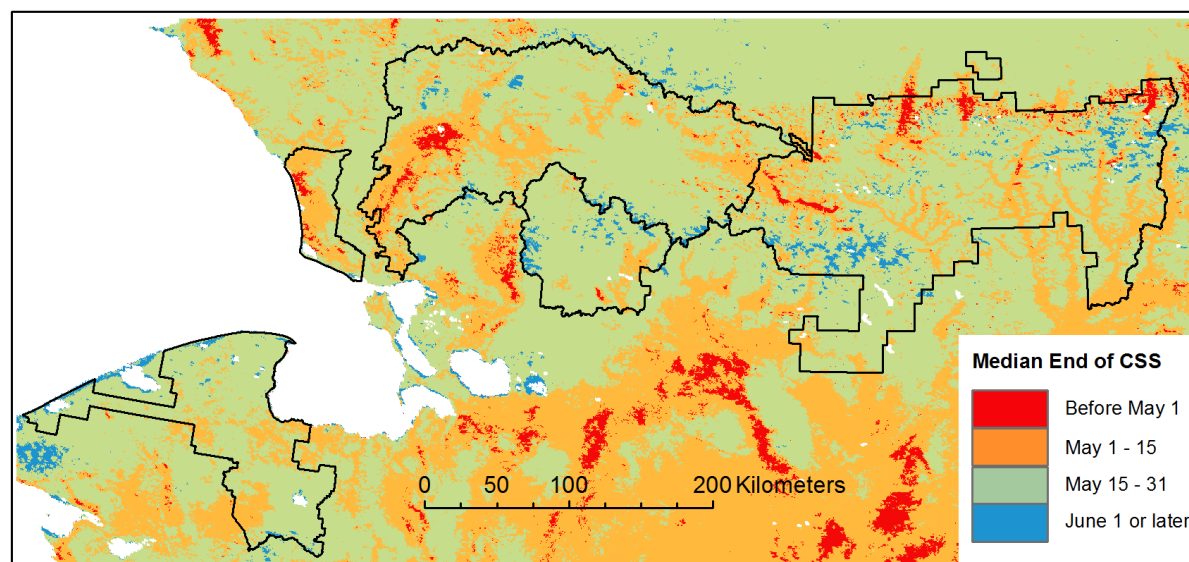
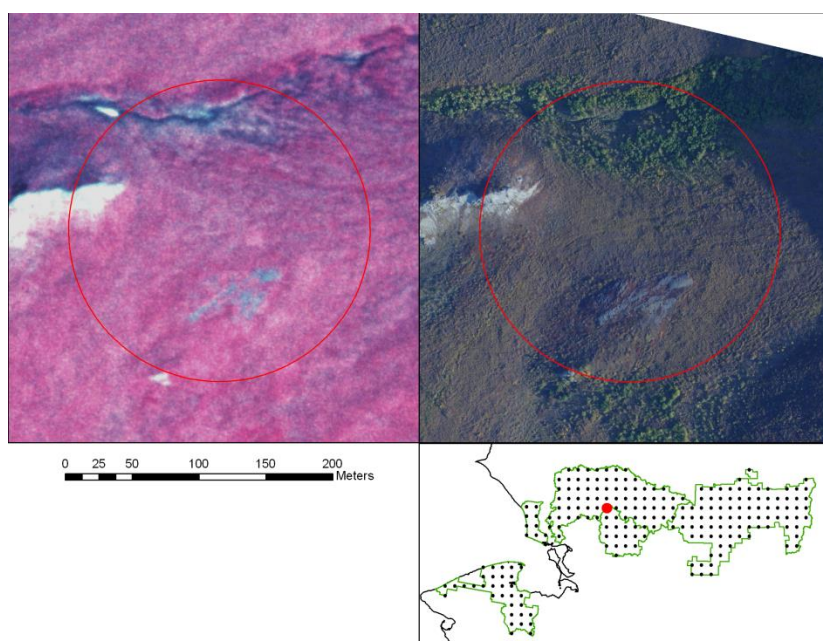




Landscape Patterns and Dynamics Monitoring Protocol for the Arctic Network

Narrative

Natural Resource Report NPS/ARC/NRR—2017/1380



ON THE COVER

Examples of monitoring projects for the ARCN Terrestrial Landscape Patterns and Dynamics Vital Sign. Above, Tall shrub increase on tundra. An area of mostly herbaceous and low shrub vegetation in 1979 (AHAP color-infrared photo, left) was colonized by tall shrubs by 2008 (small-format true color photo, right). The red dot on the inset map shows the location of the plot in the Noatak National Preserve, Alaska. Below, the median date of the end of the continuous snow season (CSS) in ARCN for the period 2001-2013.

Photograph courtesy of NPS.

Landscape Patterns and Dynamics Monitoring Protocol for the Arctic Network

Narrative

Natural Resource Report NPS/ARC/NRR—2017/1380

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February 2017

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

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All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

This report received formal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data, and whose background and expertise put them on par technically and scientifically with the authors of the information.

Views, statements, findings, conclusions, recommendations, and data in this report do not necessarily reflect views and policies of the National Park Service, U.S. Department of the Interior. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

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Abstract

The long-term monitoring vital sign “Terrestrial Landscape Patterns and Dynamics” addresses the “big-picture” of changes in ecosystems of the National Park Service (NPS) Arctic Inventory and Monitoring Network (ARCN; the five NPS units in northern Alaska). This monitoring program consists of five basic projects:

Vegetation greenness monitoring by satellite. Satellite measurements of reflected solar radiation in the red (620–670) and near-infrared (841–876 nm) bands is used to compute the Normalized Difference Vegetation Index (NDVI, an indicator of biomass). These NDVI measurements are used to track changes in the timing of the growing season and the overall greenness of the landscape across all of ARCN.

Snow cover monitoring by satellite. Satellite measurements of green (545-565 nm) and short-wavelength infrared (1628-1652 nm) light are used to track changes in the length and timing of the snow season across all of ARCN.

Vegetation and snow phenology monitoring by remote automated cameras. Cameras at five ARCN climate monitoring stations take five photographs each day through the year. These photographs are analyzed to determine the timing of the growing season and the snow season.

Land cover and landform monitoring with high-resolution aerial photographs. A systematic grid of aerial photographs taken at intervals of ten or more years to track changes in vegetation and landforms across all of ARCN.

Lake surface area monitoring by satellite. Satellite measurements of reflected short-wavelength infrared (1.55-1.75 μm) light are used to map surface water in lakes and ponds each year across all of ARCN.

Taken together these various projects provide us with broad picture of changes occurring in the dynamic landscape of Alaska’s arctic National Parks. This report contains the narrative for the Arctic Network landscape patterns and dynamics monitoring protocol.

Acknowledgments

Thanks to Matt Macander and M. Torre Jorgenson for helpful review comments. Jay Ver Hoef and Josh Schmidt provided helpful discussion about sampling design and statistical analysis, and JVH designed the trinomial analysis (See SOP #3 in the companion Standard Operating Procedures report [Swanson, 2017]).

1 Introduction

Arctic landscapes are constantly changing. Certain plants become more abundant or larger, expand into new areas, or die out; permafrost forms and thaws; wildfires burn and then vegetation grows back; rivers erode, meander, and deposit new sediment; lakes form, expand and drain; slope processes change the land shape. All of these processes are a part of landscape dynamics. The terrestrial landscape patterns and dynamics vital sign of the NPS Arctic Inventory and Monitoring Network (ARCN; Fig. 1) is concerned with the “big picture” of changes in the growing season, vegetation, length of snow season, and surface water area (Lawler et al. 2009). The length and warmth of the growing season control the amount of plant matter, which is the energy supply for all other biological processes and crucial for wildlife. Major changes in vegetation are likely to benefit some species and harm others (Jorgenson et al. 2015). A long-term increase in shrubs in the arctic has already been observed (Tape et al. 2006, Myers-Smith et al. 2011). Formation and drainage of ponds and lakes, which are important habitat for many species, are natural processes that may be accelerated by climate change (Yoshikawa and Hinzman 2003, Jones et al. 2011).

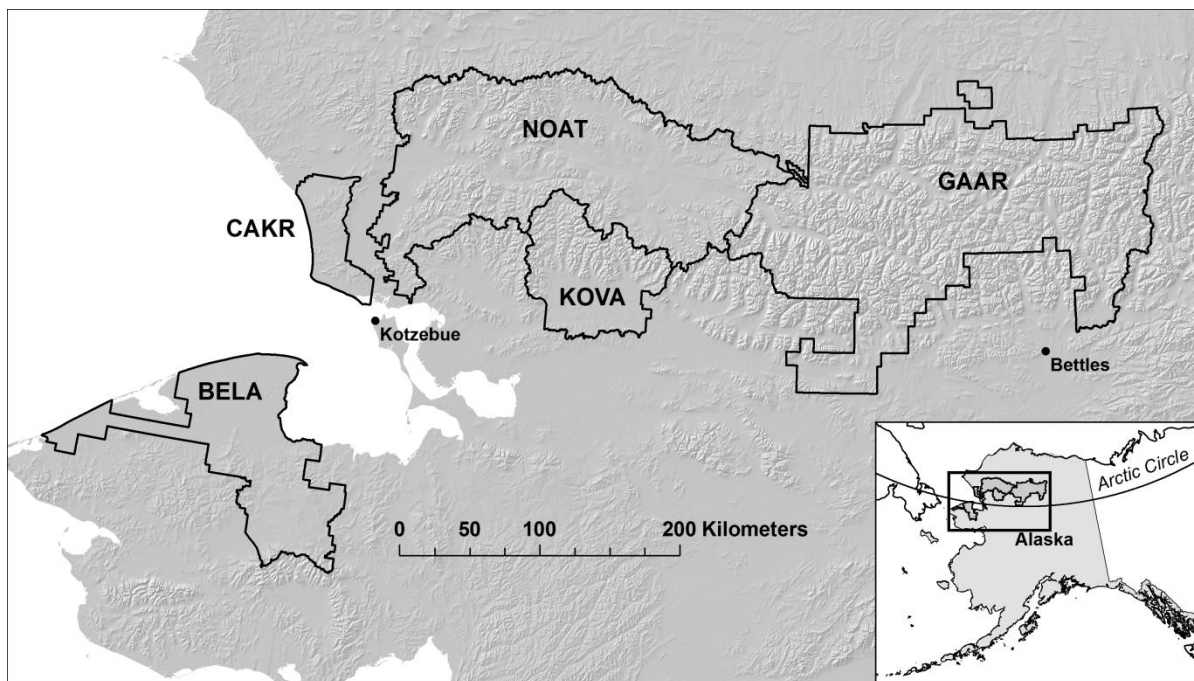


Figure 1. The NPS Arctic Inventory and Monitoring Network (ARCN). The NPS units in ARCN are the Bering Land Bridge National Preserve (BELA), Cape Krusenstern National Monument (CAKR), Gates of the Arctic National Park and Preserve (GAAR), Kobuk Valley National Park (KOVA), and the Noatak National Preserve (NOAT).

Remote sensing provides valuable tools for monitoring landscape patterns and dynamics (Stow et al. 2004). Our long-term monitoring program includes several different projects that utilize remote sensing to follow landscape change, as expressed by the following features:

Vegetation greenness and snow cover as measured from satellites. Polar-orbiting satellites with daily sampling at high latitudes have been measuring the amount of sunlight reflected from the earth in different wavelengths for over 30 years. We can compute an index of the earth's greenness from these measurements and determine the timing of the growing season and its peak greenness. We can also determine the length of time that snow is present.

Vegetation greenness and snow cover measured by remote automated cameras at ARCN climate monitoring stations. These photographs provide a close-up view of changes in the seasons that can be linked directly to weather data.

Vegetation and other land surface features visible on high-resolution aerial photographs. We have a set of detailed aerial photographs taken on a 20-km grid across the Arctic Network. On these photographs we can measure things like shrub cover, tree cover, and area of small ponds caused by thawing permafrost. We plan to repeat these photographs every 10 years and compare them across the dates to get a network-wide view of changes over time.

Area of lakes and ponds as determined from satellite images. Water levels in lakes and ponds in permafrost regions can change rapidly, and lakes sometimes drain entirely. These changes can be tracked using publicly available, moderate-resolution satellite imagery that has been collected annually since 1999 and sporadically back to 1985.

The five projects that ARCN is using to monitor these features of landscape change are described in detail in this narrative report. Standard Operating Procedures (SOPs) for this protocol are detailed in the SOP companion document (Swanson 2017).

2 Vegetation Greenness Monitoring by Satellite

2.1. Background

Vegetation productivity and phenology (green-up and senescence) can be monitored over large areas by satellite imagery. Our goal is to track both year-to-year variability and long-term changes in vegetation productivity during different parts of the growing season. This information will help us understand variations in wildlife forage availability and habitat quality (e.g. Griffith et al., 2002), as well as trends in vegetation structure and ecosystem productivity. Our specific monitoring objectives are to analyze normalized difference vegetation index (NDVI) as measured by satellite for the whole of ARCN for changes through time in the timing and overall greenness of the growing season.

Satellite measurements of NDVI are a widely accepted measure of vegetation greenness and a proxy for productivity or biomass (Tucker and Sellers 1986). Surface reflectance values for near infrared (NIR, ~850 nm) and red (R, ~645 nm) wavelengths are used to compute NDVI. Spectral reflectance at a wavelength is the ratio of the outgoing (reflected) radiation to the incoming solar radiation. Surface reflectance is spectral reflectance that has been corrected for atmospheric effects, and represents spectral reflectance at the ground surface. NDVI is computed from the surface reflectance of remotely sensed imagery: $NDVI = (NIR - R)/(NIR + R)$. Green vegetation reflects strongly in the NIR band and absorbs strongly in the R band. Thus densely vegetated areas have NDVI approaching 1, while unvegetated areas have NDVI near or below zero.

Vegetation biomass in the arctic consists almost entirely of slow growing, long-lived perennial species whose growth is limited by cold (Billings and Mooney 1968). Most of the annual rise and fall in NDVI, and the between-year variations in NDVI for a particular season, are the result of different amounts of leaf area produced by deciduous perennials in response to variations in temperature (Huemmrich 2010). The immediate effect of cold weather during May, June and July in the arctic and subarctic is to delay or reduce the formation of leafy biomass, thus reducing NDVI. Warm summers lead to greater vegetation productivity, with important implications for wildlife (Griffith et al. 2002). In contrast to short-term changes, long-term changes in NDVI (i.e., over a period of 10 or more years) suggest a change in perennial vegetation biomass and structure. Vegetation greenness has increased in recent decades across much of the circumpolar arctic (Beck and Goetz 2011, Epstein et al. 2013). Shrub tundra has a higher NDVI than herb-dominated tundra (Jia et al. 2004), and increasing greenness of arctic Alaska over the period 1982-2003 has been attributed to increasing shrub cover (Verbyla 2008).

Multi-day compositing of NDVI values helps to circumvent problems caused by clouds obscuring the ground (Holben 1986). The maximum NDVI value is selected for each pixel from a range of days (typically one or two weeks), and these maxima are displayed in a composite image that mimics a single cloud-free scene. These NDVI composite images can then be compared to track changes in vegetation greenness through the seasons or between years.

The yearly cycle of NDVI in individual pixels can also be analyzed to extract metrics such as start of the growing season and peak NDVI (Swets et al. 1999, Zhu et al. 2013). Values for these metrics can then be analyzed for trends across multiple years.

The satellite greenness monitoring described in this section is linked to other monitoring as follows. Greenness phenology is closely related to snow phenology, the subject of satellite monitoring of snow cover (Chapter 3). Our remote automated cameras (Chapter 4) provide a close-up view of the phenology changes and provide ground verification of the satellite results. Monitoring of vegetation structure and composition by remote sensing (Chapter 5) and as a part of the ARCN Vegetation and Soils Vital Sign (Swanson and Neitlich 2016) provide insights into specifically what vegetation changes are responsible for observed changes in greenness. Greenness phenology monitoring will be useful in our understanding of wildlife population dynamics, such as Dall's sheep and muskoxen (Lawler et al. 2009).

2.2. Satellite Data Sources

The NDVI data used by this protocol is computed from the MODIS (Moderate Resolution Imaging Spectroradiometer, <http://modis-land.gsfc.nasa.gov/>) sensor aboard the Terra satellite as a part of the eMODIS project (<https://lta.cr.usgs.gov/emodis>; Jenkerson and Schmidt 2009, Jenkerson et al. 2010, Brown et al. 2015). eMODIS NDVI in Alaska is currently produced only from the Terra satellite and is available at 250 m, 500 m, or 1 km resolution and Alaska Albers projection, with 7-day compositing. The eMODIS product includes a data quality image that identifies pixels covered by clouds or snow on the composite. It is available from the year 2000 to the present. Images may be downloaded as zipped GeoTIFF images from the USGS (<http://earthexplorer.usgs.gov>). The composites have been additionally processed to compute metrics by the University of Alaska Geographic Information Network for Alaska (GINA). More information is available from <http://docs.gina.alaska.edu/ndvi/modis.html>.

MODIS NDVI composites of the entire globe are also produced for 16-day periods (MOD/MYD13A2) with a sinusoidal projection by the Land Processes Distributed Active Archive Center (LP DAAC; https://lpdaac.usgs.gov/dataset_discovery/modis). This product is less prone to cloud contamination than the eMODIS composites (Verbylla 2015), and is produced using data from both the Terra and Aqua satellites, but it is highly distorted in northern Alaska due to the use of a sinusoidal projection and our distance from the project origin. This product may be used in the future, particularly if the eMODIS product is discontinued.

Another source of satellite NDVI data is the AVHRR (Advanced Very High Resolution Radiometer, <http://noaasis.noaa.gov/NOAASIS/ml/avhrr.html>) weather satellite data. These data have a longer period of record than MODIS but coarser (1 km) resolution. They have been processed into 1-km composites by the USGS-EROS (<https://lta.cr.usgs.gov/AVHRR> and <https://lta.cr.usgs.gov/NDVI>). The composites are available from 1989 to the present for periods 7 and 14-16 days long with irregular start/end dates. Images may be downloaded from the USGS <http://earthexplorer.usgs.gov>). These composites have been additionally processed to compute metrics (for 1995 to the present) by the University of Alaska Geographic Information Network for Alaska (GINA). The AVHRR data have also been processed into NDVI composites by the Global Inventory Modeling and Mapping Studies (GIMMS 3g) project of the NASA Goddard Space Center (Pinzon and Brown 2004). These data have coarser resolution (8 km pixels) and lacks cloud screening but covers the full AVHRR period of record (1982 to 2006).

Comparison of NDVI values from AVHRR and MODIS sources have shown them to have similar relative magnitudes, though NDVI values calculated from MODIS data are typically higher due to differences in the exact definitions of the wave bands (Gallo et al. 2005). The AVHRR data are important for the longer period of record that they provide (Verbylla 2008, Swanson 2010), but for future monitoring this protocol makes use of the MODIS data only, because of its ease of use (constant compositing periods between years), higher spatial resolution, and calibration issues with AVHRR.

2.3. Data Management, Analysis, and Reporting

The MODIS NDVI composites are downloaded from the USGS (<http://earthexplorer.usgs.gov>). The NDVI metrics are generated and stored at the University of Alaska Geographic Information Network for Alaska (GINA; <http://www.gina.alaska.edu>). All of these products are available as Alaska-wide images that can be cropped to the extent of ARCN, without a need for permanent storage on NPS computers. Thanks to the pre-processing completed by GINA, the metrics require less processing by ARCN, but this protocol recommends processing of the NDVI composites by ARCN in the event that the metrics from GINA become unavailable in the future and because the composites provide valuable information about the greenness of the spring and fall seasons that is not available from the GINA metrics.

2.3.1. Analysis of eMODIS NDVI composites. The NDVI composites are analyzed directly by selecting specific time intervals during the growing season and comparing these values between years. We summarize the MODIS NDVI composites for 3 key portions in the growing season: green-up (June), summer maximum greenness (late July through early August), and senescence (mid-August through early September). Green-up and senescence are of interest because they provide information on the length of the growing season and timing of the seasons (phenology). They are times of rapid change and very sensitive to annual variations. The summer peak of greenness represents the maximum biomass produced in a particular growing season.

Temporal trends can be examined by trend analysis of individual pixels through time (Verbylla 2008). For trend analysis on a pixel-by-pixel basis, we use the Mann-Kendall test, a non-parametric test for monotonic change of any kind across the time series (Helsel and Hirsch 2002). It is implemented using "raster", "rgdal", and the "rkt" or "Kendall" packages of R statistical software (Hijmans 2015, Bivand et al. 2015, McLeod 2011, Marchetto 2015).

Missing data are common in individual weekly eMODIS NDVI composites, due to clouds. NDVI changes rapidly during these time periods, and thus we cannot simply take the average or maximum of the June composites to represent green-up: if data are missing for the latter half of June the season would appear falsely "brown" because leaf-out is always less advanced in early June. An analogous problem exists for the senescence season. One solution is to compute the percentile scores for each pixel in each weekly composite relative to all the years of record. In a given season these tend to be consistent: if the second week of June was unusually "green", the third week will typically be also. We assemble all available June percentile scores for each year (up to four) and compute the mean or median to represent that year's greenup period. A Mann-Kendall trend test is then run on a per-pixel basis to determine if spring greenness has changed through time.

Another way to study the timing of green-up and senescence is to locate the midpoint of the seasonal change. In the spring this is the date when the greenness is halfway between the value just before green-up begins and the summer maximum; for fall it is the date when greenness is halfway between the summer maximum and late fall-early winter value. This method has the advantage of providing us with a concrete date of green-up or senescence, rather than an abstract rank, for each year. It is also directly comparable to the green-up and senescence midpoints computed for the phenology camera data (see section 4). This method involves computing the greenness of value for each pixel that is halfway between maximum and the value at either the start or end of greenness (available from the GINA metrics, described below); interpolating the greenness between the compositing periods; and then finding the date on the interpolated curve that crosses the half-greenup or half-senesncece value.

Yet a third measure of greenness phenology is provided by GINA's start of green season and end of green season, discussed below.

The annual maximum NDVI value can be obtained locally by scanning through the six mid- to late-summer eMODIS NDVI composites (July 9 through August 19) for the highest NDVI. (It is also available from the GINA metrics image, see below). Trend analysis is carried out directly on seasonal maximum NDVI values.

Year-to-year variations can be summarized for geographic regions such ecological sections, wildlife home ranges, or NPS administrative units, by computing the mean or median phenology metric for the region (Fig. 2). Greenness varies greatly across the landscape, but year-to-year variation tends to be roughly synchronous across different environments in any given area.

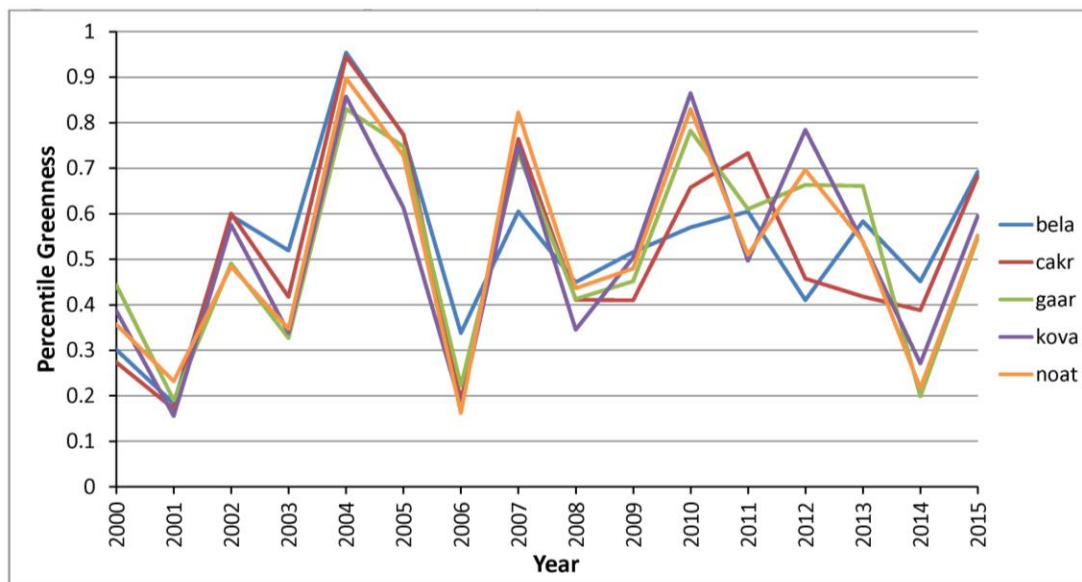


Figure 2. June NDVI converted to percentile rank and then averaged over the ARCN NPS units.

Cloud contamination of eMODIS composites is generally not a problem for analyses involving the annual maximum NDVI, since this value is derived from 6 weeks of summer composites and it is very unlikely that cloudy pixels will be chosen. The mid- to late-summer eMODIS composites also cover a seasonal window when NDVI tends to plateau. Cloud contamination is a potential problem for our spring and fall analysis, however. Our use of the median of several spring or fall composite values mitigates the problem, since the median is less strongly influenced by anomalous low values than the mean. However, the analyst should be aware that for a small study area, individual years could have erroneously low values if cloud contamination persists through the entire season.

2.3.2. Analysis of NDVI metrics from UAF GINA. A set of NDVI with metrics is derived from the MODIS and AVHRR NDVI composites by UAF GINA (Zhu et al. 2013). These metrics are stored as an image with the following 12 bands:

1. 1. Onset of greenness /Start day of Season (SOS)
2. 2. NDVI value of onset of greenness
3. 3. End of greenness /End day of Season (EOS)
4. 4. NDVI value of end of greenness
5. 5. Duration of greenness – day range between onset of greenness and end of greenness
6. 6. Day with maximum NDVI
7. 7. Value of maximum NDVI
8. 8. Range of NDVI
9. 9. Rate of green up
10. 10. Rate of senescence
11. 11. Time-integrated NDVI
12. 12. Metrics ‘flag’, where -1=no data, 0=not valid data, 1=good data

Metrics are currently available for 2000 through 2013 for MODIS and 1995 through 2012 for AVHRR. Band 7 (maximum NDVI) may be drawn from this metrics image rather than computed from the eMODIS data to save time, if the metrics are kept up-to-date. Our test analyses of bands 1 (start day of green season) and 3 (end day of green season) showed that they are close to the snow-off and snow-on days, respectively, presumably because the NDVI of bare ground, leafless plants, and plant litter is higher than snow. We are analyzing snow-on and snow-off directly using MODIS snow products in part 3 of this protocol, and thus have chosen not to analyze bands the metrics 1 and 3 for phenology information.

Data from nearby weather stations are useful for understanding trends in NDVI. Long-term records are available at Bettles and Kotzebue (Fig. 3). ARCN climate monitoring stations installed in 2011-2012 will be valuable for future analysis (Fig. 3).

2.4. Operational Requirements

Re-analysis of MODIS NDVI is planned for every 5 years, beginning in 2010. More frequent analysis may be made if an individual year is of special interest (e.g., a summer with record warmth). Every 5 years when the project is due for update, approximately 2 weeks of analyst time is required for data processing and 1 week for report preparation.

Processing of the data as described in the SOPs (Swanson 2017) is by scripts written in the Python language that run ArcGIS geoprocessing functions, and scripts that run R statistical software. The process is largely automated, but knowledge of ArcGIS, Python, and R are needed to troubleshoot the processes. Processing of NDVI data by GINA has been supported by a cooperative agreement with NPS.

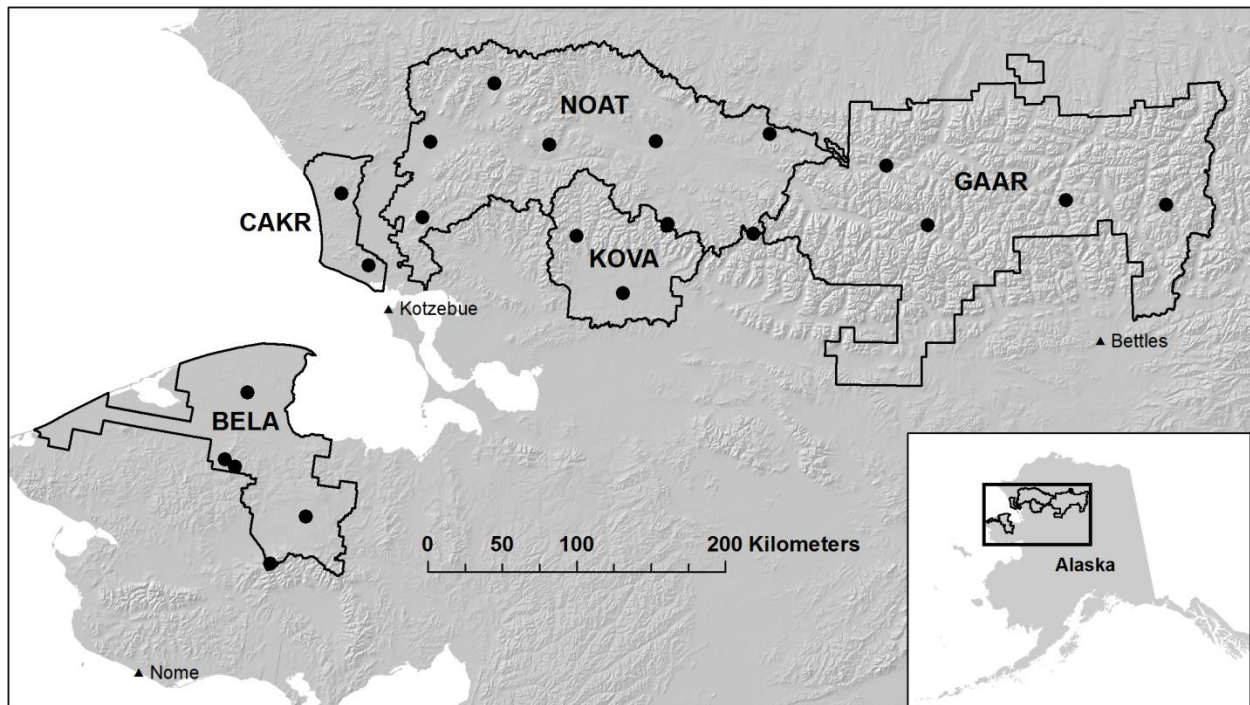


Figure 3. Location of ARCEN climate monitoring stations.

Like all satellites and sensors, the MODIS sensor and Terra satellite will eventually need replacement. Currently NASA's Visible Infrared Imaging Radiometer Suite (VIIRS) will likely be the replacement (see <https://jointmission.gsfc.nasa.gov/viirs.html> and <https://viirsland.gsfc.nasa.gov/index.html>). Revised SOPs will be needed when the time comes to switch to this different sensor.

3 Snow Cover Monitoring by Satellite

3.1 Introduction

Snow dominates the arctic environment. It covers most of the landscape for over half of the year, and all the organisms that live in the arctic beyond the short summer must be adapted to deal with snow and cold. The snow cover in the Arctic usually persists continuously through the long winter, and it disappears quickly in the spring, generating a major runoff event (Kane et al. 2000, Olsson et al. 2003). The goal of this monitoring project is to track year-to-year variability and long-term changes in the timing of snow cover establishment and loss.

Over the past century the spring snow cover area across North America has become smaller in concert with rising temperatures (Brown and Robinson 2011). A reduction in the length of the snow season since 1940 has been observed in Alaskan arctic at Barrow (Hinzman et al. 2005). Meanwhile there has been a trend toward higher total snow-water content since the late 1970s across the circumpolar Arctic (Muskett 2012). A change in snow cover duration in ARCN would have widespread ecological implications, influencing the land surface energy budget, the hydrologic cycle, the susceptibility of plants to frost damage in early spring, access by wildlife to forage, and protection of subnivalian wildlife from weather and predators (Eastland et al. 1989, Euskirchen et al. 2007, Callaghan et al. 2011, Tape et al. 2010). Shrubs have been increasing in the Arctic over recent decades, and snow depth has a positive feedback relationship with shrub cover in the arctic (Sturm et al. 2005, Tape et al. 2006).

The MODIS (Moderate Resolution Imaging Spectroradiometer) Terra satellite has been gathering data daily since February 2000 that can be analyzed to determine the extent of snow cover in ARCN. The present protocol gives procedures for future periodic reassessments of snow cover by the methods used in Swanson (2014).

The snow cover monitoring described in this section is linked to other monitoring as follows. Snow phenology is closely related to greenness phenology, the subject of satellite monitoring of snow cover (Chapter 3). Our remote automated cameras (Chapter 4) provide a close-up view of the snow cover and provide ground verification of the satellite results. Snow cover monitoring is useful in our understanding of wildlife population dynamics, such as Dall's sheep and muskoxen (Lawler et al. 2009).

3.2 Data Source

The MODIS Terra Snow Cover Daily L3 Global 500m Grid data collection 5 (MOD10A1; NASA 2013) from the National Snow and Ice Data center (NSIDC: <http://nsidc.org/data/modis/>) are used to determine the snow season. The MODIS Terra satellite gathers multispectral data daily at approximately 10:30 AM local time. Data are available from this satellite from February 2000 through the present. In cloud-free pixels, snow cover (snow present or not present), snow albedo (the percentage of solar radiation reflected), and fractional snow cover (estimated snow cover in percent) are mapped by the NSIDC using a snow mapping algorithm based on the Normalized Difference Snow Index (NDSI) and other criteria (Hall et al. 2006, Riggs et al. 2006).

Determination of the start and end of the snow season is complicated by clouds and by the fact the 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, is performed by the Geographic Information Network of Alaska (GINA) at the University of Alaska, Fairbanks (see <http://www.gina.alaska.edu/projects/modis-derived-snow-metrics>). The GINA snow metrics algorithm involves repeated passes through the daily time-series data for each pixel, forward and backward in time within each snow year. The very first and last snow days in the snow year are located, 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). For more details of the algorithm used to derive the snow cover metrics, see Zhu and Lindsay (2013) and Lindsay (2015).

The snow metrics data are posted as a single multiband image of the entire state of Alaska for each year, with data as integers representing day numbers for first snow day, last snow day, etc.

3.3 Data Analysis, Management, and Reporting

Analysis of data for 2000–2013 indicated that day numbers for first snow day and start of continuous snow season contain errors due to the failure to sense a snow cover before winter darkness arrives for the season (Swanson 2014). Long-term median values appear for these two metrics appear realistic, however. The end of continuous snow season and last snow day occur well after the sun has returned in the spring, and data appear reliable. Day numbers for the two spring snow metrics in individual pixels can be tested for long-term trends using the Mann-Kendall test as described in section 2.3.1 above. Averages or medians of day numbers such as these over large geographic areas are difficult to interpret, with much local variation due to factors such as elevation and aspect. However, the deviation of each pixel from its long-term median can be computed by year and summarized for geographic areas, such as wildlife home ranges, NPS units, or ecological units (Fig. 4).

3.4 Operational Requirement

Re-analysis of the data is planned every 5 years. A person with proper training and software can make the basic analyses of snow data for a 5-year update in about one week, with report preparation requiring a second week. Modification of processes for new sensors that will appear in the future, i.e. after about 2020, will require more time, at least twice as long, perhaps more.

This project relies on continued operation of the MODIS satellite or similar sensor, production of MODIS Terra Snow Cover Daily L3 Global 500m Grid (MOD10A1) by the National Snow and Ice Data Center, and processing of the data into metrics by UAF-GINA. UAF-GINA will probably require some level of funding support to continue to provide this service to NPS in the future. In addition, the algorithm used by GINA will require modification to perform properly with MODIS MOD10A1 collection 6 (Riggs et al 2016), which is a reprocessed and improved version of the data. The conversion between the two versions of the data was in progress in 2016. We expect the MODIS sensor to be replaced by the VIIRS sensor (Cao et al. 2013) within the next ten years. This will require modification of our workflow but not the overall concepts or goals of the protocol.

Summary of the snow metrics data from GINA for the ARCN requires a person familiar with GIS and image processing, including scripting to facilitate batch processing. The processing can be done in ArcGIS or R statistical software with using the "raster" and "rgdal" packages (Hijmans 2015, Bivand et al. 2015). The latter is more efficient for most purposes and is currently the basis for our SOPs (Swanson 2017). The Mann_Kendall trend test on a pixel-by-pixel basis is performed in R using the "Kendall" or "rkt" packages (McLeod 2011, Marchetto 2015).

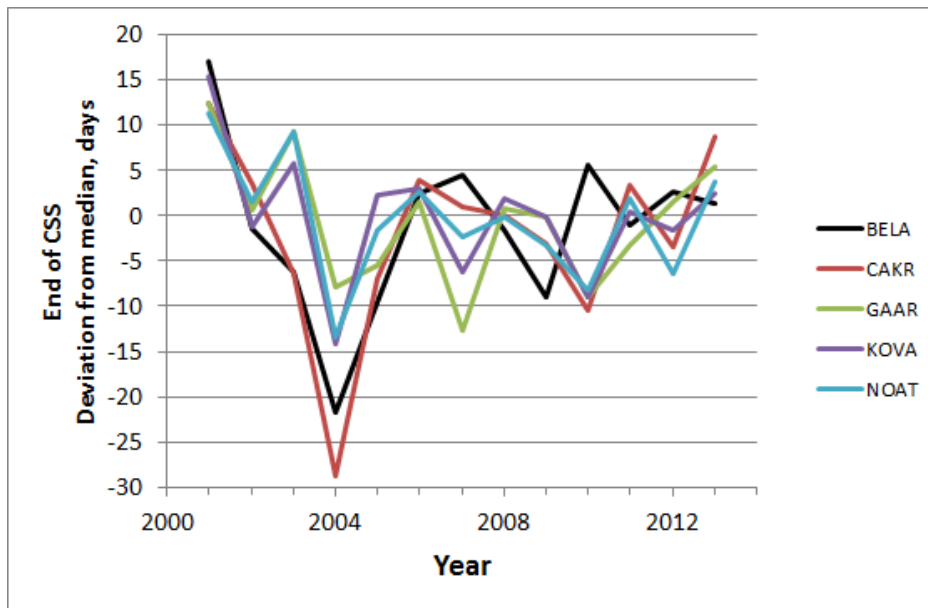


Figure 4. Mean deviation from the typical (median) end of continuous snow season by NPS unit by year (Swanson 2014). Negative value indicate median end of CSS that was earlier than the long-term median by the indicated number of days.

4 Vegetation and snow phenology monitoring by remote automated cameras

4.1 Background

Remote automated cameras allow us to monitor phenology at remote sites from a vantage point on the ground. Cameras can be used to monitor vegetation green-up and senescence, and snow cover establishment and loss (Richardson et al 2007, Sonnentag et al. 2012, Sheriff et al. 2010). The goal of this monitoring project is to obtain a detailed, long-term record of important seasonal changes in vegetation and snow at selected index sites.

For vegetation monitoring, an analysis area is defined on the photograph, and the color data are used to compute the greenness of the vegetation through the year. The snow cover in similar analysis areas can be estimated by classification of each photo pixel as snow or non-snow.

Camera data can be used as ground truth for satellite measurements of greenness and snow cover and as long-term records of representative index sites. Cameras provide a view of the landscape that closely resembles what a person on the ground would see, and hence the images are useful for time-lapse animations and other interpretive products.

In ARCN, automated cameras are co-located with climate monitoring stations, which makes installation and maintenance more economical, and allows us to directly link phenology to weather observations. Phenology camera stations were chosen from the set of all climate stations to provide a homogenous foreground area that could be used for analysis of greenness and local snow cover. Additional background analysis areas are available at some sites; these are especially useful for tracking the decline in spring snow cover.

4.2 Cameras

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 in NOAT was made in 2015 (Figs. 5 and 6; Table 1). These cameras are designed for year-round outdoor use and were installed with a solar panel and large battery to allow continuous operation through the winter. Photographs are taken at the full resolution available on the cameras (2592 by 1944 pixels, jpg format), five photos per day at hourly intervals centered at solar noon. The cameras face generally north to minimize glare from direct sunlight. A date and time stamp is embedded at the bottom of each photo and in the photos' exif metadata. Photos are saved in jpg format on an internal SD card.

4.3. Data Management and Analysis

4.3.1 Photo retrieval and storage

Photographs are retrieved once per year during the annual climate station site maintenance visit. The photos are copied to a network drive with folder structure that identifies the site name and year.

4.3.2. Analysis zones

The analysis zone(s) at each station are a rectangle defined on the photos by pixel coordinates (Fig. 7).

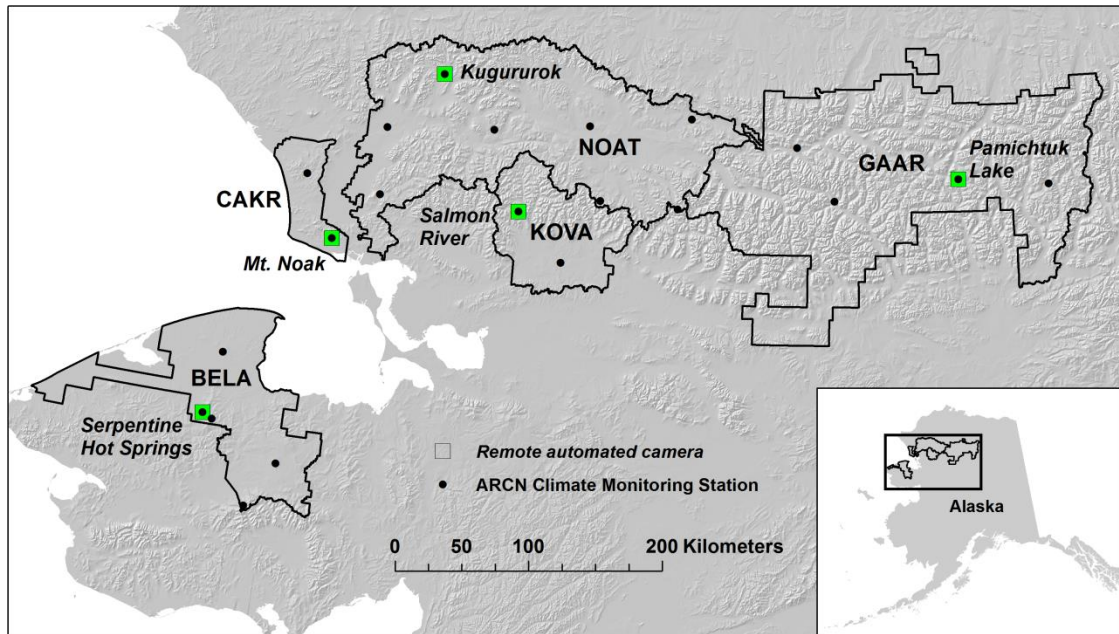


Figure 5. Location of phenology cameras in ARCEN.



Figure 6. Typical phenology camera setup. The camera is the metal cylinder marked with an arrow. Climate monitoring instruments are also attached to the tripod. The solar panel is visible facing away from the photo lower on the tripod. This is the Serpentine Hot Springs climate station in BELA.

Table 1. ARCN Phenology Camera Locations

Station Name	AICC ID	Latitude	Longitude WGS84	Latitude	Longitude	Elevation, m	NPS unit
		Deg. decimal min. WGS84		Decimal degrees WGS84			
Mt. Noak	MNO	67° 08.4860'	162° 59.6720'	66.29594°	-164.52042°	247	CAKR
Pamichtuk Lake	PAM	67° 45.977'	152° 09.854'	67.76630°	-152.16420°	956	GAAR
Salmon River	SRW	67° 27.5940'	159° 50.4750'	67.45990°	-159.84130°	385	NOAT
Serpentine Hot Springs	SRT	65° 51.1380'	164° 42.4690'	65.85230°	-164.70780°	158	BELA
Kugururok		68° 19.0030'	161° 29.5180'	68.31672°	-161.49197°	311	NOAT

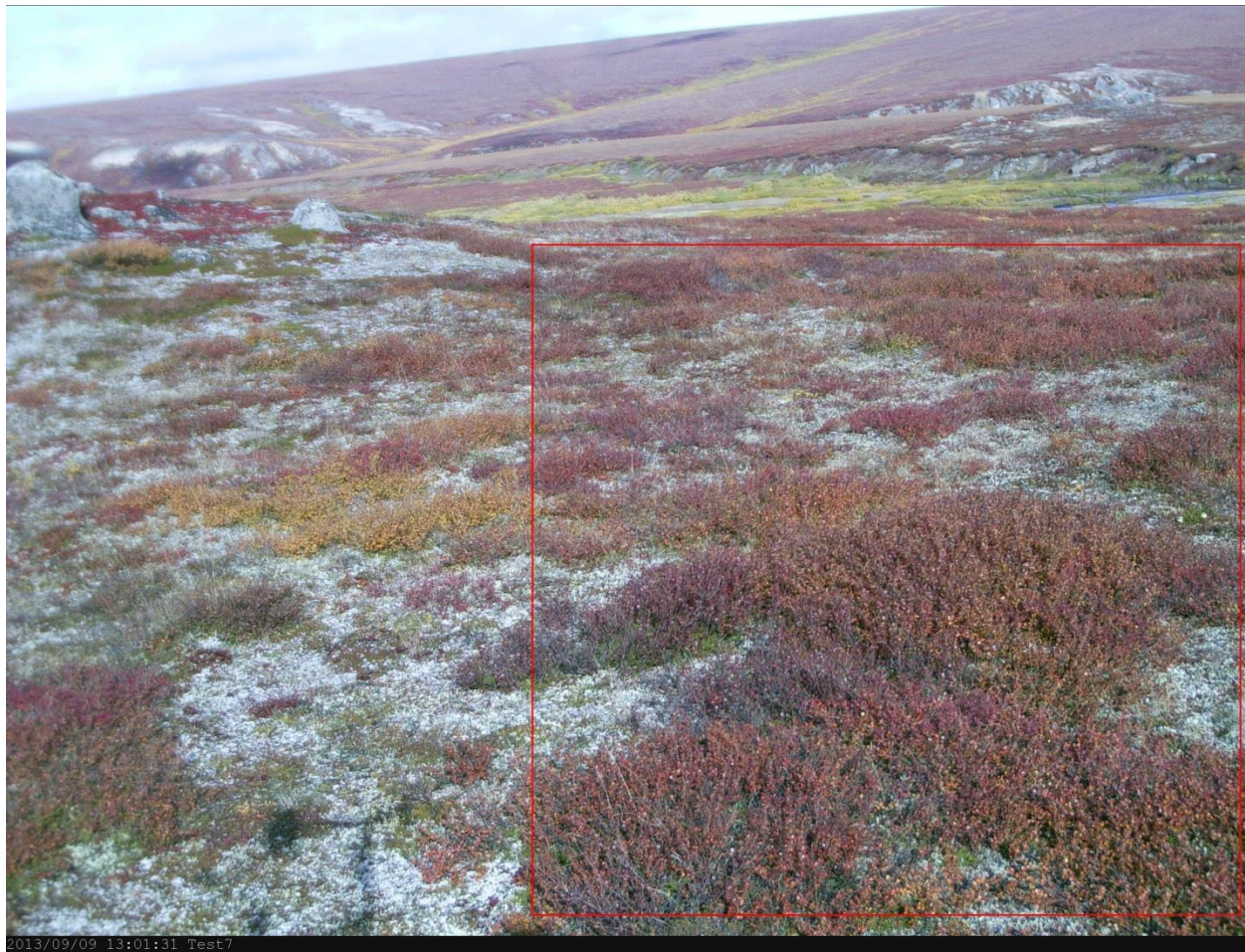


Figure 7. Example phenology camera photograph. An analysis zone with relatively uniform vegetation is outlined in red. Serpentine Hot Springs climate monitoring station, BELA, 9 Sept 2013.

4.3.3. Extracting data from photos and computing greenness

Camera images are stored as 3 digital counts: numbers between 0 (dark) and 255 (bright) for red, green, and blue (R, G, and B) in each pixel. The RGB digital counts are extracted from the analysis zone in each photograph by an automated process (a script written in the Python language, Lunh and Ellis 2002), and read into a numerical array for calculations. The data are corrected for differences in illumination (due to clouds, haze, changing sun angle, etc.) by computing greenness indices from the numerical counts for the three color bands. Two useful greenness indices for vegetation are (Richardson et al. 2007, Sonnentag et al. 2012):

“Excess green”: $\text{ExG} = 2G - (R + B)$

“Green percent”: $g\% = 100 * G / (R + G + B)$

These indicators correlate well with one another and with NDVI (a measure of vegetation productivity computed from red and near infrared light; see Chapter 2 above) as measured from the ground or satellite; they also correlate well with on-the-ground measurements of vegetation productivity (Richardson et al. 2007, Westergaard-Nielson et al. 2013). The value for each index is averaged for the analysis zone on each photo.

4.3.4 Extraction of greenness phenology metrics

To obtain a single greenness value for each day we take the median of the 5 daily measurements. The median is less sensitive to rare anomalous values than the mean. Our practice differs from that recommended by Sonnentag et al (2012) and adopted by the NPS Northeast Temperate Network (Tierney et al. 2013), where the 90th percentile value is computed for a 3-day moving window. We chose the median because our data show roughly equal scatter in both the high and low directions from a central tendency. In contrast, the NETN data is composed of many frames per day (32) over a longer time period (16 hours) and is obviously skewed, with most values clustered near an upper limit, and the low values are anomalous. In our data, illumination conditions are usually quite similar for all 5 daily frames, e.g., all sunny or all foggy, and all are within about 2 hours of noon, so the daily median provides a good summary for the daily values. Contrary to what one would expect, there is no simple relationship between time of day or cloud cover in our photos and the greenness index. Greenness on photos taken close in time (i.e. photos with similar vegetation characteristics) varies in a complex fashion with the way light is scattered from different types of clouds, haze, and wildfire smoke. This significant day-to-day variability is dealt with by the curve-fitting procedures described below.

Our objective is to find the dates that best characterize the timing of green-up and senescence at each station each year. To accomplish this we fit a sigmoid curve to the data after Richardson et al. (2007; Fig. 8):

$$y = a + \frac{b}{1 + e^{c(d-x)}}$$

where y is the canopy greenness (by either the green percent or excess green measure), x is the ordinal date (expressed as a number from 1 to 365), and a , b , c , and d are constants. The constant a is

the value of greenness before the change and b is the amplitude of change; c determines the steepness of the change and d is the day number at the midpoint of the change. The constant b is positive for green-up and negative for senescence. The constant d is of greatest interest, as it can be used to investigate changes in the timing of green-up or senescence between years. The rate constant c can be used to determine if the rate of green-up or senescence differs between years. This constant has units of days^{-1} and alone is difficult to interpret, but if we choose representative start and end positions on the curve, it can be converted into a time interval in days that represents the length of the green-up or senescence season. Here we use the number of days between 10% and 90% green-up, i.e. the interval between points on the curve where $y_1 = a + 0.1b$ and $y_2 = a + 0.9b$ (Fig. 8). Substituting these y values into the equation above, we obtain the quantity $4.39/c$. For example, if $c = 0.2$, the time interval in days between points with 10% and 90% of total green-up is $4.39/0.2 = 22$ days. This interval is centered over the point of most rapid change (day d , the midpoint); the rate of change declines in both directions from the midpoint down to a rate 0.36 of the maximum at both ends of the 0.1 to 0.9 interval. An analogous time interval with y declining from $y = 0.9b$ to $y = 0.1b$ is used to quantify the rate of senescence.

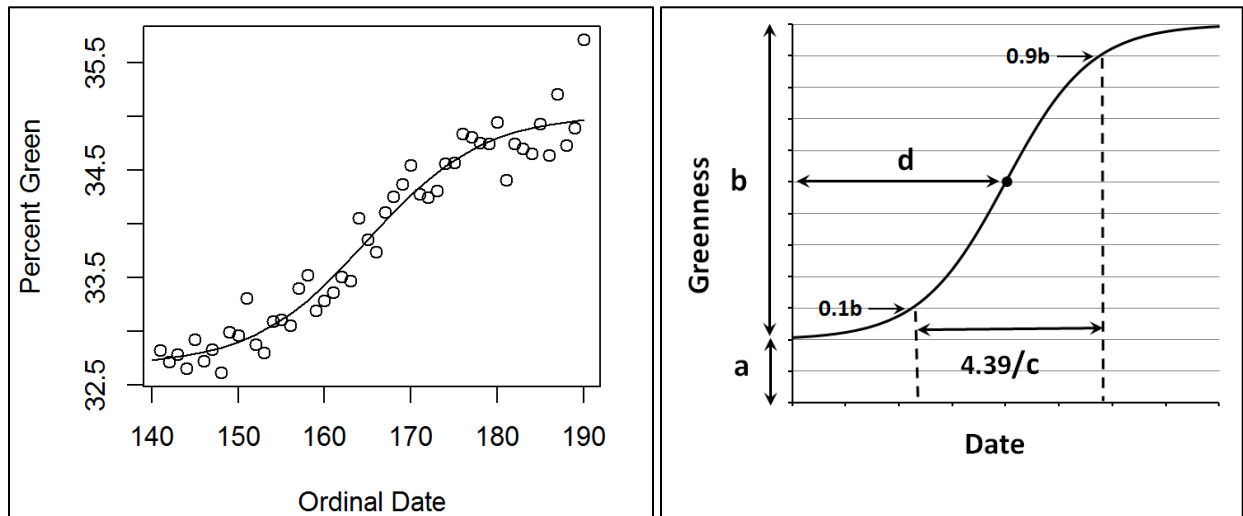


Figure 8. Greenness data from a remote automated camera and sigmoid curve fitting. Left, data from the right foreground analysis zone from Serpentine Hot Springs, spring of 2014 (Fig. 7) and fitted sigmoid curve. Right, explanation of the sigmoid curve constants.

The date range used for curve fitting is chosen manually for each year and location, and stored in the database for reproducibility. A constant date range for each location with long, flat "tails" at each end would obviously be preferred, but trials showed this not to be practical because the timing of the green-up or senescence period can vary by nearly a month between years, and long "tails" (which in principle could encompass the entire possible range where green-up or senescence occur) often encounter anomalous greenness data that confound the curve fitting algorithm. Anomalies are usually due to snow (on the lower end) or scenes illuminated by smoke-scattered light (on the upper end). Thus the analyst sometimes must adjust the endpoints or screen out a few points in the tail regions to get a good fit in the area of interest, the green-up or senescence period.

Some analysis windows are dominated by tundra plants that have strong red senescence colors (Fig. 9). The senescence trend in these cases does not follow a sigmoid pattern, but instead shows a steep decline to a distinct minimum that represents maximum red colors, followed by a recovery of greenness back to a level below the summer value but well above the minimum. In these cases we use the day of minimum greenness (corresponding to maximum fall colors) to quantify the timing of senescence. Due to the scatter in the data, smoothing is required to locate the fall minimum in greenness. Daily medians are smoothed by the least-squares method (Swets et al. 1999, Schwartz and Hanes 2010, Zhu et al. 2013): a linear regression (greenness index vs. date) is computed for a 1-week period centered at each date, and greenness value predicted by the regression for the center date is used as the smoothed value.

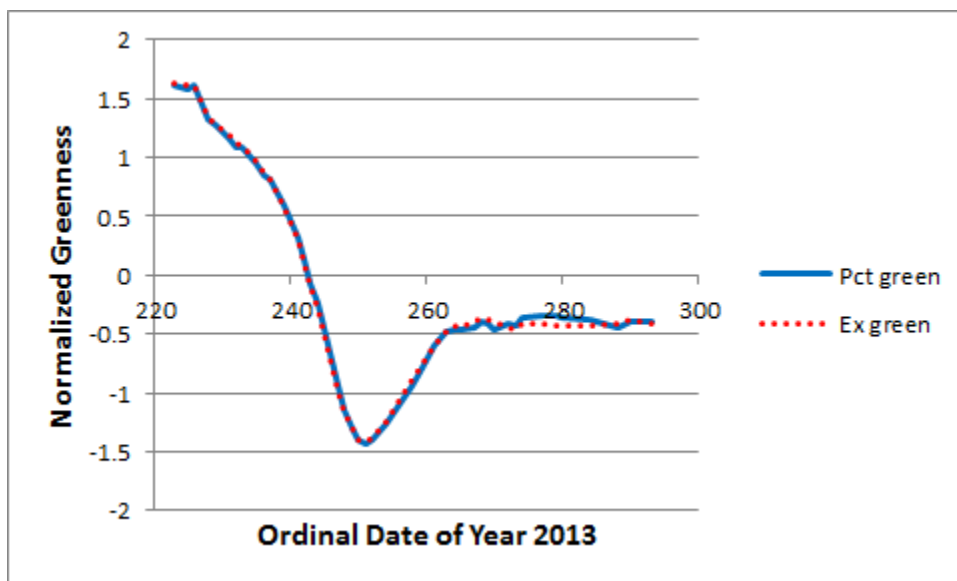


Figure 9. Greenness data for an analysis zone with red fall colors. The right foreground analysis zone from Serpentine Hot Springs, fall of 2013 (Fig. 7). The daily greenness indices were smoothed by computing a linear regression for a moving 7-day window. The two daily greenness index values were normalized as z-scores (daily value minus mean divided by standard deviation) to allow them to be plotted on the same axis. The minimum greenness, corresponding to peak of red fall colors, occurred on day 251 (8 Sept) by both indices, the day before the photo in Fig. 7.

4.3.5 Snow cover analysis

Quantitative snow cover analysis is performed on two kinds of analysis windows: 1) an area of uniform vegetation near to the climate station (i.e. the same analysis windows as greenness analysis); and 2) a more distant area that represents a heterogeneous landscape of snowbanks and windblown areas. Each pixel in the analysis window on each photograph is classified as “snow” or “no snow” by a semi-automated process, and then the proportion of snow pixels in the window is plotted against date through the year. Dates of important events are then identified and tracked across multiple years at each station.

Classification of snow and non-snow pixels. Snow is surprisingly difficult to identify by automated means on auto-exposed photographs. It is, of course, often white (R, G, and B bands all near the

maximum value of 255 digital counts), but the automatic exposure adjustment of the camera will darken a mostly snow-covered scene to an intermediate brightness averaging around 140 digital counts for each of R, G, and B (i.e. medium gray). Snow in shadows on a sunny day can be even darker than this, while adjacent unshaded snow is bright white. Furthermore, under the low-angle sun of arctic winters, snow takes on the hues of scattered light that is often blue or occasionally pink. As a result, no single classification rule (e.g., “snow is pixels with R, G, B of 200, 200, 200 or higher”) will produce good results on multiple photographs from different times. Snow classification may become easier in the future if cameras are programmed to provide detailed exposure information or a raw photo format.

While absolute values for brightness and hue of snow on photos vary, in any given scene snow is nonetheless usually brighter than non-snow, and this is especially true for the blue digital band. Non-snow areas tend to be both darker and browner than adjacent snow areas. Thus the blue color band is most useful for identifying and mapping snow.

In most partly snow-covered scenes, the two features of greatest contrast in the scene are light-colored snowy areas and darker colored non-snow areas. Thus to map snow on photographs we use an algorithm that searches for the blue digital count value in an analysis window that separates the pixels into the two most distinct groups possible. The criterion used to judge the distinctness of the two groups produced by any given “breakpoint” blue value is the same as that used in a one-way analysis of variance (AOV), i.e., it searches for the breakpoint that maximizes the ratio of the between-groups to within-groups mean square deviation. The brighter of the two resulting groups is then classified as snow and the darker group as non-snow.

This algorithm works well for scenes that are about half snow and half non-snow. In a scene that is dominantly non-snow with just a few percent of snow, the AOV algorithm will typically choose a breakpoint that separates dark and light non-snow areas, with the few snow pixels grouped into the latter. To deal with this situation, we first manually estimate the snow cover value of the analysis window in each photo, and use this to create a more optimal 50/50 snow/non-snow analysis. For example, if we estimate that the window has 10% snow cover, the algorithm will search only the brightest 25% of all pixels for the 2 natural groups (snow and light-colored ground). In a window estimated to have 90% snow and 10% non-snow, the algorithm will search the darkest 25% of pixels to find the breakpoint separating the darkest snow from the non-snow. Once the breakpoint has been located, it is applied to the entire analysis window to compute the fraction snow cover and produce a map of snow distribution as a check. During the manual photo review process we also flag photos where the ground is obscured by clouds or fog, which cannot be differentiated from snow by our process.

We have placed targets of known color (a white fence post cap) in the frame where possible (i.e. where a fence has been erected to discourage bear damage) to aid in adjustments for the exposure settings on the camera. This target may help us to further automate snow recognition in the future.

Identification of snow cover events. Establishment of snow cover in the fall typically involves one or more early snowfalls that melt, followed by establishment of a season-long snow cover. For remote

sensing purposes we define “continuous” snow cover as that which persists for 2 weeks or more; the snow year is defined as August 1 to July 31 (see section 3 above and Zhu and Lindsay 2013). In ARCN, a snow cover that persists for 2 weeks or more usually last the entire winter (Swanson 2014). Thus the key event that we record in the fall are the first date of 50% snow cover and the first date of 50% snow cover that persists for at least 2 weeks.

Loss of snow cover in the spring is typically a more progressive process that can be fitted with a sigmoid curve of the same type used in greenness monitoring (Fig. 10). As in the case of greenness monitoring, the midpoint day of snow cover loss (the constant d in the equation in the previous section) and the rate of snow cover loss (expressed in days between the points representing 10% and 90% of snow cover loss, computed from $4.39/c$; Fig. 8) are used to track changes between years.

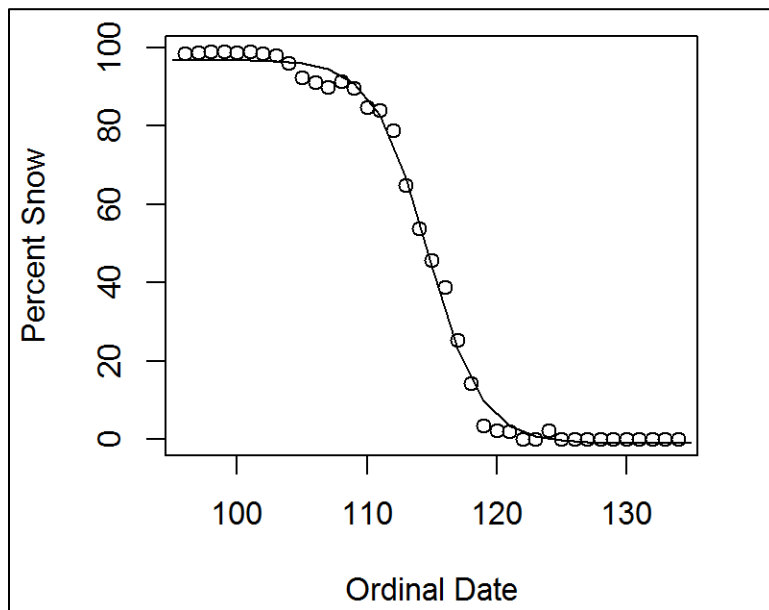


Figure 10. Spring snow cover and curve fitting. Serpentine Hot Springs climate monitoring station, right foreground analysis area spring of 2014 (Fig. 7). The midpoint of snow loss was on day 115 (25 April).

4.3.6 Comparison with climate data

Our co-location of phenology observations with detailed climate data provides an opportunity to study the relationship between the two. A simple and useful analysis is to compute the sum of degree-days to the spring phenological events: end of the continuous snow season and the midpoint of green-up. In arctic environments, a degree-day base temperature of 0°C is useful for plant phenology (Molau et al. 2005, Barrett et al. 2015). This base temperature (also known as thaw degree-days) is also useful for understanding the progress of snowmelt Rango and Martinec 1995). We expect the sum of thaw degree-days to snow cover loss and vegetation green-up to be predictable for a particular location, and useful for extrapolating to similar environments elsewhere in ARCN.

4.3.7 Time series analysis and comparison with satellite data

The time series of dates for phenological events obtained from camera data may be analyzed by the same methods as time series of dates for the analogous event from individual pixels of satellite data

(Sections 2 and 3). The Mann-Kendall trend test should be useful, as well as linear regression where trends are linear.

Dates of phenological events based on camera data can be plotted against date of the same events, derived from satellite data, for the pixel in which the camera is located. The land area sampled and snow recognition algorithm differ between the two methods, and hence perfect correspondence is not expected; but nonetheless the cameras provide a general check on the accuracy of the satellite-derived dates.

4.3.8 Creation of time-lapse video animations

A photo time series created by a phenology camera can be readily merged into a time-lapse video. These videos are interesting interpretive products that illustrate the seasons of the arctic, and they also provide a convenient way for an analyst to quickly review a large number of photographs. Our still photo-to-video conversion consists of two steps: 1) reformatting of the photos to add the location, date, and NPS logo to the margins of the photo, and resize to 1920 x 1080 pixels (standard high-definition video format); and 2) conversion to video. For step 1 we use the open-source Python language to manage files and run image the processing "convert.exe" software by Image Magick (www.imagemagick.org). The step 2 we use the open source software ffmpeg (<http://ffmpeg.org>) to convert from the time series of jpg images to a video in mp4 format.

4.4 Operational Requirements

Field visits to retrieve data and troubleshoot operation of the cameras are made by the personnel servicing the climate monitoring stations. The cameras thus require a little extra time at the site, ranging from just a few minutes to set up the download data from a functioning camera (the download itself takes about 20 minutes), to about half an hour if the camera or power source must be replaced. The technician must be trained in operation of the camera and have a field laptop with which to download photos and check settings on the camera.

In 2012, the Campbell Scientific CC5MPX-8G camera, low-temperature SD card, camera mounting kit, power and data cable, rechargeable power supply, and solar panel together cost about \$3600.

Re-analysis is planned at 5-year intervals. The analyst performing the 5-year data summaries should be familiar with the scripting language used to automate the computations, or have access to such a person to troubleshoot script operation. At the present time, we use the Python scripting language with libraries "PIL" (Lundh and Ellis 2002) and "numpy" to summarize data for the analysis zones. The sigmoid curve-fitting is performed using the R open-source statistical software (R Core Team 2014). Allow approximately 2 weeks to analyze the data for both greenness and snow cover, and another week to write up the results.

5 Land cover and landform monitoring with high-resolution aerial photographs

5.1. Background

The goal of this monitoring project is to obtain an ARCN-wide view of landscape change with the level of detail available from high-resolution imagery (pixel size 1 m or less). High-resolution imagery reveals great detail about landscape change, but it is difficult to analyze by automated methods. Our solution to this dilemma is to create a systematic grid with 20 km point spacing across ARCN (Fig. 11), and acquire and manually analyze high-resolution imagery at these points. This set of 210 plots is a compromise between the desire for a large sample and the time required for manual photo interpretation. As described below, a circular 4-ha plot is placed at each location. These are intended as permanent plots that will be re-sampled for change detection. As described further below, a two-tiered sampling design is applied to the plots: 1) the presence or absence of a particular change is identified for the 4-ha plot as a whole, and 2) the plot is divided into 37 subplots (and 37 points) to allow for areal estimates of vegetation or landform changes.

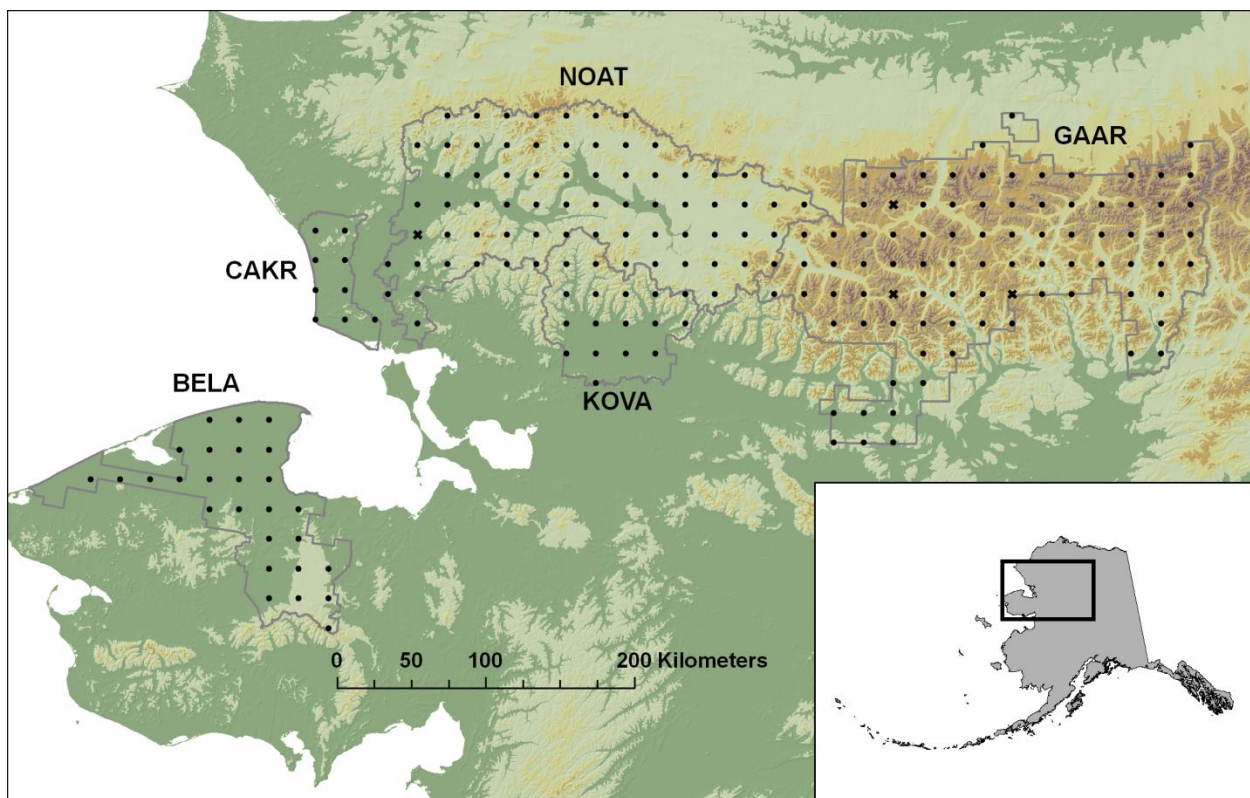


Figure 11. The sample grid of plots spaced at 20-km intervals across the NPS Arctic Inventory and Monitoring Network (ARCN). The four plots marked with an “x” were not sampled in the first sampling instance (Swanson 2013b) due to missing images.

5.1.1. Whole-plot change sampling

Many changes in vegetation and landforms can be recognized quickly and reliably by visual comparison of two images, even when the characteristics of the image differ greatly. For example, comparison of a sample circle as seen on 1980s-era AHAP color-infrared photograph with a recent small-format photograph (Fig. 12) instantly reveals that shrub cover has increased. Thus a fast and reliable method of change detection is to choose a characteristic (e.g. shrub cover), compare images from two dates, and simply classify the change on the plot as a whole as “increase”, “no change”, or “decrease”. The change process can also be readily classified, e.g. “shrubs increase on tundra” in Fig. 12. This is analogous to frequency (presence-absence) sampling of plants, which is known for ease and speed (Elzinga 1998). In addition, changes in any ice-wedge polygons between low- and high-centered morphology in the plot are noted.

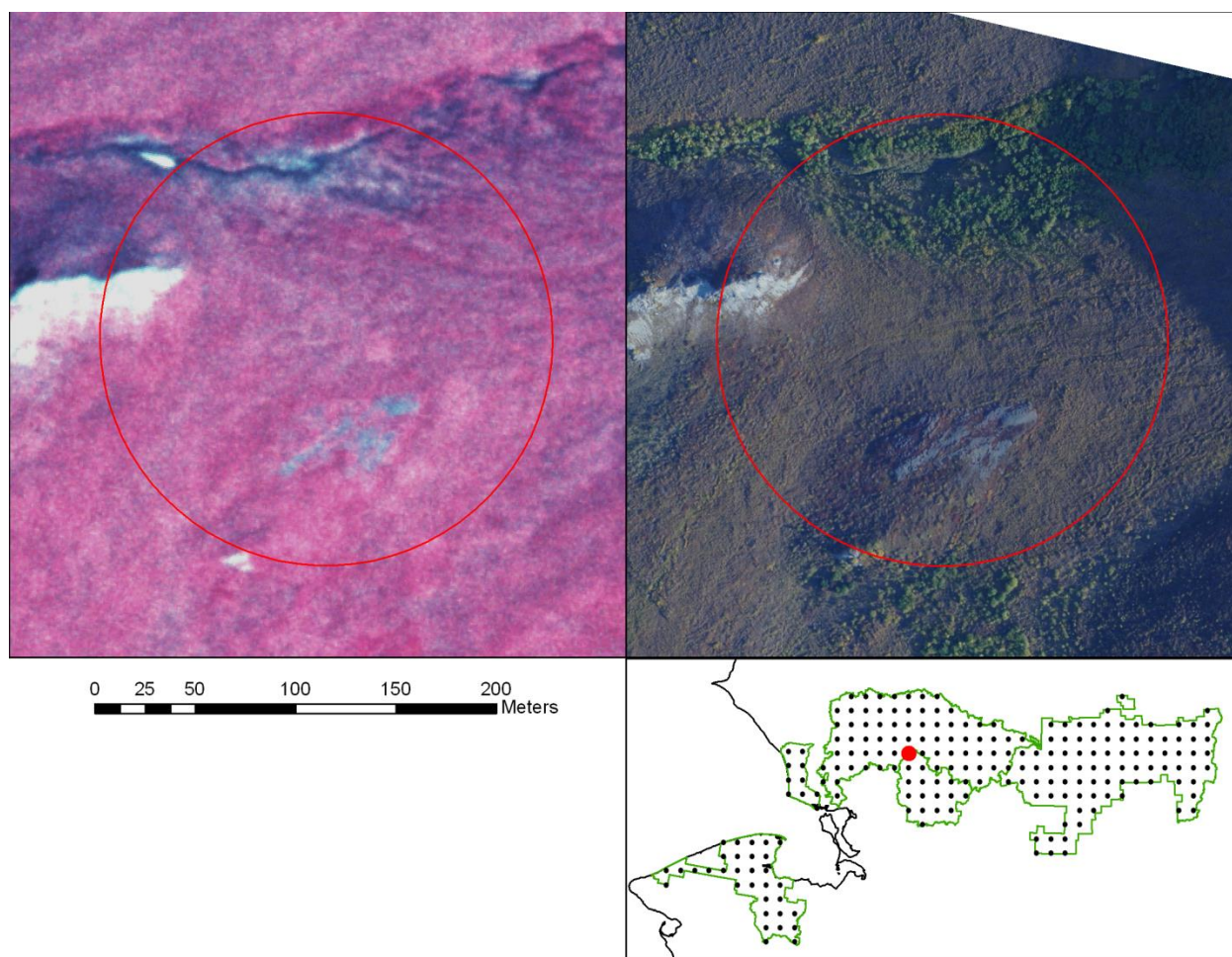


Figure 12. Example of shrub increase on tundra in a 4-ha sample plot located at the grid point marked in red on the inset map.

5.1.2. Subplot (cell) change sampling

While the whole-plot change detection method just described is fast and reliable to implement, it does not provide a measure of the area affected by change in vegetation/cover type. To obtain this useful measure of change, we also subdivide the 4-ha circular plot (Fig. 12) into 37 smaller hexagonal cells (Fig. 13) and classify the ecotype (vegetation/land cover) of each cell at different image dates. The ecotype classification was developed for the ARCN Ecological Land Survey and Land Cover Map (Jorgenson et al. 2009). This classification scheme is based on numerous field plots and allows direct upscaling to the ARCN-wide ecotype GIS layer. Each hexagon covers about 867 m² in area (quite similar in size to the 30 m by 30 m Landsat Thematic Mapper pixels for which our classification was devised).

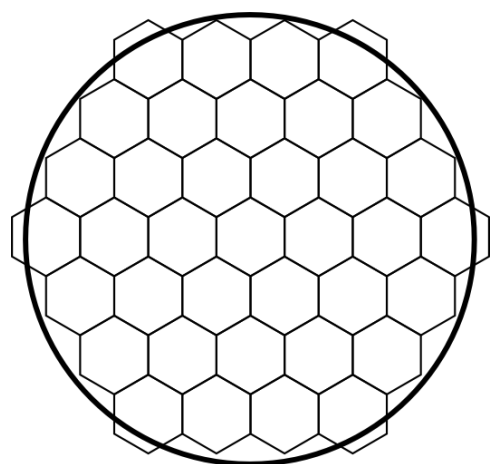


Figure 13. Subdivision of 4-ha photointerpretation change plot into a hexagonal grid of 37 cells for ecotype classification.

The cell center points are used in point-intercept sampling for areal cover estimates of ice wedge polygons by morphological type (high-centered, flat, and low-centered). Additional analysis of ice-wedge polygon degradation is found in the ARCN permafrost monitoring protocol. The 37 points could in the future be used to quantify the areal cover of additional landforms, such as thermokarst pits, after Jorgenson et al. (2007).

The sample grid has been sampled using 1980s-era aerial photographs and small format (35 mm) high-resolution aerial photographs (2008–2010)(Swanson 2013b). The present protocol gives procedures for future periodic reassessments of landscape change by the methods used in Swanson (2013b).

5.2. Data Sources

We obtained high-resolution scans of historical aerial photograph, recent high-resolution satellite images, and small-format aerial photographs for the 20-km grid (Table 2). Earlier (c. 1950) panchromatic aerial photographs are available for part of the network, but these were not included in

the study because of the difficulty in discerning features for change detection and their incomplete coverage of the sample grid.

At the present time, high-resolution satellite imagery is available at no charge to government agencies through the US Geological Survey's CRSSP (Commercial Remote Sensing Space Policy) program (<http://crssp.usgs.gov/>). This system is designed to deliver imagery for compact, individual areas of interest and not many systematically dispersed scenes. Thus, at the present time it appears that for future sampling, small-format photographs will provide the best combination of high resolution (0.2 m), stereo coverage, cost, timeliness, and ability to target our area of interest.

Stereo viewing provides a 3-dimensional view of both landforms and vegetation. It is useful for distinguishing shrubs from trees by crown shape, for example. Stereo photos are viewed using a monitor that supports row-interlaced polarized stereo viewing. The monitor projects data from the left and right photographs of a stereo pair onto alternating rows of screen pixels, and these rows emit alternately vertically and horizontally polarized light. A simple pair of polarizing glasses with left and right lenses polarized correspondingly separate the two images between the left and right eye for stereo viewing. Stereo viewing is only possible with images of the same area taken from different perspective points. Aerial photographs are typically taken with overlap along flight lines, making stereo viewing possible, while most satellite images are gathered as single scenes from one perspective point and stereo viewing is not possible. Stereo satellite imaging capabilities are improving and may be an option for 3D viewing in the future.

Table 2. Image sources for analysis of landscape change

Image Type	Dates	Image Type	Scale/Resolution	Approximate Footprint	Note
AHAP (Alaska High-Altitude Aerial Photography) color-infrared aerial photographs	June, July, August, 1977 to 1985	Large-format (9 inch by 9 inch negative) color-infrared aerial photography	Original negatives: approximately 1:60,000; Scanned at 14 μ m (1800 dpi, approximately 0.9 m resolution)	12 X 12 km	The effective resolution ("grain") of the photographs is slightly greater than the scan resolution, approximately 1-2 m
IKONOS satellite images	June, July, August, Sept 2006 to 2009	4-band multispectral Blue 0.445-0.516 μ m Green 0.506-0.595 μ m Red 0.632-0.698 μ m Near IR 0.757-0.853 μ m	4 m multispectral pixels, pan-sharpened to 1 m	Variable, 12 to 20 km by 6 to 14 km	Orthorectified using image parameters and the best available digital elevation model (DEM)
Small-format vertical digital aerial photographs	August, Sept 2008 to 2010	35 mm color digital photography NIKON D2X (23.7 x 15.7 mm sensor; 4288 x 2848 pixels) and NIKON D700 (36 x 23.9 mm sensor; 4256 x 2832 pixels)	0.15 to 0.20 m	400 to 600 m by 600 to 900 m	Stereo coverage allows stereographic 3D viewing

5.3 Data Analysis, Management, and Reporting

5.3.1. The 4-ha circular plots

Our sample area is a 4-ha circle centered at each ARCN 20-km grid point. A 4-ha circle has a radius of 112.84 m, which is about the largest size that can be reliably fit inside a single frame of our high-resolution, small-format photography. A sample area of this size usually has a simple slope and aspect, and thus can be projected fairly accurately onto photographs that have been georeferenced but not been formally orthorectified. Georeferencing involves a fairly quick and simple process of locating 3 to 10 tie points between the photograph and orthorectified reference imagery, which in our first sampling instance (Swanson 2013b) was IKONOS 1-m resolution imagery orthorectified using the 60 m National Elevation Dataset. Our experience with georeferencing photographs by affine transformation shows that in nearly all cases it is possible to make all landmarks within the 4-ha circle match a reference ortho-image within 5 m linear distance. Georeferencing may be done by automated process in the future, using structure-from-motion software and accurate GPS and aircraft positioning equipment.

5.3.2. Whole-plot level change analysis

The list of change types and change mechanisms to search for on the aerial photographs is in Table 3. The change type, or “no change”, is recorded for each plot and each pair of photo dates.

Table 3. Land cover change types and mechanisms.

Change type	Change mechanism
Shrub_increase	increase on tundra post-fire succession floodplain succession increase on wetland other primary succession
Shrub_decrease	fire floodplain erosion succession to trees wetland expansion
Tree_increase	increase on tundra post-fire succession floodplain succession increase on wetland other primary succession infilling below treeline
Tree_decrease	fire floodplain erosion wetland expansion
Lichen_increase	succession

Table 3 (continued). Land cover change types and mechanisms.

Change type	Change mechanism
Lichen_decrease	fire erosion wetland expansion shrub increase herbivory/other
Barren_increase	fire floodplain erosion snowfield/icing expansion mass movement
Barren_decrease	floodplain vegetation increase vegetation increase on snowfield/icing upland vegetation increase
Wetland_increase	thermokarst non-thermokarst water level rise paludification
Wetland_decrease	thermokarst non-thermokarst water level drop
Water_increase	thermokarst non-thermokarst water level rise stream channel migration
Water_decrease	outlet incision non-thermokarst water level drop stream channel migration

The frequency of increase, no change, or decrease is then computed across all of the plots sampled. A trinomial distribution is used to test the significance of any changes observed between image dates in the proportion of increase/no-change/decrease observations for each characteristic (Table 3).

5.3.3. Areal cover analysis with the 37 hexagonal cells

Changes in ecotype are viewed in a cross-tab format that lists the count of hexagonal grid cells in each class at each image date. For example, in the plot shown in Fig. 12, 4 cells changed from ecotype “Upland Birch Ericaceous Willow Low Shrub” to “Upland Alder Willow Tall Shrub”. In addition, the total count of cells with an ecotype, divided by the total number of cells sampled, provides an estimate of the proportional coverage of ARCN by that ecotype.

The ecotype cover data may also be analyzed with plots treated as sample units. The cover by any selected ecotype or group of ecotypes in a plot on a given sample date is obtained from the count of hexagonal cells of that type or types. The plots can then be tested for change in cover by the ecotype(s) of interest between two sample dates with use of a paired test. The non-parametric Wilcoxon signed rank test is normally most appropriate, because the data are not normally distributed due to the presence of many zeros (i.e., there usually are many plots with no change recorded). In the future, when a time series of cover values is available for each plot, trends may be investigated using a linear mixed model with the plot as a random effect (Laird and Ware 1982, Hedeker 2005).

The center points of the 37 hexagonal cells are also available for use as an unbiased, network-wide, point-intercept sample of other features, such as thermokarst landforms. At the present time, we have implemented point-intercept sampling of landforms only for ice-wedge polygons (Swanson 2013). Count data for the ice-wedge polygon types can be analyzed by the same methods outlined above for ecotypes. Jorgenson et al. (2007) used point-intercept sampling on high-resolution aerial photographs to document areal coverage by a variety of thermokarst landforms in Interior Alaska. A similar approach could be used to sample aerial coverage by other landforms in ARCN (in addition to ice-wedge polygons) and monitor change over time. This would require development of a legend and identification criteria for the selected landforms in addition to the sampling itself.

5.4 Operational Requirements

Small-format aerial photographs are fairly expensive. Flight distances between grid points alone amount to about 4200 km (2600 mi), or 15-20 hours of flight time. Aircraft may be staged and refueled in Bettles (for GAAR), Dahl Creek (near Kobuk village; for GAAR, KOVA, and NOAT), and Kotzebue (for BELA, CAKR, KOVA, and NOAT). Ferrying between the grid points and these staging areas over 5 days adds at least another 2000 km (1200 mi), or about 8 hrs of flight time. Ferrying between the aircraft's home base (e.g. Fairbanks or Anchorage) and the project area adds another 2 to 4 hours of flight time in each direction. Thus flight time alone for the whole network is on the order of 40 hours, to which must be added salary, meals, and lodging costs for one or two people for approximately 10 days, bringing the total cost as high as \$50,000 at 2014 prices. However, this is at least an order of magnitude cheaper than ground-based sampling of the same plots would be. In the future, unmanned aircraft systems (UAS) may be available that could reduce these costs and risks. Future cameras are likely to have higher resolution and perhaps infrared capability also.

The analyst must be familiar with GIS to georeference the photographs, and familiar with interpretation of aerial photographs to recognize change and identify ecotypes. Jorgenson et al (2009) and Wells and Macander (2010) are essential guides to ARCN ecotypes, and Swanson (2013b) has examples of change types on imagery. A significant amount of analyst time is required to georeference the photos and record the data at each plot. Automated georeferencing of the photos in the future could reduce the georeferencing workload. The most time-consuming part of the process is interpreting the ecotype change in the hexagonal cells. An average of 4 to 5 plots per hour is a reasonable estimate for the time required to georeferencing and analysis. To prevent fatigue, this work should be only performed for about half a working day at a time. Thus about 2 weeks of photo interpretation time, and another week of report writing, are required for resampling. Based on the

slow rates of change observed to date (Swanson 2013b), resampling could be as infrequent as once every 20 years if funding is limited. However, sampling at a 10-year interval would allow us to develop trend lines and capture episodes of sudden change. .

6 Lake surface area monitoring

6.1. Background

Lake surface area in Alaska has been highly dynamic in recent decades, and concerns about the potential loss of lake area has motivated several studies (Carroll et al. 2011, Jones et al. 2011, Riordan et al. 2006, Roach et al. 2011, Yoshikawa and Hinzman 2003). Mechanisms for lake area decrease include an increase in watershed evapotranspiration, reduced precipitation, catastrophic drainage by breaching of banks (usually by thaw of permafrost combined with bank erosion), increased percolation of water through the lake bottom due to loss of sub-lake permafrost, and terrestrialization (infilling by sedimentation and growth of plants from the shore; see the previous references and Jorgenson and Osterkamp 2005). Loss of lake area has widespread implications, especially for aquatic wildlife. It could also indicate a fundamental drying of the landscape associated with climate change. Lake and pond area could also increase as a result of enlargement of basins or formation of new basins by thermokarst (Jorgenson and Osterkamp 2005, Jones et al. 2011). Lake area analysis is also part of the Central Alaskan Inventory and Monitoring Network protocol (Larsen et al. 2011).

Fortunately, lakes are readily mapped using remotely sensed imagery. Water bodies are unique in their strong absorption of shortwave-infrared radiation, allowing them to be differentiated from other land cover types. Lake mapping can be automated by computer classification of modern multispectral satellite images, and by manual delineation on early aerial photos, which date back to about 1950 in ARCN.

A time series of lake extents for the whole of Arctic Network has been developed from satellite images for the period 1985-2011 (Swanson 2013a). The present protocol gives procedures for future periodic reassessments of lake area by the methods used in Swanson (2013a).

6.2. Imagery

The most useful data for modern analysis of lake area across large regions such as ARCN is the 30-m resolution multispectral scanner data from the “Thematic Mapper” (TM) sensor and its successors (the Enhanced Thematic Mapper Plus and the Operational Land Imager) that have operated from the various Landsat satellites, starting in 1984 in Alaska with Landsat 4 (Goward et al. 2006, NASA 2016d). These sensors combine the necessary wavelength bands for differentiation of water, adequate spatial resolution, numerous image dates, and, at the present, free access to data (Fig. 14). The 30 m pixel resolution of Landsat data is a good compromise between resolution, coverage by individual images, and memory/speed issues: all of ARCN can be covered by about 2.5 GB of data, as compared to the hundreds of GB in multiple tiles required to cover the network in high-resolution (e.g., 1-m pixels) imagery. The seasonal composite images generated by the WELD program (Roy et al. 2010, and <http://landsat.usgs.gov/WELD.php>) for 2003-2012 provide cloud-free coverage that also fills in most of the gaps produced by the satellite's scan-line corrector malfunction that affected all Landsat 7 data collected after May 2003 (NASA 2016a). With the launch of a new satellite Landsat 8 in 2013 (NASA 2016b), the European Space Agency's Sentinel-2A in 2015 (ESA 2016), and plans for Landsat 9 (NASA 2016c) and additional Sentinel-2 missions, we should continue to be

able to acquire data similar to the TM in future decades. The WELD program has expanded to include a global product (USGS 2016) that will provide data back to 1985.

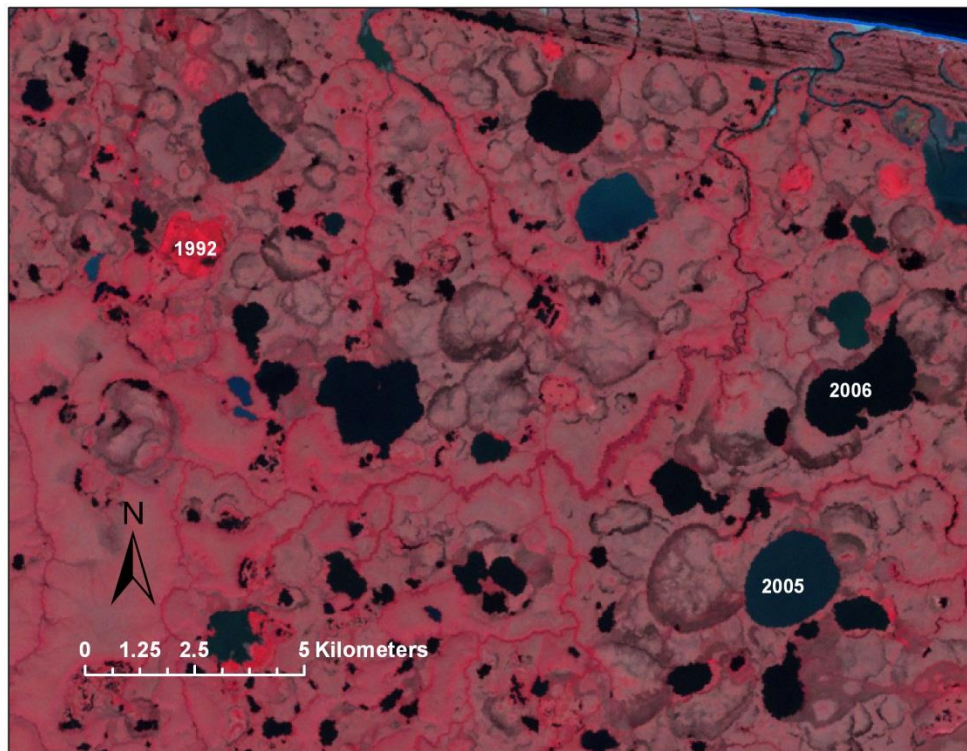


Figure 14. Landsat image of a lake-rich region of BELA, shown in the color-infrared color scheme, 2002. The numerous lakes and ponds here occupy basins produced by thermokarst (thaw and subsidence of ice-rich permafrost). Roughly circular outlines of former lake basins that have drained are visible between existing lakes. The bright red basin labeled “1992” drained between images taken in 1992 and 1995 and is bright colored due to lush vegetation. The basins labeled 2005 and 2006 were last full in those years. Lake “2005” was nearly empty of water by 2006, while lake “2006” drained partially over the next two years.

6.3. Data Management, Analysis, and Reporting

The WELD Landsat composites are created using data from multiple passes of the satellite, similar to the eMODIS composites described previously. The composites consist of the “best” pixel values observed over a chosen time span (ranging from weekly to seasonal), as judged by a complex algorithm that incorporates cloud recognition, maximum brightness temperature, and NDVI (Roy et al. 2010). These images provide a cloud-free view of the earth, in addition to filling in gaps caused by the satellite malfunction. While gap-filling will be less important in the future, composites will still be needed to deal with persistent cloudiness during arctic summers. The WELD composites have been calibrated to top-of-atmosphere reflectance, and the Alaska product has been projected to our preferred Alaska Albers projection. Inspection of data from ARCN shows that clouds obscure part of the network on most weekly or monthly composites, while the full-summer composites are usually nearly cloud-free. The drawback with using a summer composite is that some of the year-to-year variation in lake area in the summer composite could actually be due to the date of available clear summer imagery interacting with seasonal events such as spring runoff or late-summer flooding.

Fortunately, our environments are dominated by perennial water bodies and lake area is controlled primarily by multi-year lake expansion or catastrophic drainage events, rather than reversible annual cycles of filling and drying. In addition, our analysis method (described below) helps to screen out year-to-variation in lake area.

Lake area change is monitored by analysis of Landsat spectral band 5 (middle infrared, 1.55-1.75 μm), which is as effective in differentiating water as complex combinations of other spectral bands (Frazier and Page 2000). We compute the median band 5 value for each pixel across 3 consecutive years and assign the value to the middle year. This avoids some persistent cloudy or cloud-shadowed pixels that appear even on summer-long composites. This step may be unnecessary in the future when we are able to use data from Landsat 8 (which does not have the missing data stripes of Landsat 7). An image composed of 3-year medians is classified by a threshold pixel value of 600 (i.e., reflectance of 0.06) to separate water (< 600) from land (≥ 600).

Lake area is summed for each year by ecological subsection (Boggs and Michaelson 2001, Jorgenson 2001, Jorgenson et al. 2001, Swanson 2001a, 2001b). Subsections are areas of land with a relatively uniform climate and a consistent pattern of landforms, soils, and vegetation. Subsections help us to partition the variability in lake surface area across the landscape, because lakes within a subsection have similar hydrologic conditions. In addition, subsections provide a way to avoid various non-target water areas (e.g. salt water lagoons and large rivers). We analyze the lake area trends for all lowland subsections with at least 1% cover by surface water bodies, excluding those where surface water is dominantly rivers or salt water.

Linear least-squares regressions of summed water area (in each subsection) are computed to detect trends where they appear to be linear (Fig. 15), and the drainage dates for specific lakes are recorded in tabular form. Non-linear trend analysis procedures may also be appropriate in the future.

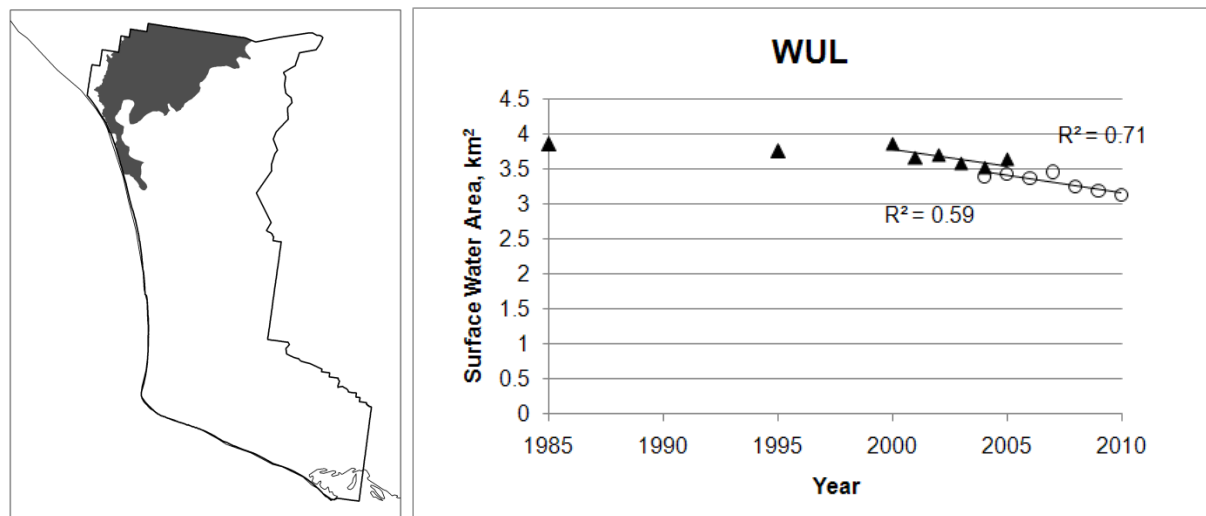


Figure 15. A typical subsection, the Wulik Lowland in CAKR (left) with a plot of total surface water area vs. year (right). The circles represent Landsat data obtained from the WELD composites described in this protocol, which are only available back to 2002. The triangles represent earlier data compiled in Swanson 2013a.

In the future we expect Landsat-like data to be available indefinitely while the power of computers and the accuracy of mapping method could improve. We envision periodic re-analyses of the whole Landsat time series, benefitting from the longer data record as time goes on, probably in combination with improved methods to discern trends.

6.4. Operational Requirements

Data analysis and reporting will occur at 5-year intervals. Complete coverage of ARCN with one year of WELD Landsat images requires 12 tiles that can be downloaded in about 2 hours and requires 3 GB of disk space. Images produced by analysis require less than 1 GB additional space per year. Preparation of the data files for analysis takes about another half hour per year. The images may be downloaded yearly, or at 5-year intervals before analysis.

Processing 5 years of data for all of ARCN can be completed in a few hours after all of the input images have been downloaded and prepared, but up to a week may be needed to adapt to potential changes in the received data and software. Allow several more days for interpretation of the analyses and reporting of results.

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