

**CAKN Permafrost and Carbon Cycling Monitoring Protocol:
Implementing and Validation of Standard Operating Procedures for the Eight Mile Lake Site
and Measurement of New Permafrost Index Sites in Denali National Park
FINAL REPORT**

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SUMMARY

Long-term monitoring of changes in ecosystem carbon cycling in response to permafrost thaw and ground subsidence (thermokarst) development is an important component of understanding the rate at which northern ecosystems are changing. The Central Alaska Inventory and Monitoring Network of the National Park Service is in the process of developing a comprehensive permafrost monitoring program that can contribute significantly to this understanding. This report provides data from a pilot study for monitoring ecosystem carbon cycling processes that can be affected as a result of permafrost thaw. The initial study site is located in the Eight Mile Lake watershed near the northeast corner of Denali National Park and Preserve. This report summarizes the datasets available from this study site, and links previously collected data with the new effort. This report is an update for data collected in 2013 still kept in context with previously collected data. This report also presents data from new thermokarst transects that were established in 2013.

ACTIVITIES AND FINDINGS

This report summarizes data that have been collected at the Eight Mile Lake permafrost thaw gradient monitoring site. It combines data collected in the last funding period with previously collected data. Some data streams have been discontinued or funded by other sources, whereas data streams that have continued monitoring are noted below. Interpretations of many of these data are reported in a recent publication (Trucco et al. 2010). Data presented in this report are publically accessible and archived at the Bonanza Creek Long Term Ecological Research site (<http://www.lter.uaf.edu>). This report is an update from the 2012 report and includes 2013 data from the datasets that are currently active. This report also reports the establishment of new thermokarst transects in the late summer of 2013.

Eight Mile Lake Study Site Description & History

The permafrost monitoring makes use of a study site located in a watershed in the northern foothills of the Alaska Range just outside the Denali National Park boundary near the end of the Stampede Road. Ground temperature has been monitored for several decades at this site, before and after the permafrost was observed to thaw on a gentle north-facing slope (Osterkamp et al. 2009). The thaw area drains down to Eight Mile Lake, which lies at the foot of these slopes. While permafrost thaw can sometimes result in inundation depending on local topography, the terrestrial site is relatively well drained. The Eight Mile Lake watershed is relatively small ($< 8 \text{ km}^2$) and is bounded on two sides by moraines deposited by early Pleistocene glaciers. Water enters Eight Mile Lake through a single small stream on the southeast side, and there are some small rivulets off the hillsides where the permafrost is thawing directly into the lake. The lake has a single channelized outflow.

The biogeochemistry of C cycling has been studied in the watershed since 2004, funded by a series of 3-5 year grants from federal agencies (NASA, NSF, DOE) lead by Principal investigator Schuur. This work has focused on quantifying losses of old carbon, measuring export of carbon between land and freshwater ecosystems, and more recently, experimental manipulations of temperature and moisture. All of this work is aimed at understanding change in these tundra ecosystems and the potential for permafrost carbon to be mobilized in a warmer climate. The site is now co-sponsored by the Bonanza Creek Long Term Ecological Research program based at the University of Alaska, Fairbanks where Schuur is a Senior Investigator. For the basis of this report, this site is also an important monitoring location for vital signs important to the National Park Service. Lastly, an adjacent site will be instrumented by the National Ecological Observation Network as a relocatable site in the Boreal Domain in the next few years. As one of more than 60 sites distributed across the North American continent, Eight Mile Lake will be connected directly to this much larger network. New NEON datasets that will come online in 3-5 years represent value added to this NPS-supported monitoring site, which will provide replication and historical context that would otherwise not be available to NEON.

In this area, we have established three terrestrial sites that represent differing amounts of disturbance from permafrost thaw: **1)** relatively undisturbed tussock tundra, dominated by the tussock-forming sedge *Eriophorum vaginatum* with *Sphagnum spp* mosses and shrubs

(hereafter called '**Minimal Thaw**'), **2**) a site adjacent to the borehole that started documented permafrost thaw established in 1985 ('**Moderate Thaw**'), and **3**) a site located where permafrost appeared to have thawed more than three decades prior to the thawing at the borehole based on visual observation of thermokarst features from 1951 aerial photographs ('**Extensive Thaw**'). The warming ground temperature and loss of ice wedges from these sites has had multiple direct and indirect effects on the tundra ecosystem. In addition to warmer soil temperature and deeper thaw depth, soil moisture and the overall hydrology of the area has been altered where ice wedges have thawed and drained away. The soil surface collapsed in areas overlying ice wedges, and the undulating surface microtopography (thermokarst) caused water to accumulate in lower areas, leaving higher areas dry. While there are no significant differences among sites in the mean moisture, the coefficient of variation in moisture is higher where subsidence is more pronounced. These thermokarst features are most dramatic in the Extensive Thaw site, are just starting to develop in the Moderate Thaw site, and are largely absent in the Minimal Thaw site. Together, these three terrestrial sites are a natural experimental gradient that represents the long-term (decadal scale) effects of permafrost thawing and thermokarst on terrestrial ecosystem dynamics in upland tundra.

This site is one of two worldwide that are intensively measuring carbon balance in ecosystems that are highly impacted by permafrost thaw (the other site being Abisko, located in Northern Sweden). Because this site is located in the discontinuous permafrost zone, processes already underway at this location are thought to be an analog for future ecosystem response in the continuous permafrost zone, such as the North Slope of Alaska, if climate warming continues as forecasted (Schuur et al. 2007). This site is also part of the Thermal State of Permafrost borehole network that has been monitoring increases in permafrost temperature in Alaska and globally (Romanovsky et al. 2010) over the past several decades. Because of the size and nature of the carbon pool frozen in permafrost soils, thawing permafrost and the decomposition of previously frozen organic C is one of the more likely positive feedbacks from terrestrial ecosystems to the atmosphere in a warmer world (Schuur et al. 2011). The site provides an important and unique observatory to understand and quantify the magnitude, timing, and form of carbon release from permafrost ecosystems to the atmosphere in a warmer world.

New Thermokarst Site Description & History

In 2013, new permanent survey transects were established at 7 sites within the DNPP boundary at locations that had been visually surveyed by park researchers over the past decade. With park permission, transects were established with high-precision GPS inside and outside of known ground subsidence features that were a result of permafrost degradation. Some of these locations were known from previous aerial surveys over the past decade to be actively expanding. Transects were established to span edges of active thaw determined by visual observation and aerial photos. Transects were 100 m long except when we surveyed a burned area, in which case two 50 m transects were set up in parallel burned and unburned areas. Generally transects were set up with the start point in the unthawed, relatively undisturbed vegetation (typically tussock tundra). Transects then continued over a transition area where permafrost degradation appeared to be initiating, and then continued into an area of subsidence and visible permafrost degradation. Standing at the starting point and facing the

length of the transect, we walked on the left side of the transect line and sampled measurement points on the right side to minimize possible disturbance. Data were collected at 5 m intervals along the transect, starting at 0m on the transect line for 21 observation points per 100m transect. A typical sampling point consisted of a 1x1m quadrat (e.g. 5m mark to 6m mark on transect, extending as a 1x1 m² to right of transect). At each quadrat, we measured a GPS location and elevation and a depth of thaw measurement the left lower corner (e.g at 5m mark on transect). Within the quadrat, the vertical height from ground/moss surface of the tallest shrub was measured, and a NDVI photo of the plant canopy was taken. At the left upper corner of the quadrat (e.g. at 6m mark on transect), depth of the organic layer was measured. Additional details of these measurements are provided in the next section. A water sample was collected at the same site, but not on the transect itself. This was processed for radiocarbon of dissolved inorganic and dissolved organic carbon, and was typically collected either from a nearby stream connected to the thermokarst feature, or in standing water within the thermokarst itself in some cases. These measurement were designed to be relatively quick and non-destructive so that multiple transects could be measured in the campaign period, and so that transects could be resurveyed periodically (1-5 year intervals).

Transect locations were determined from previous park surveys and the naming convention followed what these sites had been called in the past. Transects were established at: Boundary, Lower East Fork Cabin, Lower East Fork, Pitchfork, Wigand Creek, and Wigand Weather Station (this last site consisted of two transects: burned, unburned and was not located in a thermokarst subsidence feature, as were all other sites/transects). GPS locations with lat/long are provided in Map 1 & 2.

Thaw Gradient Measurement Variables

Standard meteorological data have been collected at the thaw gradient site (Eight Mile Lake) using an HOBO weather station (Bourne, MA). Photosynthetically active radiation (PAR, $\mu\text{mol m}^{-2} \text{s}^{-1}$), air temperature (T_{air} , °C), relative humidity, precipitation (mm), wind speed and direction and atmospheric pressure were measured continuously and averaged over a period of 30 minutes. Data is presented as average during the growing season, defined here by the fixed dates of May 1st – Sept 30th (**Table 1**). Data will be continued to be collected for the upcoming funding period.

Soil temperature was measured continuously at multiple depths in the soil profile at three different locations within each one of the sites representing a gradient of the permafrost thaw (**Table 2**). These sites are referred to by the extent of thaw and ground subsidence: Extensive (Ext), Moderate (Mod), Minimal (Min). Please see previous publications for a complete description of the study site (Schuur et al. 2009, Osterkamp et al. 2009). Type T thermocouples controlled by a CR10X data logger (Campbell Scientific, Logan, Utah) were used to measure soil temperature. Data was averaged for each site during the growing season. At the end of 2009, the depth at which soil temperature sensors were installed was changed in order to monitor surface conditions in more detail. Data will be continued to be collected for the upcoming funding period.

Water table and depth of thaw were manually measured throughout the growing season (**Table 3, Figure 1**). Water table was measured within ~3" diameter PVC wells and reported as

distance from moss/soil surface to the water table surface (DWT). Active layer depth (ALD) is the maximum extent of soil thaw during the summer growing season and is reported by averaging the two last measurements in September. Thaw depth (TD) is measured as the average of all weekly measurements taken during the growing season. Data will be continued to be collected for the upcoming funding period.

Chamber-Based Carbon Fluxes were measured by enclosing a small patch (50x50 cm) of vegetation and soil with a clear chamber. Air is withdrawn from the chamber and circulated through an infra-red gas analyzer (IRGA) to determine the CO₂ concentration, and then returned back to the chamber. By monitoring the CO₂ concentration over several minutes, a rate of C exchange with the atmosphere can be determined (units of mg C m² hour). In daytime conditions in the summer, chamber CO₂ concentrations typically decline as photosynthesis (called GPP=gross primary productivity) is greater than respiration (called R_{eco}) and net C is moving into the ecosystem from the atmosphere. This net flux can reverse in the dark, or in winter, when respiration is higher than photosynthesis. These measurements were made at 6 replicate point locations at the three thaw gradient sites, and instantaneous fluxes were aggregated to units of carbon exchange per season and per year (**Table 4, Figure 2, Figure 3**). These measurements were discontinued after the summer of 2010 and replaced with eddy covariance tower measurements of carbon exchange (see below).

Vegetation productivity was measured non-destructively on the same point locations as the chamber carbon fluxes. Data was collected using a point-intercept method to describe the frequency of plant species and tissue types. The point-intercept data was combined with an off-plot destructive harvest where all plant species were harvested, sorted into new and old growth, dried and weighed. This allows the calculation of biomass from frequency measurements taken non-destructively. Aboveground net primary productivity (ANPP) was quantified by separating and weighing newly-grown plant parts during the destructive harvest. This represents the fraction of the plant biomass that grew in that measurement period. These measurements were made in 2004, and 2006-2009, and then discontinued thereafter (**Figure 2**).

Tower-Based Carbon Fluxes are monitored using the eddy covariance technique (Lee et al. 2004) to monitor CO₂ exchange. Here, no chamber is needed to enclose the ecosystem but instead a tower is deployed with instruments above the vegetation canopy. Along with CO₂ concentration measurements as described above, the 3-D wind velocity is also measured. These continuous measurements, along with measurements of the ecosystem energy budget and micrometeorological conditions, can be used to determine net ecosystem CO₂ exchange (NEE) as eddies of wind move air past the sensing station. The NEE can be separated into the influence of plant uptake (GPP) and the influence of respiration (R_{eco}) on the movement of carbon. Instantaneous fluxes are aggregated seasonally and annually (**Table 5, Figure 4**). These measurements started in 2008 to overlap with chamber-based carbon flux measurement and continue until present. The 2012 season will be reported in May 2013 as it will include the winter 2012/2013 period.

Soil Decomposition Rates are assessed with cellulose filter papers that are placed in the surface soil profile at two depths (10cm, 20cm) and left for one year, then recollected. The change in mass of the dried filter paper is an index of microbial activity in the surface soil (**Figure 5**). Interannual variability of this metric is comparable to carbon flux measurements of ecosystem respiration. The former is a metric of microbial activity, whereas the latter is an index of both plant and microbe activity combined. Data will be continued to be collected for the upcoming funding period.

Ecosystem Respiration Radiocarbon is measured on CO₂ leaving the ecosystem, which is a mixture of plant metabolism and microbial decomposition of soil organic matter (**Figure 6**). Radiocarbon values (reported as $\Delta^{14}\text{C}$) are currently declining in the atmosphere because radiocarbon-free fossil fuel carbon is accumulating in the atmosphere. In ecosystems, radiocarbon provides information on whether ecosystem respiration is dominated by the respiration of plants or soils. In general, ecosystem respiration $\Delta^{14}\text{C}$ near atmospheric values indicates that plants are the dominant source of respiration because plant $\Delta^{14}\text{C}$ is very close to the current year atmosphere due to continual CO₂ uptake by photosynthesis. Ecosystem respiration $\Delta^{14}\text{C}$ values higher than the atmospheric value indicates that microbial decomposition of soil organic matter in the soil surface (~ 0-15 cm) is a primary source because this layer was enriched in radiocarbon as a result of atmospheric nuclear weapons testing in the 1950s and early 1960s. Ecosystem respiration $\Delta^{14}\text{C}$ lower than the atmospheric value indicates the addition of substantial respiration from the decomposition of deep soil organic matter (~>15cm), which is lower in radiocarbon due to natural radioactive decay. These differences in the radiocarbon values of soil and plant sources allow the relative contribution of plant and soil sources to ecosystem respiration to be determined.

New Thermokarst Transect Measurement Variables

Thaw Depth (TD) is measured as the surface of the live moss to the depth of the frozen soil at the date of sampling. This is done manually using a steel thaw probe pushed into the soil and removed for measurement. One measurement is made each 5m on the transect co-located with the GPS point.

Organic Soil Depth is measured in a non-destructive manner by inserting a sharpshooter shovel through the moss/organic soil and manually determining the organic/mineral interface by texture (touch). This depth was measured with a hand ruler. No hole was dug, nor was soil removed.

Vegetation Height is measured as the vertical distance from the moss surface to the top on the tallest shrub branch within the 1x1 m quadrat and measuring of the branch. This represents a rapid assessment of vegetation structure.

Normalized Difference Vegetation Index (NDVI) is measured using a Tetracam ADC to photograph the vegetation canopy within the 1x1 m sample quadrat. Due to nature of camera, this does not include entire 1 m² area. Images were processed in PixelWrench2 v.1.8.0.4 according to Schuur lab protocol (version, updated July 2013).

GPS Location/Elevation is measured using the Denali National Park Trimble R6 RTK GPS system. AKRO's Trimble R8 RTK system was used in 2013. For general RTK instructions see Joel Cusick's AK RTK User Guide or the DENA RTK Protocol made in 2013. A GPS topo point location was recorded each 5m mark along the transect (Topo point = 5 second measurement interval). An Observed Control Point (3 minute measurement interval) was recorded at the beginning and end of each transect.

Observations and Interpretations: Permafrost Thaw Gradient

These measurements were designed to monitor changes in permafrost and the influence of its degradation on ecosystem C balance in upland tundra. The site is instrumented so that we observe this process both over a nine-year time period of the dataset (interannual time scale) but also across a permafrost thaw gradient. This gradient represents decades of permafrost thaw at the site. In brief, we observed increasing permafrost degradation from 2004 to 2010, which was detected as increased ALD (**Figure 1b**) but this pattern abruptly reversed in 2011. Active layer was deeper in 2012 than 2011 but still shallower than the previous few years.

Based only on the data from 2004-2010, the increasing trend matched the permafrost thaw gradient observation of deeper ALD in sites with a longer history of thaw and ground subsidence. Permafrost degradation that occurred at both annual and decadal time scales was correlated with increased plant productivity (**Figure 2**). However, while R_{eco} was higher with decadal-scale permafrost degradation at Moderate and Extensive Thaw sites, annual increases in ALD did not result in detectable increases in R_{eco} , perhaps as a consequence of increased soil saturation (decreased water table depth) (**Figure 1a**). As a result, summer C exchange (NEE), which did not differ among sites, also increased during the seven-year study period (**Figure 3**). While all sites were C sinks during the growing season, winter respiration, in part, offset summer C uptake. However, despite the important role of winter R_{eco} in determining whether the system acted as an annual net C source or sink, C exchange during the winter period is the least well-characterized component of annual C balance. Based on the winter measurements calculated here, sites with low and intermediate levels of permafrost thaw (Minimal and Moderate Thaw) acted as annual net C sinks, while the site with most thaw (Extensive) was C neutral on an annual basis. The increasing sink strength during the seven-year measurement interval shifted the most thawed site from a C source to C neutral, and shifted the least thawed site from C neutral to a C sink. The addition of tower-based carbon fluxes (**Figure 4**) has greatly improved the sampling of wintertime respiration and should improve our understanding of how this period influences overall annual carbon exchange.

Finally, there has been an overall decline in ecosystem respiration radiocarbon values that generally matches the decline of the atmospheric due to fossil fuel burning (**Figure 6**). The three thaw gradient sites did not differ in ecosystem respiration radiocarbon (Repeated measures ANOVA; $p=0.64$). However, when data were analyzed using active layer depth at each sampling point as a continuous variable, there was significantly lower ecosystem respiration $\Delta^{14}C$ values as active layer depth increased ($p=0.013$). Therefore, areas with greater permafrost

thaw and active layer depth are likely releasing more old soil carbon as microbes decompose organic matter that has been stored in these ecosystems over hundreds to thousands of years.

Observations and Interpretations: New Thermokarst Transects

These variables were measured on transects as a baseline for future surveys. Site names are: Wigand Weather Station (WWS – burned and unburned), LEF Cabin, Pitchfork, Wigand Creek, Boundary, Lower East Fork. Two replicate transects were established at Pitchfork and Lower East Fork. The two transects at WWS represent burned and adjacent unburned tundra. Large differences in elevation reflect how transects crossed from control tundra into thermokarst features. Variation in thaw depth and organic layer depth are plotted against elevation and distance on transect (**Figures 7-15**). Vegetation height and NDVI are plotted against elevation and distance on transect (there are no vegetation measurements for the burned transect) (**Figures 16-23**).

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Table 1. Average photosynthetically active radiation (PAR), cumulative PAR, cumulative precipitation and average air temperature for eight consecutive growing seasons (May 1-September 30), at Eight Mile Lake watershed, AK.

Year	Average PAR ($\mu\text{mol m}^{-2} \text{sec}^{-1}$)	Cumulative PAR (mol m^{-2})	Precipitation (mm)	Air Temp ($^{\circ}\text{C}$)
2004	342	-	153	11.5
2005	341	4523	145	10.8
2006	354	4689	227	9.1
2007	375	4936	331	10.3
2008	357	4670	346	8.1
2009	376	4978	178	9.7
2010	356	4706	182	9.9
2011	368	4784	164	9.4
2012	360	4705	223	9.2
2013	413	5463	124	9.7

Table 2. Average growing season (May 1-September 30) soil temperature (Ts) at different depths for three sites (Minimal, Moderate, Extensive) representing a gradient of the permafrost thaw at Eight Mile Lake watershed.

SITE	YEAR	Ts(5cm)	Ts(10cm)	Ts(20cm)	Ts(30cm)	Ts(40cm)
Min	2004	---	6.7 ± 0.07	4.1 ± 0.04	2.1 ± 0.02	1.0 ± 0.02
Mod	2004	---	6.4 ± 0.06	3.5 ± 0.04	1.6 ± 0.02	0.6 ± 0.01
Ext	2004	---	7.0 ± 0.07	4.2 ± 0.04	2.4 ± 0.02	1.2 ± 0.02
Min	2005	---	7.2 ± 0.04	4.0 ± 0.03	1.8 ± 0.02	0.9 ± 0.02
Mod	2005	---	---	---	---	---
Ext	2005	---	6.6 ± 0.04	4.0 ± 0.03	2.5 ± 0.02	1.5 ± 0.02
Min	2006	---	6.8 ± 0.04	3.6 ± 0.02	1.4 ± 0.01	0.5 ± 0.01
Mod	2006	---	---	---	---	---
Ext	2006	---	6.1 ± 0.04	3.3 ± 0.03	1.5 ± 0.02	0.6 ± 0.02
Min	2007	---	7.0 ± 0.05	4.5 ± 0.02	2.1 ± 0.01	1.1 ± 0.01
Mod	2007	---	---	---	---	---
Ext	2007	---	7.2 ± 0.05	4.4 ± 0.04	2.6 ± 0.03	1.5 ± 0.02
Min	2008	---	5.9 ± 0.04	3.6 ± 0.02	1.5 ± 0.01	0.7 ± 0.01
Mod	2008	---	3.7 ± 0.03	2.2 ± 0.02	1.1 ± 0.01	0.6 ± 0.01
Ext	2008	---	---	---	---	---
Min	2009	---	6.8 ± 0.06	4.2 ± 0.02	1.7 ± 0.01	0.7 ± 0.01
Mod	2009	---	4.7 ± 0.04	2.5 ± 0.02	1.0 ± 0.01	0.4 ± 0.01
Ext	2009	---	---	---	---	---
Min	2010	---	6.6 ± 0.05	3.8 ± 0.02	1.7 ± 0.02	0.9 ± 0.01
Mod	2010	---	---	---	---	---
Ext	2010	---	6.3 ± 0.04	3.9 ± 0.03	2.3 ± 0.02	1.3 ± 0.02
Min	2011	6.6 ± 0.05	4.6 ± 0.03	2.2 ± 0.02	1.0 ± 0.01	0.3 ± 0.01
Mod	2011	7.9 ± 0.06	5.9 ± 0.04	2.6 ± 0.02	1.0 ± 0.02	0.5 ± 0.01
Ext	2011	7.3 ± 0.05	5.5 ± 0.04	2.8 ± 0.02	1.6 ± 0.02	1.2 ± 0.01
Min	2012	5.8 ± 0.05	5.2 ± 0.04	3.0 ± 0.02	1.8 ± 0.02	1.3 ± 0.01
Mod	2012	6.2 ± 0.06	5.8 ± 0.05	1.5 ± 0.02	---	0.6 ± 0.01
Ext	2012	6.8 ± 0.07	5.3 ± 0.06	3.3 ± 0.04	2.4 ± 0.03	1.7 ± 0.03
Min	2013	5.3 ± 0.05	3.8 ± 0.04	1.6 ± 0.02	0.6 ± 0.01	0.3 ± 0.01
Mod	2013	6.8 ± 0.07	5.2 ± 0.05	2.2 ± 0.02	0.7 ± 0.01	0.1 ± 0.01
Ext	2013	6.5 ± 0.06	5.2 ± 0.04	3.1 ± 0.03	2.1 ± 0.02	1.6 ± 0.02

Table 3. Average growing season depth to water table (DWT), active layer depth (ALD), growing season thaw depth (TD), for three sites varying in degree of permafrost thaw). †

Site	Year	DWT (cm)	ALD (cm)	TD (cm)
Minimal	2004	31 ± 3	58 ± 2 ab	41 ± 2
Moderate	2004	30 ± 3	57 ± 2 a	41 ± 2
Extensive	2004	30 ± 4	68 ± 7 b	48 ± 6
Minimal	2005	22 ± 4	62 ± 1 a	46 ± 2 a
Moderate	2005	20 ± 4	73 ± 5 b	51 ± 3ab
Extensive	2005	17 ± 6	76 ± 6 b	58 ± 7 b
Minimal	2006	23 ± 2	59 ± 2	37 ± 1
Moderate	2006	21 ± 2	62 ± 2	40 ± 2
Extensive	2006	20 ± 6	69 ± 7	45 ± 6
Minimal	2007	19 ± 5	65 ± 2	46 ± 1
Moderate	2007	16 ± 3	68 ± 2	47 ± 2
Extensive	2007	15 ± 6	71 ± 6	53 ± 5
Minimal	2008	15 ± 5	65 ± 2	43 ± 2 a
Moderate	2008	11 ± 2	66 ± 3	46 ± 2 ab
Extensive	2008	11 ± 4	73 ± 8	51 ± 6 a
Minimal	2009	18 ± 6	62 ± 2 a	34 ± 1
Moderate	2009	17 ± 3	66 ± 3 ab	35 ± 1
Extensive	2009	19 ± 2	73 ± 8 b	40 ± 4
Minimal	2010	16 ± 7	66 ± 2	35 ± 1A
Moderate	2010	13 ± 1	67 ± 2	36 ± 1a
Extensive	2010	15 ± 2	72 ± 6	40 ± 3B
Minimal	2011	14 ± 3	59 ± 2	38 ± 3
Moderate	2011	13 ± 1	56 ± 2	36 ± 3
Extensive	2011	17 ± 1	63 ± 5	34 ± 3
Minimal	2012	17 ± 2	64 ± 2	42 ± 4
Moderate	2012	17 ± 2	61 ± 3	41 ± 4
Extensive	2012	18 ± 1	68 ± 4	44 ± 4
Minimal	2013	21 ± 3	66 ± 2	39 ± 4
Moderate	2013	24 ± 3	63 ± 2	38 ± 3
Extensive	2013	26 ± 3	67 ± 2	47 ± 4

*May through September, with the exception of DWT, which began in June.

†Letters denote significant site difference (paired comparisons) for each year at $\alpha = 0.1$; capital letters denote $\alpha = 0.05$.

Table 4. Seasonal and annual chamber-based carbon fluxes for three sites varying in degree of permafrost thaw.[†]

Site	Year	Growing Season (May - September)			Winter (Oct - Apr)	Annual	
		GPP	R _{eco}	NEE	R _{eco}	Annual R _{eco}	Annual NEE
Minimal	2004	327 ± 20 a	-288 ± 12 a	39 ± 15 a	-75 ± 12	-362 ± 15 a	-36 ± 16 a
Moderate	2004	445 ± 48 a	-339 ± 27 ab	105 ± 26 b	-79 ± 14	-418 ± 25 a	26 ± 26 b
Extensive	2004	450 ± 56 a	-404 ± 37 b	46 ± 22 a	-104 ± 18	-507 ± 35 b	-58 ± 23 a
Minimal	2005	300 ± 14 a	-276 ± 9 a	29 ± 6 a	-48 ± 10	-324 ± 14 a	-19 ± 04 b
Moderate	2005	377 ± 34 a	-341 ± 24 ab	43 ± 24 a	-50 ± 11	-390 ± 23 ab	-7 ± 24 b
Extensive	2005	376 ± 28 a	-393 ± 36 b	-18 ± 13 b	-61 ± 16	-454 ± 29 b	-78 ± 13 a
Minimal	2006	322 ± 24 a	-266 ± 18 a	62 ± 14 a	-57 ± 11	-324 ± 16 a	5 ± 14 a
Moderate	2006	424 ± 51 a	-313 ± 30 ab	117 ± 35 a	-60 ± 12	-373 ± 24 ab	57 ± 36 a
Extensive	2006	474 ± 83 a	-359 ± 58 b	121 ± 31 a	-81 ± 17	-440 ± 39 a	40 ± 31 a
Minimal	2007	382 ± 33 a	-290 ± 21 a	92 ± 17 a	-47 ± 9	-337 ± 21 a	45 ± 17 a
Moderate	2007	431 ± 19 ab	-373 ± 19 b	58 ± 24 a	-50 ± 10	-423 ± 19 b	8 ± 24 a
Extensive	2007	527 ± 58 b	-406 ± 34 b	121 ± 32 a	-66 ± 14	-472 ± 34 b	55 ± 31 a
Minimal	2008	370 ± 21 a	-288 ± 22 a	82 ± 7 a	-54 ± 10	-342 ± 22 a	28 ± 7 a
Moderate	2008	514 ± 22 b	-399 ± 20 b	115 ± 26 a	-58 ± 12	-457 ± 20 b	57 ± 26 a
Extensive	2008	507 ± 51 b	-380 ± 27 b	127 ± 27 a	-78 ± 17	-458 ± 27 b	49 ± 27 a
Minimal	2009	486 ± 37 a	-321 ± 16 a	164 ± 35 a	-45 ± 9	-366 ± 16 a	119 ± 36 a
Moderate	2009	617 ± 40 a	-348 ± 22 ab	268 ± 33 a	-49 ± 10	-397 ± 21 a	220 ± 33 a
Extensive	2009	584 ± 68 a	-410 ± 23 b	173 ± 65 a	-64 ± 14	-475 ± 23 b	109 ± 64 a
Minimal	2010	370 ± 24 a	-282 ± 22 a	88 ± 30 a	-78 ± 6	-360 ± 22	10 ± 30
Moderate	2010	527 ± 43 a	-377 ± 44 b	150 ± 48 a	-84 ± 6	-461 ± 44	66 ± 48
Extensive	2010	487 ± 83 a	-345 ± 18 ab	142 ± 80 a	113 ± 9	-458 ± 18	29 ± 80
Minimal	Average	364 ± 15 a	-287 ± 10 a	80 ± 14 a	-57 ± 5	-344 ± 9 a	20 ± 12 a
Moderate	Average	475 ± 30 b	-356 ± 18 b	122 ± 30 a	-61 ± 6	-417 ± 16 b	58 ± 26 a
Extensive	Average	484 ± 59 b	-385 ± 28 b	102 ± 34 a	-82 ± 8	-467 ± 31 b	19 ± 27 a

[†] Letters denote significant site difference in each year at $\alpha = 0.05$. Units are in grams CO₂-C m⁻².

Table 5. Growing season and annual carbon fluxes (g C m^{-2}) in a tundra ecosystem measured using the eddy covariance approach.

YEAR	Growing season				Winter	Annual	
	<u>NEE</u>	<u>GPP</u>	<u>Reco</u>	<u>Re/GPP</u>	<u>Reco</u>	<u>NEE</u>	<u>Reco</u>
2008	115	324	-208	0.64	-171	-55	-379
2009	126	479	-352	0.73	-182	-55	-534
2010	116	325	-205	0.63	-156	-40	-361
2011	182	400	-218	0.55	-106	+87	-324
2012	111	318	-208	0.65	-149	+38	-357

Figure 1. Growing season **(a)** average distance to water table (June-September) and **(b)** active layer depth measured at three sites varying in degree of permafrost thaw (September).

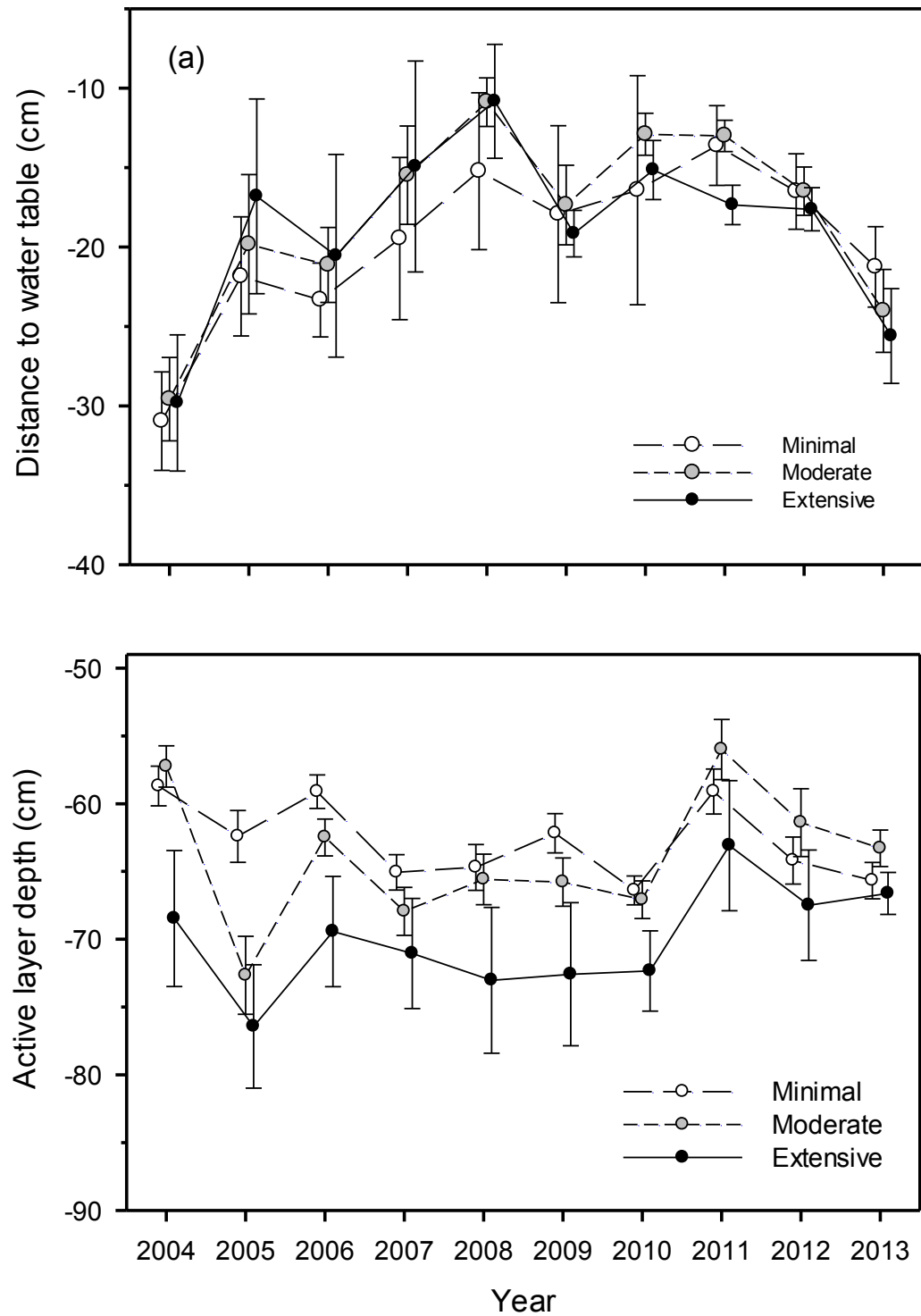


Figure 2. Cumulative Growing season (May-September) (a) Net ecosystem carbon exchange (NEE), (b) ecosystem respiration (R_{eco}), (c) Gross primary productivity (GPP), and (d) aboveground net primary productivity (ANPP) measured at three sites varying in degree of permafrost thaw.

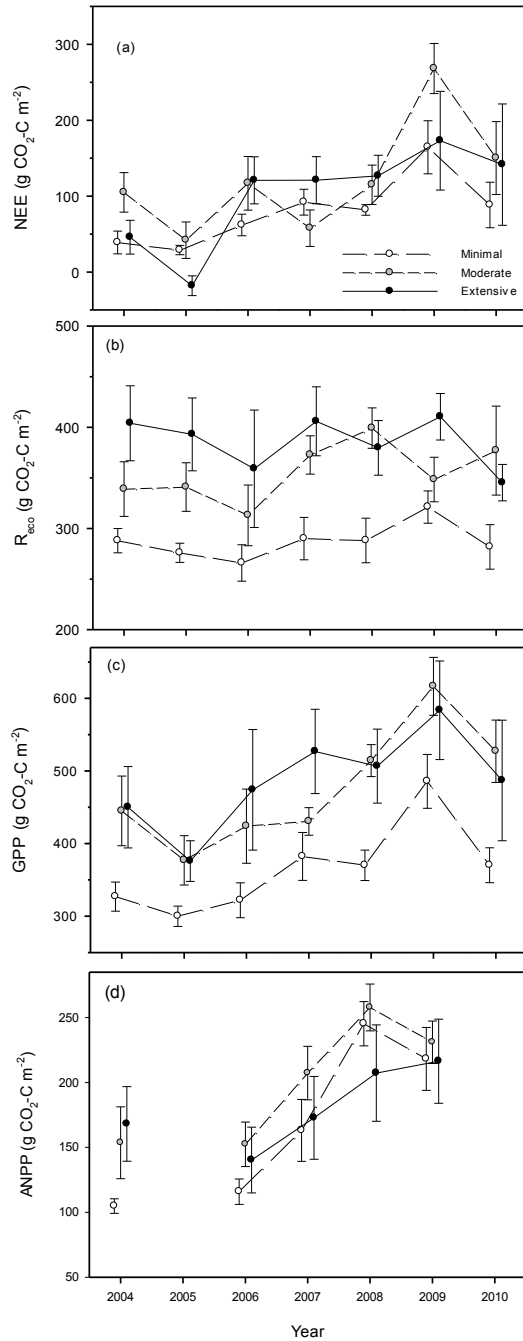


Figure 3. Cumulative (a) winter Reco (October – April), (b) annual Reco, and (c) annual NEE measured during seven consecutive years at three sites varying in degree of permafrost thaw.

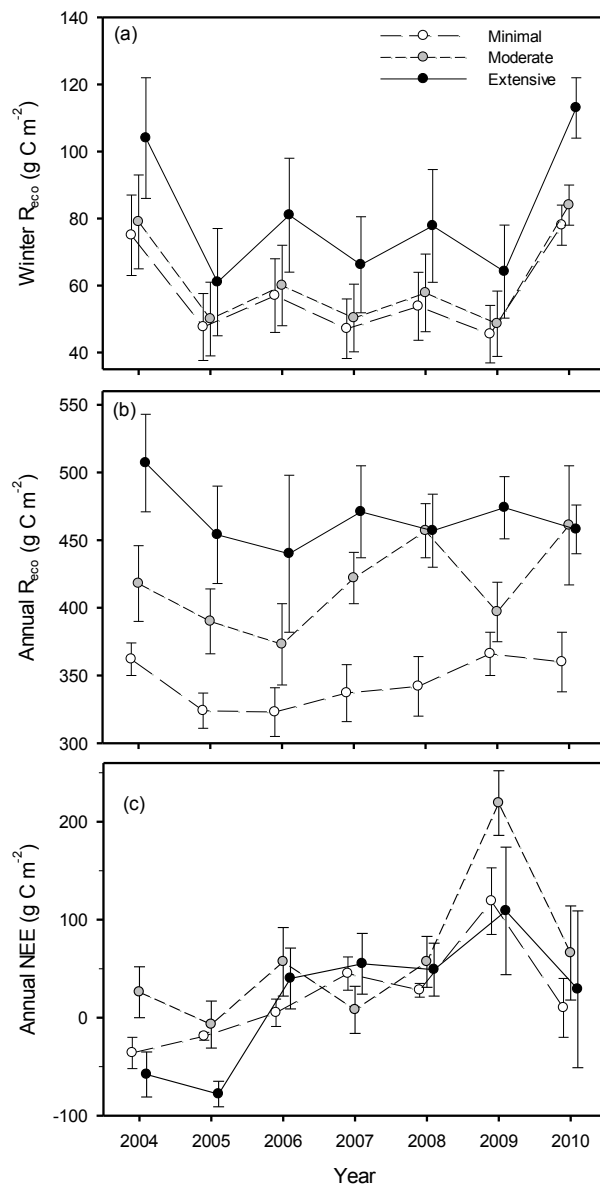


Figure 4. Growing season NEE, GPP and Reco **(a)**, and ecosystem respiration **(b)** measured by the eddy covariance approach.

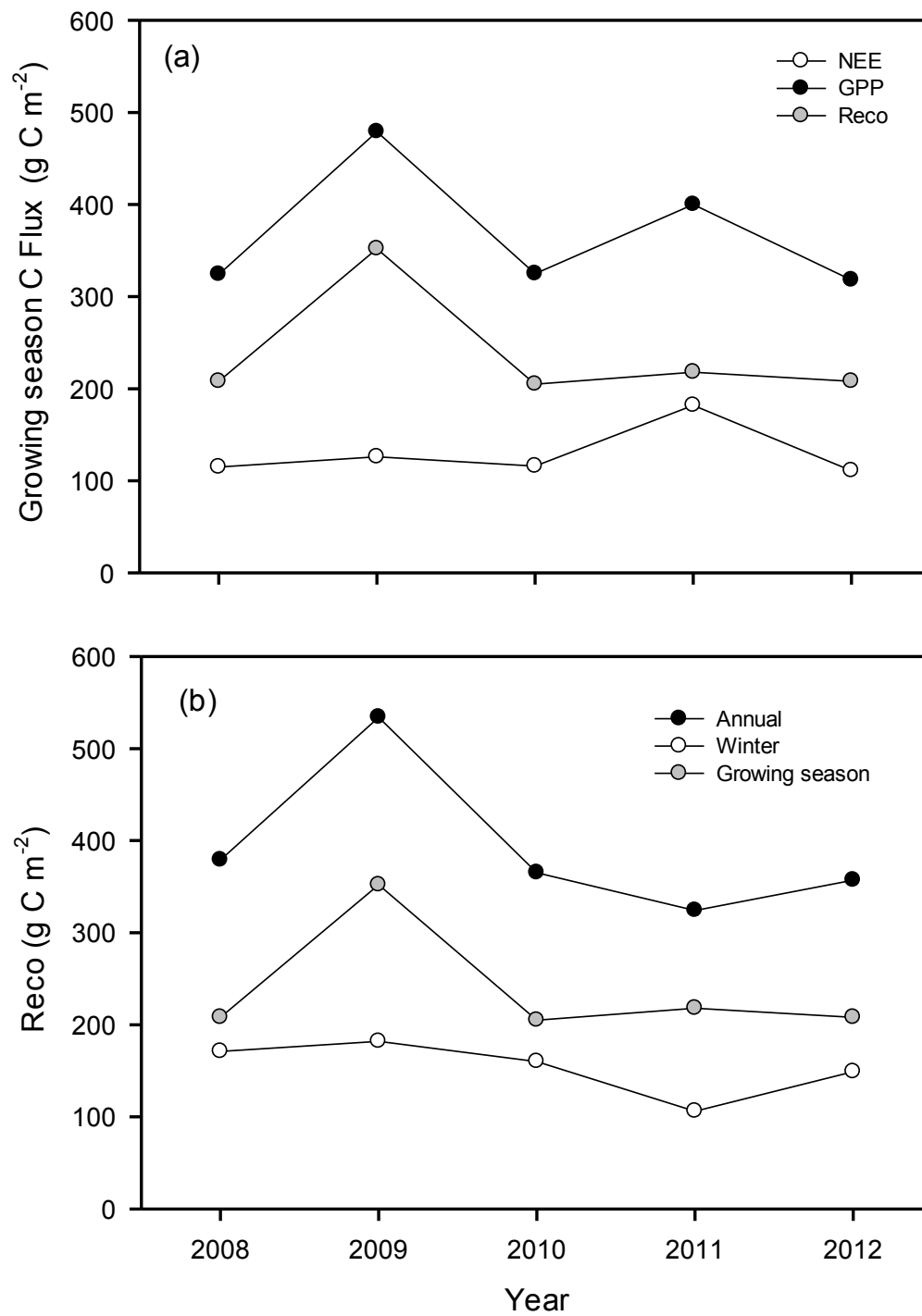


Figure 5. Mass loss of cellulose filter paper at three sites varying in degree of permafrost thaw. Mass loss was measured at two depths in the soil profile on an annual basis, with the filters replaced each September. The year reported on the x-axis represents the calendar year of the summer occupied by a set of filters.

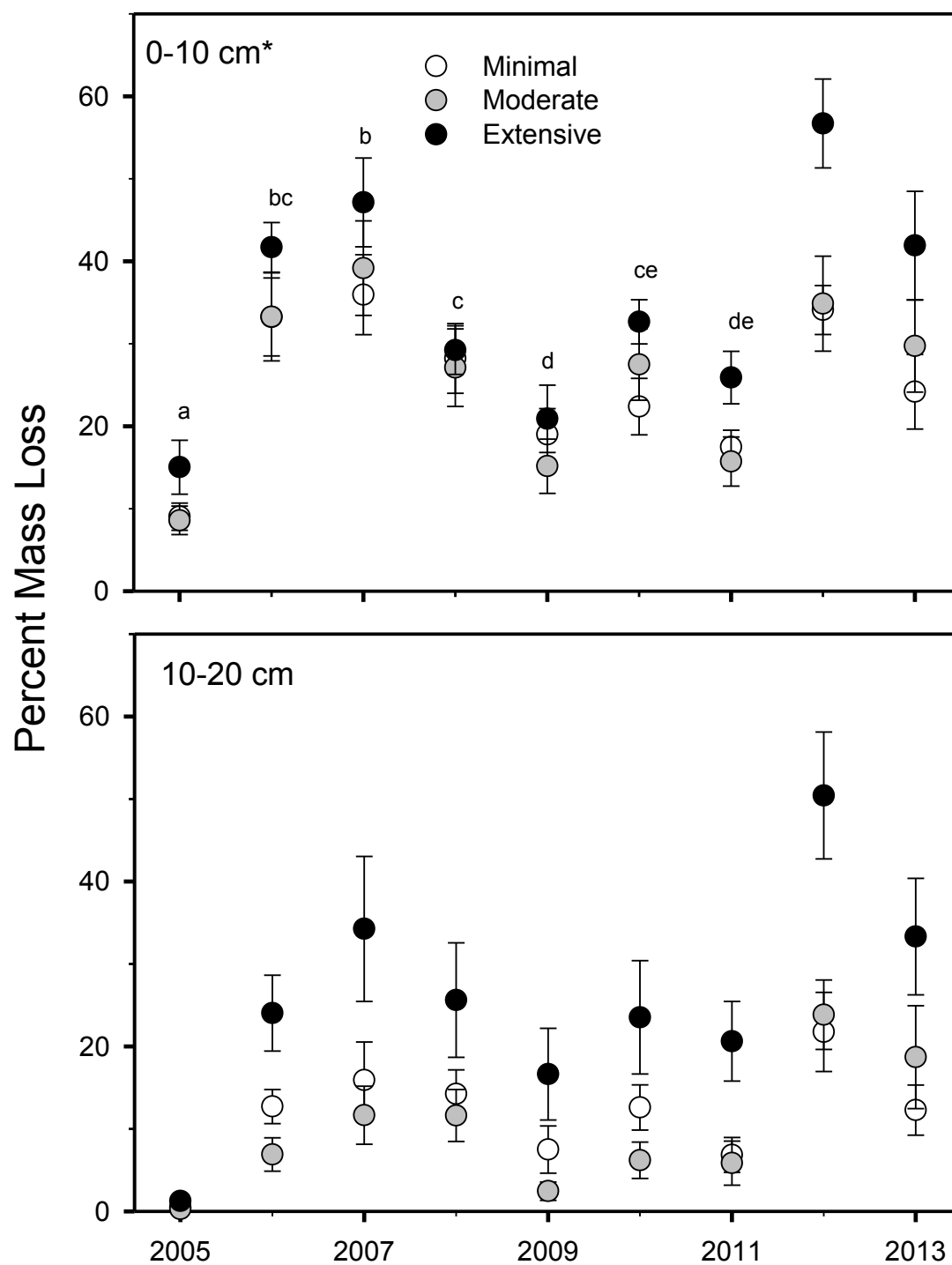


Figure 6. Radiocarbon measured in ecosystem respiration (CO_2) periodically during the growing season (May-Sept) across the permafrost thaw gradient. Data are grouped here in three bins according to the active layer depth of each particular respiration sampling location. Radiocarbon of the atmosphere is shown as a reference; it is currently declining as radiocarbon-free fossil fuel carbon is accumulating in the atmosphere. Respiration radiocarbon values below the atmosphere show the strong imprint of old carbon that has negative radiocarbon values.

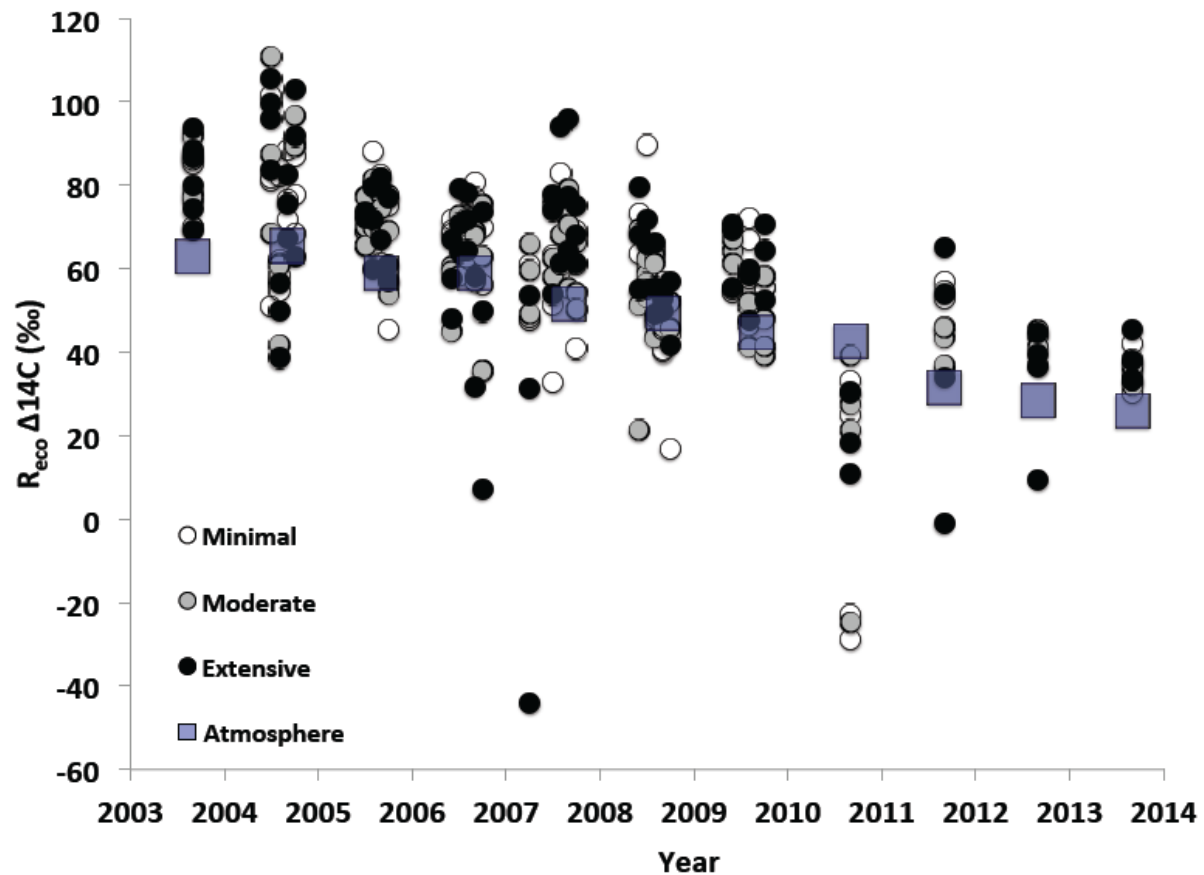


Figure 7

Pitchfork Transect 1

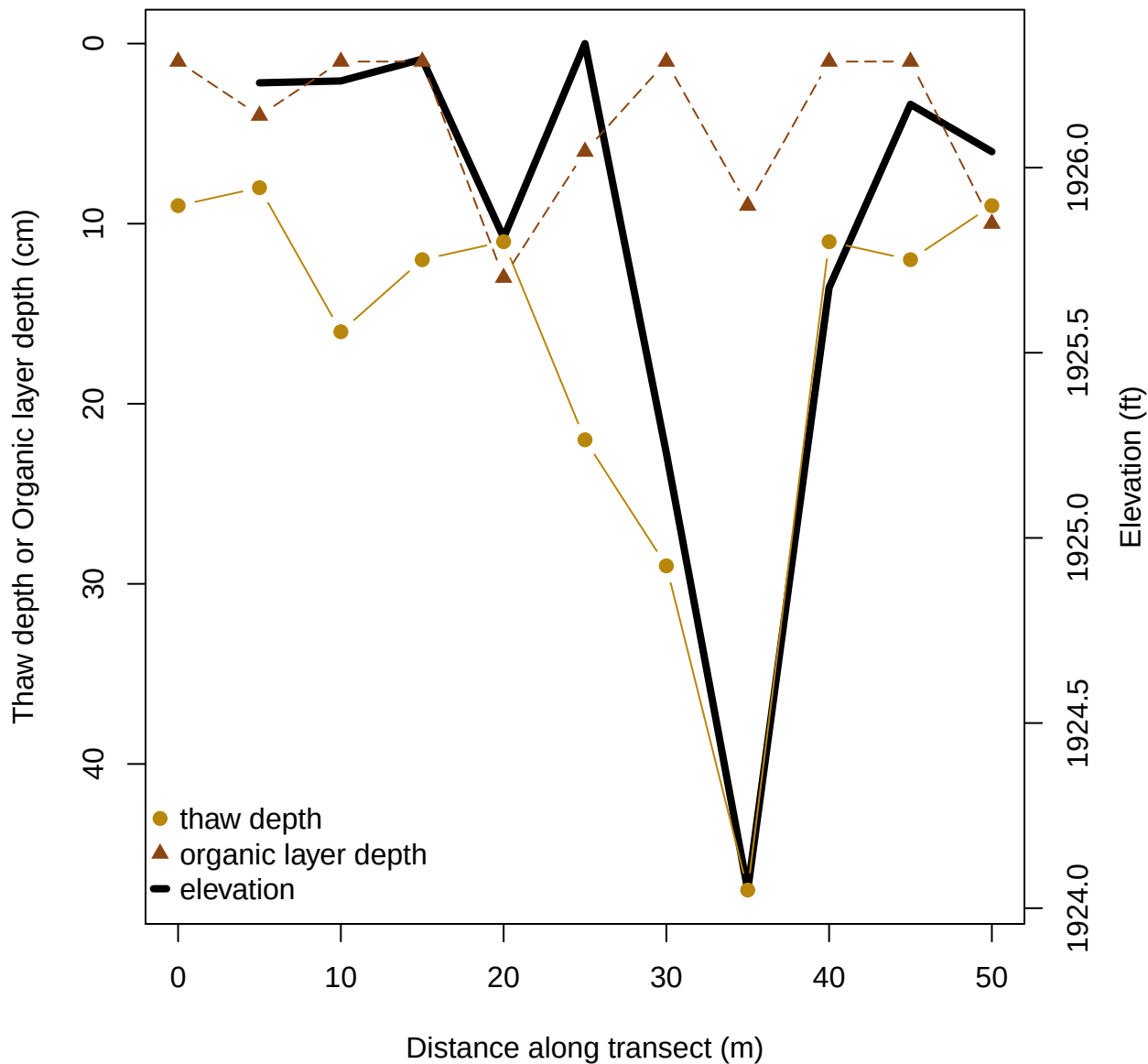


Figure 8

Pitchfork Transect 2

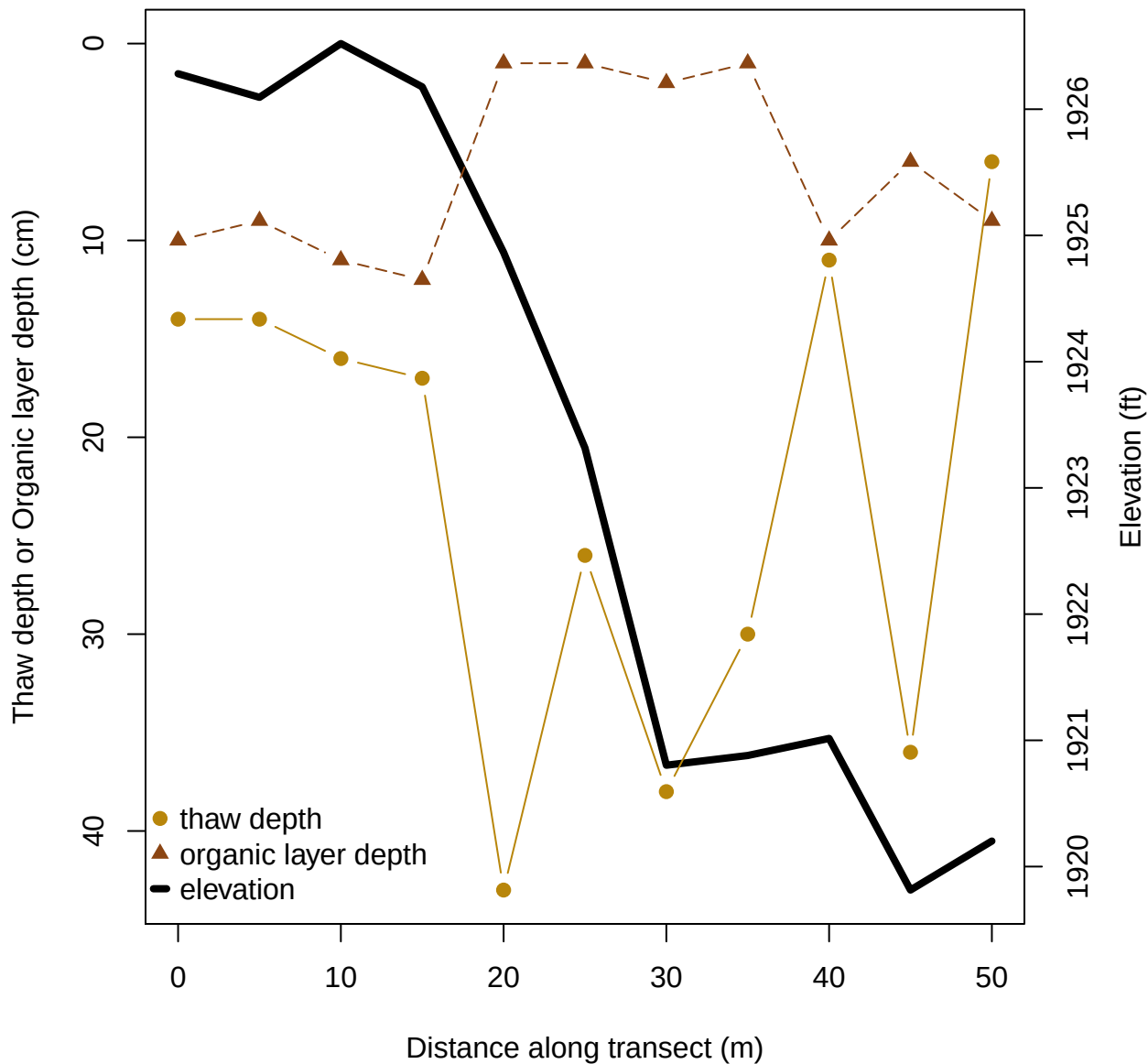


Figure 9

Wigand Creek

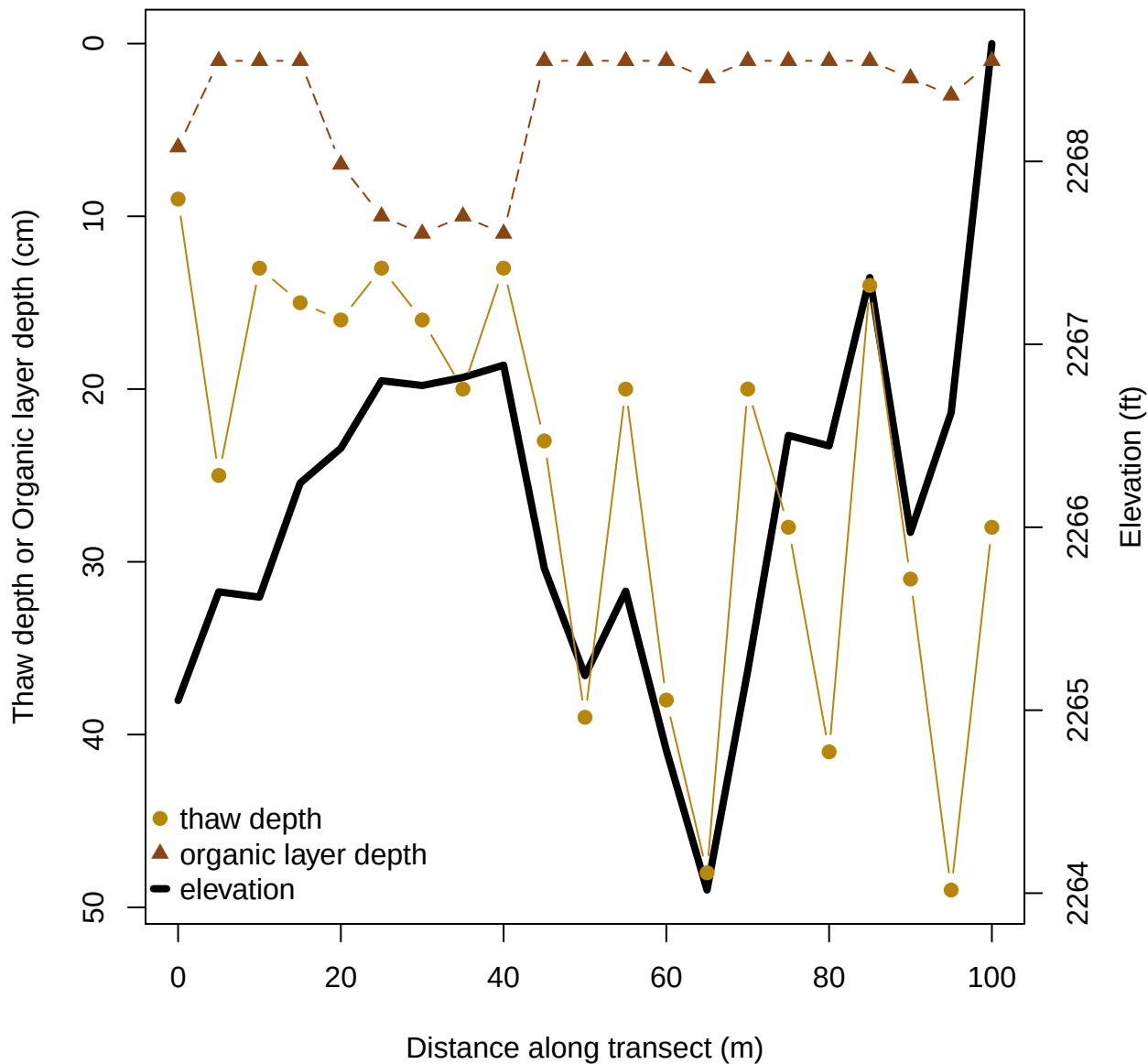


Figure 10

Boundary

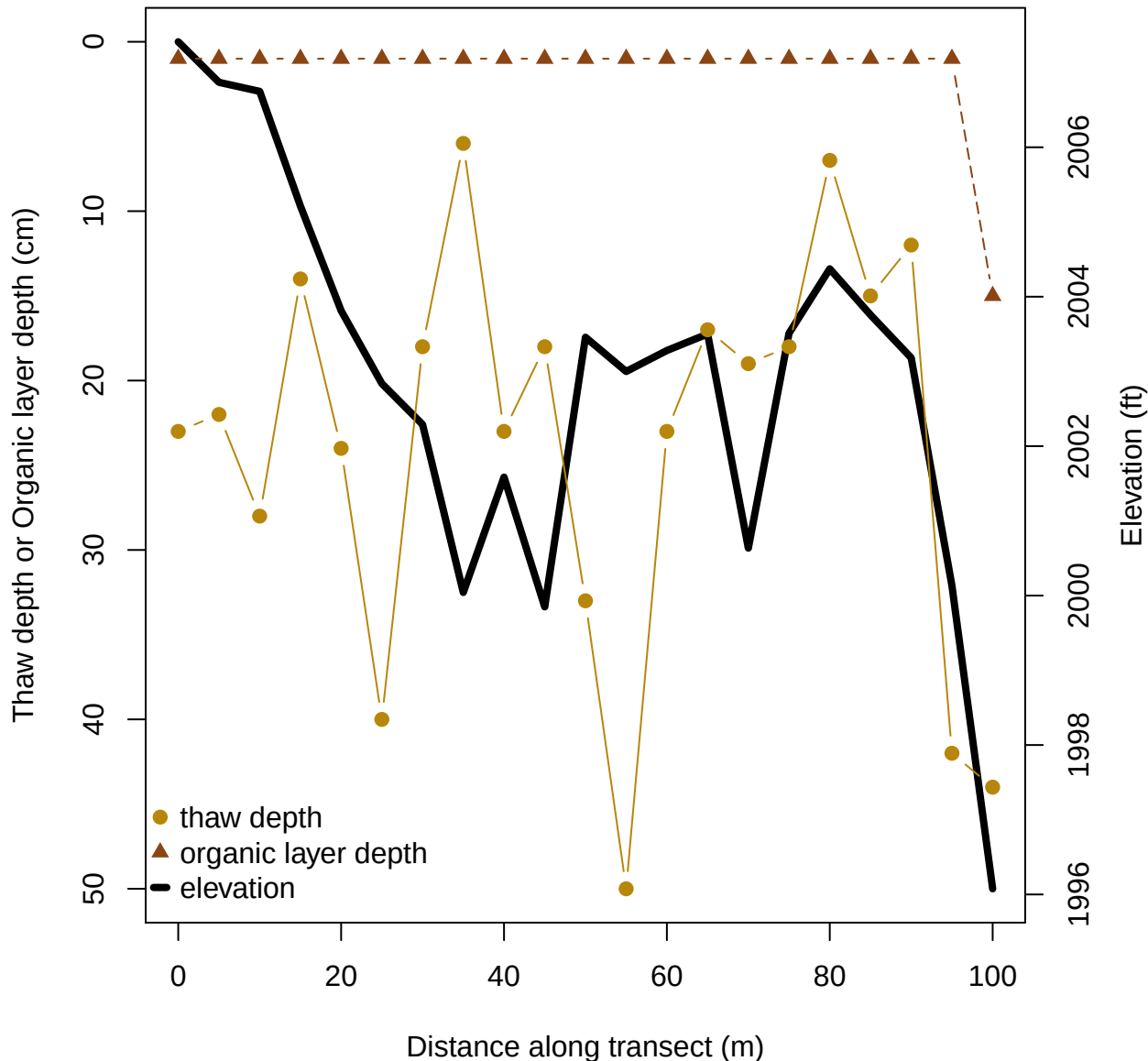


Figure 11

LEF Cabin

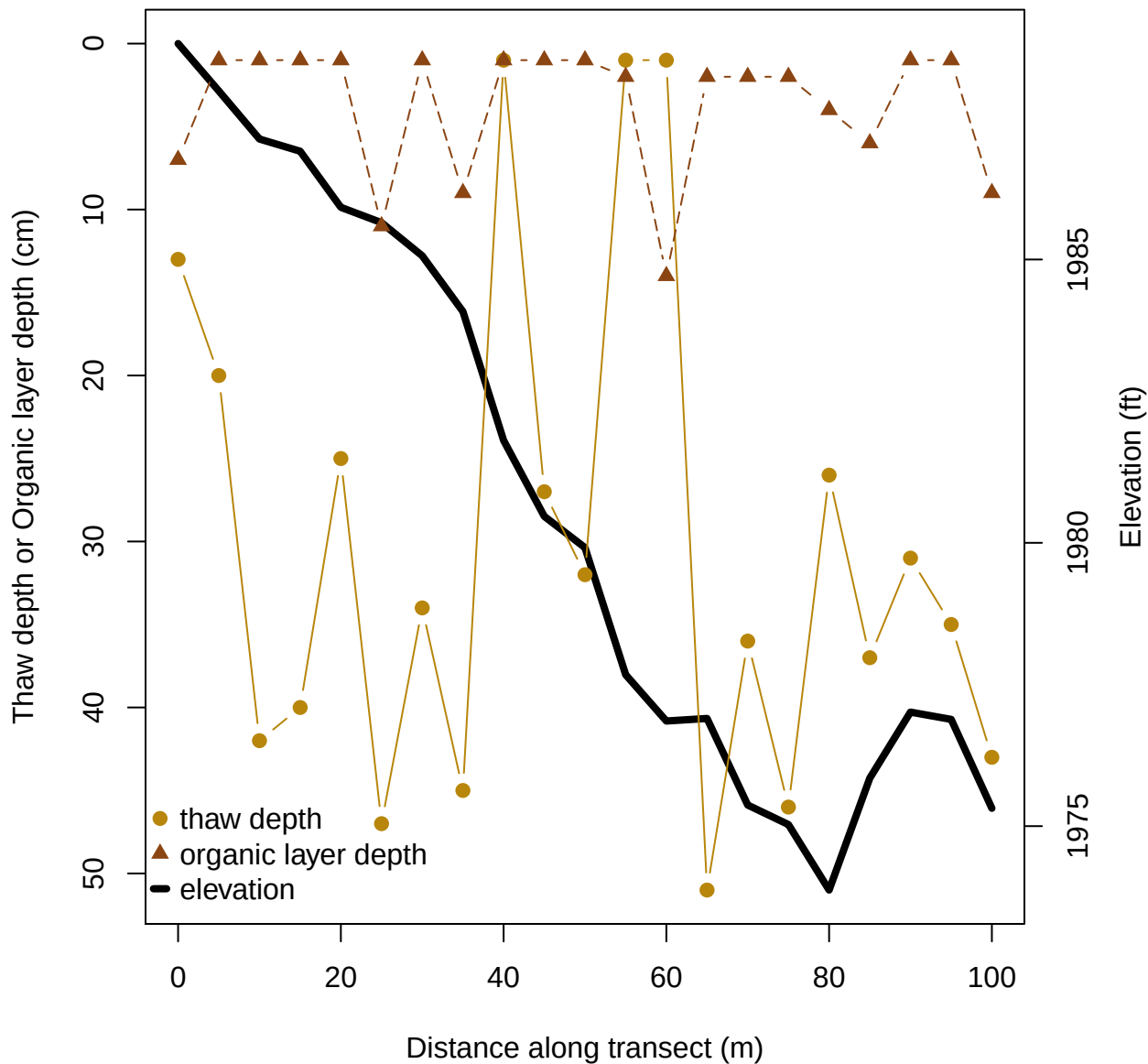


Figure 12

Lower East Fork Transect 1

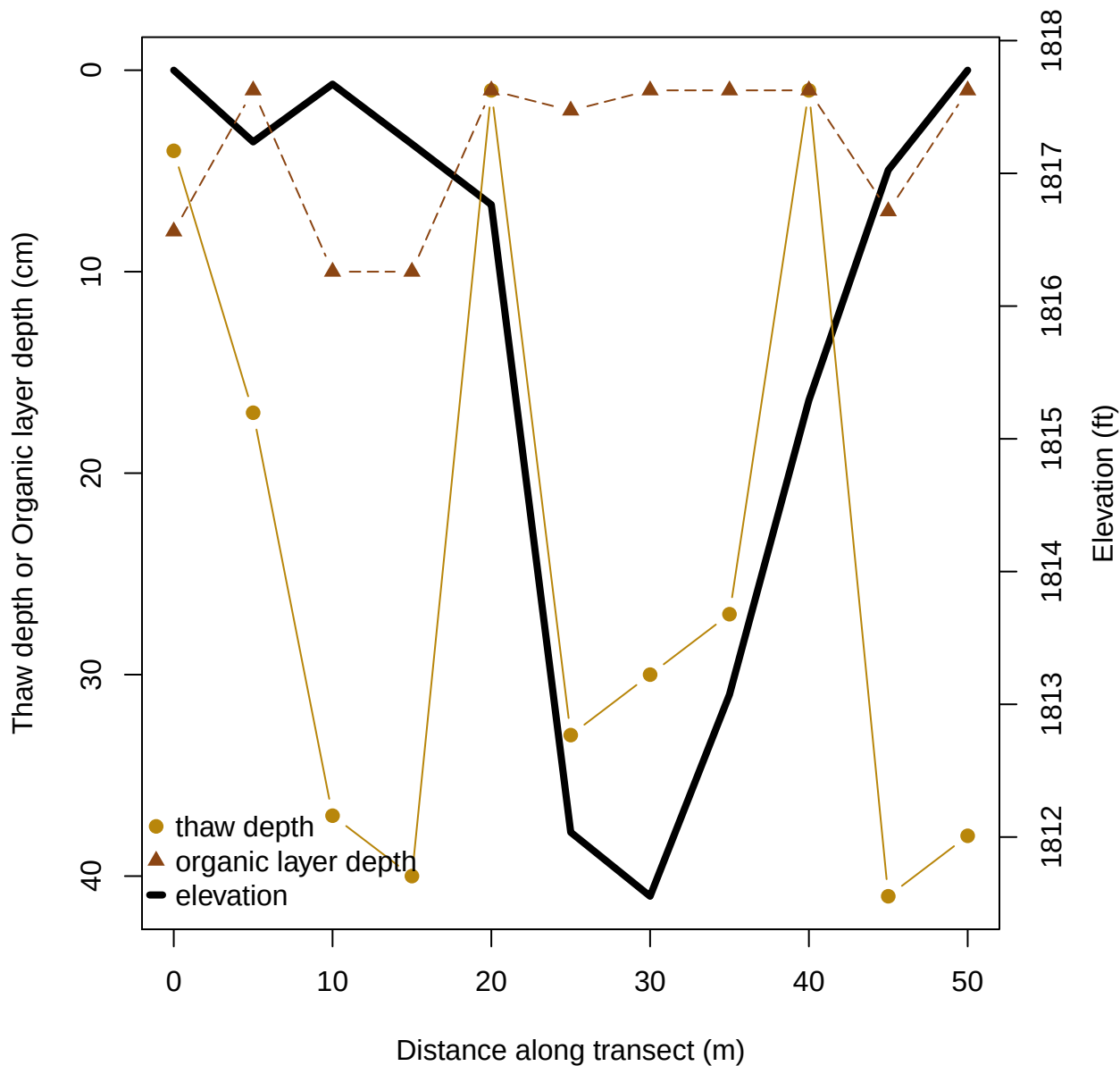


Figure 13

Lower East Fork Transect 2

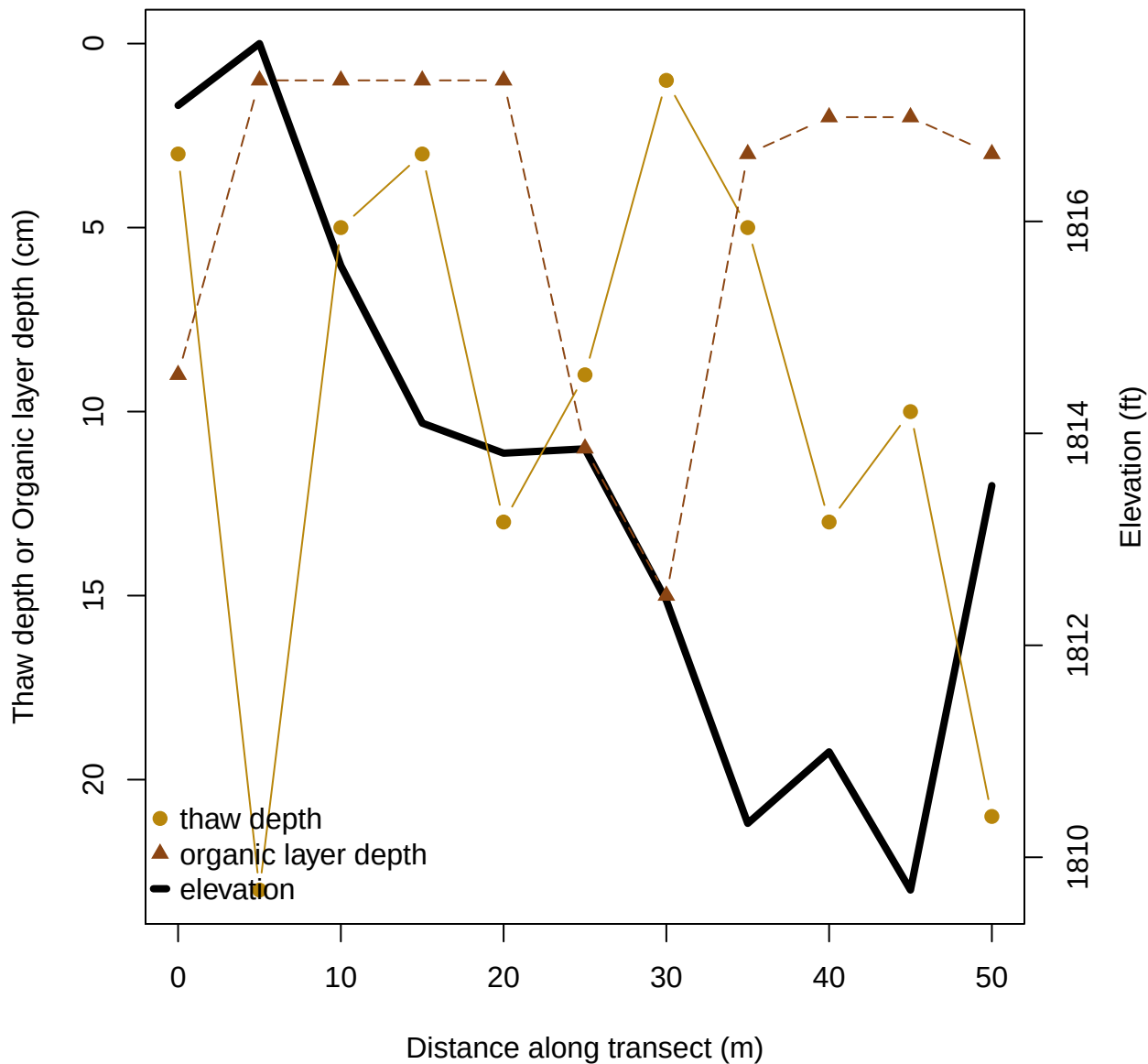


Figure 14

WWS burned

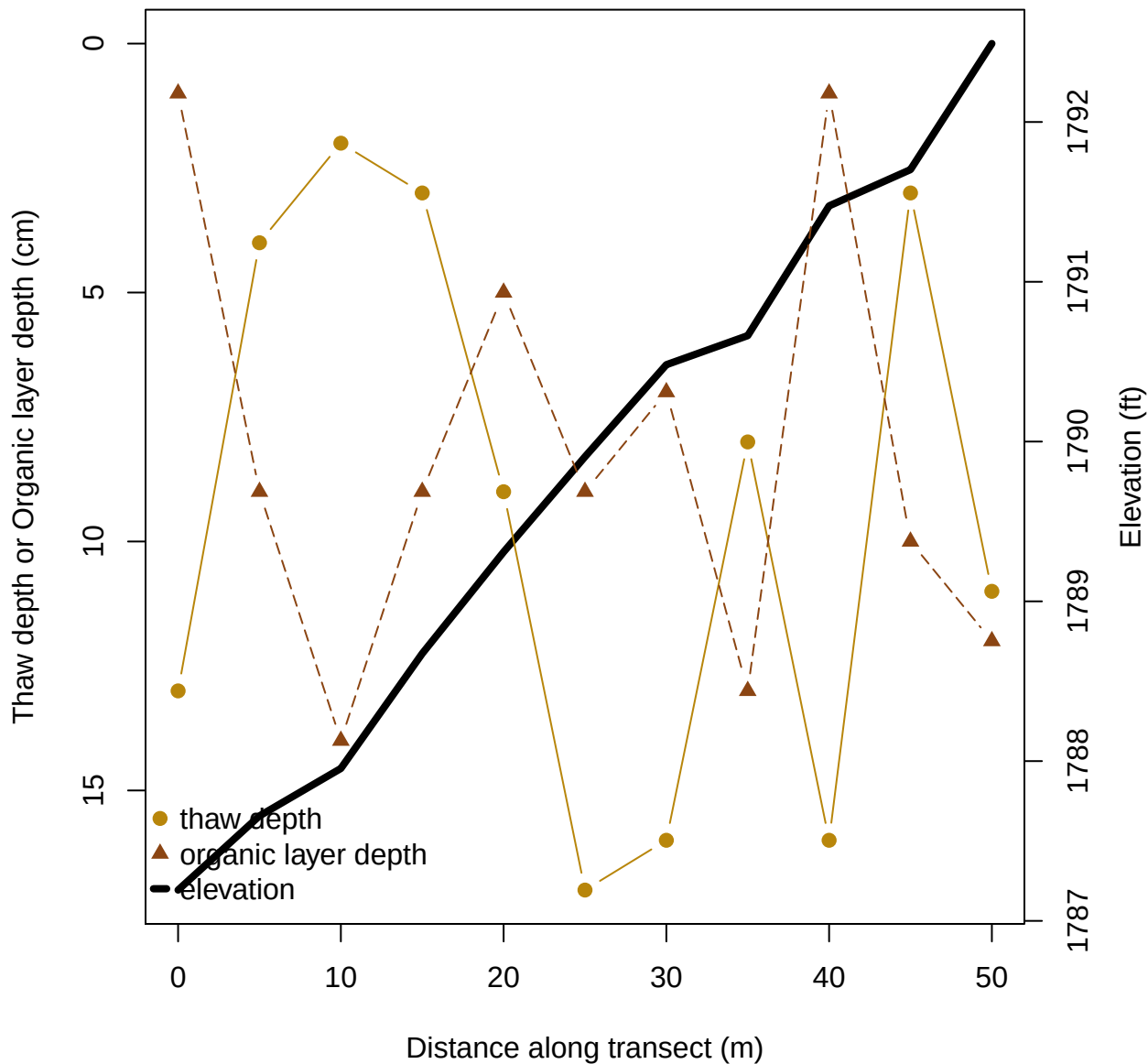


Figure 15

WWS unburned

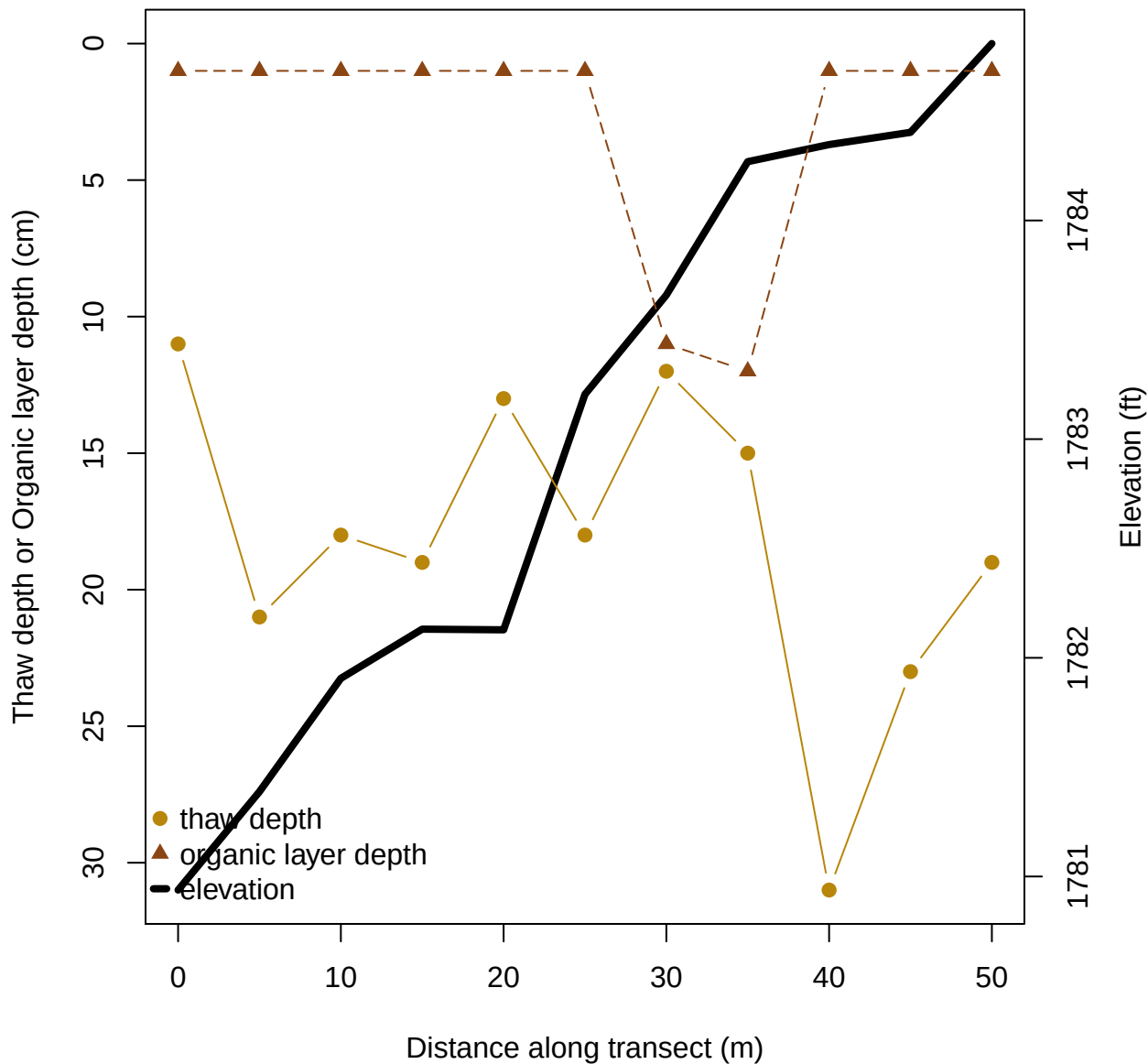


Figure 16

Pitchfork Transect 1

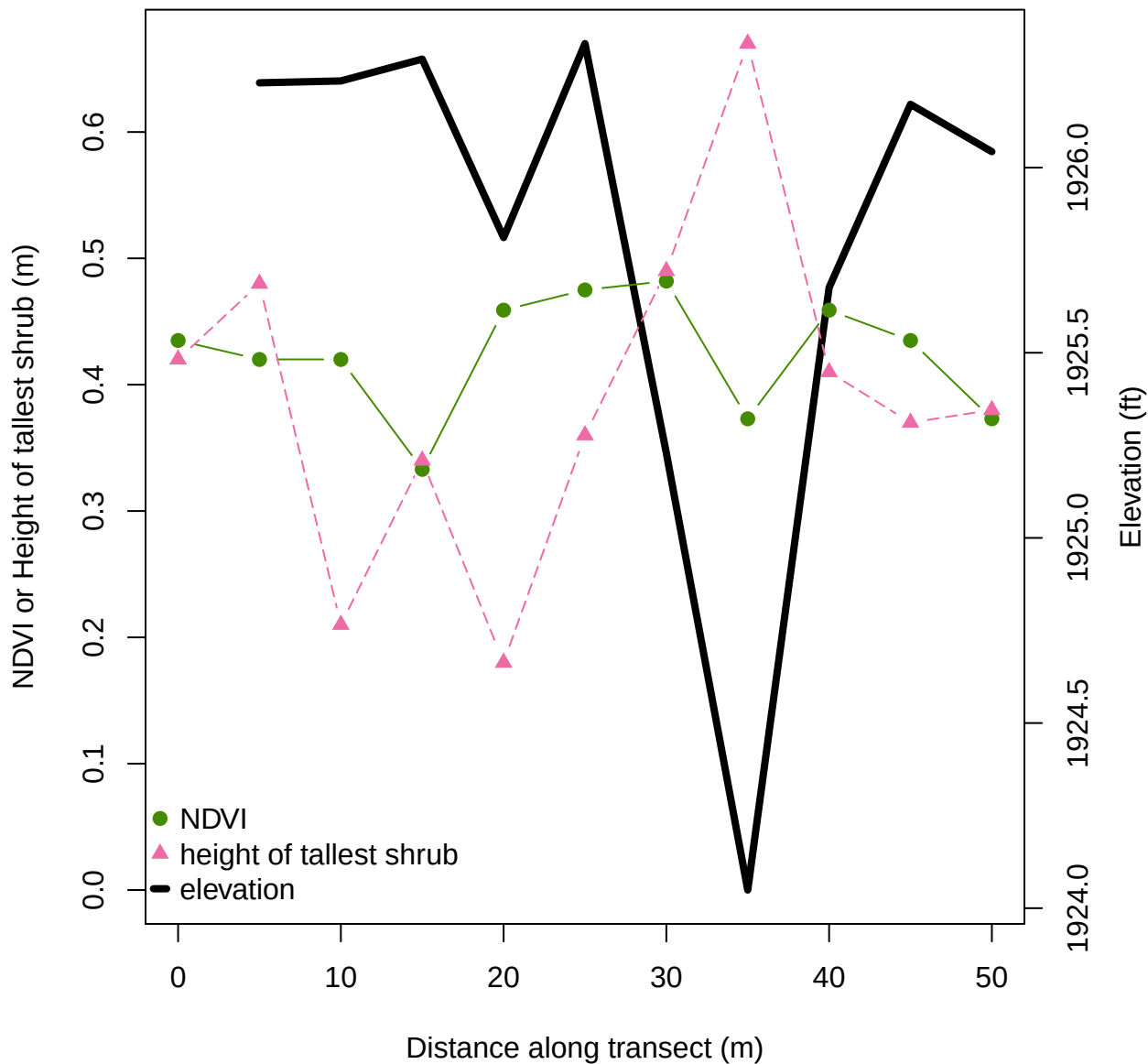


Figure 17

Pitchfork Transect 2

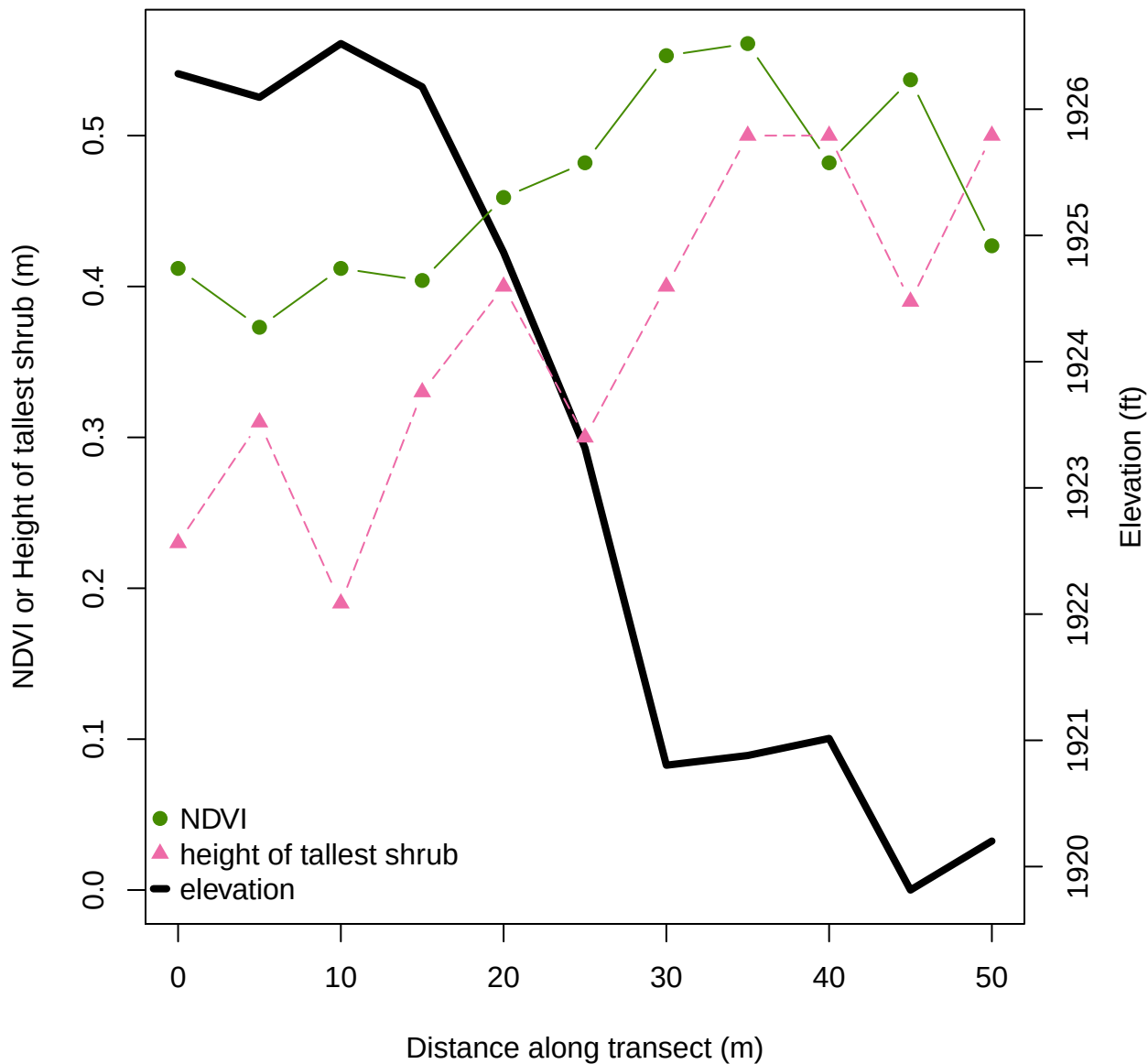


Figure 18

Wigand Creek

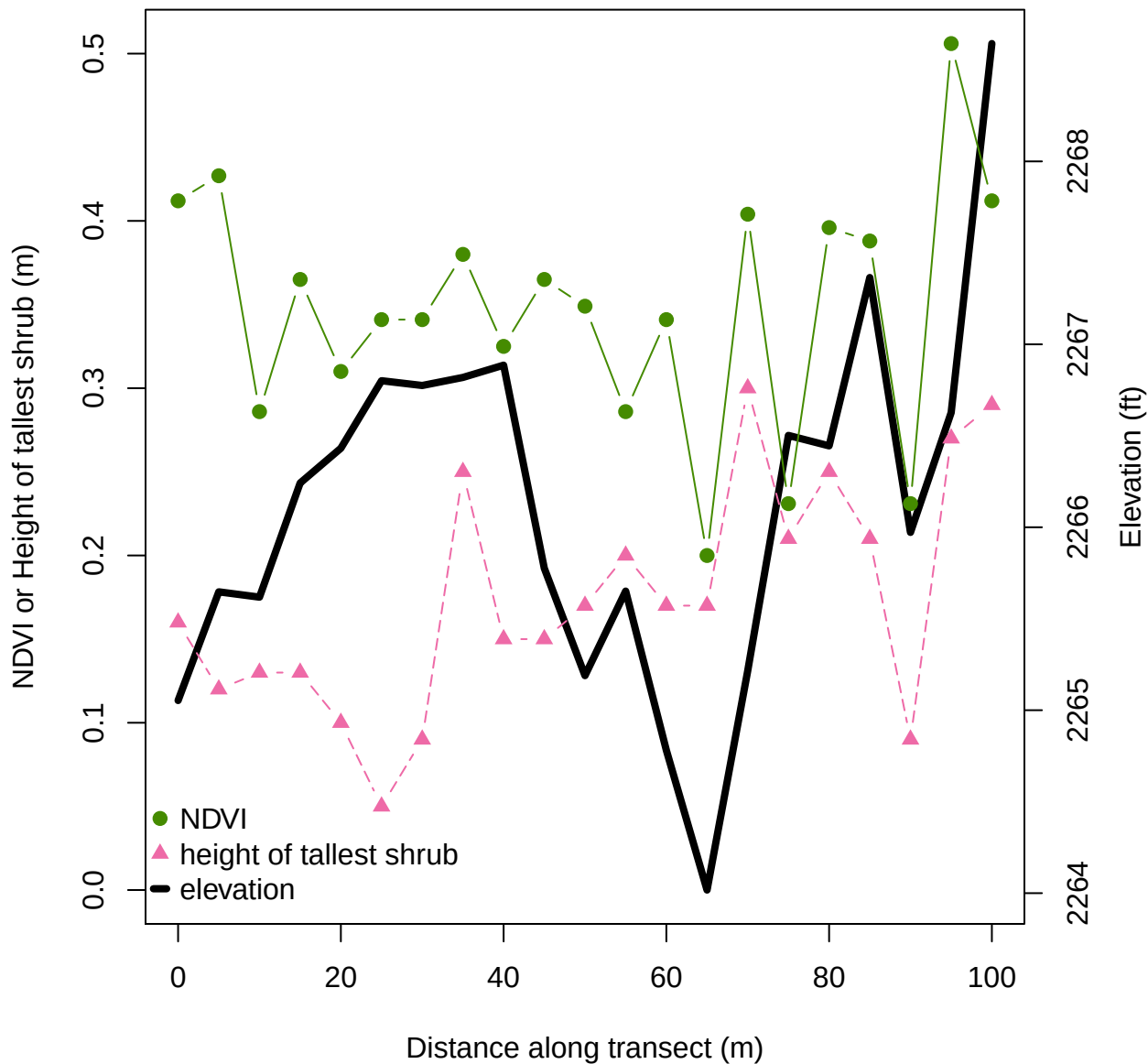


Figure 19

Boundary

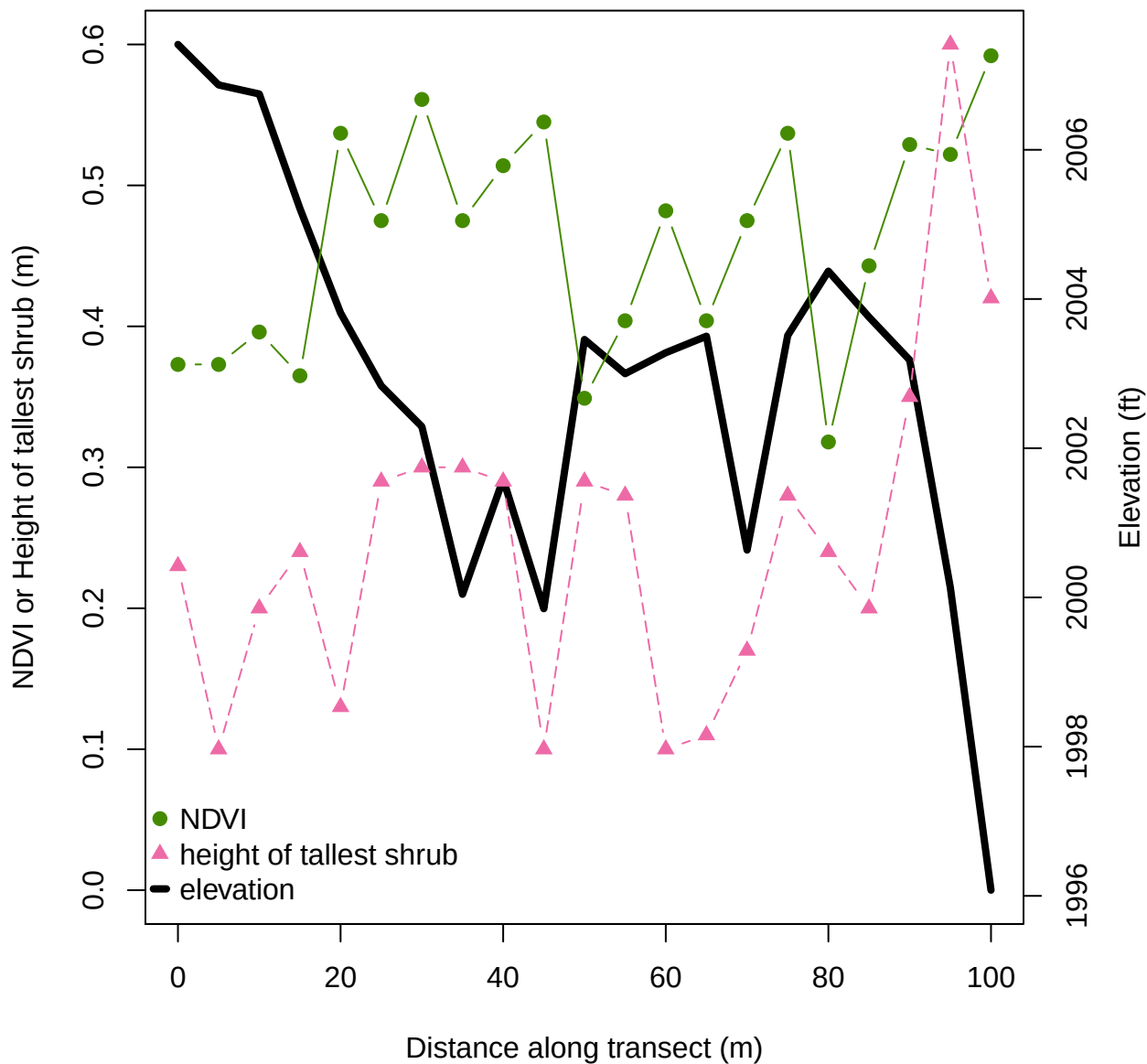


Figure 20

LEF Cabin

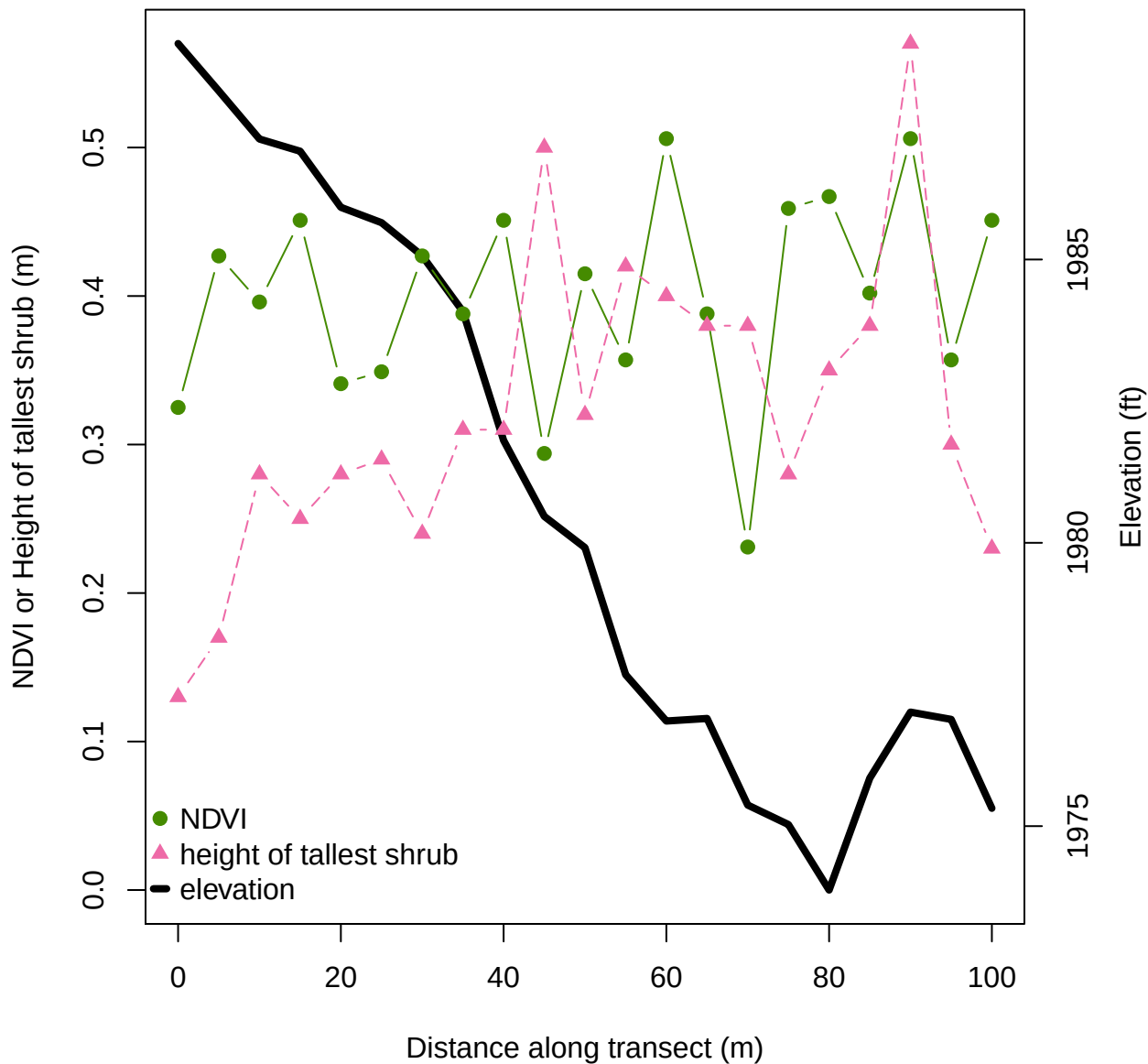


Figure 21

Lower East Fork Transect 1

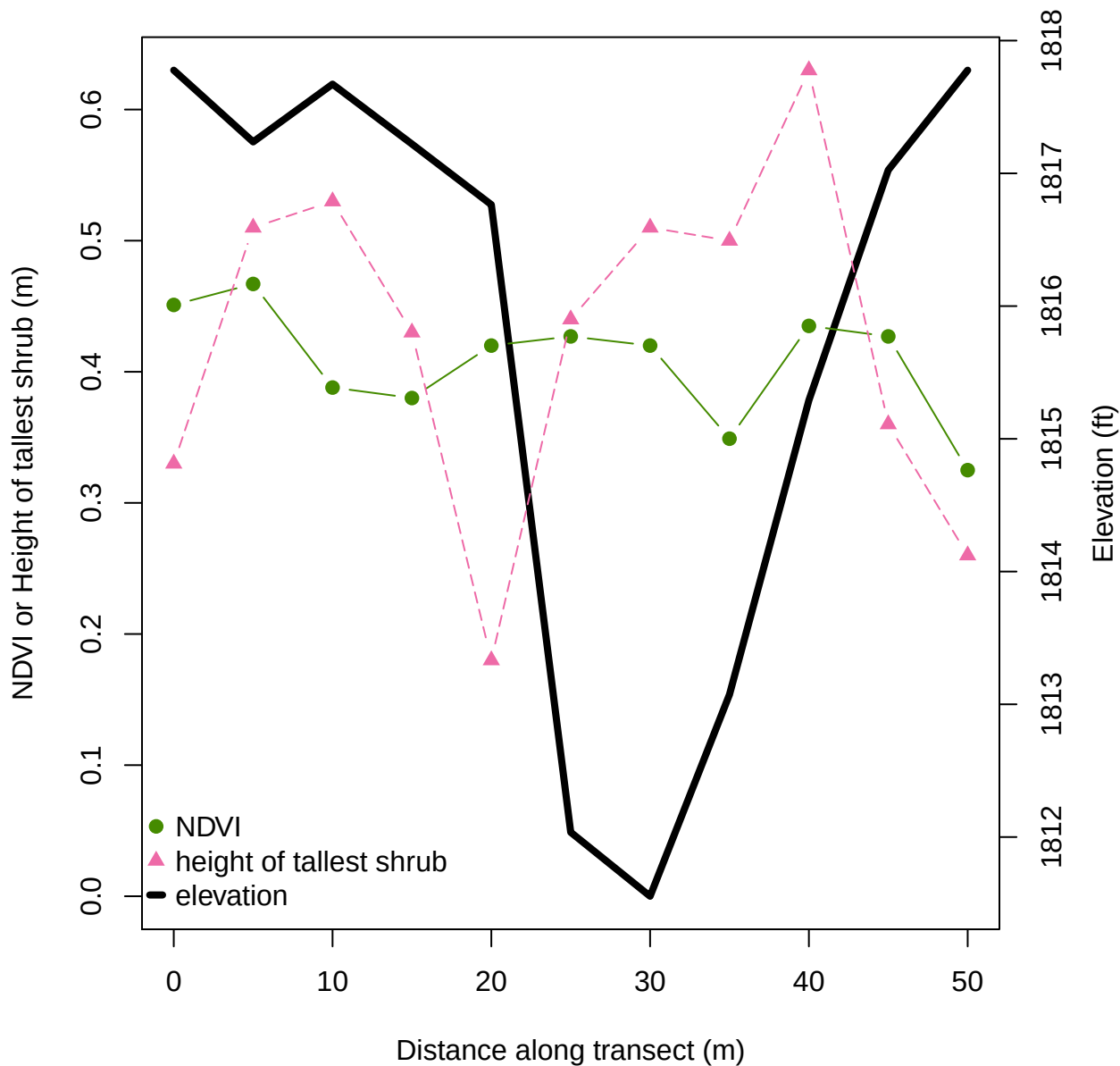


Figure 22

Lower East Fork Transect 2

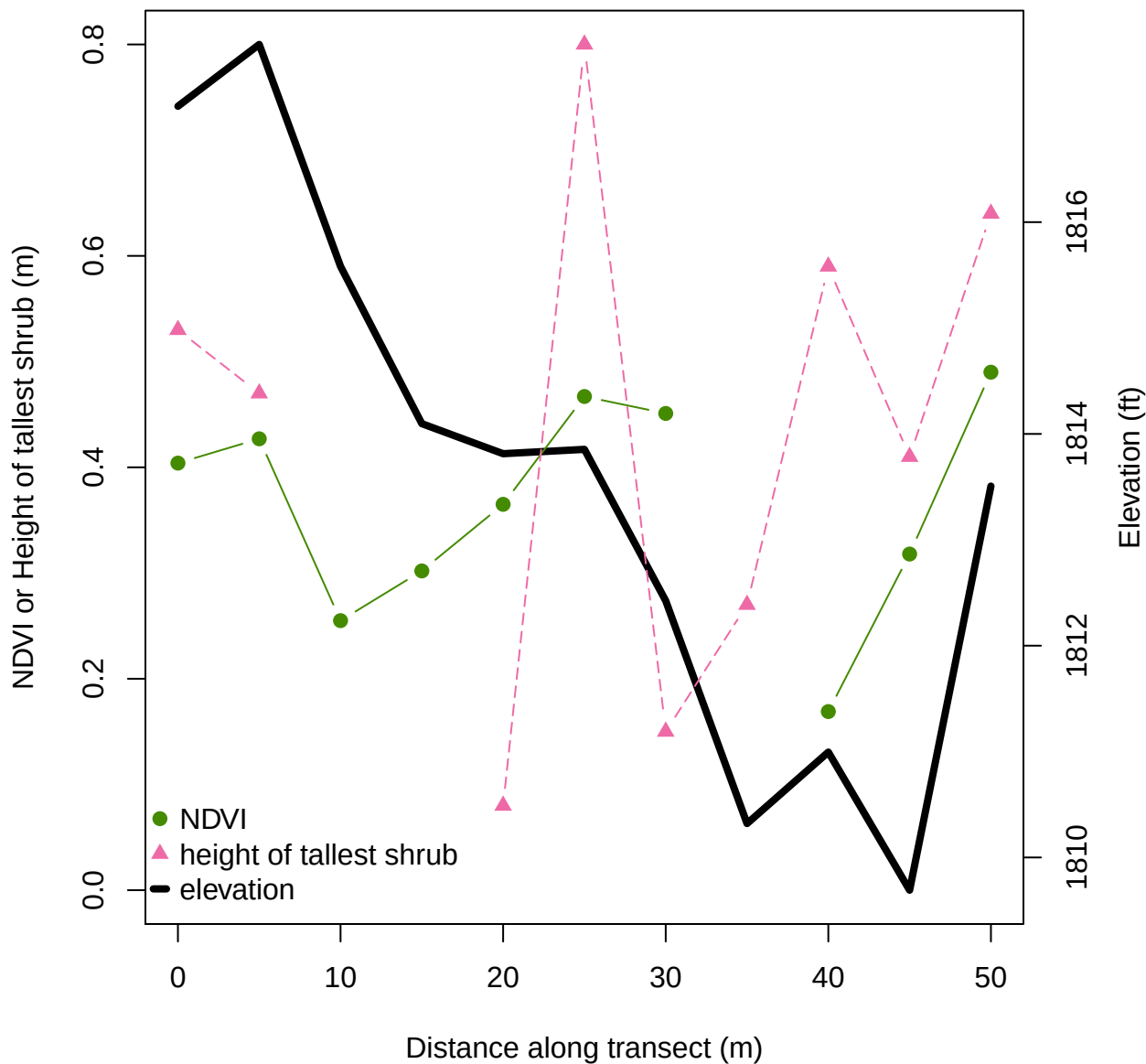
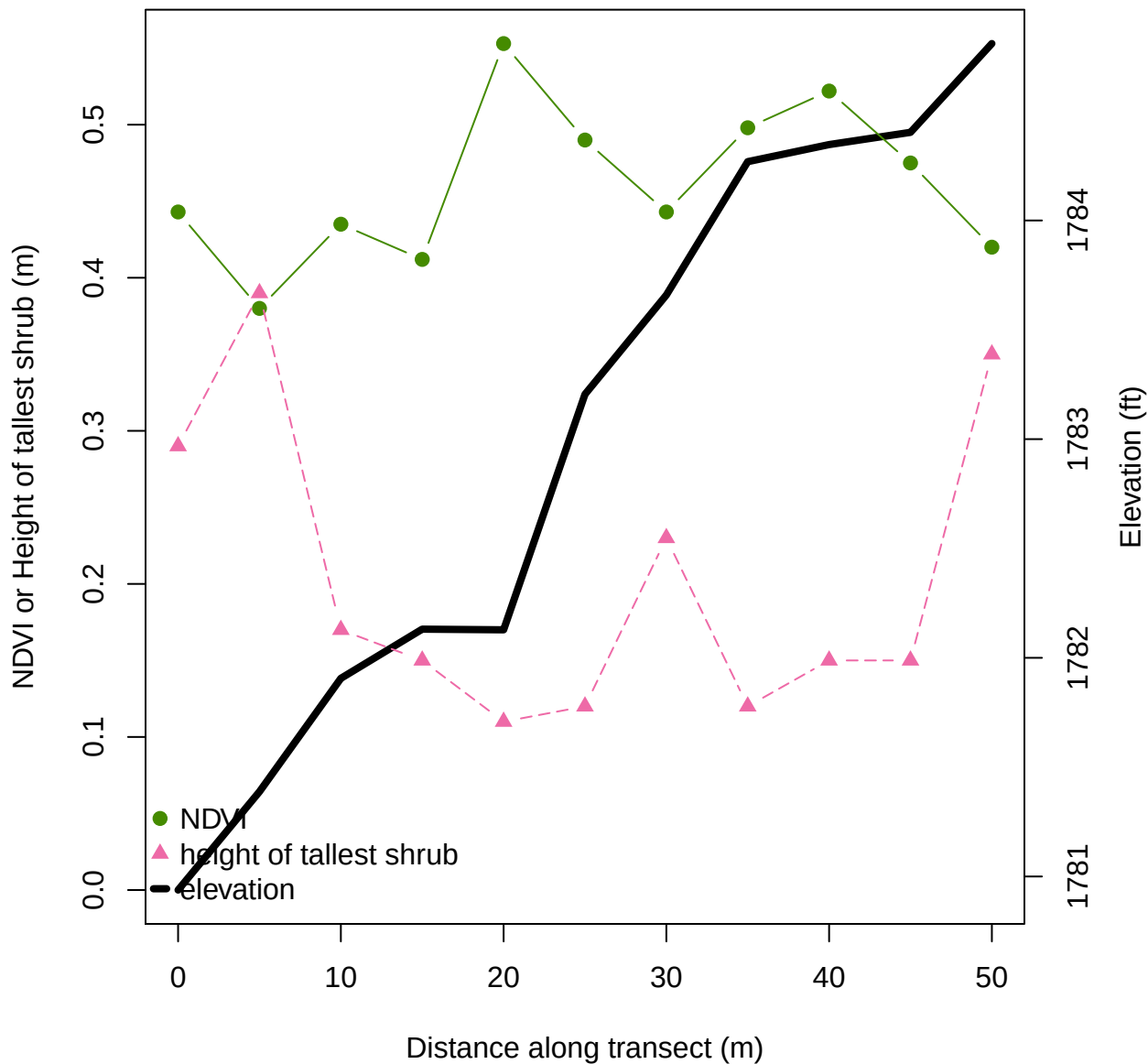
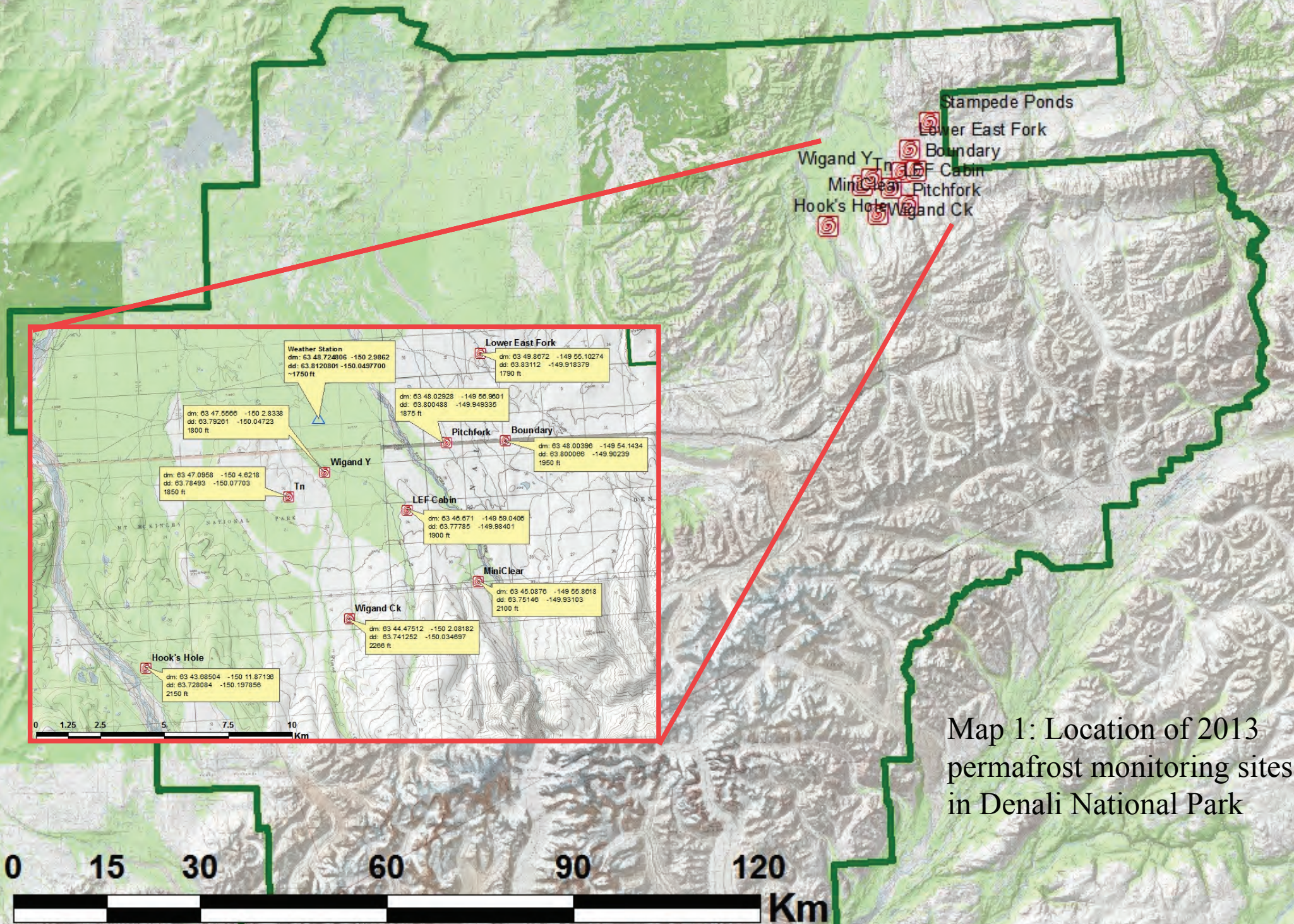


Figure 23

WWS unburned



Map 1



Map 1: Location of 2013 permafrost monitoring sites in Denali National Park

Map 2

Stampede Ponds

Lower East Fork

Wigand Weather Station

Pitchfork

Boundary

Wigand Y

Tn

LEF Cabin

MiniClear

Wigand Ck

Hook's Hole

Toklat Basin Thermokarsts

× Surveyed in 2013

⬮ Thermokarst Sites

N



0 1.25 2.5 5 Km