Remote Sensing Indicators for Greater Moose's Tooth – 2

Map User Guide and Accuracy Assessment

Version 1.0 (December 2022)

Version 1.0 remote sensing indicators for Greater Moose's Tooth – 2 (GMT-2) derive from the Version 1.0 (May 2021) *Continuous Foliar Cover of Plant Species and Aggregates in North American Beringia*[1]. Version 1.0 relates to U.S. National Vegetation Classification (USNVC) Version 2022-05-01.

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[1] Nawrocki, T.W., M.L. Carlson, A.F. Wells, M.J. Macander, E.J. Trammell, F.D.W. Witmer, C.A. Roland, K. Baer, and D.K. Swanson. 2021. Continuous Foliar Cover of Plant Species and Aggregates in North American Beringia. Version 1.0 (May 2021). Available: https://doi.org/10.5281/zenodo.3897482

Cover photograph:

Assessment, Inventory, and Monitoring crew conducts line-point intercept survey at field plot in late July of 2021 within the Greater Moose's Tooth – 2 study area.

Note on photographs: Unless otherwise noted, all photos were taken by Timm Nawrocki and should be considered Creative Commons Zero.

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Introduction

The Alaska Center for Conservation Science (ACCS) at University of Alaska Anchorage conducted Assessment, Inventory, and Monitoring (AIM) in the Greater Moose's Tooth – 2 (GMT-2) area for Bureau of Land Management (BLM) during 2019 and 2021. In addition to the field measure core and supplemental AIM indicators, we provide remote sensing indicators, described in this user guide. AIM remote sensing indicators extend site-level monitoring measurements across entire landscapes and expand the suite of measured variables beyond those practical to measure extensively in the field. The AIM remote sensing indicators for GMT-2 relate to the National Petroleum Reserve – Alaska (NPR-A) ecosystem conceptual model developed for the AIM NPR-A pilot project (Boucher et al. 2018). Table 1 provides an overview of the remote sensing indicators as well as the datasets that we developed for each indicator.

Table 1. Overview of remote sensing supplemental indicators and datasets for AIM in the GMT-2 area of northern (Arctic) Alaska.

AIM Supplemental Indicator	**Dataset description**
Surficial permafrost features	Categorical map of surficial features, including permafrost-driven features
Surface water	Continuous map of growing season surface water percentage from 2017 through 2021
Vegetation pattern	Predicted continuous foliar cover for 11 species or aggregates that relate to USNVC alliances
Area by vegetation type	Categorical map of vegetation types that relate to USNVC alliances
Productivity	Continuous maps of net primary production downscaled from MODIS Terra and Aqua annual measurements at 5-year intervals from 2001 through 2020
Phenology	Continuous maps of day-of-year downscaled from MODIS annual land cover dynamics at 5-year intervals from 2001 through 2020

In developing methods for the remote sensing indicators, we applied the "SMART" criteria (Specific, Measureable, Attainable, Realistic, and Timely) as described in Boucher et al. (2018). We applied four additional criteria to ensure that the GMT-2 remote sensing indicators can be easily updated and expanded as needed in the future:

1. Scalable (can be expanded to all of NPR-A or entire state)
2. Repeatable (can be re-mapped using consistent methods to assess change over time)
3. Consistent (can be compared across BLM lands in Alaska)
4. Flexible (can adapt to future changes in USNVC to facilitate temporal comparisons)

General Methods

In the *General Methods* section, we describe only those methods that pertain to all indicators. Methods for individual remote sensing indicators are covered within each indicator section. Specific methods for every non-manual processing step are recorded in scripts in the script repository[2]. We provide an overview of all source datasets used in map development in Appendix 1.

Standards

The datasets developed for the GMT-2 remote sensing indicators are intended to monitor ecosystem change associated with vegetation and therefore follow the standard set by the Federal Geographic Data Committee (FGDC) that all vegetation maps relate to the U.S. National Vegetation Classification (USNVC; FGDC 2008). We followed the most recent version of USNVC available upon the publication date: version May 2022 (2022-05-01). In addition to following the FGDC standard, the GMT-2 remote sensing indicators also follow the *Standards for Mapping Vegetation in Alaska Version 1.1 (August 2022)* set by the Alaska Geospatial Council (VTWG 2022).

Image Segments

Alaska Department of Natural Resources provided Maxar and Spot imagery composites in accordance with license agreements. While the Maxar imagery composite has higher resolution and more recent acquisition dates than the Spot imagery composite, it suffers from some cloud and snow/ice cover that prevented development of image segments in small areas of the GMT-2 study area. We masked the obscured areas from the Maxar imagery composite and replaced the Maxar data with data from the Spot imagery composite. Subsequently, we resampled the resulting imagery composite to 2 × 2 m resolution.

To produce image segments (hereafter referred to as "segments"), we loaded the combined imagery composite into Google Earth Engine (GEE) and calculated enhanced vegetation index-2 (EVI-2), normalized difference vegetation index (NDVI), and normalized difference water index (NDWI). We calculated segments on the blue, red, green, near infrared, EVI-2, NDVI, and NDWI bands using simple non-iterative clustering (Achanta and Susstrunk 2017). To ensure that we captured stream, river, and floodplain boundaries, we further divided the segments based on hydrologic parameters developed from manually digitized flowlines and the U.S. Geological Survey (USGS) 3D Elevation Program (3DEP) IFSAR 5 × 5 m Digital Elevation Model (DEM). To support the analyses of remote sensing indicators by segment, we summarized numerous spectral, textural, topographic, hydrographic, and ancillary data to the segments as mean, standard deviation, and/or range (see Appendix 1).

Minimum mapping unit

We calculated minimum mapping unit for the categorical datasets as the area covered by four of the coarsest pixels from source imagery. Since we relied on the Sentinel-2 system, the coarsest resolution imagery was 20 × 20 m, corresponding to a minimum mapping unit of approximately 0.5 acres. The minimum mapping unit is not relevant to the continuous maps.

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[2] Script repository available at: https://github.com/accs-uaa/remote-sensing-gmt2

Software and Reproducibility

The analyses presented in this user guide are possible because of the development of numerous software packages and platforms. All non-manual steps of data acquisition, analyses, and map post-processing were scripted so that the entire mapping workflow can be repeated or adapted to regions outside of the GMT-2 study area.[3] We conducted tasks using software as follows:

1. Spatial processing and manual delineation in ArcGIS Pro 3.0.3 with Python 3.9.11.
2. Spectral and textural data acquisition with Google Earth Engine (Gorelick et al. 2017) and the Anaconda 2022.05 distribution of Python 3.9.12 with Google API Python Client 2.66.0.
3. Data formatting using R 4.2.1 and RStudio 2022.07.1+554 with dplyr 1.0.9, stringr 1.4.1, and tidyr 1.2.0 (Wickham et al. 2019).
4. Statistical modeling in the Anaconda 2022.05 distribution of Python 3.9.12 with scikit-learn 1.1.2 (Pedregosa et al. 2011), pandas 1.4.2 (McKinney 2010), and numpy 1.21.5 (Harris et al. 2020).
5. Prediction raster conversion and raster data extraction using R 4.2.1 and RStudio 2022.07.1+554 with fasterize (Ross et al. 2022), raster (Hijmans 2022), and sf (Pebesma 2018).

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[3] Script repository available at: https://github.com/accs-uaa/remote-sensing-gmt2

Surface Water

Surface water represents the dynamic growing season extent of water without overtopping vegetation. The dynamic growing season extent is expressed as a percentage of observations made during the growing season in which the surface was water without overtopping vegetation (Figure 1). The *surface water* indicator is represented by the *growing season surface water percentage* dataset (Table 2).

Figure 1. Comparison of water without overtopping vegetation (left; June 27, 2018) and water with overtopping vegetation (right; July 30, 2018) from the Utqiagvik phenological monitoring site (Richardson et al. 2018). The photograph on the left would be classified as surface water while the photograph on the right would be classified as not surface water.

Table 2. Metadata for the *growing season surface water percentage* dataset.

Metadata	**Value**
Dataset filename	GMT2_SeasonalWater_Percentage.tif
Dataset name	Growing season surface water percentage
Data type	Continuous
Scale	1:24,000
Boundary resolution	2 × 2 m
Minimum mapping unit	N/A
Coordinate system	Alaska Albers Equal Area Conic (EPSG 3338)
Units	Percentage of growing season
Scale factor (modifies the units)	1
Theoretical unit range	0-100
Time range	2017-2018 & 2020-2021

Methods

We selected areas from the Maxar imagery composite with acquisition dates in June and July of 2020. In GEE, we developed Sentinel-1 Surface Aperture Radar (SAR) Vertical-Vertical polarization (VV) 40-day median composites centered around mid-June and early July of 2020 to approximately align with the selected acquisition dates. Based on interpretation of the Maxar imagery, we manually classified points across the areas covered by the selected acquisition dates as either surface water or not surface water. Each point represented an area of at least 100 m^2. Finally, we created a simple threshold-based model to distinguish surface water from not surface water by the VV value where the accuracy percentage of both states was as close to equal as possible by minimizing the absolute value difference between sensitivity and specificity.

In GEE, we created VV 40-day median composites for 2017-2018 and 2020-2021 around the following dates: 06-01 through 07-10, 06-20 through 07-20, 07-20 through 08-20, and 08-01 through 09-10. Using 40-day median composites rather than the individual raw measurements helped reduce the influence of measurement errors (i.e., "speckling"). For each median composite, we applied the VV threshold to create a binary representation of surface water extent where surface water had a value of one (1) and not surface water had a value of zero (0). To develop a *growing season surface water percentage* per grid cell, we found the mean value of all thresholded median composites. To reduce the influence of errors within individual grid cells and provide a greater level of generalization, we summarized the mean growing season surface water percentage per contiguous area of predicted *surficial features*.

The resulting *growing season surface water percentage* represents the proportion of median composite observations when surface water was present with no overtopping vegetation within the entire observed 10 × 10 m grid cell. Areas of sedge wetlands and freshwater marshes often start the growing season without overtopping vegetation. Once emergent sedges and grasses grow above the water surface, the area no longer is surface water because the surface is vegetated. A *subsurface water* indicator could complement the *surface water* indicator by capturing typical moisture regime (rather than dynamic moisture regime) below vegetation and soil at peak growing season.

Accuracy Assessment

The performance of the threshold-based water classifier for the test months of June and July 2020 was 95.6% based on a mean selected VV threshold of -15.179. Because the threshold minimized the absolute value difference between sensitivity and specificity, the performance of surface water and not surface water is approximately the same.

Surficial Permafrost Features

Surficial permafrost features delineate boundaries between different permafrost-driven geophysical surface regimes. The *surficial permafrost features* indicator is represented by the *surficial features* dataset (Table 3). We defined permafrost features according to a schema that relates to hydrology (Figure 2) rather than shape for three reasons: 1) permafrost feature shapes strongly intergrade and are only distinct in their extreme forms; 2) hydrologic differences relate better to differences in plant community composition and structure than do differences in permafrost feature shape; and 3) delineations of hydrology are more apparent in high and moderate resolution satellite imagery than are delineations of permafrost feature shape. See Appendix 2 for the full map class schema for *surficial features*. The *surficial features* dataset is most appropriate for visual interpretation or data summarization, rather than statistical analyses.

Figure 2. Example difference between two map classes of surficial permafrost features: *thermokarst troughs, non-polygonal or indistinctly polygonal* (left) and *polygonal, mesic* (right).

Table 3. Metadata for the *surficial features* dataset.

Metadata	**Value**
Dataset filename	GMT2_SurficialFeatures.tif
Dataset name	Surficial features
Data type	Categorical
Scale	1:24,000
Boundary resolution	2 × 2 m
Minimum mapping unit	0.5 acre
Coordinate system	Alaska Albers Equal Area Conic (EPSG 3338)
Units	N/A
Scale factor (modifies the units)	N/A
Theoretical unit range	Appendix 2
Time range	Circa 2020

The *surficial features* classes are mutually exclusive by design. There are, however, some areas that include features smaller than the minimum mapping unit and other areas that are ambiguous between two or more classes. To capture gradients and ambiguities between classes, we provide the *surficial features* as the predicted probabilities for each class (Table 4). The predicted probabilities represent each *surficial feature* as a non-exclusive gradient; the *surficial feature probabilities* are therefore most appropriate for statistical analyses, rather than visual interpretation or data summarization.

Table 4. Metadata for the *surficial feature probabilities* dataset.

Metadata	**Value**
Dataset filenames	1. GMT2_Probability_barren.tif 2. GMT2_Probability_dunes.tif 3. GMT2_Probability_nonpatterned_drained.tif 4. GMT2_Probability_nonpatterned_floodplain.tif 5. GMT2_Probability_nonpatterned_mesic.tif 6. GMT2_Probability_nonpolygonal_wet.tif 7. GMT2_Probability_thermokarst_troughs.tif 8. GMT2_Probability_polygon_mesic.tif 9. GMT2_Probability_polygon_wet.tif 10. GMT2_Probability_freshwater_marsh.tif 11. GMT2_Probability_stream_corridor.tif 12. GMT2_Probability_tidal_marsh.tif 13. GMT2_Probability_salt_killed.tif 14. GMT2_Probability_vegetated_beach.tif 15. GMT2_Probability_water.tif
Dataset name	Surficial feature probability
Data type	Continuous
Scale	1:24,000
Boundary resolution	2 × 2 m
Minimum mapping unit	N/A
Coordinate system	Alaska Albers Equal Area Conic (EPSG 3338)
Units	Percentage prediction probability
Scale factor (modifies the units)	1
Theoretical unit range	0-100
Time range	Circa 2020

Methods

To generate a training dataset of segments with class labels, we manually delineated *surficial features* by interpreting the Maxar imagery composite and a 2022 growing seasonal median composite of Sentinel-2 imagery. Samples of all classes occur relatively equally across the GMT-2 study area; classes of specific types, however, are limited in occurrence by uneven distributions. We checked a portion of our manually delineated samples against previous high resolution ecotype mapping work accomplished in an overlapping region (Wells et al. 2021). We labeled *surficial features* for a total of 538,504 segments.

A random forest classifier statistically associated labeled segments with a suite of textural, spectral, topographic, and hydrographic covariates. Because the number of labeled samples depended on the rarity of the feature, we applied a class balance weighting equal to the inverse proportion of samples out of the total. We then predicted all segments from the trained classifier and converted the predictions to rasters. In addition to predicting the non-overlapping categorical *surficial features*, we also predicted overlapping probabilities for each *surficial feature*.

To reduce the potential for optimistic bias in model performance metrics because of spatial autocorrelation, we conducted a spatially blocked cross validation (see Macander et al. 2022) to estimate model performance. Spatial blocks were 10 × 10 km and did not overlap with one another. During each iteration of the cross validation, the labeled samples within a single spatial block were retained as independent test data (i.e., not used to train the classifier) such that labeled samples from each spatial block were predicted once. We calculated user's and producer's accuracy from the combined predictions of all cross validation iterations.

Accuracy Assessment

Table 5 provides the user's and producer's accuracy for each map class. User's accuracy indicates the likelihood that the mapped class is accurate to the location in reality. Producer's accuracy is the percentage of observed samples that match the predicted samples. The full confusion matrix is provided in the model results of the project deliverable. All accuracies are based on number of segments rather than area to avoid overly optimistic bias in reported accuracies. Accuracies ranged from 76% to 100%. The *infrastructure* and *pipeline* classes were added to final results from manually digitized vector data and are therefore not included in the accuracy assessment.

Table 5. User's and producer's accuracies for each map class in the *surficial features* dataset.

Feature	**User's Accuracy (%)**	**Producer's Accuracy (%)**
Barren	98	98
Dunes	90	87
Non-patterned, drained (indistinctly patterned)	94	89
Non-patterned, floodplain	92	86
Non-patterned, mesic (indistinctly patterned)	95	93
Non-polygonal, wet (stringers, indistinctly patterned)	85	86
permafrost troughs, non-polygonal or indistinctly polygonal	87	79
Polygonal, mesic	77	85
Polygonal, wet	85	89
Freshwater marsh	89	84
Stream corridor	96	98
Tidal marsh	92	86
Salt-killed tundra or marsh	84	90
Vegetated coastal beach	81	76
Water	100	100

Vegetation Pattern

Vegetation pattern represents the distribution and abundance of plant species and aggregates that relate to USNVC alliances (Figure 3), per FGDC standards (FGDC 2008). We quantified *vegetation pattern* as percentage absolute foliar cover for 11 widespread, frequently dominant, or key plant species or aggregates (Table 6). Detailed methods and results for the production of the *foliar cover* datasets are provided in Nawrocki et al. (2021). For the GMT-2 study area, we post-processed the *foliar cover* maps by summarizing them to segments and setting areas where *surficial features* were predicted as barren or water to 0%. The number of species and aggregates can be increased in the future following additional data integration to the Alaska Vegetation (AKVEG) Plots Database[4].

Table 6. Metadata for the *foliar cover* datasets.

Metadata	**Value**
Dataset filenames (xxxxxx = abbreviation)	GMT2_foliar_xxxxxx.tif
Dataset name (abbreviation)	1. Foliar cover of *Alnus* shrubs (alnus)
	2. Foliar cover of *Betula* shrubs (betshr)
	3. Foliar cover of *Dryas* shrubs (dryas)
	4. Foliar cover of *Empetrum nigrum* (empnig)
	5. Foliar cover of *Eriophorum vaginatum* (erivag)
	6. Foliar cover of *Rhododendron* shrubs (rhoshr)
	7. Foliar cover of *Salix* shrubs (salshr)
	8. Foliar cover of *Sphagnum* (sphagn)
	9. Foliar cover of *Vaccinium uliginosum* (vaculi)
	10. Foliar cover of *Vaccinium vitis-idaea* (vacvit)
	11. Foliar cover of wetland sedges (wetsed)
Data type	Continuous
Scale	1:24,000
Boundary resolution	2 × 2 m
Minimum mapping unit	N/A
Coordinate system	Alaska Albers Equal Area Conic (EPSG 3338)
Units	Percentage absolute foliar cover
Scale factor (modifies the units)	1
Theoretical unit range	0-100
Time range	Circa 2019

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[4] Available: https://akveg.uaa.alaska.edu

Figure 3. The selected species or aggregates, such as wetland sedges (left; *Carex saxatilis* ssp. *laxa* (Trautv.) Kalela) and non-dwarf *Salix* shrubs (right; *Salix richardsonii* Hook.), relate to USNVC alliances.

Accuracy Assessment

The accuracy assessment for the *foliar cover* datasets includes multiple scales. Here, we provide R^2, mean absolute error (MAE), and root mean squared error (RMSE) at the site and landscape scales (Table 7). Depending on how the data are used or interpreted, different scales of assessed accuracy should be applied. The site scale accuracy pertains to comparisons in space or time of multiple sites (i.e., areas the size of 10 × 10 m grid cells to approximately the size of a square of nine adjacent AIM plots). The landscape scale accuracy pertains to summary comparisons of areas larger than approximately 32,400 m^2 (8 acres; the area of a square of nine adjacent AIM plots). We calculated performance metrics from the merged independent test partitions of 10-fold cross validation.

Table 7. R^2, MAE, and RMSE for *foliar cover* maps of 11 species and aggregates at the site scale, calculated for Northern Alaska, and the landscape scale, calculated for all of boreal and Arctic Alaska.

Map Group	**Site Scale**			**Landscape Scale**		
	R^2	MAE	RMSE	R^2	MAE	RMSE
Alnus Shrubs	0.56	2.23	7.58	0.69	2.81	4.91
Betula Shrubs	0.44	4.58	9.59	0.77	3.16	4.85
Dryas Dwarf Shrubs	0.4	2.96	7.29	0.65	1.73	3.33
Empetrum nigrum	0.22	1.46	3.77	0.74	2	3.51
Eriophorum vaginatum	0.45	3.63	8.33	0.7	2.17	4.18
Rhododendron Shrubs	0.44	3	6.06	0.75	2.04	3.39
Salix Low-Tall Shrubs	0.41	7.95	14.6	0.57	5.43	7.87
Sphagnum	0.53	5.72	12.37	0.64	3.85	6.84
Vaccinium uliginosum	0.29	2.75	5.88	0.77	2.15	3.68
Vaccinium vitis-idaea	0.43	2.83	5.81	0.58	1.62	2.68
Wetland Sedges	0.49	7.61	14.92	0.71	4.12	6.88

Area by Vegetation Type

Area by Vegetation Type is the two-dimensional ground area occupied by the existing plant community (i.e., vegetation) type. The *area by vegetation type* indicator is represented by the *existing vegetation type* dataset (Table 8). *Existing vegetation type* is an abstraction of the dominant composition and structure of the plant community within a particular area (equal to or larger than the 0.5 acre minimum mapping unit), whether the plant community is homogenous or heterogenous (Figure 4). *Existing vegetation types* are therefore most appropriate for visual interpretation or data summarization. For statistical analyses, we recommend instead using the *foliar cover* datasets, which capture heterogeneity as gradients (see Nawrocki et al. 2020). Map classes for *existing vegetation types* relate to USNVC alliances (see Appendix 3), per FGDC standards (FGDC 2008).

Figure 4. Vegetation types are abstractions of plant community composition and structure, which often are heterogenous and occur as gradients in nature.

Table 8. Metadata for the *existing vegetation type* dataset.

Metadata	**Value**
Dataset filename	GMT2_ExistingVegetationType.tif
Dataset name	Existing vegetation type
Data type	Categorical
Scale	1:24,000
Boundary resolution	2 × 2 m
Minimum mapping unit	0.5 acre
Coordinate system	Alaska Albers Equal Area Conic (EPSG 3338)
Units	N/A
Scale factor (modifies the units)	N/A
Theoretical unit range	Appendix 3
Time range	Circa 2020

Methods

Vegetation types in the USNVC are a particular set of opinions on major patterns of plant community composition and structure and geophysical characteristics. For this reason, we mapped *existing vegetation types* as a derivative of *vegetation pattern* and *surficial features*. First, we developed a schema relating USNVC alliances to mappable classes (see Appendix 3). We then created a programmatic key to the mappable classes based on the *foliar cover* values and assigned *surficial feature* per segment. The distributions for predicted *foliar cover* maps differ from those for foliar cover observed in the field. Thresholds in the programmatic key reflect the predicted distributions and may therefore sometimes differ from what might be most appropriate in a field key. Refer to the accuracy assessments for *vegetation pattern* and *surficial features*.

Area Results

To calculate *area by vegetation type* for a particular area of interest, the *existing vegetation type* raster can be extracted to the area of interest. Cell counts for each type in the extracted raster should be multiplied by 4 m^2 to get *area by vegetation type* in m^2. We provide the *area by vegetation type* summary for the GMT-2 study area (Table 9).

Table 9. Area and percentage (%) of total per *existing vegetation type* within the GMT-2 study area (1,890.7 km^2; 467,202 acres). All values are rounded to the nearest decimal.

Existing vegetation type	Area (km^2)	%	Existing vegetation type	Area (km^2)	%
coastal & estuarine barren	56.4	3	Arctic herbaceous inland dune	3.5	0.2
freshwater floodplain barren	33.5	1.8	Arctic sedge meadow, wet	569.4	30.1
salt-killed tundra or marsh	32.7	1.7	Arctic Dryas-ericaceous dwarf shrub, acidic	20.6	1.1
stream corridor	0.7	0	Arctic birch low shrub, wet	0	0
water	512.1	27.1	Arctic willow low shrub, mesic	0.4	0
pipelines	0.6	0	Arctic willow low shrub, wet	5.6	0.3
infrastructure	3.3	0.2	Arctic alder floodplain	0.2	0
Arctic freshwater marsh	86	4.5	Arctic willow floodplain	44.1	2.3
Arctic herbaceous & dwarf shrub coastal beach	7.8	0.4	Arctic willow inland dune	28.8	1.5
Arctic herbaceous & shrub coastal dune	3.2	0.2	Arctic tussock dwarf shrub tundra	278	14.7
Arctic herbaceous coastal salt marsh	59.1	3.1	Arctic tussock low shrub tundra	144.8	7.7

Productivity

Productivity is the production of organic compounds through photosynthetic activity minus the consumption of organic compounds through respiratory activity by plants and lichens (i.e., net primary production). Organic compounds store energy in a biologically available form that can be transferred between organisms; thus, net primary production (NPP) is a measure of the energetic input into an ecosystem. Photosynthesis captures atmospheric carbon in organic compounds while respiration releases carbon stored in organic compounds back into the atmosphere. Although NPP quantifies energetic input into an ecosystem, it can be measured as kg of Carbon per m^2 because energetic transfers are mediated by carbon-based organic compounds. NPP varies by plant community structure because of differences in the density of photosynthetic tissues (Figure 5).

Figure 5. On average, *Arctic tussock low shrub tundra* (left) has higher NPP than *Arctic tussock dwarf shrub tundra* (right) because taller woody stems can increase the density of photosynthetic tissues per unit area.

The *productivity* indicator is represented by *net primary production* datasets in 5-year intervals from 2001 through 2020 (Table 10).

Table 10. Metadata for the *net primary production* datasets.

Metadata	**Value**
Dataset filenames (yyyy = end year)	GMT2_Productivity_yyyy.tif
Dataset name	Net primary production start year-end year
Data type	Continuous
Scale	1:24,000
Boundary resolution	2 × 2 m
Minimum mapping unit	N/A
Coordinate system	Alaska Albers Equal Area Conic (EPSG 3338)
Units	kg of Carbon per m^2
Scale factor (modifies the units)	0.0001
Theoretical unit range	1-∞ (0 indicates unvegetated)
Time range	5-year intervals: 2001-2005, 2006-2010, 2011-2015, 2016-2020

Methods

The USGS Earth Resources Observation and Science (EROS) Center calculates annual, calibrated, gap filled NPP from MODIS Terra and Aqua platforms (MOD17A3HGF.006 and MYD17A3HGF.006, respectively). Without further processing, the MODIS NPP data have two problems: 1) the data are spatially incomplete, leaving large gaps for any given year; and 2) the data are spatially coarse, which hinders direct comparisons to plant community composition and structure, *existing vegetation types*, or *surficial features*. We filled missing data and re-scaled the data to the 1:24,000 scale by decomposing the MODIS NPP measurements into constituent contributions from mapped species and aggregates, *surficial feature* probabilities, distance from coast or estuary, and infrastructure and pipelines.

First, we combined the NPP measurements from the Terra and Aqua platforms as the mean per grid cell for each year from 2000 through 2020 (all years for which data exist on GEE). We then re-scaled all covariates to match the 0.5 × 0.5 km resolution of the MODIS NPP data. A random forest regressor statistically associated NPP measurements with the contributions of each covariate to detect trends according to plant community composition and structure and *surficial feature*. We included distance from coast to enable the model to detect latitudinal trends that relate to broad climate patterns and the influence of proximity to the Beaufort Sea on local climate. Additionally, we included the number of years since 2000 to detect the change-over-time trend.

As with the assessment for *surficial features*, we used a spatially block cross validation to test the performance of the re-scaling model. See the methods for *surficial features* for details on the spatially blocked cross validation. In addition to controlling optimistic bias caused by spatial autocorrelation, the spatially blocked design also controlled for temporal autocorrelation because all years of data for each block were reserved as validation data per iteration. We calculated R^2, MAE, and RMSE from the merged validation partitions of the cross validation.

Because all covariates that we used to train the model were quantitative, we could alter the spatial scale of the model predictions without necessitating changes to the units or quantitative scales of the covariates. Therefore, we predicted the model to covariates summarized by segment for each year from 2001 through 2020. Finally, we calculated 5-year means to represent smoothed patterns in NPP rather than interannual variation. Trends through time can be assessed by comparing the 5-year means.

Accuracy Assessment

The model for *net primary production* had an R^2 of 0.71, a MAE of 137.7, and a RMSE of 180.2. The units for the MAE and RMSE are kg of Carbon per m^2. The accuracy assessment is relative to the 0.5 × 0.5 km resolution of the original MODIS NPP data.

Phenology

Phenology is the cycle of vegetation annual growth. We represent *phenology* as day-of-year through four transitions based on MODIS land cover dynamics calculated from annual EVI-2 amplitude. Because snow cover in the GMT-2 study area alters how the EVI-2 amplitude relates to vegetation annual growth, we define the transition periods differently than they are defined in the MODIS land cover dynamics for the same EVI-2 thresholds (Figure 6):

1. Greenup: date when EVI-2 first crosses 50% of the EVI-2 amplitude; represents the beginning of vegetation annual growth for the year.
2. Maturity: date when EVI-2 first crosses 90% of the EVI-2 amplitude; represents the start of the period of peak photosynthetic activity.
3. Senescence: date when EVI-2 last crosses 90% of the EVI-2 amplitude; represents the end of the period of peak photosynthetic activity.
4. Greendown: date when EVI-2 last crosses 50% of the EVI-2 amplitude; represents the point at which most annual (i.e., non-evergreen) photosynthetic plant tissues have died.

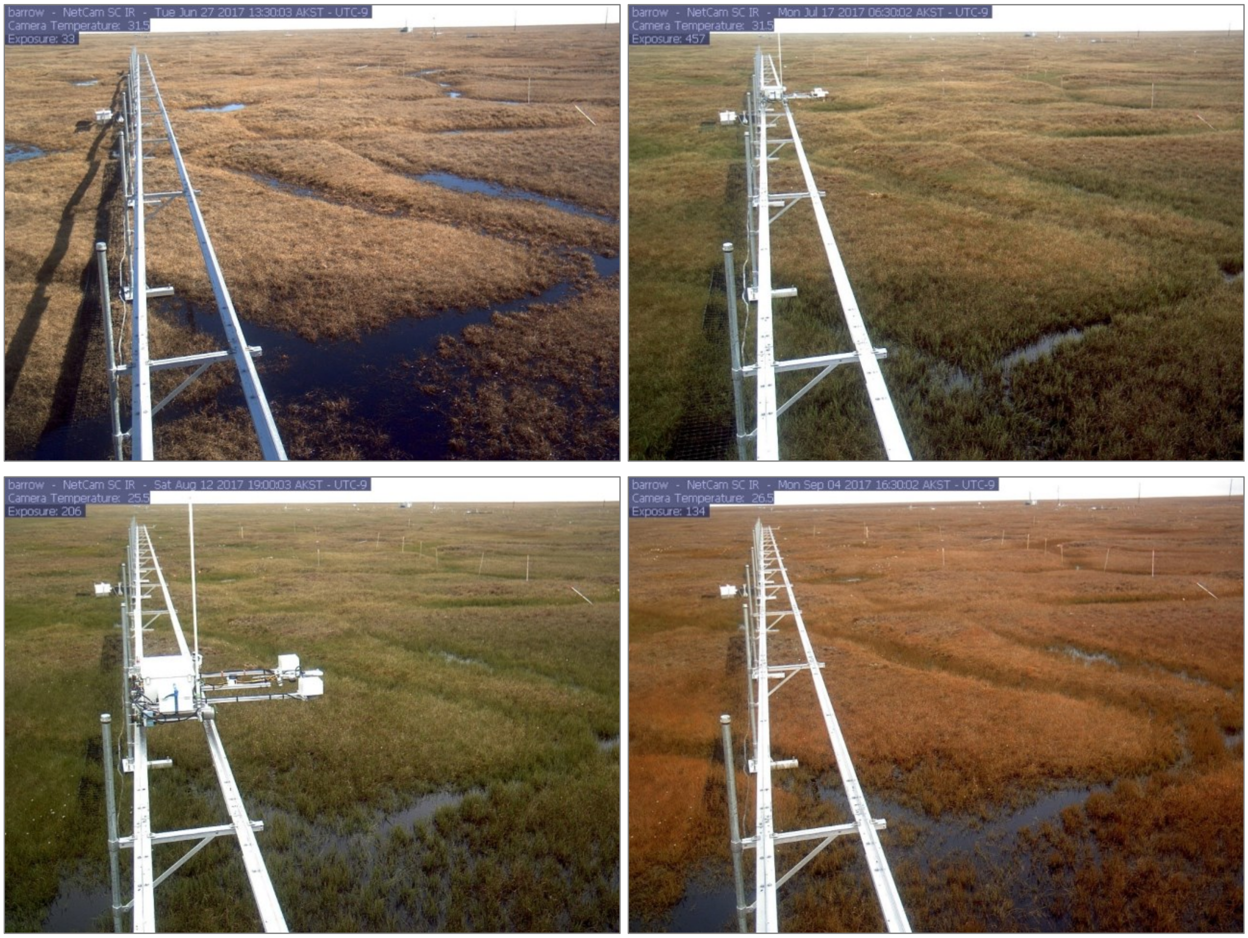

Figure 6. Example of visual differences for phenological transition points using photographs taken during 2017 from the Utqiagvik phenological monitoring site (Richardson et al. 2018). Photograph dates relate to mean predicted dates for a similar site in the northern GMT-2 study area for the 5-year

interval 2016-2020 based on MODIS EVI-2 amplitude thresholds. Greenup (top left) date is June 27, maturity (top right) date is July 17, senescence (bottom left) date is August 12, and greendown (bottom right) date is September 4.

The *phenology* indicator is represented by *greenup*, *maturity*, *senescence*, and *greendown* datasets in 5-year intervals from 2001 through 2020 (Table 11).

Table 11. Metadata for the *phenology* datasets.

Metadata	Value
Dataset filenames (yyyy = end year)	1. GMT2_Phen_Greenup_yyyy.tif 2. GMT2_Phen_Maturity_yyyy.tif 3. GMT2_Phen_Senescence_yyyy.tif 4. GMT2_Phen_Greendown_yyyy.tif
Dataset name	1. Greenup start year-end year 2. Maturity start year-end year 3. Senescence start year-end year 4. Greendown start year-end year
Data type	Continuous
Scale	1:24,000
Boundary resolution	2 × 2 m
Minimum mapping unit	N/A
Coordinate system	Alaska Albers Equal Area Conic (EPSG 3338)
Units	Day-of-year
Scale factor (modifies the units)	1
Theoretical unit range	1-365 (0 indicates unvegetated; see Appendix 4)
Time range	5-year intervals: 2001-2005, 2006-2010, 2011-2015, 2016-2020

Methods

The USGS EROS Center calculates calibrated annual phenology from MODIS EVI-2 amplitudes (MCD12Q2.006). Similar to MODIS NPP, the MODIS phenology data have two problems: 1) the data are spatially incomplete, leaving large gaps for any given year; and 2) the data are spatially coarse, which hinders direct comparisons to plant community composition and structure, *existing vegetation types*, or *surficial features*. Additionally, the MODIS phenology data contain obvious errors in dates (e.g., *greenup* date before snow has melted). To remove obvious errors, we found the mean day-of-year across the study area for all years per phenology transition and removed all data values that were not within 20 days of the mean in either direction. We filled missing data and re-scaled the data to the 1:24,000 scale by decomposing the MODIS phenology date measurements into constituent contributions from mapped species and aggregates, *surficial feature* probabilities, distance from coast or estuary, and infrastructure and pipelines.

First, we processed dates from the MODIS land cover dynamics to day-of-year per cell for each year from 2001 through 2019 (all years for which data exist on GEE). We then re-scaled all covariates to match the 0.5 × 0.5 km resolution of the MODIS phenology data. For each phenology transition, a random forest regressor statistically associated the day-of-year measurements with the contributions of each covariate to detect trends according to plant community composition and structure and *surficial feature*. As with *productivity*, we included distance from coast to enable the model to detect latitudinal trends that relate to broad climate patterns and the influence of proximity to the Beaufort Sea on local climate. Additionally, we included the number of years since 2000 to detect the change-over-time trend.

Our calculation of performance metrics and prediction of models to segments matched the process described for NPP. We calculated 5-year means to represent smoothed patterns in phenology transitions rather than interannual variation.

Accuracy Assessment

The performance metrics for the *phenology* datasets combine the errors in the original MODIS land cover dynamics and the generalization introduced by the model. The accuracy assessment is relative to the 0.5 × 0.5 km resolution of the original MODIS land cover dynamics data. Because the MODIS land cover dynamics are imperfect measurements even after filtering out obvious errors, the generalization in the model results smooths errors in the original gridded product (Table 12).

Table 12. R^2, MAE, and RMSE for the *greenup*, *maturity*, *senescence*, and *greendown* datasets across all years.

Phenology transition	**R^2**	**MAE (days)**	**RMSE (days)**
Greenup	0.66	3.3	4.2
Maturity	0.71	2.5	3.3
Senescence	0.63	2.6	3.4
Greendown	0.45	3.8	5.0

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Appendix 1: Mapping Covariates

Table 13 lists mapping covariates used to develop the remote sensing indicators for GMT-2. For the development of the *vegetation pattern* remote sensing indicators, refer to the user guide for the *Continuous Foliar Cover of Plant Species and Aggregates in North American Beringia*.[5] Remote sensing indicators are listed by number as follows:

1. Image segmentation
2. Seasonal surface water percentage
3. Surficial features
4. Existing vegetation type
5. Productivity
6. Phenology – Greenup
7. Phenology – Maturity
8. Phenology – Senescence
9. Phenology – Greendown

The following conventions are used to denote additional clarifying characteristics pertaining to one or more datasets:

* 40-day median composites representing late June, mid-July, early August, and end of August 2017-2018 and 2020-2021 (2019 data missing in Google Earth Engine)

Ŧ Growing season median composite 2020-2022

ǂ 40-day median composites representing mid-June, late July, mid-August, and mid-September 2019-2022

§ Derived from USGS 3DEP IFSAR Digital Elevation Model

¶ Derived from manual delineation

** Source data from Nawrocki et al. 2021

ŦŦ Source data from Macander et al. 2022

ǂǂ Combined measurements from Terra and Aqua platforms per year for 2000-2020

§§ Annual measurements for 2001-2019

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[5] Nawrocki, T.W., M.L. Carlson, A.F. Wells, M.J. Macander, E.J. Trammell, F.D.W. Witmer, C.A. Roland, K. Baer, and D.K. Swanson. 2021. Continuous Foliar Cover of Plant Species and Aggregates in North American Beringia. Version 1.0 (May 2021). Available: https://doi.org/10.5281/zenodo.3897482

Table 13. Textural, spectral, topographic, hydrographic, and other ancillary covariates represented biotic, abiotic, and anthropogenic gradients and features in models of remote sensing indicators.

Type	**Dataset (name abbreviation)**	**Original Resolution**	**Use**
Gridded	Sentinel-1 SAR Vertical-Vertical polarization[*]	10 × 10 m	2
Segment Mean	Sentinel-1 SAR Vertical-Vertical polarization (s1_vv)[‡]	10 × 10 m	3
Segment Mean	Sentinel-1 SAR Vertical-Horizontal polarization (s1_vh)[‡]	10 × 10 m	3
Segment Mean	Sentinel-2 Band 2: Blue (s2_mm_02_blue)[‡]	10 × 10 m	3
Segment Mean	Sentinel-2 Band 3: Green (s2_mm_03_green)[‡]	10 × 10 m	3
Segment Mean	Sentinel-2 Band 4: Red (s2_mm_04_red)[‡]	10 × 10 m	3
Segment Mean	Band 5: Red Edge 1 (s2_mm_05_rededge1)[‡]	20 × 20 m	3
Segment Mean	Band 6: Red Edge 2 (s2_mm_06_rededge2)[‡]	20 × 20 m	3
Segment Mean	Band 7: Red Edge 3 (s2_mm_07_rededge3)[‡]	20 × 20 m	3
Segment Mean	Band 8: Near Infrared (s2_mm_08_nearir)[‡]	10 × 10 m	3
Segment Mean	Band 8a: Red Edge 4 (s2_mm_08a_rededge4)[‡]	20 × 20 m	3
Segment Mean	Band 11: Shortwave Infrared 1 (s2_mm_11_shortir1)[‡]	20 × 20 m	3
Segment Mean	Band 12: Shortwave Infrared 2 (s2_mm_12_shortir2)[‡]	20 × 20 m	3
Segment Mean	Enhanced Vegetation Index-2 (s2_mm_evi2)[‡]	10 × 10 m	3
Segment Mean	Normalized Burn Index (s2_mm_nbr)[‡]	20 × 20 m	3
Segment Mean	Normalized Difference Moisture Index (s2_mm_ndmi)[‡]	20 × 20 m	3
Segment Mean	Normalized Difference Snow Index (s2_mm_ndsi)[‡]	20 × 20 m	3
Segment Mean	Normalized Difference Vegetation Index (s2_mm_ndvi)[‡]	10 × 10 m	3
Segment Mean	Normalized Difference Water Index (s2_mm_ndwi)[‡]	10 × 10 m	3
Gridded	Maxar + Spot Composite Blue	2 × 2 m	1
Segment Mean	Maxar + Spot Composite Blue (comp_01_blue)	2 × 2 m	3
Segment Std. Dev.	Maxar + Spot Composite Blue (comp_01_blue_std)	2 × 2 m	3
Gridded	Maxar + Spot Composite Green	2 × 2 m	1
Segment Mean	Maxar + Spot Composite Green (comp_02_green)	2 × 2 m	3
Segment Std. Dev.	Maxar + Spot Composite Green (comp_02_green_std)	2 × 2 m	3
Gridded	Maxar + Spot Composite Red	2 × 2 m	1
Segment Mean	Maxar + Spot Composite Red (comp_03_red)	2 × 2 m	3

Type	Dataset (name abbreviation)	Original Resolution	Use
Segment Std. Dev.	Maxar + Spot Composite Red (comp_03_red_std)	2 × 2 m	3
Gridded	Maxar + Spot Composite Near Infrared	2 × 2 m	1
Segment Mean	Maxar + Spot Composite Near Infrared (comp_04_nearir)	2 × 2 m	3
Segment Std. Dev.	Maxar + Spot Composite Near Infrared (comp_04_nearir_std)	2 × 2 m	3
Gridded	Maxar + Spot Composite Enhanced Vegetation Index-2	2 × 2 m	1
Segment Mean	Maxar + Spot Composite Enhanced Vegetation Index-2 (comp_evi2)	2 × 2 m	3
Segment Std. Dev.	Maxar + Spot Composite Enhanced Vegetation Index-2 (comp_evi2_std)	2 × 2 m	3
Gridded	Maxar + Spot Composite Normalized Difference Vegetation Index	2 × 2 m	1
Segment Mean	Maxar + Spot Composite Normalized Difference Vegetation Index (comp_ndvi)	2 × 2 m	3
Segment Std. Dev.	Maxar + Spot Composite Normalized Difference Vegetation Index (comp_ndvi_std)	2 × 2 m	3
Gridded	Maxar + Spot Composite Normalized Difference Water Index	2 × 2 m	1
Segment Mean	Maxar + Spot Composite Normalized Difference Water Index (comp_ndwi)	2 × 2 m	3
Segment Std. Dev.	Maxar + Spot Composite Normalized Difference Water Index (comp_ndwi_std)	2 × 2 m	3
Segment Std. Dev.	Maxar Normalized Difference Vegetation Index (maxar_ndvi_std)	0.5 × 0.5 m	3
Segment Range	Maxar Normalized Difference Vegetation Index (maxar_ndvi_rng)	0.5 × 0.5 m	3
Segment Std. Dev.	Maxar Normalized Difference Water Index (maxar_ndwi_std)	0.5 × 0.5 m	3
Segment Range	Maxar Normalized Difference Water Index (maxar_ndwi_rng)	0.5 × 0.5 m	3
Segment Mean	Topography – Aspect (top_aspect)[§]	5 × 5 m	3
Segment Mean	Topography – Elevation (top_elevation)[§]	5 × 5 m	3

Type	Dataset (name abbreviation)	Original Resolution	Use
Segment Mean	Topography – Exposure (top_exposure)§	5 × 5 m	3
Segment Mean	Topography – Heat Load Index (top_heat_load)§	5 × 5 m	3
Segment Mean	Topography – Position (top_position)§	5 × 5 m	3
Segment Mean	Topography – Radiation (top_radiation)§	5 × 5 m	3
Segment Mean	Topography – Roughness (top_roughness)§	5 × 5 m	3
Segment Mean	Topography – Slope (top_slope)§	5 × 5 m	3
Segment Mean	Topography – Surface Area (top_surface_area)§	5 × 5 m	3
Segment Mean	Topography – Surface Relief (top_surface_relief)§	5 × 5 m	3
Segment Mean	Topography – Wetness Index (top_wetness)§	5 × 5 m	3
Gridded	Hydrography – Streams¶	2 × 2 m	3
Segment Mean	Hydrography – Streams (hyd_streams)¶	2 × 2 m	3
Segment Mean	Hydrography – Distance from Stream (hyd_stream_dist)¶	2 × 2 m	3
Segment Mean	Hydrography – River Position (hyd_river_position)§¶	2 × 2 m	3
Segment Mean	Hydrography – Stream Position (hyd_stream_position)§¶	2 × 2 m	3
Segment Mean	Hydrography – Distance from Coast or Estuary (hyd_estuary_dist)¶	2 × 2 m	3-9
Segment Mean	Hydrography – Seasonal Surface Water Percentage (hyd_seasonal_water)	10 × 10 m	3-9
Gridded	Ancillary – Infrastructure¶	2 × 2 m	3-9
Segment Mean	Ancillary – Infrastructure (inf_developed) ¶	2 × 2 m	3-9
Gridded	Ancillary - Pipelines¶	2 × 2 m	3-9
Segment Mean	Ancillary – Pipelines (inf_pipelines)¶	2 × 2 m	3-9
Segment Mean	Foliar cover of *Alnus* shrubs (foliar_alnus)**	10 × 10 m	3-9
Segment Mean	Foliar cover of *Betula* shrubs (foliar_betshr)**	10 × 10 m	3-9
Segment Mean	Foliar cover of *Dryas* shrubs (foliar_dryas)**	10 × 10 m	3-9
Segment Mean	Foliar cover of *Empetrum nigrum* (foliar_empnig)**	10 × 10 m	3-9
Segment Mean	Foliar cover of *Eriophorum vaginatum* (foliar_erivag)**	10 × 10 m	3-9
Segment Mean	Foliar cover of *Rhododendron* shrubs (foliar_rhoshr)**	10 × 10 m	3-9

Type	**Dataset (name abbreviation)**	**Original Resolution**	**Use**
Segment Mean	Foliar cover of *Salix* shrubs (foliar_salshr)[**]	10 × 10 m	3-9
Segment Mean	Foliar cover of *Sphagnum* (foliar_sphagn)[**]	10 × 10 m	3-9
Segment Mean	Foliar cover of *Vaccinium uliginosum* (foliar_vaculi)[**]	10 × 10 m	3-9
Segment Mean	Foliar cover of *Vaccinium vitis-idaea* (foliar_vacvit)[**]	10 × 10 m	3-9
Segment Mean	Foliar cover of wetland sedges (foliar_wetsed)[**]	10 × 10 m	3-9
Segment Mean	Foliar cover of forbs (foliar_forb)[††]	30 × 30 m	3-9
Segment Mean	Foliar cover of graminoids (foliar_graminoid)[††]	30 × 30 m	3-9
Segment Mean	Foliar cover of light-colored macrolichens (foliar_lichens)[††]	30 × 30 m	3-9
Gridded	MODIS Annual Net Primary Production (npp_yyyy)[‡‡]	0.5 × 0.5 km	5
Gridded	MODIS Greenup day-of-year defined as when EVI-2 first crossed 50% of the segment EVI-2 amplitude (phen_yyyy_01_greenup)[§§]	0.5 × 0.5 km	6
Gridded	MODIS Maturity day-of-year defined as when EVI-2 first crossed 90% of the segment EVI-2 amplitude (phen_yyyy_02_maturity)[§§]	0.5 × 0.5 km	7
Gridded	MODIS Senescence day-of-year defined as when EVI-2 last crossed 90% of the segment EVI-2 amplitude (phen_yyyy_03_senescence)[§§]	0.5 × 0.5 km	8
Gridded	MODIS Greendown day-of-year defined as when EVI-2 last crossed 50% of the segment EVI-2 amplitude (phen_yyyy_04_greendown)[§§]	0.5 × 0.5 km	9
Gridded	Surficial feature predicted probabilities	2 × 2 m	5-9

Appendix 2: Map Class Schema for Surficial Features

The map class schema for *surficial features* is intended to represent major groupings of permafrost-driven features. Additionally, geophysical features for which permafrost is not a driver (or not the primary driver) are included to ensure that the map classes are exhaustive for the GMT-2 study area.

Barrens

Barrens are unvegetated surfaces with exposed mineral soil. In the GMT-2 study area, they occur from hydrologic erosion and deposition along rivers (Figure 1Figure 7), streams, and tidal zones. Barrens may be covered by surface water for part of the year along floodplains or daily in tidal zones.

Figure 7. Example of *barrens* along a river floodplain.

Dunes

Dunes are an assemblage of moving and/or stabilized dunes, together with sand plains, interdune areas, and the ponds, lakes, or swamps produced by the blocking of waterways by migrating dunes. A dune is a low mound, ridge, bank, or hill of loose, windblown, subaerially deposited granular material (generally sand). Dunes can be (mostly) barren and capable of movement from place to place or (mostly) covered and stabilized with vegetation but retaining their characteristic undulating shape. In the GMT-2 study area, dunes generally formed near streams and rivers on the sand sheet (or emerging from and carrying material from the sand sheet) or along the coast. When fully vegetated, *dunes* intergrade with *non-patterned, drained*. The latter are distinguished by the lack of an undulating surface. *Dunes* provide habitat for several rare plant species on the BLM sensitive species list in the GMT-2 study area (Figure 8).

Figure 8. Example of *dunes* adjacent to a river floodplain (left; photo taken by ACCS staff). *Dunes* provide habitat for several rare plant species on the BLM sensitive species list in the GMT-2 study area, including *Koeleria asiatica* Domin (right).

Non-patterned, drained (indistinctly patterned)

Non-patterned, drained (indistinctly patterned) areas either have relatively high slope, which prevents the soil from holding moisture, or are underlain by sand, which enables water to drain from the soil efficiently (Figure 9). *Non-patterned, drained* areas are usually not patterned because they do not retain water well and are therefore not substantially influenced by the freeze-thaw action of ice. They are common on the sand sheet and adjacent to rivers and streams flowing out of (and transporting sediments from) the sand sheet. Occasionally, *non-patterned, drained* areas show some indistinct polygon formation or other patterning. The organic soil layer is generally thin or absent and exposed mineral soil is common. *Non-patterned, drained* areas provide habitat for several rare plant species on the BLM sensitive species list in the GMT-2 study area.

Figure 9. Example of *non-patterned, drained (indistinctly patterned)* in the vicinity of Inigok on the sand sheet.

Figure 10. Example of *non-patterned, floodplain* along a large stream. *Salix* shrubs are dense and organic soil is poorly developed.

Non-patterned, floodplain

Non-patterned, floodplains are well-drained, though frequently flooded, areas in the active floodplain of rivers and large streams. The class does not comprise the entire active floodplain zone. Tall to low *Salix* species are common on *non-patterned, floodplains* (Figure 10), and tall to low *Alnus* shrubs are also present and sometimes dominant in the southernmost portion of the GMT-2 study area. The organic soil layer is generally thin or absent and exposed mineral soil is common. *Non-patterned, floodplains* are usually not patterned because of the combination of well-drained mineral soil and subsurface water flow, both of which hinder permafrost development. *Non-patterned, floodplains* are therefore not substantially influenced by the freeze-thaw action of ice.

Non-patterned, mesic (indistinctly patterned)

Non-patterned, mesic (indistinctly patterned) areas are underlain by permafrost and have thick organic soil layers but have not formed polygons or other patterns (or have formed indistinct or inconsistent high-center polygons). The surface is generally homogenous in topography and hydrography (Figure 11). Thermokarst troughs are absent. Water above the soil surface is absent except during and just after snowmelt and in the depressions between tussocks. The typical moisture regime is mesic because the underlying permafrost prevents water drainage, but the topography does not cause accumulation of water.

Figure 11. Example of *non-patterned, mesic (indistinctly patterned)* with no patterning visible and homogenous topography and hydrography.

Non-polygonal, wet (stringers or indistinctly polygonal)

Non-polygonal, wet (stringers or indistinctly polygonal) areas are underlain by permafrost and have thick organic soil layers but have not formed polygons (or have formed indistinct or inconsistent flat- or low-center polygons). Some areas are not patterned, but patterning in the form of stringers is also common (Figure 12). Thermokarst troughs are generally absent. The water table is generally near or just above the soil surface. The typical moisture regime is hygric to hydric (to hydric-aquatic heterogenous) because the underlying permafrost prevents water drainage and the topography causes accumulation of water.

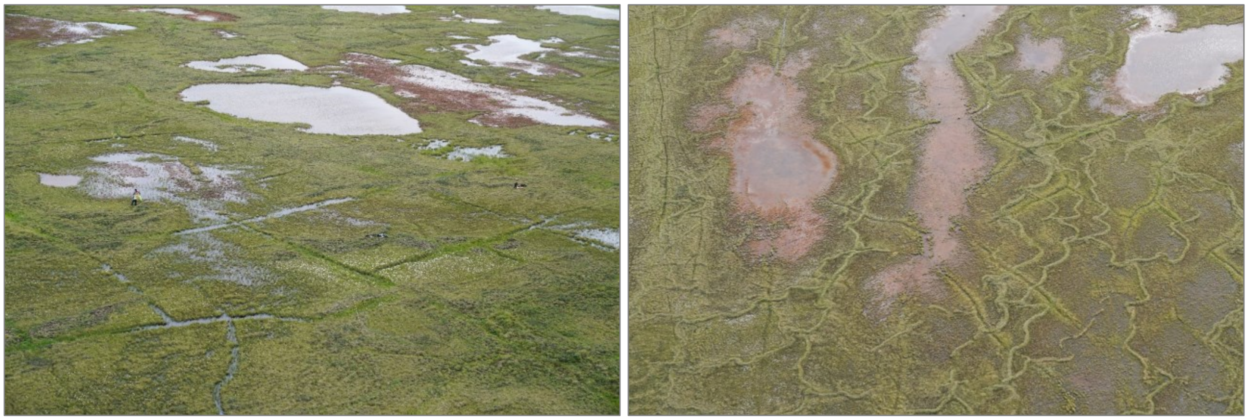

Figure 12. Examples of *non-polygonal, wet* with indistinct polygons (left) and stringers (right).

Thermokarst troughs, non-polygonal or indistinctly polygonal

Thermokarst troughs, non-polygonal or indistinctly polygonal, are areas underlain by permafrost where water-filled depressions have formed because of permafrost thaw but polygons have not formed (or are indistinct). This class forms from *non-patterned, mesic (indistinctly patterned)* as permafrost thaws, causing portions of the landscape to sink into depressions. Apart from the water-filled depressions, the typical moisture regime is mesic because the underlying permafrost prevents water drainage but the topography does not cause accumulation of water. This class captures the area in which thermokarst troughs form rather than just the trough itself (Figure 13).

Figure 13. Example of *thermokarst troughs* with indistinct polygons. The road to GMT-2 oil pads is visible in the background.

Figure 14. Example of *polygonal, mesic* high-center polygons with inundated troughs.

Polygonal, mesic

Polygonal, mesic areas are underlain by permafrost and have thick organic soil layers. Distinct polygons have formed and at least the polygon centers are mesic. Polygons in this category are most frequently high-center polygons with inundated troughs (Figure 14). High-center polygons with unsaturated troughs are also included and present in the GMT-2 study area. Thermokarst troughs may be present as well, but they are typically contiguous with inundated troughs and are not mapped as distinct from *polygonal, mesic*. This class intergrades with *non-patterned, mesic* and *thermokarst troughs*, where polygon troughs become indistinct or inconsistent.

Polygonal, wet

Polygonal, wet areas are underlain by permafrost and have thick organic soil layers. Distinct polygons have formed and at least the polygon centers are hygric to aquatic. Polygons in this category can take several forms. The most common in the GMT-2 study area, especially along river floodplains, are low-center polygons with mesic rims and inundated troughs. This class also includes low-center polygons with mesic rims and unsaturated troughs and flat- or low-center polygons separated by permafrost ridges (Figure 15). Thermokarst troughs may be present as well, but they are typically contiguous with inundated troughs and are not mapped as distinct from *polygonal, wet*. This class intergrades with *polygonal, mesic* where the centers of high-center polygons collapse and transition to low centers with mesic rims. *Polygonal, wet* also intergrades with *non-polygonal, wet* in transitional forms from wet sedge meadows with stringers to wet sedge flat- or low-center polygons with wet centers separated by permafrost ridges.

Figure 15. Example of *polygonal, wet* with flat- and low-center polygons separated by permafrost ridges.

Figure 16. Example of a small *freshwater marsh* surrounded by *non-polygonal, wet*.

Freshwater Marsh

Freshwater marshes are consistently inundated areas with emergent vegetation (usually *Arctophila fulva* or *Carex aquatilis*) at the edges of deep waterbodies, in draining/drained waterbodies, or in shallow waterbodies (Figure 16). Often no patterned ground has formed or is apparent because of the consistent inundated state. In some cases, stringers are present where *freshwater marsh* intergrades to *non-polygonal, wet* or partial polygons are present where the *freshwater marsh* intergrades to *polygonal, wet*.

Stream Corridor

Stream corridors are zones around stream beds that are filled with water for at least part of the year. The *stream corridor* is usually narrowly restricted to the area adjacent to the stream bed (Figure 17). A primary difference between a *stream corridor* and a floodplain is that the *stream corridor* does not receive substantial deposition of materials from the stream flow. We only mapped stream corridors that were approximately 2 m across with visible water in the Maxar imagery composite (or obvious connection between pools in beaded streams) that flowed into rivers or the ocean. Streams that do not meet the mapping criteria are present in the GMT-2 study area but not represented in the *surficial features* dataset.

Figure 17. Example of a *stream corridor* bounded by the tops of tall banks around a small stream.

Figure 18. Example of a *tidal marsh* with tidal water channels. Photograph by ACCS staff.

Tidal marsh

Tidal marshes are coastal wetlands that are frequently inundated with marine or brackish water from tidal action and storm surges (Figure 18). Tidal marshes are generally near sea level and adjacent to the coast but can also be found further inland along the Colville River Delta. Permafrost features are generally absent because of the warming effect of proximity to the ocean, but tidal marshes sometimes form polygons. In cases where polygons have formed within tidal marshes, we have mapped them as *tidal marsh* rather than as *polygonal, wet*. Tidal marshes provide important summer habitat for waterfowl and shorebirds.

Salt-killed tundra or marsh

Salt-killed tundra or marsh are areas adjacent to saline waterbodies where changes in elevation, sea level, and/or storm surges have caused inundation with salt water where salt water was previously absent. All or much of the non-saline adapted vegetation is killed in the process, and the *salt-killed* areas have low photosynthetic activity. Salt-killed tundra or marsh often also show polygon development (Figure 19). Because the inundation by salt water has shifted the disturbance regime away from a permafrost-driven regime, we have mapped polygonal features subject to salt kill as *salt-killed tundra or marsh* rather than as one of the polygonal classes.

Figure 19. Example of *salt-killed tundra* in the foreground of the photograph. The *salt-killed tundra* area also shows high-center polygons, but would not be mapped as *polygonal, mesic*. The background of the photograph shows an adjacent *tidal marsh*. Photograph by ACCS staff.

Figure 20. Example of *vegetated coastal beach* along the sparsely vegetated upper beach.

Vegetated Coastal Beach

Vegetated coastal beach are adjacent to marine or estuarine waters, have exposed mineral soils, and are partially or sparsely vegetated (Figure 20). Tidal action and storm surges are the primary disturbance regimes. Patterned ground is absent.

Water

Water is mapped where water persists as the reflectance surface without emergent vegetation throughout the growing season and as an approximate mid-point across seasonal changes in river flow levels and tidal action.

Infrastructure and Pipelines

Infrastructure and *pipelines* represent the direct anthropogenic alteration of the landscape. *Infrastructure* includes gravel pads, roads, and buildings (Figure 21). *Pipelines* are a separate class because they are elevated such that they have different impacts from other infrastructure.

Figure 21. Example of *infrastructure* and *pipelines* in the GMT-2 area.

Appendix 3: Map Class Schema for Existing Vegetation Type

Per standards set by the Federal Geographic Data Committee (FGDC), map classification schemas for vegetation maps created by or for federal entities must relate to vegetation types in the U.S. National Vegetation Classification (USNVC). The map class schema for *existing vegetation type* is derived USNVC (version 2022-05-01) and targets the alliance level (Table 14). In the current version, USNVC contains inconsistencies and errors for Alaska. We therefore lumped some alliances together into map classes and split one alliance into two. Additionally, we omitted some erroneous alliances from the map class schema. The map class schema only contains the alliances that occur within the GMT-2 study area. Providing descriptions and field keys for the USNVC is beyond the scope of this study; however, such work is a critical data need to aid consistent application and interpretation of USNVC in the future.

Table 14. Map class schema for *existing vegetation type* and correspondence to USNVC alliances (version 2022-05-01).

Map Vegetation Class	USNVC Alliances (version 2022-05-01)
Coastal & estuarine barren	N/A
Freshwater floodplain barren	N/A
Salt-killed tundra or marsh	N/A
Stream corridor	N/A
Water	N/A
Pipelines	N/A
Infrastructure	N/A
Arctic freshwater marsh	Arctophila fulva - Carex aquatilis Arctic Freshwater Marsh Arctophila fulva - Equisetum fluviatile - Hippuris vulgaris Arctic Freshwater Marsh
Arctic herbaceous & dwarf shrub coastal beach	Arctic coastal beach
Arctic herbaceous & shrub coastal dune	Arctic coastal dune
Arctic herbaceous coastal salt marsh	Arctic brackish tidal mudflats Puccinellia phryganodes - Salicornia borealis - Hippuris tetraphylla Salt Marsh
Arctic herbaceous inland dune	Arctic inland forb & grass dune
Arctic sedge meadow, wet	Arctic Acidic Wet Meadow Arctic Nonacidic Wet Meadow Carex aquatilis - Dupontia fisheri Wet Meadow

Map Vegetation Class	**USNVC Alliances (version 2022-05-01)**
Arctic Dryas-ericaceous dwarf shrub, acidic	Arctic Acidic Dryas Dwarf-shrub Tundra Arctic Ericaceous Dwarf-shrub Tundra
Arctic birch low shrub, wet	Betula nana - Ericaceous Arctic Wet Shrubland
Arctic willow low shrub, mesic	Arctic Acidic Low Willow Tundra Arctic Nonacidic Low Willow Tundra
Arctic willow low shrub, wet	Arctic Willow Wet Shrubland
Arctic alder floodplain	Arctic Tall Alder Wet Shrub Tundra
Arctic willow floodplain	Arctic Tall Willow Wet Shrub Tundra Chamerion latifolium - Salix alaxensis Arctic Floodplain
Arctic willow inland dune	Arctic Inland Willow Shrub Dune
Arctic tussock dwarf shrub tundra	Arctic Tussock Sedge Tundra
Arctic tussock low shrub tundra	Arctic Tussock Sedge Tundra

Appendix 4: Day-of-year calendar

We provide a calendar to aid the interpretation of datasets for the *phenology* indicator (Table 15).

Table 15. Calendar relating day-of-year to month and day. Adapted from NSIDC (2022).

Day of Month	May	June	July	August	September
1	121	152	182	213	244
2	122	153	183	214	245
3	123	154	184	215	246
4	124	155	185	216	247
5	125	156	186	217	248
6	126	157	187	218	249
7	127	158	188	219	250
8	128	159	189	220	251
9	129	160	190	221	252
10	130	161	191	222	253
11	131	162	192	223	254
12	132	163	193	224	255
13	133	164	194	225	256
14	134	165	195	226	257
15	135	166	196	227	258
16	136	167	197	228	259
17	137	168	198	229	260
18	138	169	199	230	261
19	139	170	200	231	262
20	140	171	201	232	263
21	141	172	202	233	264
22	142	173	203	234	265
23	143	174	204	235	266
24	144	175	205	236	267
25	145	176	206	237	268
26	146	177	207	238	269
27	147	178	208	239	270
28	148	179	209	240	271
29	149	180	210	241	272
30	150	181	211	242	273
31	151		212	243	