# Cary Metadata Template

## Title of project or data set

A permafrost and soil-surface organic layer module for simulating high-latitude forests with process-based vegetation models

## Abstract

(what/where/why/when/how)

Climate change and increased fire are eroding the resilience of boreal forests. This is problematic because boreal vegetation and the cold soils underneath store approximately 30% of all terrestrial carbon. Society urgently needs projections of where, when, and why boreal forests are most likely to change. Permafrost (i.e., subsurface material that remains frozen for at least two consecutive years) and the thick soil-surface organic layers (SOLs) that insulate permafrost are important controls of boreal forest dynamics and carbon cycling. However, both are rarely included in the process-based vegetation models used to simulate future ecosystem trajectories. To address this challenge, we developed a new computationally efficient permafrost and SOL module that operates at fine spatial (1 ha) and temporal (daily) resolutions. The module mechanistically simulates daily changes in depth to permafrost, annual SOL accumulation, and their complex effects on boreal forest structure and functions. We coupled the module to an established forest landscape model, iLand, and benchmarked the model in interior Alaska at spatial scales of stands (1 ha) to landscapes (61,000 ha) and over temporal scales of days to centuries. The coupled model could generate intra- and inter-annual patterns of snow accumulation and depth to permafrost consistent with independent observations in 17 instrumented forest stands. The model was also skilled at representing the distribution near-surface permafrost presence in a topographically complex landscape. We simulated 34.6% of forested area in the landscape as underlain by permafrost; nearly identical to the estimate of 33.4% of forested area from the benchmarking product. We further determined that the model could accurately simulate moss biomass, SOL accumulation, fire activity, tree-species composition, and stand structure at the landscape scale. Modular and flexible representations of key biophysical processes that underpin 21st-century ecological change are an essential next step in vegetation simulation to reduce uncertainty in future projections and to support innovative environmental decision making. We show that coupling a new permafrost and SOL module to an existing forest landscape model increases the model’s utility for projecting forest futures at high latitudes. Process-based models that represent relevant dynamics will catalyze opportunities to address previously intractable questions about boreal forest resilience, biogeochemical cycling, and feedbacks to regional and global climate.

## Creators

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## Keywords

Carbon cycling; Ecological legacies; Forest resilience; Permafrost; Surface organic layer

## Funding of this work:

|  |  |  |  |  |  |  |
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| PI First Name | PI Middle Initial | PI Last Name | PI ORCID ID (optional) | Title of Grant | Funding Agency | Funding Identification Number |
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|  |  |  |  |  |  |  |

## Timeframe

* Begin date: 07/01/2018
* End date: 07/01/2023
* Data collection ongoing/completed?

Completed

## Geographic location

## 65.1366, -147.457

## Taxonomic species or groups

Trees

## Methods

We used a pattern-oriented modeling framework to evaluate skill of a new module by simulating forests of interior Alaska at stand and landscape scales over days to centuries. Pattern oriented modeling is an approach to benchmarking where patterns of many variables operating at multiple temporal and spatial scales are compared to observational datasets. We chose interior Alaska because it is located in the discontinuous permafrost zone where permafrost presence, moss production, and SOL accumulation vary with dominant forest type, disturbance history, and topography. We first evaluated whether the module could generate realistic daily patterns of snow accumulation/melting and active layer thawing/freezing at the stand level. We then simulated a ~ 61,000 ha forested landscape to test whether the approach could realistically generate complex mosaics of near-surface permafrost presence, moss productivity, and SOL accumulation. To ensure robust simulations, we updated an existing iLand tree-species parameter set for interior Alaska and parameterized the iLand carbon cycle using values derived from the literature.

To evaluate whether the module could generate realistic intra- and inter-annual patterns of snow accumulation and active layer depth, we selected 17 forested sites in interior Alaska that were instrumented with temperature probes to measure daily soil temperature at depths of zero to six m between 2014 and 2018. Seven of the sites were recorded as having an annual maximum active layer depth of less than 2 m (permafrost present). Ten of the sites had an annual maximum active layer deeper than 2 m (permafrost absent). We used the 2 m depth cutoff because it is the maximum effective soil depth assumed in iLand. The sites were initialized from field inventories selected to match the species composition recorded in the soil temperature database. Soil information used to initialize iLand were extracted from the global SoilGrids250m V. 1.0 (for effective soil depth) and 2.0 (for % sand, silt, and clay). Relative soil fertility, expressed as plant available nitrogen, was set to 45 kg ha-1 yr-1. Depth of the SOL was not recorded in the soil temperature database for the 17 sites. Thus, we used photos from the instrumented sites and dominant forest type to assign initial SOL depths to the iLand stands. Sites where researchers recorded dominance of deciduous trees, or where SOLs appeared absent or shallow in photographs were assigned a depth of 0 or 0.07 m to match independent field estimates of SOL depths in deciduous forests. Sites dominated by black spruce, or where photographs suggested a deep SOL, were assigned a depth of 0.25 m based on field surveys of black spruce stands. Stands dominated by white spruce were assigned an intermediate depth of 0.16 m.

Stands were simulated in iLand with 2001-2018 daily climate (minimum and maximum daily temperature, precipitation, shortwave solar radiation, and vapor pressure deficit) from the 1-km Daymet product. We benchmarked simulated maximum annual snow depth and timing of snow melt for the period 2001-2017 (the period when snow observations were available) using a gridded snow product. This product was developed by integrating downscaled reanalysis data with satellite imagery to provide a continuous estimate of snow depth at 1-km spatial grain.

We compared simulated and observed daily changes in active layer depth for 2014-2018, the period where soil temperature observations were available, at the seven permafrost sites and maximum annual freezing depth for the 10 non-permafrost sites with root mean squared error (RMSE). We converted observed daily soil temperatures at depths of 0.03, 0.5, 1, 1.5, 2, 4, and 6 m to active layer depth by identifying the zero isoline with linear interpolation. We also compared the day of year when maximum active layer depth and freezing depth were reached in simulations and observations.

We evaluated whether the module, coupled with iLand, could simulate landscape-scale mosaics of near-surface permafrost (≤ 1 m deep), moss production, and SOL accumulation in a large forested area (~61,000 ha of land area). We initialized the model with tree-species composition map based on a remotely sensed plant functional type (PFT) product that classified vegetation as spruce, deciduous, mixed forest, or non-forest and reflected fire history. We further decomposed PFTs into black spruce, white spruce, trembling aspen, Alaskan birch, mixed forest, potential forest (i.e., areas currently unforested that could support forest in the future), and nonforest using rules based on aspect, elevation, and a permafrost map. While this approach allowed us to disaggregate PFTs to the species level, we lack robust datasets to evaluate the accuracy of the map. This is a challenge as dominant tree species determines SOL accumulation and permafrost distribution. In the future, well validated remotely sensed tree-species composition maps would markedly reduce initial condition uncertainty of forest simulations in interior Alaska.

Initial stand densities, tree sizes, and forest-floor carbon pools (litter, coarse wood, live and dead moss) for the appropriate tree species were initialized in the model as early postfire (11 years old) forest based on field inventories. Because the forest landscape was initialized as entirely early postfire, it did not reflect variation in forest stand age. Thus, we ran a 200-year spin up as a function of historical climate (climate years 1950-2005 recycled randomly with replacement) and simulated fire dynamically to generate spatial heterogeneity consistent with internal model logic, following protocols established in previous iLand studies. We then simulated forests for another 100 years; the period used in all analyses.

We want to eventually conduct simulations with future 21st century climate. Thus, we used daily meteorological data from the historical period of the CMIP5 generation CCSM4 General Circulation Model (GCM) to force landscape-level simulations instead of DAYMET (as was used in the stand-level experiment). This GCM corresponds closely with observed historical climate in Alaska, and we statistically downscaled it to a 1-km spatial resolution using quantile matching with Daymet as the observational grid.We extracted soils data from the same sources as the stand-level experiment that geographically corresponded to the 1-ha grid-cells in our simulated landscape. Because fire is stochastic in iLand, and an important determinant of permafrost dynamics, SOL depth, tree-species composition, and stand structure, we ran ten replicates and analyzed output from the run with the smallest difference between modeled and observed mean annual burned patch size and annual probability of a fire event.

We compared fire from simulation years 201-300 to observations in the Alaska Large Fire Database from the period 1980 - 2021. This database contains perimeters for larger fires (size threshold for inclusion has varied over time, ranging from 10-1,000 ha) and point locations for smaller fires. We combined these datasets to ensure comprehensive coverage and assumed a circular shape for the smaller fires when perimeters were unavailable. Fire is a stochastic process in iLand, so, we did not expect perfect correspondence between modeled and observed individual fire sizes and locations. Instead, we aimed for the model to generate fire characteristics that were generally consistent with the observational record. We took two approaches for benchmarking. First, we compared modeled and observed annual probability of fire occurrence and mean annual burned patch size, as well as the proportion of stems and basal area killed by fire. Second, we compared simulated and observed fire characteristics from the landscape with observed fire characteristics in all of forests of interior Alaska broken into 625 ~ 61,000ha landscapes. This allowed us to determine how the dynamic fire module in iLand performed for our landscape, specifically, and how the model performed relative to the spatial variation in fire regimes across interior Alaska.

We compared the proportion of the landscape underlain by near-surface permafrost in the last 30 years of simulation (years 271-300) to a remotely sensed product of near-surface permafrost presence. This product was created by integrating satellite records and other geospatial datasets to predict the probability of near-surface permafrost presence at a 30m spatial resolution with machine learning. Because iLand operates at 1-ha spatial resolution for permafrost, we aggregated the remotely sensed data from 30-m to 1-ha grid cells by calculating the mean probability of near-surface permafrost presence in each 1-ha grid cell. We then used a ≥ 50% probability of permafrost presence, the same cutoff used in the original analysis, to map the permafrost distribution. In iLand, near-surface permafrost was considered present in any grid cell where the annual maximum active layer depth was ≤ 1 m for 15 or more years. This cutoff ensured we only included areas that were underlain by frozen ground most years. We compared the total proportion of the landscape underlain by near-surface permafrost and how permafrost presence varied as a function of aspect in simulations and the benchmarking product. We also evaluated how permafrost presence varied as a function of modeled dominant tree species, but did not compare to the benchmarking product because we lack tree species composition maps in interior Alaska.

We compared SOL carbon in simulation year 300 separated by forest type to field inventories. While benchmarking data was unavailable, we also evaluated landscape variability in total SOL and live moss depth. We assessed SOL combustion by fire in different forest types for model years 260-300, to ensure a sufficient number of fires, as compared to two extensive sets of postfire field plots.

Because near-surface permafrost presence and moss productivity are affected by and feedback to influence forest dynamics, we determined whether the model could realistically represent landscape-level patterns of tree-species composition and stand structure.

We explored how landscape patterns of dominant forest type shifted through 300 years of simulation and compared modeled stand density and basal area of each forest type from the end of the simulation with two field inventories. The first was a regional network of permanent plots in interior Alaska collected by the Bonanza Creek Long Term Ecological Research Network site. The second inventory was the Cooperative Alaska Forest Inventory, which is a set of permanent plots covering interior Alaska, south-central Alaska, and the Kenai Peninsula.

We also compared modeled aboveground live tree biomass from the end of the simulation with remotely-sensed estimates of aboveground live woody biomass for the same landscape. This dataset is a 30-m product that characterizes annual live woody biomass for the years 1984-2014. We aggregated 2014 biomass estimates to the 1-ha spatial resolution of iLand using bilinear interpolation. We further benchmarked snag and coarse wood carbon pools in model year 300 with published field observations.

To quantify the underpinning drivers of landscape variability in tree-species composition and aboveground live and dead biomass, we compared modeled variation in postfire tree-seedling density from years 260-300 by species and SOL depth with field observations. Finally, we analyzed the computational efficiency of the module by simulating the landscape with and without the permafrost module turned on to quantify its memory requirement and run time.

Dominant forest type was determined using species importance values (IV), a measure of stand dominance based on the relative proportions of species density and basal area. It ranges from zero to two. We considered stands dominated by a particular species if their IV was greater than one. Stands were considered mixed-spruce or mixed-deciduous forest if black spruce and white spruce or aspen and birch IVs summed to greater than one, respectively. Averages in the text are presented as medians and inter-quartile ranges (IQRs) (25th-75th percentiles). Benchmarking analyses were conducted in R statistical software V. 4.0.4 using the packages tidyverse and terra.

## Data Table

**1. Table name(s): Daily\_soil-temp.txt**

**Table description(s): Daily temperature data from borehole sites around interior Alaska used to benchmark iLand active layer depth simulations**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Column name | Description | Unit | Code explanation or date format | Empty value code |
| Date | Date of measurement | date | Month/day/year | NA |
| Temp\_0.03m | Daily mean soil temperature at 0.03m depth | °C |  | NA |
| Temp\_0.05m | Daily mean soil temperature at 0.05m depth | °C |  | NA |
| Temp\_1.0m | Daily mean soil temperature at 1.0m depth | °C |  | NA |
| Temp\_1.5m | Daily mean soil temperature at 1.5m depth | °C |  | NA |
| Temp\_2.0 | Daily mean soil temperature at 2.0m depth | °C |  | NA |
| Temp\_4m | Daily mean soil temperature at 4.0m depth | °C |  | NA |
| Temp\_6m | Daily mean soil temperature at 6.0m depth | °C |  | NA |
| Site.name | Name of borehole site |  |  | NA |
| Latitude | latitude of site | Decimal degrees |  | NA |
| Longitude | Longitude of site | Decimal degrees |  | NA |
| year | Year of measurement | Year |  | NA |
| Month | Month of measurement | month |  | NA |
| day | Day of measurement | Day |  | NA |

**2. Table name(s): bore.hole.snow.depth.txt**

**Table description(s): Weekly snow depth at boreal hole sites described above derived from a gridded snow depth product Yi, Y., J. Kimball, and C. E. Miller. 2020. ABoVE: High Resolution Cloud-Free Snow Cover Extent and Snow Depth, Alaska, 2001-2017. ORNL DAAC.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Column name | Description | Unit | Code explanation or date format | Empty value code |
| Site.name | Name of borehole site |  |  |  |
| Veg.type | Classified vegetation type of borehole site |  |  |  |
| Snow.depth | Depth of the snow pack | Meters |  |  |
| date | Date of snow measurement | date | Year-month-day |  |

**3. Table name(s):** Landscape\_stand-structure-RSN-validation.txt

**Table description(s):** Bonanza Creek regional site network stand structure plots used for validation of forest landscape stand structure.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Column name | Description | Unit | Code explanation or date format | Empty value code |
| Siteid | Site id |  |  |  |
| Geoname | Site name |  |  |  |
| Fire.year | Year since fire (estimated) |  | Years |  |
| Count.total.ad.sap\_Pima | Density of Pima saplings and adults | Stems ha-1 |  |  |
| Count.total.ad.sap\_Pigl | Density of Pigl saplings and adults | Stems ha-1 |  |  |
| Count.total.ad.sap\_Bene | Density of Bene saplings and adults | Stems ha-1 |  |  |
| Count.total.ad.sap\_Potr | Density of Potr saplings and adults | Stems ha-1 |  |  |
| Ba.total.ad.sap\_Pima | Basal area of Pima saplings and adults | M2 ha-1 |  |  |
| Ba.total.ad.sap\_Pigl | Basal area of Pigl saplings and adults | M2 ha-1 |  |  |
| Ba.total.ad.sap\_Bene | Basal area of Bene saplings and adults | M2 ha-1 |  |  |
| Ba.total.ad.sap\_Potr | Basal area of Potr saplings and adults | M2 ha-1 |  |  |
| MeanDBH\_Pima | Average diameter at 1.35m height of Pima | cm |  |  |
| MeanDBH\_Pigl | Average diameter at 1.35m height of Pigl | cm |  |  |
| MeanDBH\_Bene | Average diameter at 1.35m height of Bene | cm |  |  |
| MeanDBH\_Potr | Average diameter at 1.35m height of Potr | cm |  |  |
| Total.density.ad.sap | Total density of all tree species in plot including saplings and adults | Stems ha-1 |  |  |
| Total.ba.ad.sap | Total basal area of all tree species in plot including saplings and adults | M2 ha-1 |  |  |
| IV.ad.sap\_Pima | Species importance value of Pima intregrates relative density and basal area | Index, ranges from 0-2 |  |  |
| IV.ad.sap\_Pigl | Species importance value of Pigl intregrates relative density and basal area | Index, ranges from 0-2 |  |  |
| IV.ad.sap\_Bene | Species importance value of Bene intregrates relative density and basal area | Index, ranges from 0-2 |  |  |
| IV.ad.sap\_Potr | Species importance value of Potr intregrates relative density and basal area | Index, ranges from 0-2 |  |  |

**4. Table name(s):** landscape\_structure-CAFI-validation.txt

**Table description(s):** Cooperative Alaska Forest Inventory data used for validation of forest landscape stand structure.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Column name | Description | Unit | Code explanation or date format | Empty value code |
| Site |  |  |  |  |
| Count.total.ad.sap\_Bene | Density of Bene saplings and adults | Stems ha-1 |  |  |
| Count.total.ad.sap\_Pigl | Density of Pigl saplings and adults | Stems ha-1 |  |  |
| Count.total.ad.sap\_Potr | Density of Potr saplings and adults | Stems ha-1 |  |  |
| Count.total.ad.sap\_Pima | Density of Pima saplings and adults | Stems ha-1 |  |  |
| Ba.total.ad.sap\_Bene | Basal area of Bene saplings and adults | M2 ha-1 |  |  |
| Ba.total.ad.sap\_Pigl | Basal area of Pigl saplings and adults | M2 ha-1 |  |  |
| Ba.total.ad.sap\_Potr | Basal area of Potr saplings and adults | M2 ha-1 |  |  |
| Ba.total.ad.sap\_Pima | Basal area of Pima saplings and adults | M2 ha-1 |  |  |
| Total.density.ad.sap | Total density of all tree species in plot including saplings and adults | Stems ha-1 |  |  |
| Total.ba.ad.sap | Total basal area of all tree species in plot including saplings and adults | M2 ha-1 |  |  |
| IV.ad.sap\_Pima | Species importance value of Pima intregrates relative density and basal area | Index, ranges from 0-2 |  |  |
| IV.ad.sap\_Pigl | Species importance value of Pigl intregrates relative density and basal area | Index, ranges from 0-2 |  |  |
| IV.ad.sap\_Bene | Species importance value of Bene intregrates relative density and basal area | Index, ranges from 0-2 |  |  |
| IV.ad.sap\_Potr | Species importance value of Potr intregrates relative density and basal area | Index, ranges from 0-2 |  |  |

**5. Table name(s): AK\_CA\_Soil\_Profile\_Synthesis.csv**

**Table description(s): Soil characteristics including carbon from Walker, X. J., B. M. Rogers, S. Veraverbeke, J. F. Johnstone, J. L. Baltzer, K. Barrett, L. Bourgeau-Chavez, N. J. Day, W. J. de Groot, C. M. Dieleman, et al. 2020. Fuel availability not fire weather controls boreal wildfire severity and carbon emissions. Nature Climate Change 10:1130–1136. Meta data and methods can be found at** [**https://daac.ornl.gov/ABOVE/guides/ABoVE\_Plot\_Data\_Burned\_Sites.html**](https://daac.ornl.gov/ABOVE/guides/ABoVE_Plot_Data_Burned_Sites.html)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Column name | Description | Unit | Code explanation or date format | Empty value code |

**6. Table name(s): SOL\_coarse\_wood\_carbon.txt**

**Table description(s): Sol and coarse wood carbon stocks and variability published in** Alexander, H. D., and M. C. Mack. 2016. A canopy shift in interior Alaskan boreal forests: Consequences for above- and belowground carbon and nitrogen pools during post-fire succession. Ecosystems 19:98–114.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Column name | Description | Unit | Code explanation or date format | Empty value code |
| Compartment | The ecosystem pool (soil organic layer or coarse wood) |  | SOL=Soil organic layer  Coarse wood = coarse wood |  |
| Form | Source and the age class of forest | years | 20-39, 40-59, or 60-100 years old |  |
| Species | Dominate tree species in stand |  |  |  |
| Mean.value | Mean carbon stock of the pool | g m2 |  |  |
| SE.value | Standard error of mean carbon stock of the pool | G m2 |  |  |

**7. Table name(s): 342\_JFSP\_sitedata.txt**

**Table description(s): Site level measurements from the plots referenced in Johnstone, J. F., G. Celis, F. S. Chapin, T. N. Hollingsworth, M. Jean, and M. C. Mack. 2020. Factors shaping alternate successional trajectories in burned black spruce forests of Alaska. Ecosphere 11:e03129. Metadata can be found at** [**https://www.lter.uaf.edu/data/data-detail/id/342**](https://www.lter.uaf.edu/data/data-detail/id/342)

**8. Table name(s): 398\_2004burns\_seedlings.txt**

**Table description(s): seedling measurements from the plots referenced in Johnstone, J. F., G. Celis, F. S. Chapin, T. N. Hollingsworth, M. Jean, and M. C. Mack. 2020. Factors shaping alternate successional trajectories in burned black spruce forests of Alaska. Ecosphere 11:e03129. Metadata can be found at** [**https://www.lter.uaf.edu/data/data-detail/id/398**](https://www.lter.uaf.edu/data/data-detail/id/398)

## Spatial data objects

1. Cpcrw-1ha-repr.tif – probability of near surface permafrost presence for the simulated landscape clipped from Pastick, N. J., M. T. Jorgenson, B. K. Wylie, S. J. Nield, K. D. Johnson, and A. O. Finley. 2015. Distribution of near-surface permafrost in Alaska: Estimates of present and future conditions. Remote Sensing of Environment 168:301–315. Product was interpolated to 1ha spatial resolution. This layer is used in permafrost\_SOL-depth\_script-1\_09-30-2022.Rmd
2. Aspect\_repr.tif – aspect raster for simulated landscape. This product is used in permafrost\_SOL-depth\_script-1\_09-30-2022.Rmd
3. Dem\_repr.tif – digital elevation raster for simulated landscape. This product is used in permafrost\_SOL-depth\_script-1\_09-30-2022.Rmd and in forest-cover\_stand-density\_ba\_script-2\_09-30-2022.Rmd
4. hydro\_63360\_py\_repr\_cpcrw.shp – shape file of water bodies for the simulated landscape. This product is used in permafrost\_SOL-depth\_script-1\_09-30-2022.Rmd and in forest-cover\_stand-density\_ba\_script-2\_09-30-2022.Rmd
5. cpcrw\_streams.shp – shape file of streams in simulated landscape. This product is used in permafrost\_SOL-depth\_script-1\_09-30-2022.Rmd and in forest-cover\_stand-density\_ba\_script-2\_09-30-2022.Rmd
6. forest\_species.init.tif – raster of initial tree species composition for the simulated landscape. This product is used in forest-cover\_stand-density\_ba\_script-2\_09-30-2022.Rmd
7. ABoVE\_AGB\_Bh06v05.tif – multi layer raster of remotely sensed forest aboveground biomass for our simulated landscape clipped from Wang, J. A., A. Baccini, M. Farina, J. T. Randerson, and M. A. Friedl. 2021. Disturbance suppresses the aboveground carbon sink in North American boreal forests. Nature Climate Change 11:435–441. Used in forest-carbon\_script-3\_09-30-2022.Rmd.
8. AK\_fire\_location\_polygons.shp – Polygon of fire of all fires in Alaska from the Alaska Large fire Database. Used in fire-regime-script-5\_09-30-2022.Rmd
9. Perimeters\_clipped- polygon of fires in our simulated landscape from the Alaska large fire database. Used in fire-regime-script-5\_09-30-2022.Rmd
10. AK\_polygon.shp – polygon of Alaska outline used in fire-regime-script-5\_09-30-2022.Rmd

## Ancillary files: software, code, protocols

1. iLand source code including permafrost and SOL source code
   1. executable\_qt512.6.zip – The QT library and iLand executable used in simulations. Also includes source code for iLand version used in simulations.
2. Model run project directories for the two experiments
   1. Permafrost\_bore.hole\_project.zip – Project directory for recreating stand level simulations of snow depth and permafrost active layer depth. Zip file includes all inputs, project file, and the sqlite databases of outputs.
   2. CPCRW\_sm\_project.zip – Project directory for recreating landscape level simulations of permafrost distribution, stand structure, and fire regime including inputs, project file, and sqlite databases of outputs.
3. R analysis scripts for processing outputs
   1. Borehole\_analysis\_4-1-2021.Rmd – R script for analyzing outputs of the stand level simulations
   2. permafrost\_SOL-depth\_script-1\_09-30-2022.Rmd – R script for analyzing permafrost distribution in the landscape level simulations.
   3. forest-cover\_stand-density\_ba\_script-2\_09-30-2022.Rmd – R script for analyzing forest structure in the landscape level simulations
   4. forest-carbon\_script-3\_09-30-2022.Rmd. - R script for analyzing above ground live and dead carbon in the landscape level simulations
   5. seedling\_regeneration\_script-4\_09-30-2022.Rmd – R script for analyzing seedling regeneration in the landscape level simulations.
   6. fire-regime\_script-5\_09-30-2022.Rmd – R script for analyzing the fire regime in landscape level simulations.