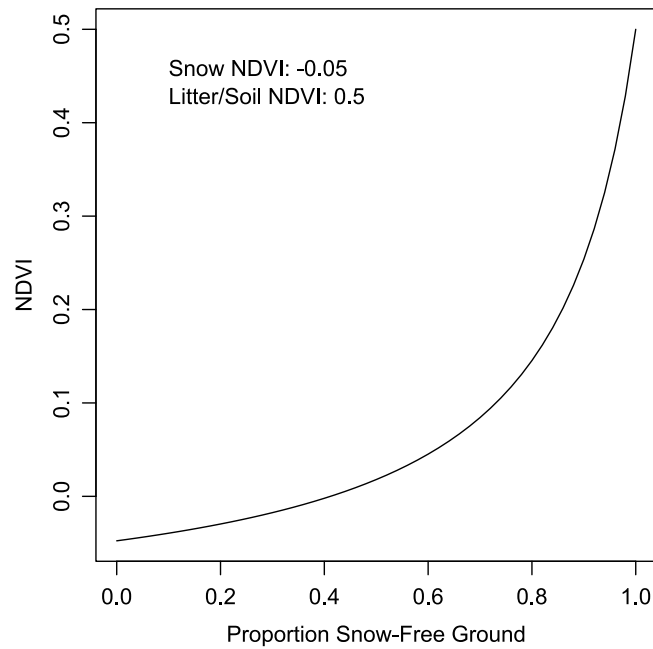


Figure 14. Plot of NDVI vs proportion of snow cover from a simple mixing model, assuming typical reflectance values observed for the MODIS pixel containing the Kugururok climate station: litter red 0.05, litter near infrared 0.15, snow red 0.77, snow near infra-red 0.7.

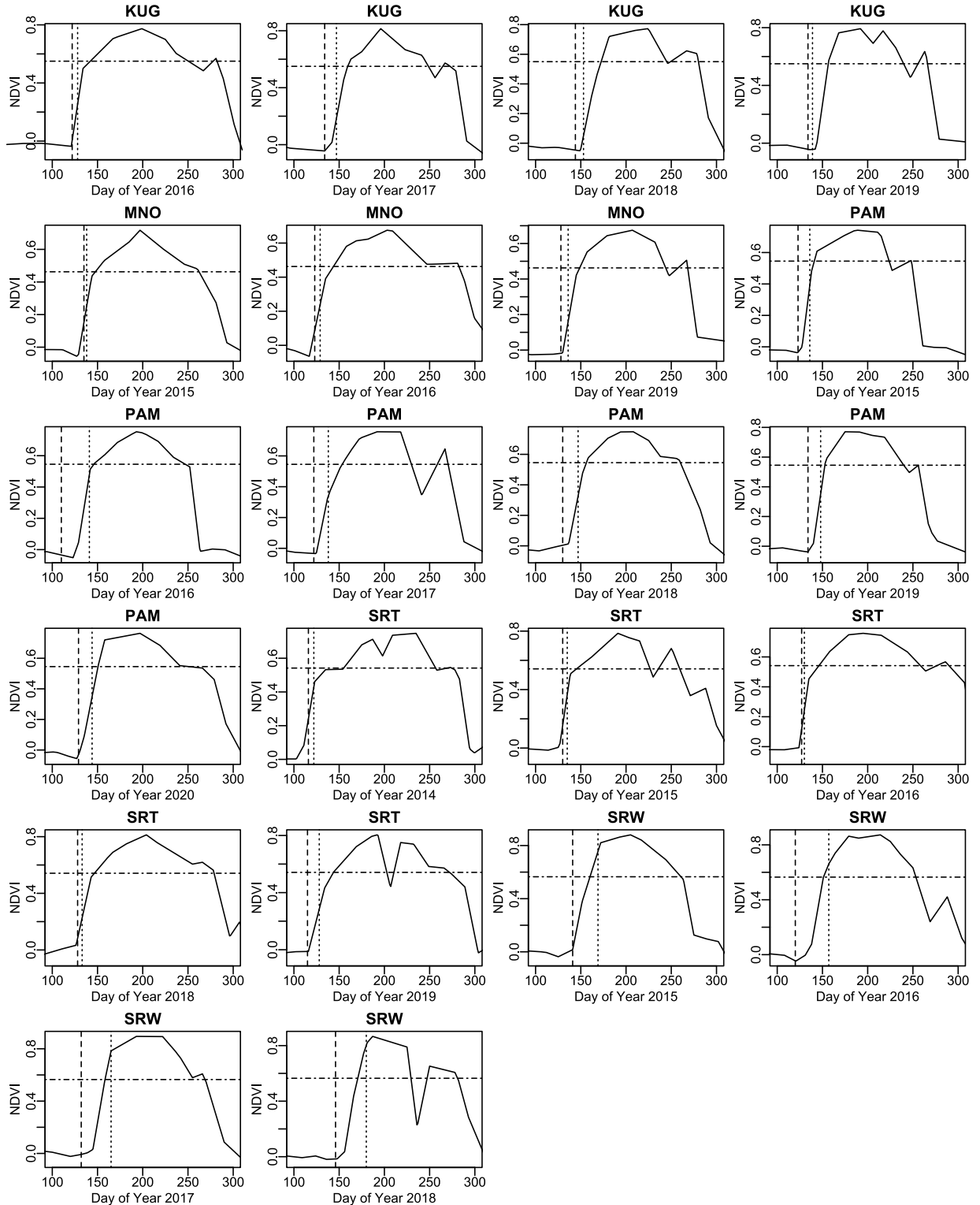


Figure 15. Relationship between annual NDVI curves and spring camera observations of first date of 50% snow cover (vertical dashed line) and first date of no snow cover (vertical dotted line). Curves are 90% quantile splines fitted to daily NDVI values from MODIS satellite data for the year indicated. The horizontal line is the NDVI value for senesced vegetation, soil, and rock obtained from multi-year data for the fall season as described previously.

The overall trend in ARCN across the 20 years was toward earlier SOG and later EOG (Figs. 16–18). The 90% confidence interval for residuals from the linear model fit to SOG at each location was -11.7 to +12.6 days; in other words, we can expect a range of about 24 days in SOG in any 10 years at any location. For EOG the 90% interval was wider, -14.3 to +15.3, or about 30 days in any 10 years at a single location. A linear model fit to SOG vs. year for all 184 points had a slope of -0.544 days yr^{-1} (± 0.020 days yr^{-1} standard error), suggesting an average advance of 11.4 days (± 0.4 days standard error) in the date of spring green-up over the period 2000–2020. Mann-Kendall trend tests of individual points showed highly significant ($p < 0.05$) negative trends in SOG at 77 of the 184 points and a majority (114) with trends significant at $p < 0.10$. Points with significant negative trend in SOG were well distributed across the study area (Fig. 17). The slope of the linear model fit to EOG dates at the 184 points ($+0.527 \pm 0.026$ days yr^{-1}) suggest that EOG became 11.1 (± 0.5) days later over the 21 years of data. Mann-Kendall trend tests of individual points showed that fewer individual points had trends significant at $p < 0.05$ ($n = 45$) or $p < 0.1$ ($n = 70$) than for SOG (Fig. 18). Maps of example years with early and late EOG and SOG are in Appendix B.

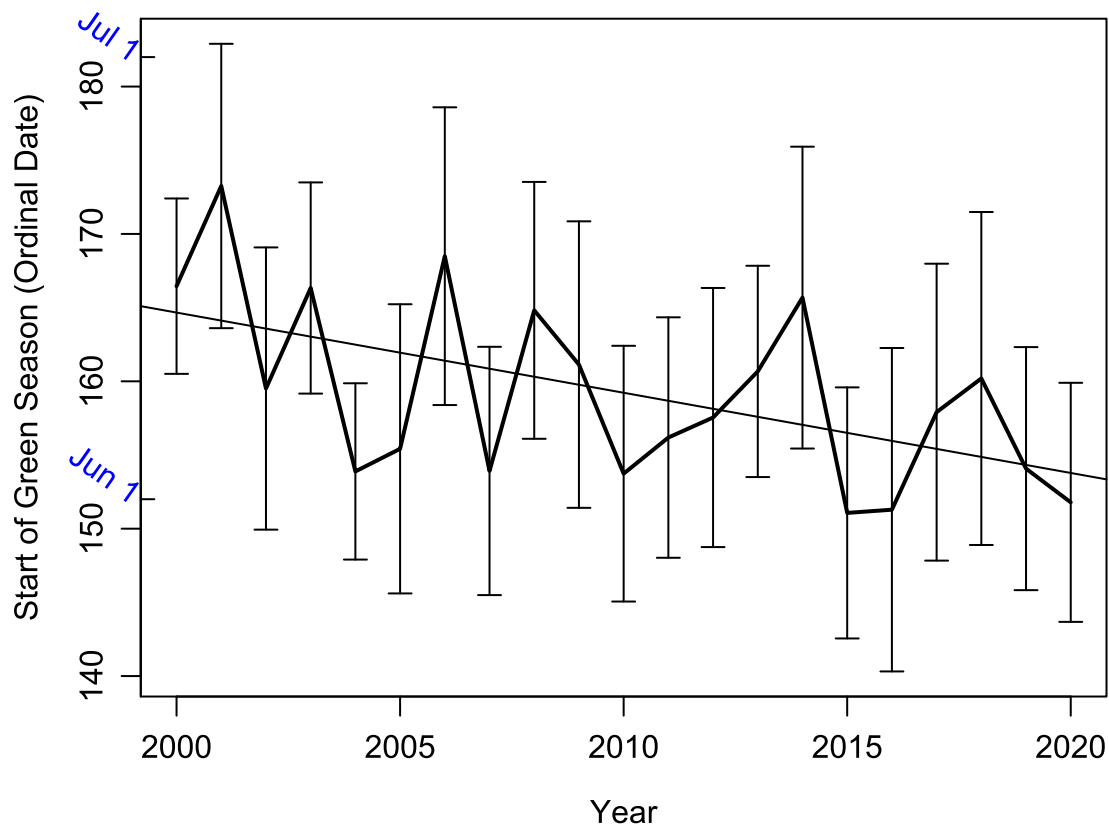


Figure 16. Mean start of green season (SOG) vs. year from MODIS NDVI, for 184 of the 210 sample points with substantial green vegetation (maximum NDVI > 0.4). Error bars give the standard deviation. The trendline is a linear mixed effect model of SOG vs. Year with the sample point intercept as a fixed effect, $y = 1252.99 - 0.5442x$; intercept standard error 40.77 days, slope 0.02028 days yr^{-1} .

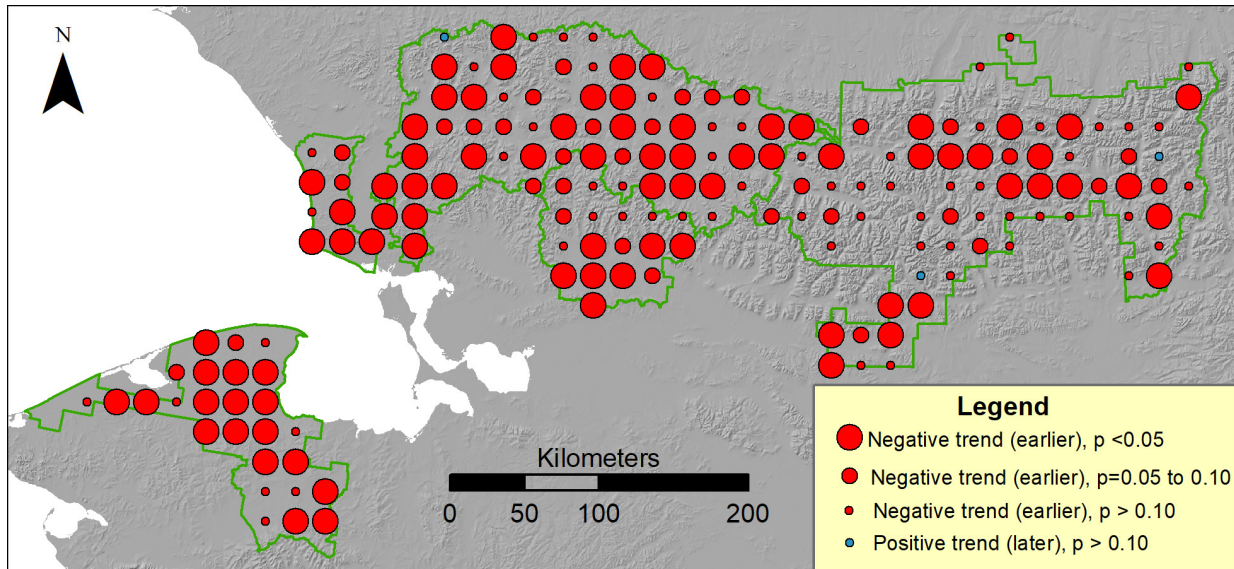


Figure 17. Map of results from Mann-Kendall trend tests of SOG. Map symbols portray the trend direction and significance level of SOG date based on satellite NDVI data at sample points for years 2000–2020.

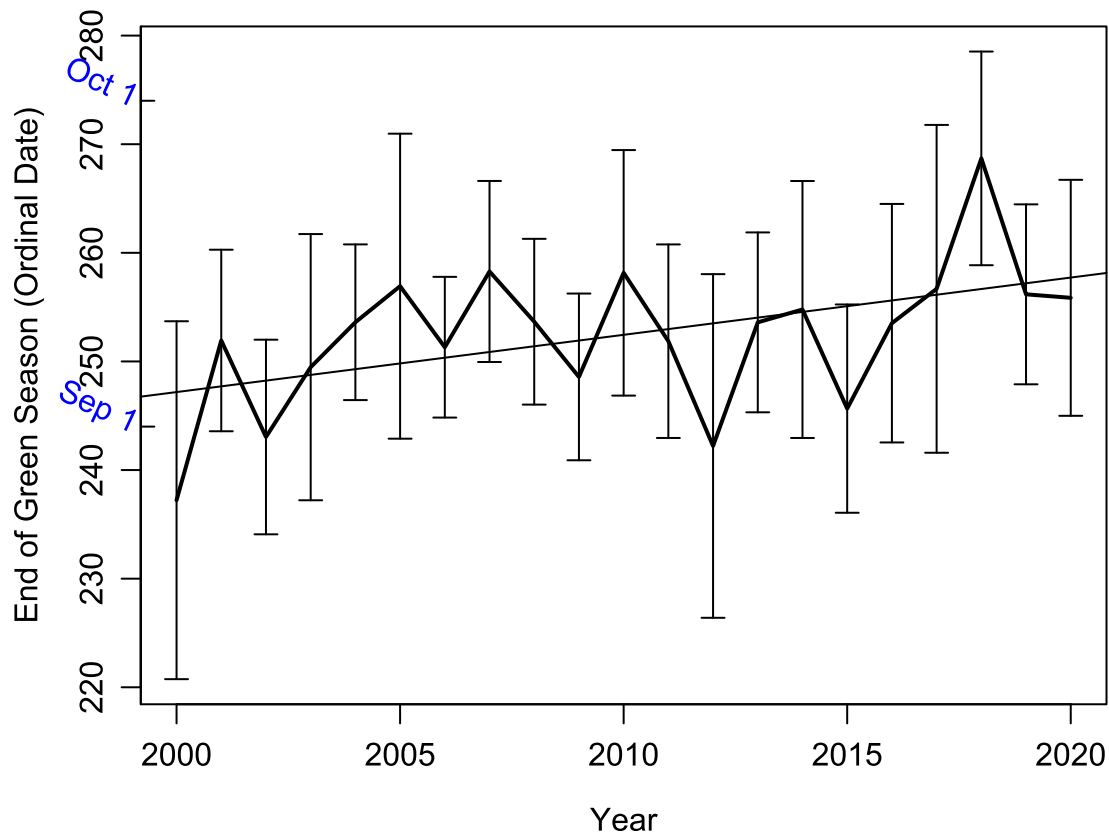


Figure 18. Mean end of green season (EOG) vs. year from MODIS NDVI, for 184 of the 210 sample points with substantial green vegetation (maximum NDVI > 0.4). Error bars give the standard deviation. The trendline is a linear mixed effect model of EOG vs. Year with the sample point intercept as a fixed effect, $y = -807.08 + 0.52713x$, intercept standard error 52.00 days, slope $0.02587 \text{ days yr}^{-1}$.

The observed decline in the date of SOG during the past 21 years suggests a follow-up question: were SOG dates unusually late in the early 2000s, such that the observed decline represents a return to “normal” from an anomalous high? Or did SOG recently decline to historically unprecedented early values? Long-term temperature records at Kotzebue suggest that SOG in the early 2000s were not unusually late, and that recent early green-up dates were indeed unprecedented. To compare the 2000–2020 SOG trend to a longer record, I computed the date in the spring when thaw degree-days reached 140°C-days for the long historical climate time series (1937–2020) at Kotzebue. In a previous study I found a good relationship between 140°C-days at Kotzebue and SOG in nearby tundra lowlands (Swanson 2015). Comparison of MODIS SOG dates and camera spring phenology events with accumulated degree-days at our climate monitoring stations suggests that 140°C-days is indeed a reasonable substitute for SOG at windswept tundra locations with minimal snow cover: the mean accumulated degree-days at the time of MODIS SOG at our three low-shrub/herb tundra monitoring stations MNO, PAM, and SRT were 131, 127, and 76 °C-days, respectively (Table 8). Our two other stations with mid- and tall shrubs and deeper snowpacks (KUG and SRW) had higher degree-day totals at the time of MODIS SOG (224 and 264 °C-days, respectively). A plot of the date when 140°C-days was reached at Kotzebue vs. year for 1937–2020 revealed a gradual long-term trend toward earlier dates amid considerable year-to-year variation (Fig. 18). A linear regression for the full period of record had a slope of $-0.15 \text{ days yr}^{-1}$, i.e., considerably slower than our 2000–2020 MODIS SOG decline of $-0.54 \text{ days yr}^{-1}$ noted above. All years in 2014–2020 were below the average predicted by the long-term linear regression (Fig. 19). (Data from 2019 are missing for Kotzebue, but temperature data from the nearby NPS station MNO show that 2019 was similar to 2017 and 2018.) A degree-day threshold of 260°C-days (corresponding to the later green-up in mid- to tall-shrub environments) yielded similar results: slope of $-0.15 \text{ days yr}^{-1}$ for 1937–2020 and dates for 2015–2020 all below this regression line.

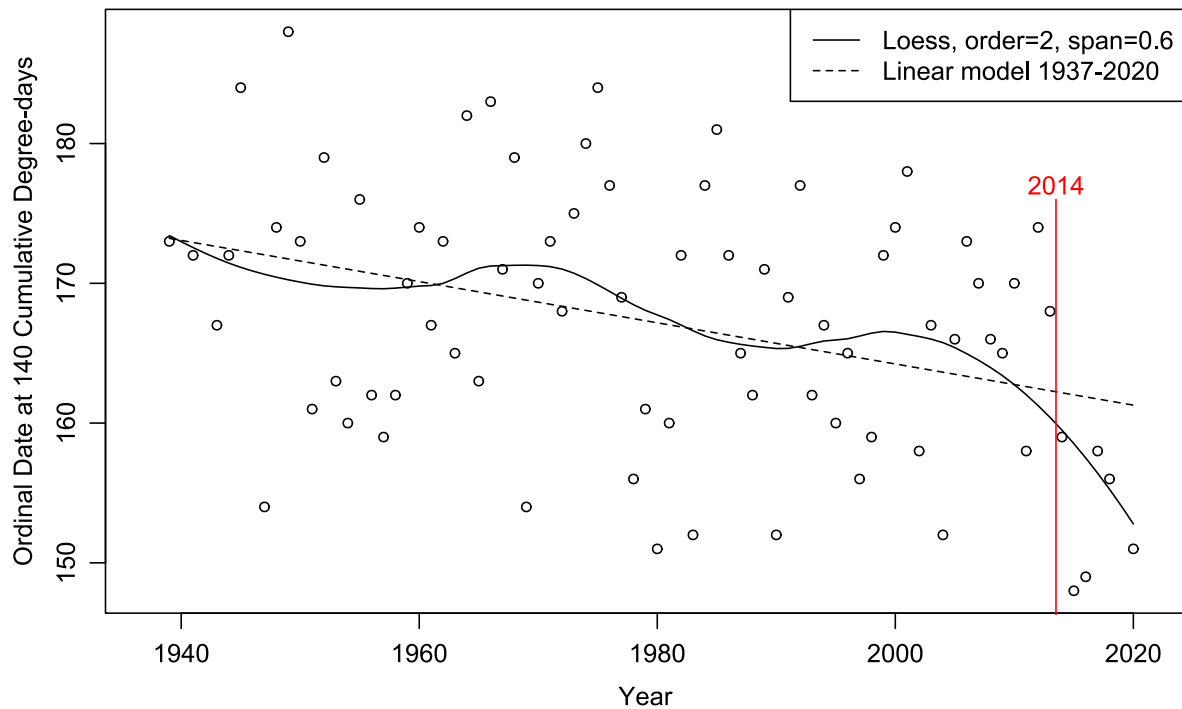


Figure 19. Date when thaw degree-days exceeded 140°C-days at Kotzebue, 1937–2020. The solid line is smoothing by the “loess” method (R Core Team 2017) with degree=2, span=0.6. The dashed line is a linear regression for 1937–2020 with formula $y = 458.89 - 0.15x$, $r^2 = 0.13$, $p = 0.001$. The red vertical line separates out years 2014–2018 and 2020 (data for 2019 are missing).

Maximum NDVI

Average of maximum MODIS NDVI across all 210 samples showed relatively minor year-to-year variations (Fig. 20). The 90% confidence interval for 21-year mean maximum NDVI at individual points was ± 0.05 NDVI units. In other words, in any given 10-year period the NDVI was likely to range across just 0.1 NDVI units at any given point. The wide error bars on each point reflect the wide range in environments sampled, from dense vegetation to barren areas. The relatively low maximum NDVI years (2001, 2006, and 2014) match years of late green-up (Figs. 16 and 20). A slight upward trend in study-area wide average maximum NDVI is supported by the linear mixed-effect model slope of $0.00155 (\pm 0.00008 \text{ standard error})$ NDVI units per year. This implies that, on average, $64.4 (\pm 3.4 \text{ standard error})$ years would be required to increase 0.1 NDVI units. Of the 210 sample points, 44 individual points had highly significant increases in NDVI (Mann-Kendall test $p < 0.05$), and 66 had increases at $p < 0.10$. One point showed a decrease at $p = 0.09$, all other decreases had $p > 0.10$ (Fig. 21). Significant increases in maximum NDVI occurred across the full range of NDVI values, from tall shrub and forest communities with NDVI over 0.8 to rocky high-altitude areas with NDVI of less than 0.3. Locations with increasing NDVI were scattered across all of the parks, with an apparent concentration in KOVA and adjacent NOAT (Fig. 21). I did not find evidence of widespread “browning” in NOAT in the past two decades as in Potter and Alexander (2019).

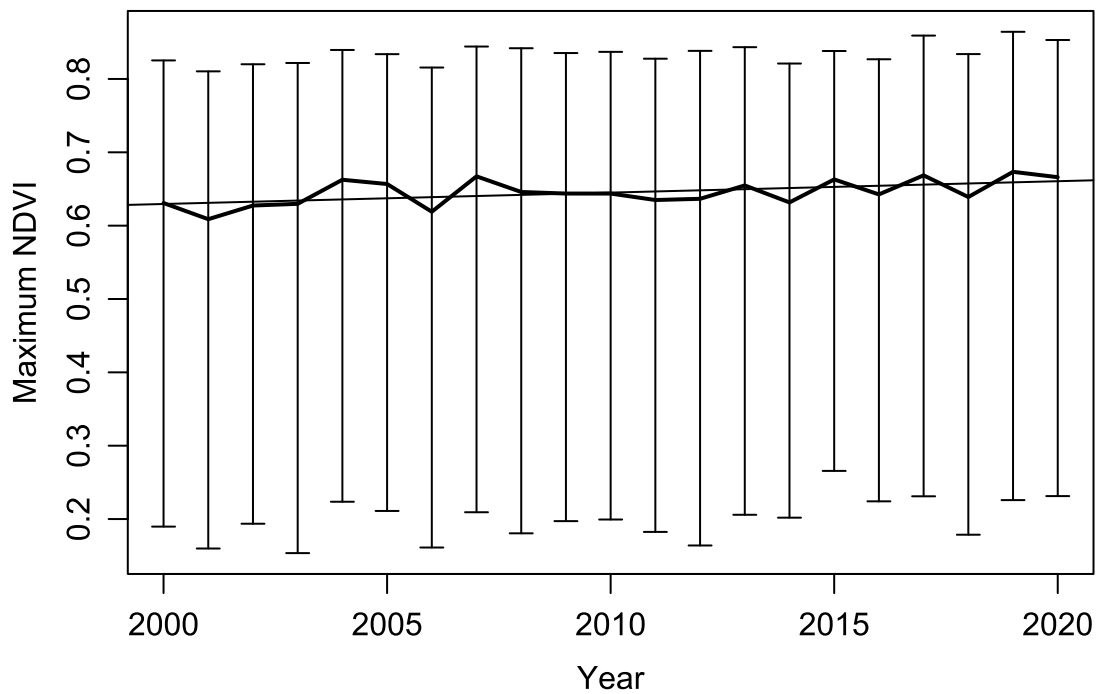


Figure 20. Mean maximum NDVI vs. year for 210 sample points. Error bars give the 90% confidence interval. The trendline is a linear mixed effect model of NDVI vs. Year with the sample point intercept as a fixed effect, $y = 0.001553x - 2.476$, intercept standard error 0.1626, slope 0.00008066.

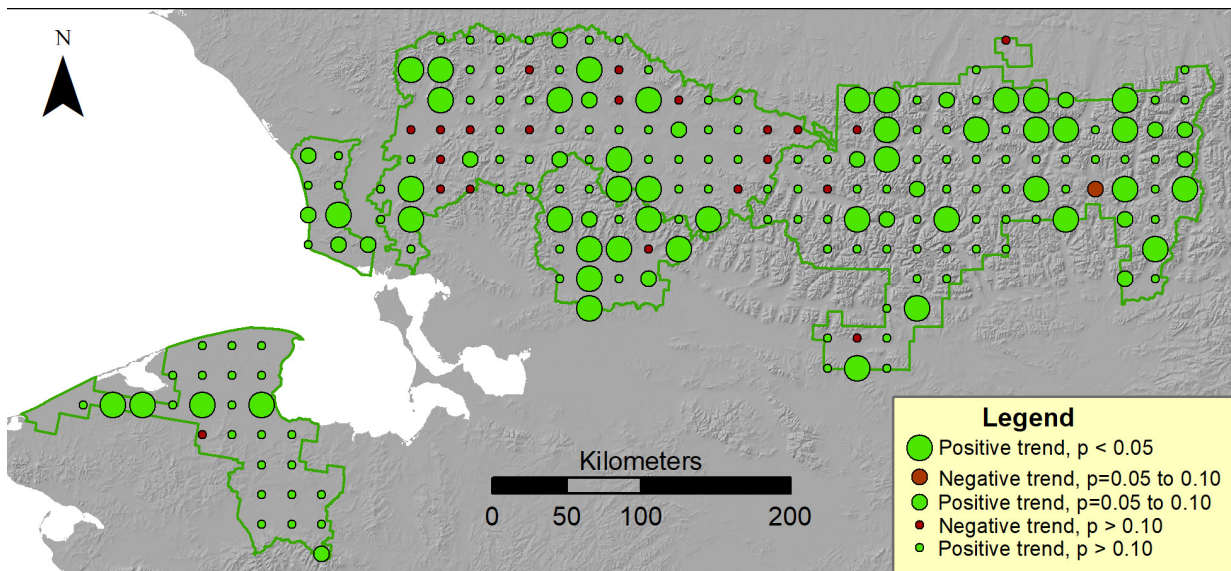


Figure 21. Map of results from Mann-Kendall trend tests of maximum NDVI. Map symbols portray the trend direction and significance level based on satellite NDVI data at sample points for years 2000–2020.

Phenology and Solar Radiation

Daily total solar radiation shows the extreme variation through the year that is expected at locations near the Arctic Circle. Daily solar energy inputs (or daily light integral, DLI) ranges from over 8000 $\text{W}\cdot\text{h m}^{-2} \text{ day}^{-1}$ ($60 \text{ mol m}^{-2} \text{ day}^{-1}$) on clear days near the summer solstice to zero near the winter solstice (Fig. 22). Clear-day radiation is controlled largely by astronomical factors (sun angle and day length) and thus is symmetrical around the summer solstice (near 20 June, day 171), but actual solar radiation is skewed toward the spring in our study area due to greater cloudiness in the late summer and fall (Fig. 22). The average date when half the annual solar radiation was received at the five camera stations ranged from 160 at KUG to 162 at PAM and SRW and 163 at MNO and SRT; i.e. June 9 to 12, or about 8 to 11 days before summer solstice. Thus, cloudiness enhances the seasonal mismatch of the summer green season to available solar radiation. For example, green leaves appeared on birch shrubs at station SRT in early June near the time of the annual maximum solar radiation, when median DLI values were between 40 and 50 $\text{mol m}^{-2} \text{ day}^{-1}$ (Fig. 22); these values are comparable to temperate latitudes at that time of year (Faust and Logan 2018). Senescence occurred in early September when median DLI had dropped to below 20 $\text{mol m}^{-2} \text{ day}^{-1}$ and was declining rapidly to be near 10 $\text{mol m}^{-2} \text{ day}^{-1}$ by 1 October. When DLI is less than 20 $\text{mol m}^{-2} \text{ day}^{-1}$, productivity for most species is strongly limited by irradiance (Poorter et al. 2019). Thus, variations in the timing of green-up have much larger consequences for total annual photosynthetic productivity than variations in timing of senescence.

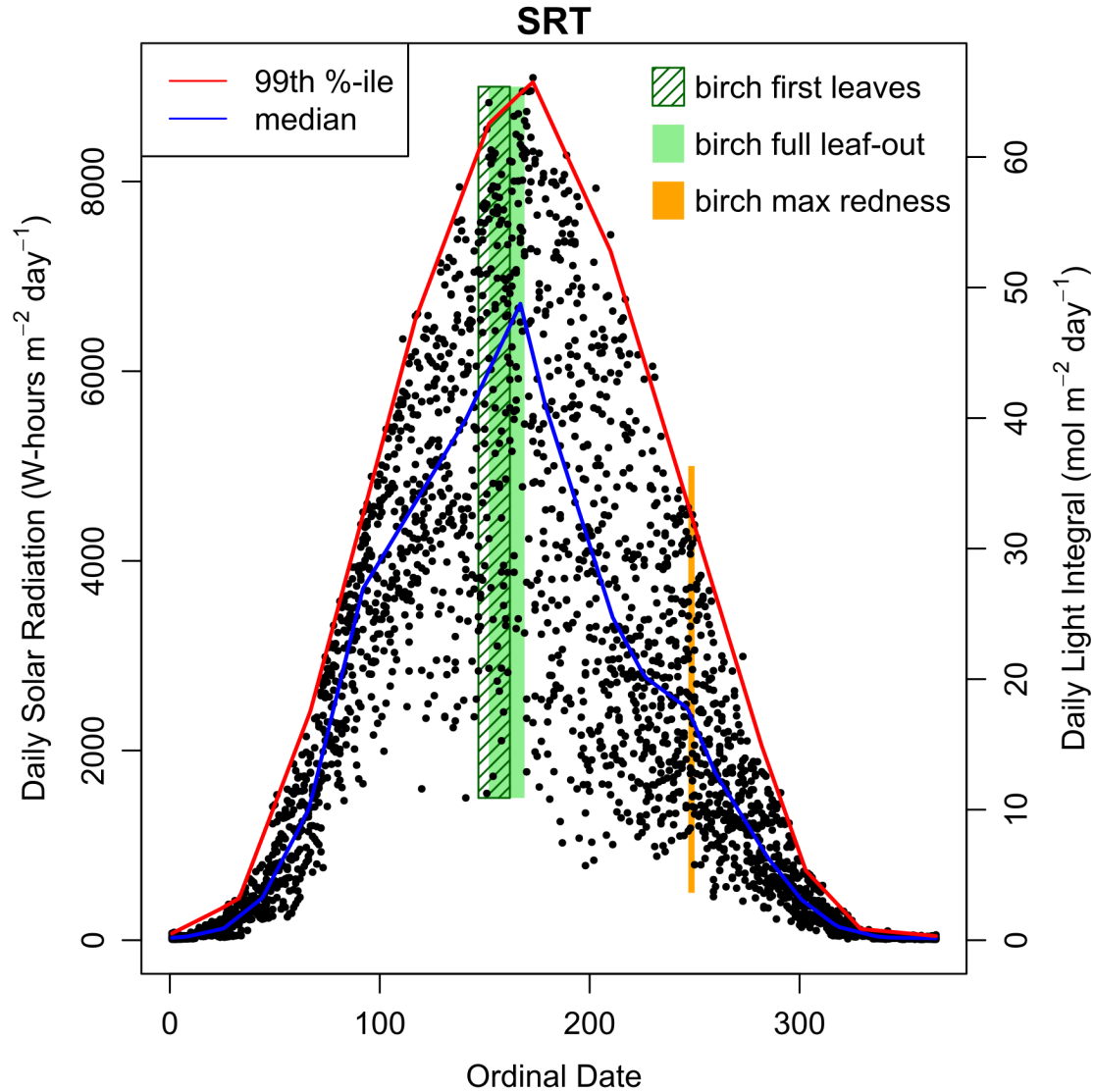


Figure 22. Annual cycle of solar radiation at station SRT in relation to birch shrub (*Betula nana*) leaf-out and senescence. Points represent all available daily total solar radiation values (2011–2019), with axes scaled for sum of daily radiation in W-h (the instrument output) and in $\text{mol m}^{-2} \text{day}^{-1}$ (daily light increment, the units often used in plant physiology studies and horticulture; converted by the factor $0.007265 \text{ mol Wh}^{-1}$, (Faust and Logan 2018). The red line is the 99th percentile quantile spline and the blue line is the median spline. Shaded rectangles give the range of dates for three phenological events observed in the station photographs: birch first green leaves, birch full leaf-out, and birch maximum fall redness.

Comparison of MODIS and VIIRS for Green Season

The point clouds for the multi-year VIIRS data at the camera stations (Fig. 23) are less dense than the corresponding point clouds for the MODIS data (Fig. 13), owing to the shorter period of record (2012–2020 for VIIRS, vs 2000–2020 for MODIS). The overall shapes are very similar and the fall “plateau” areas corresponding to senesced, snow-free vegetation are apparent as they were in the MODIS data.

I located the NDVI levels of the fall “plateau” corresponding to senesced vegetation with the VIIRS data for the 20-km grid points and used them to locate the year green-up and senescence dates in the same fashion as described previously for MODIS. I restricted the analysis as before to the stations with significant vegetation cover (MODIS NDVI > 0.4, $n = 184$).

The difference in start of green season between VIIRS and MODIS for the period of overlap (2012–2020) was 7.7 days root mean square difference and -1.7 days mean difference (the negative sign indicates the VIIRS data yielded slightly earlier dates). In other words, in any given year and point location the two sensors yielded dates that differed by about a week, but the average across the study area differed by less than 2 days. The root mean square difference for the fall end of green season was larger, 12.0 days, but the mean difference was again small at $+0.7$ days (the positive sign indicates slightly later average dates for VIIRS). The year-to-year trends in the VIIRS SOG and EOG averaged across the 20-km grid points were very similar to the MODIS-derived versions (Figs. 24 and 25). These results suggest that VIIRS data will serve well for continued study of long-term trends in greenness phenology after the MODIS satellites become inoperable, when the data averaged over a large area. However, caution is appropriate when interpreting the phenological results from any single point or pixel.

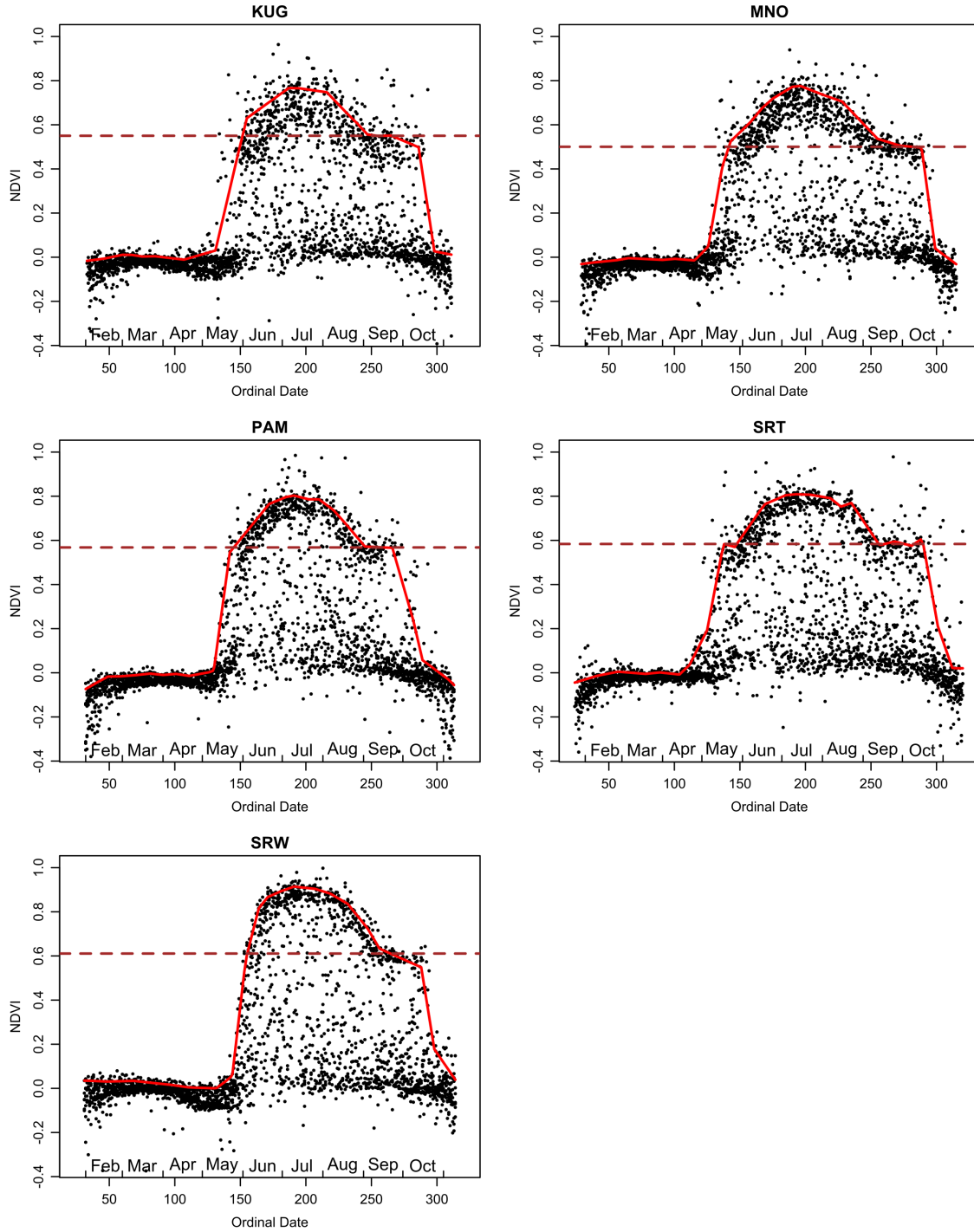


Figure 23. VIIRS NDVI vs. date for all years of data (2012–2020) for the ARCNC camera climate stations. The red curves are quantile splines fit to the 90th percentile value (Koenker 2016); the horizontal dashed lines give the NDVI level of senesced fall vegetation as determined by the flattest portion of the fall “plateau” region.

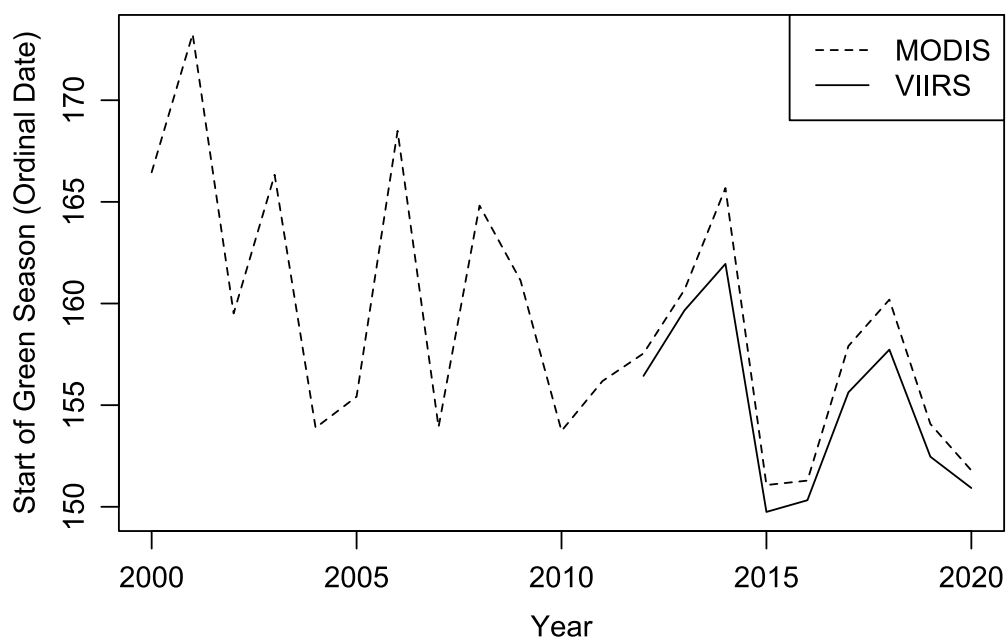


Figure 24. Mean date of start of green season computed from MODIS and VIIRS data in all available years of data for 20-km systematic sample points across ARCN ($n = 184$, stations with maximum NDVI > 0.4).

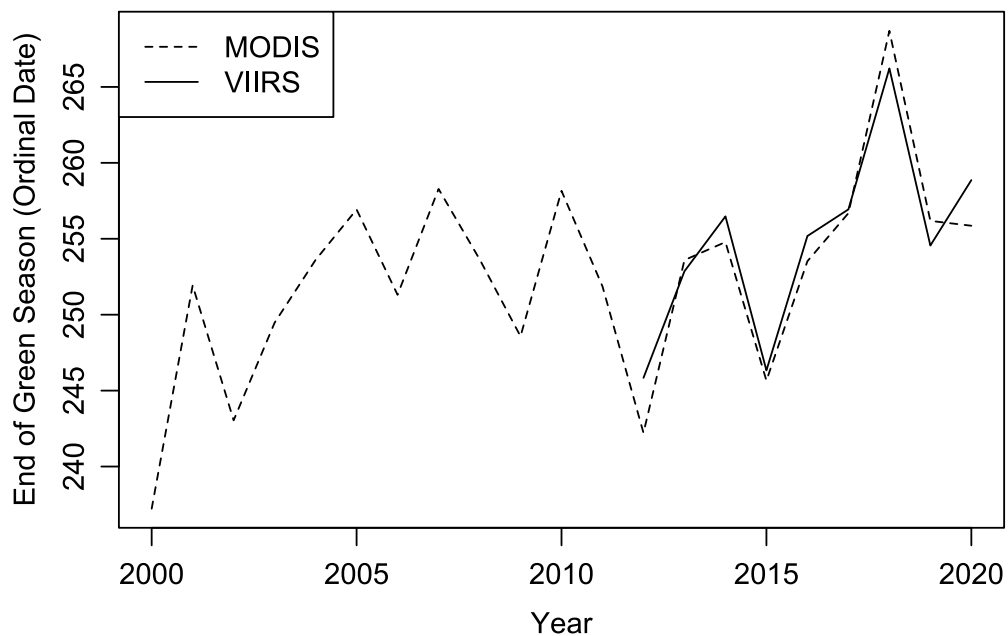


Figure 25. Mean date of end of green season computed from MODIS and VIIRS data in all available years of data for 20-km systematic sample points across ARCN ($n = 184$, stations with maximum NDVI > 0.4).

Conclusions

The correspondence between ground observations and MODIS satellite-derived dates for the end of continuous snow season, start of green season, and start of continuous snow season are good and give us confidence in the satellite measures. MODIS end of green season dates did not correspond closely to observed shrub senescence dates, and thus we are less certain of the reliability of these data. The lack of correspondence could be due either to problems with curve-fitting in the fall due to clouds and snow cover; or, senescence of non-shrub plants may be influencing the MODIS results.

The 21-year MODIS record documents significant lengthening of the snow-free and green-vegetation seasons, amidst large year-to-year variations. Study-area wide averages based on systematic sample of pixels suggest that average snow-off and green-up have become about 8 days and 11 days earlier, respectively, over the period of observation. Average end of green season has become about 10 days later (though again we are uncertain of the data reliability here) and start of snow season about 5 days later. These changes are impressive, but still smaller than the year-to-year variations of about a month in all of these measures.

Results for start and end of the green season from the newer VIIRS satellite are similar to MODIS, and thus VIIRS should provide a good opportunity to continue our monitoring beyond the lifetime of the MODIS satellite.

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Appendix A: Snow Season Maps

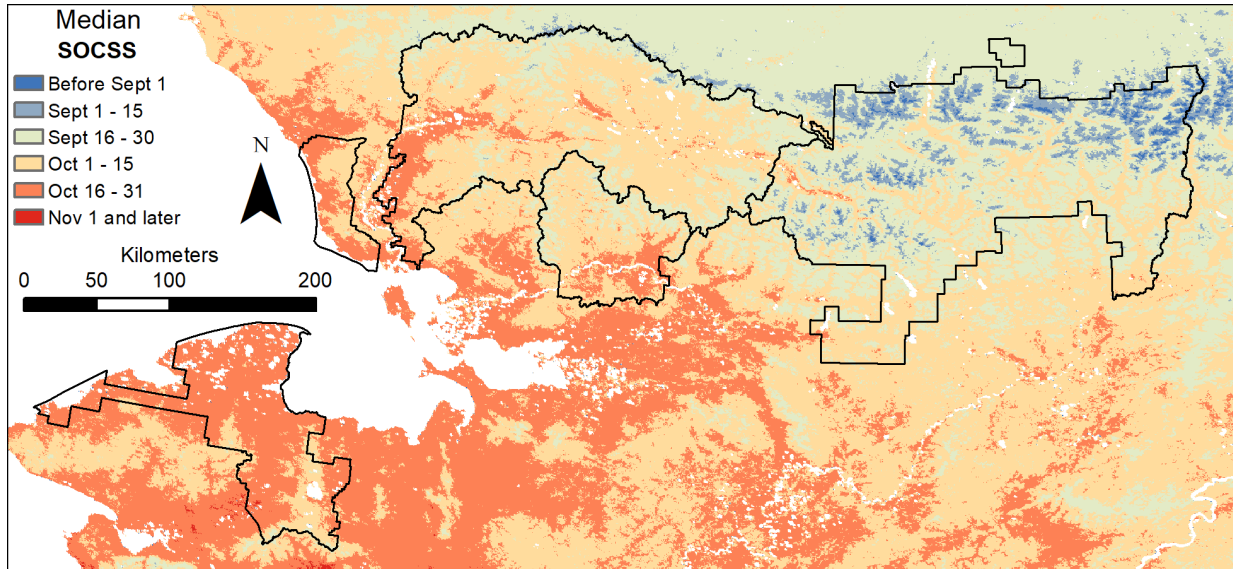


Figure A1. Median start of the continuous snow season, 2000–2019.

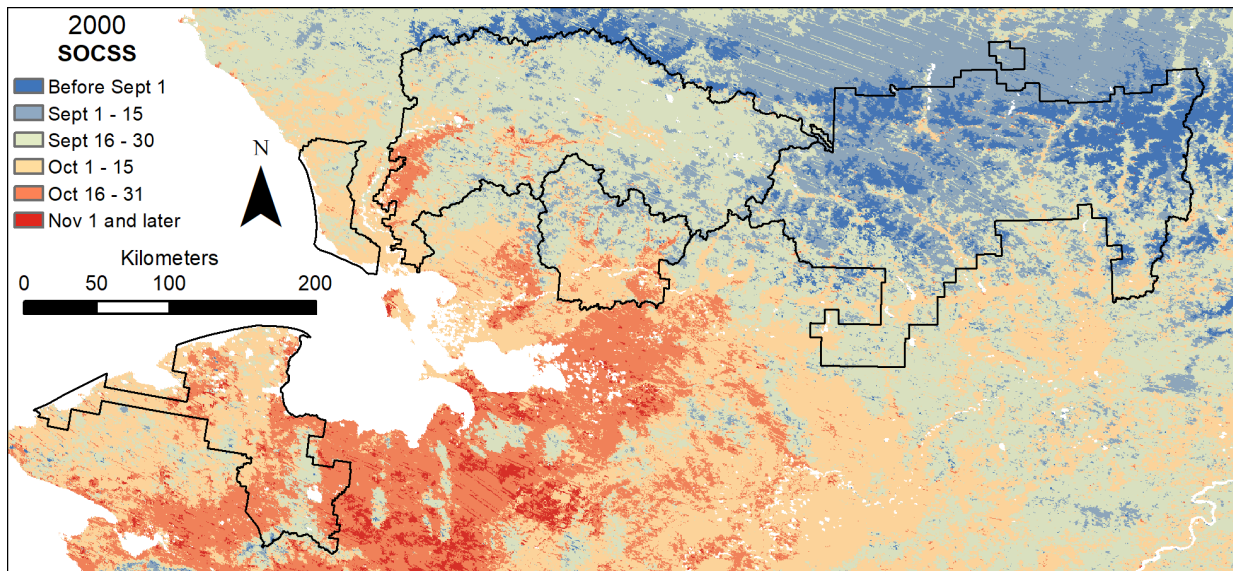


Figure A2. Start of the continuous snow season in the year with the earliest snow-on, 2000.

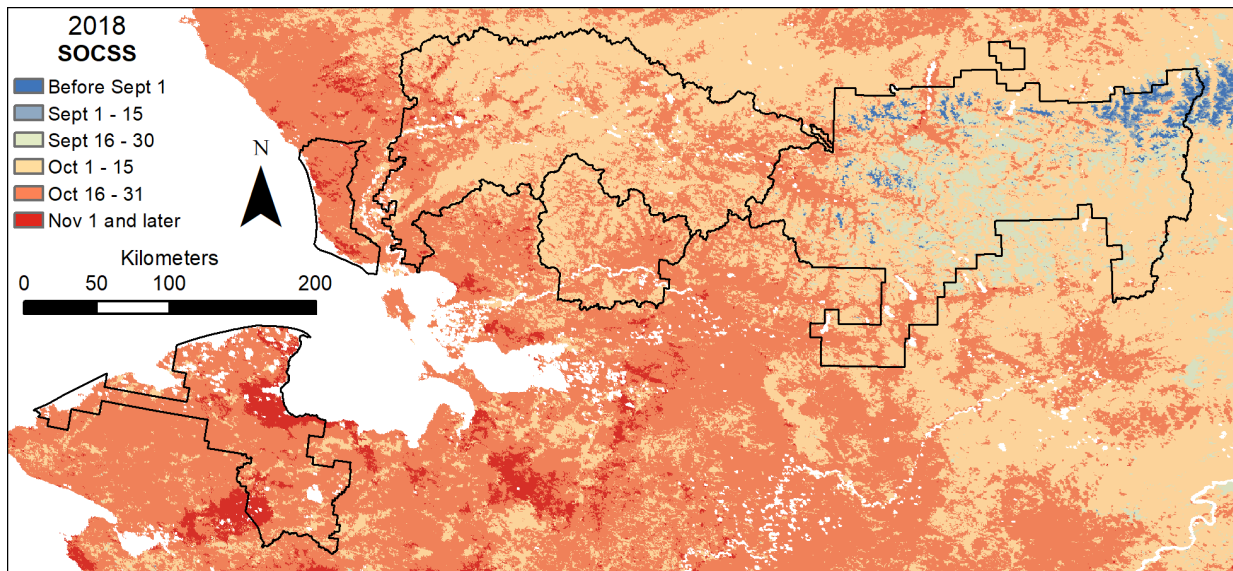


Figure A3. Start of the continuous snow season in the year with the latest snow-on, 2018.

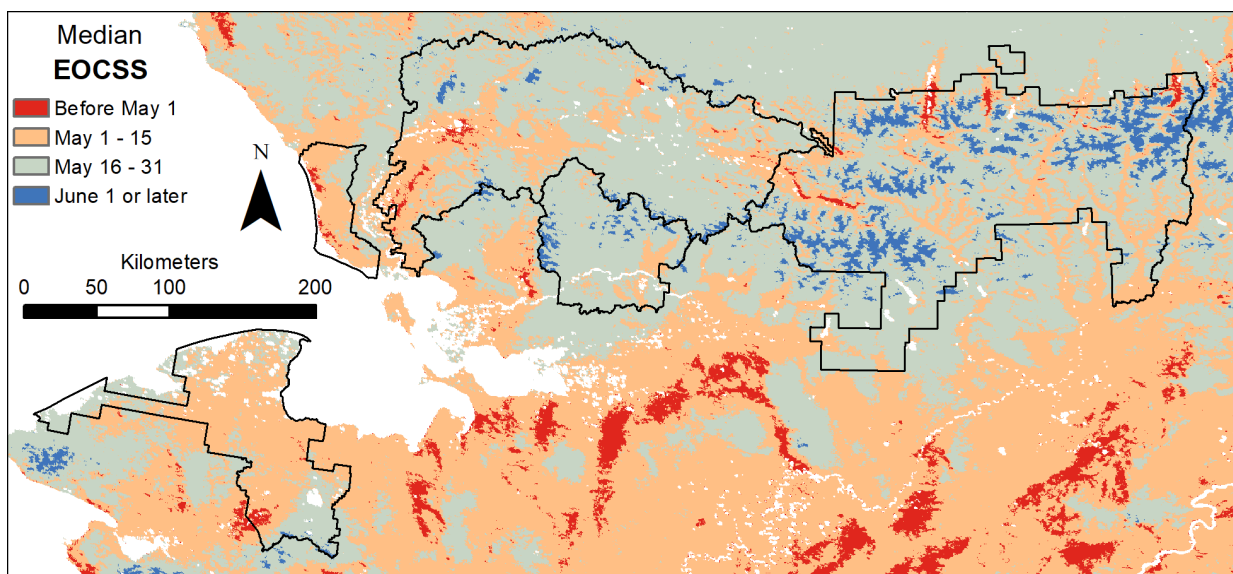


Figure A4. Median end of the continuous snow season, 2001–2020.

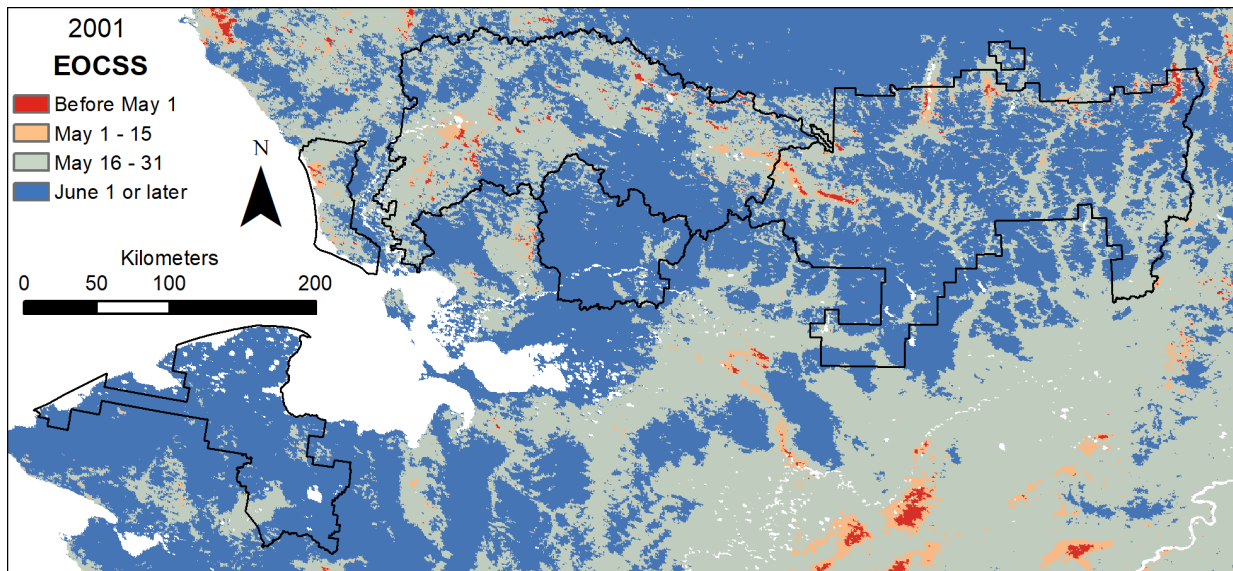


Figure A5. End of the continuous snow season in the year with the latest snow-off, 2001.

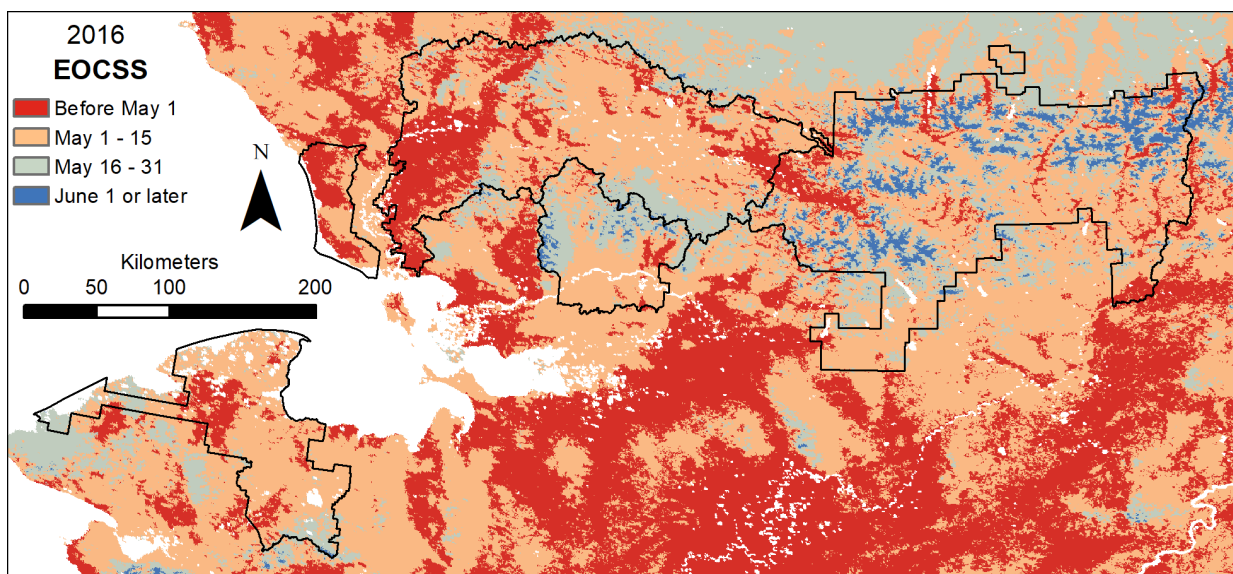


Figure A6. End of the continuous snow season in 2016, which was tied with 2004 for the earliest snow-off.

Appendix B: Green Season Maps

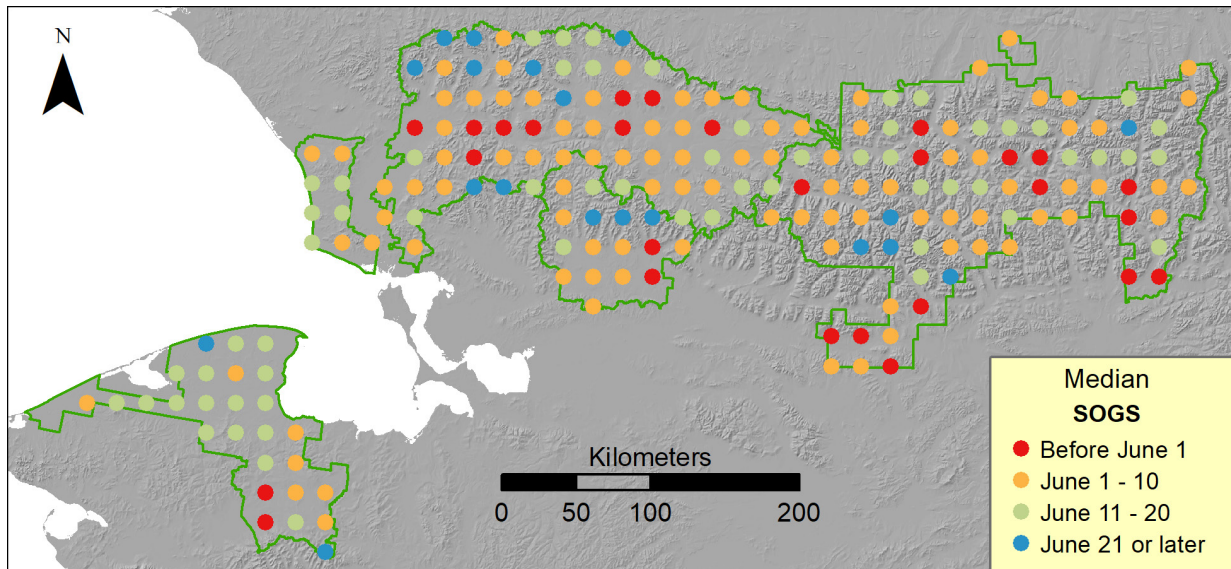


Figure B1. Median start of the green season, 2000–2020.

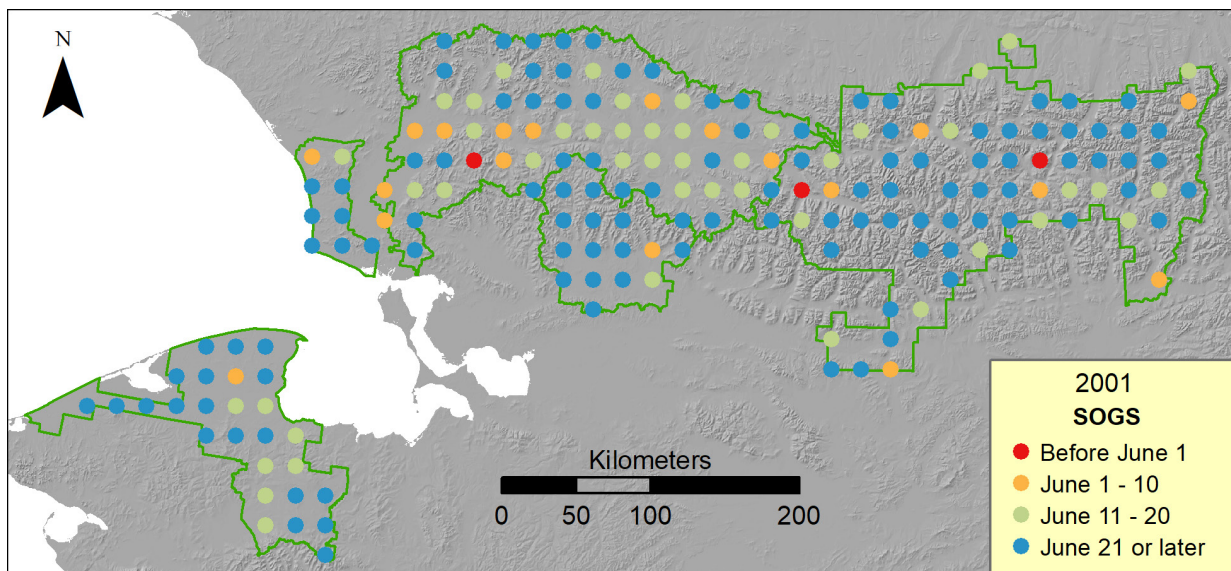


Figure B2. Start of the green season in year with the latest green-up, 2001.

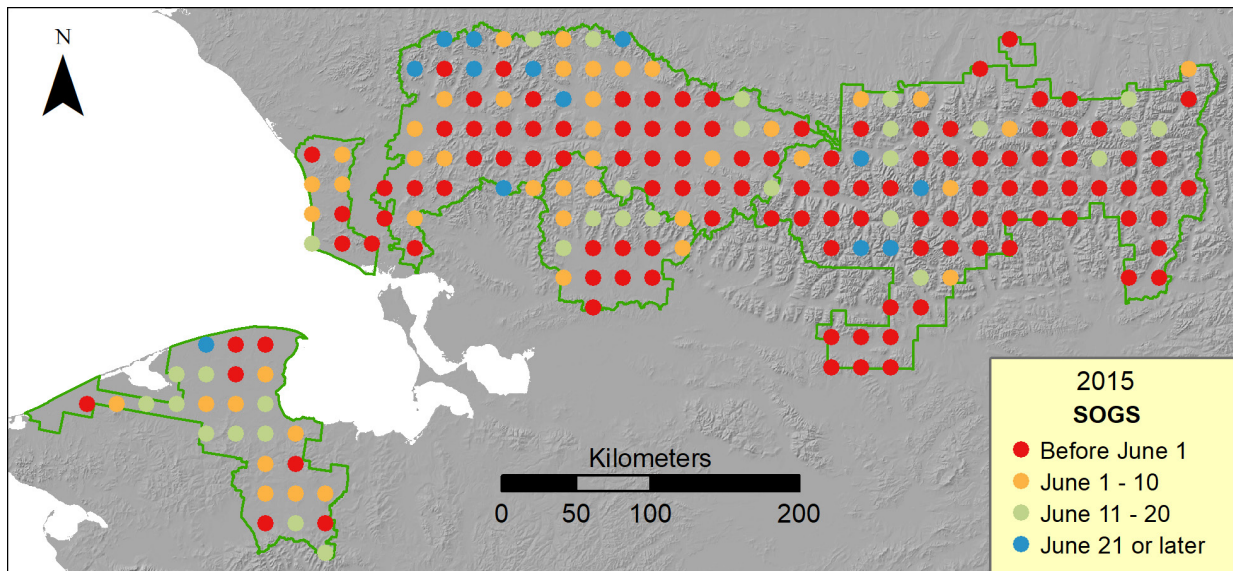


Figure B3. Start of the green season in the year with the earliest green-up, 2015.

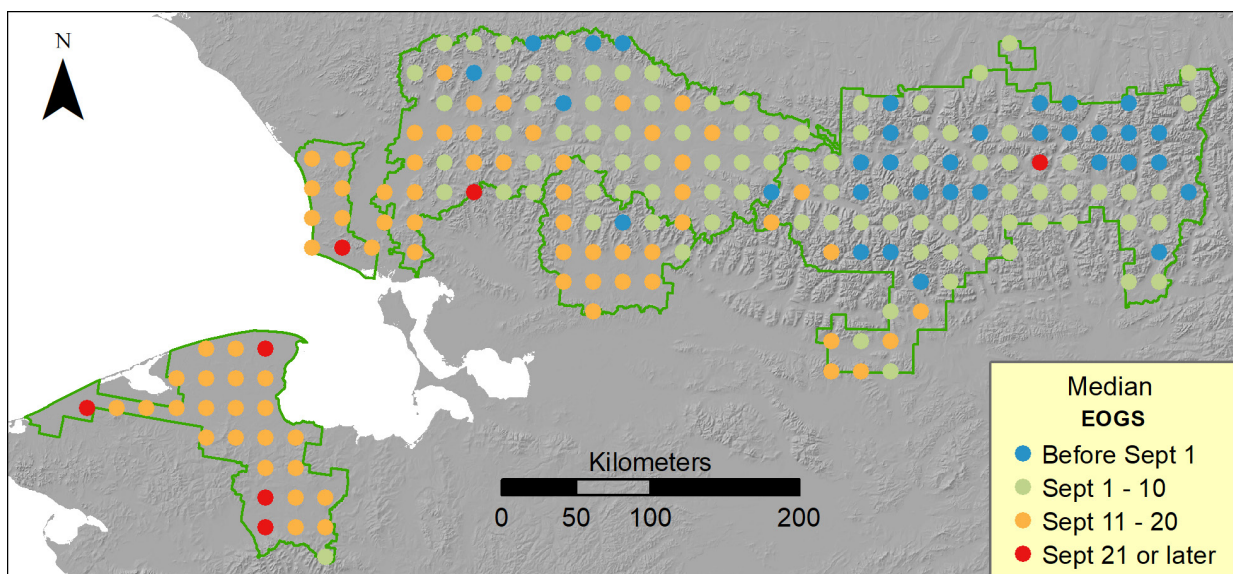


Figure B4. Median end of the green season, 2000–2020.

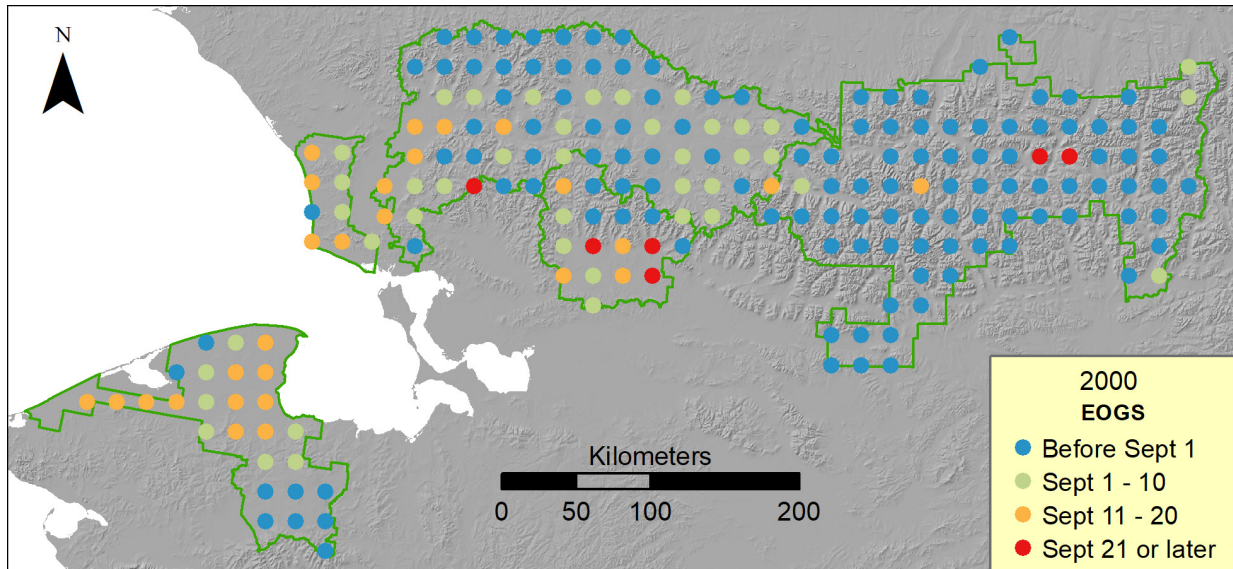


Figure B5. End of the green season in the year with the earliest senescence, 2000.

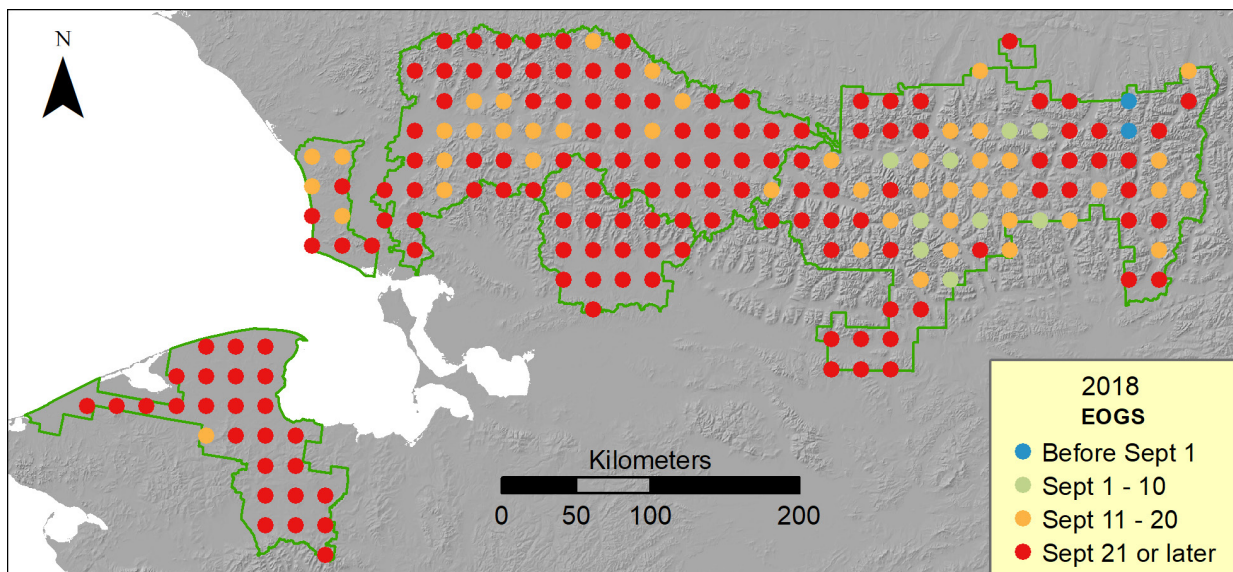


Figure B6. End of the green season in the year with the latest senescence, 2018.

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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