Northern Peatlands to Monitor Recent and Future Warming

Final report of CCAF project A313

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Executive Summary

The objective of this project was to examine and quantify the impacts and magnitude of recent warming upon permafrost stability in peatlands of the upper Mackenzie Valley. Permafrost has a significant impact upon carbon storage in peatlands, with frozen peatlands generally accumulating carbon at lower rates than unfrozen peatlands. We used a time-series of aerial photographs and high-resolution satellite images spanning at least 50 years to quantify thaw at four locations (total 6 sites) ranging in latitude from 60 to 64^{o}N.

Significant thaw of permafrost has occurred at all sites over the past 50 years, ranging from a 33.9 to 79.2% increase in unfrozen peatland area. On average, the amount of thawed peatland increases by 1% per year in this region. There is a trend of lesser increases in thawed area with increasing latitude.

Mean lateral thaw (the lateral movement of the frozen – unfrozen boundary) range from 18.6 to 7.0 m over the time period of study (Table 2). This translates into a range of 0.127 to 0.351 m per year over the 50-55 years of study. Maximum thaw rates reach over 1.0 m per year at several sites. There are also locations at the Liard site where very large peat plateaus, up to 200 x 225 m have completely thawed in the 53 years between images. Of course there are many locations that appear to be stable (not thawing), or in rare cases permafrost may be aggrading.

One of the most interesting results of this study is the recognition that many of the thawed areas at the Liard River sites are becoming more and more interconnected and contiguous over time, resulting in improved drainage and a decrease in the dominance of permafrost. In contrast, sites other than the Liard River area are still permafrost-dominated, although the trend is certainly towards ongoing thaw, the coalescence of thaw features, the development of an integrated drainage basin, and a landscape becoming more dominated by unfrozen peatlands. A result of the dominace of unfrozen peatlands and improved drainage is the establishment of drier, shrub and tree dominated peatlands that have higher carbon accumulation rates than permafrost-dominated sites.

Introduction

The objective of this project was to examine and quantify the impacts of recent warming upon permafrost stability in peatlands of the upper Mackenzie Valley. Northern peatlands offer a unique opportunity to monitor permafrost thaw visually and inexpensively, as the presence or absence of permafrost can often be determined from aerial photographs and/or satellite images. Peatlands are unlike any other landform for this ability to discriminate frozen and unfrozen peat based upon aerial photographs or satellite images. Using a time-series of images allows the quantification of thaw and changes in permafrost distribution over the period of image availability, in this case >50 years.

Permafrost in many northern peatlands is discontinuous with permafrost being heavily influenced by developmental history and hydrology (autogenic factors) on a local scale. However, on a more regional scale, climate (allogenic factor) also plays a major role in the presence or absence of permafrost in peatlands. The influence of autogenic controls is so strong that there can be permafrost thaw co-existing with permafrost aggradation within one peatland even if the climate is stable (Zoltai, 1972). Thus, the presence of thaw at a single site could not be proven to be an impact of climate warming. However, studies over large regions would be expected to show a trend of permafrost degradation dominating over aggradation or stability if the climate were warming (Robinson and Moore, 2000).

Most studies that suggest that a climate warming will result in a net carbon source to the atmosphere through increased decomposition are from sites with continuous permafrost (Billings, 1987; Oechel and Vourlitis, 1994). The response of carbon pools in the discontinuous permafrost zone may be more complicated as peatland-permafrost relationships are influenced more by vegetation patterns and hydrology, and result in peat landforms with significantly different rates of carbon storage (Robinson and Moore, 1999).

Background

Peatlands cover 14% of Canada and contain about 150 Gt of carbon, or more than 10% of the 1395 Gt in the world soil carbon pool. Most peatlands occur in the boreal forest region, where they occupy nearly 30% of the land surface area and account for 80% of the soil carbon mass. Three recent CCAF –sponsored workshops highlighted the needs for monitoring permafrost (Permafrost, Glaciers and Ice Caps Monitoring Networks Workshop, Ottawa, Jan 28-29, 2000) and wetlands (Wetlands Database and Modelling Needs Workshop, Ottawa, January 24-25, 2000; International Workshop on Carbon Dynamics of Forested Peatlands, Edmonton, March 23-24, 2001) in northern Canada.

Contrary to other landforms in the discontinuous permafrost zone, the presence or absence of permafrost in peatlands is closely tied to the particular peat landform. Peat pleateaus and palsas contain permafrost, while almost without exception fens in the upper Mackenzie Valley do not. In many cases, peat plateaus are large, tree covered (dark) and with sharply defined boundaries (Figure 1). Unfrozen peatlands in the discontinuous permafrost zone generally do not contain trees in this area and thus the lighter tone of ground surface vegetation (*Sphagnum* mosses and sedges) can also be easily distinguished (Figure 1).

In the sporadic permafrost zone of Canada, aerial photographs have been used to show a decrease in areal extent of peat plateaus over time (Thie, 1974; Halsey *et al*., 1995) in response to recent warming. No work has been conducted further north in the discontinuous or widespread permafrost zones with the exception of Horvath (1998) in the Macmillan Pass area. In many areas of the north, the most recent aerial photographs were taken in the late 1970's. With the launching of the Ikonos satellite in 1999, high resolution (1 m) panchromatic images can now be obtained in near-real time. These images can be used as replacement aerial photographs and in this project provide coverage at the selected area for the year 2000. Initial aerial photographs in the Mackenzie Valley date from the late 1940's, and thus there are now over 50 years worth of data to be utilized in this study of changes in peramfrost distribution.

In addition to being a visual clue to permafrost degradation and hence possible impact of climate warming, the thaw of permafrost has significant impact upon carbon cycling in peatlands. It is expected that permafrost thaw in peat plateaus near Fort Simpson, N.W.T. may result in a doubling of carbon accumulation (Robinson and Moore, 2000).

This research in the Mackenzie Valley will increase our understanding of the role that climate change may play in the degradation of northern permafrost-affected peatlands. There are linkages between these processes and changes in carbon accumulation that may be explored in future work. Complementary hydrologic modelling is ongoing in several of the basins that are under consideration for this study.

The Mackenzie Valley is particularly well suited for the proposed study of past and contemporary impacts because (1) it contains vast areas of permafrost-affected peatlands (more than 30% of Canada's total peatlands); (2) the area is known to have experienced a 1.7^{o}C rise in mean annual air temperature over the past 100 years, the greatest of any region in Canada; (3) there is a large body of published geological, biological, and cultural information from past assessment studies for pipeline or other infrastructure development, and (4) air photo coverage extends back to the late 1940's, and Ikonos satellite images available from the year 2000 onwards.

Research Activities:

Site Selection and Image Acquisition:

Site selection was conducted in July 2000 through the examination of aerial photographs available from the National Air Photo Library. We attempted to select five sites that were within easy access of the Norman Wells pipeline route (for combined field logistics), that showed extensive and distinct unfrozen and frozen peatlands, and that spanned a latitudinal range of approximately 60 to 64^{o}N.

Once the five sites were selected (Table 1; Figure 1), Ikonos satellite images were ordered, and the images were obtained for dates in August or September, 2000.

Table 1. Sites selected for analysis of permafrost thaw in peatlands. Note that the site names are informal and are based upon nearby geographical features.

Site name	Location	Elevation (m)	Reconstructed mean annual air temperatures (MAAT)(°C)	Image years used for analysis
Trout Lake	60°32'N 120°39'W	560	-2.0	1950, 2000
Liard River	61°26'N 121°50'W	230	-2.7	1947, 2000
Wrigley Ferry	62°17'N 122°34'N	280	-3.8	1945, 1977, 2000
Eentsaytoo Lake	64°02'N 124°13'W	170	-4.3	1948, 2000
Big Smith	64°36'N 124°10'W	150	-4.4	Site not used

Figure 1. Site map with the locations of the investigated peatlands.

Field Checking:

All sites were visited in late September 2000 and photographed in order to confirm that the features in question were in fact peatland thaw features. All sites were confirmed to be composed of discontinuously frozen peatlands. Field evidence of recent permafrost thaw was confirmed at all sites. Site photographs are presented in Appendix A. Following field checking and a preliminary analysis of the images, it was decided not to include the Big Smith site in the analysis. It was felt that the peatland morphology was actually controlled by the underlying topography and drainage to a great extent, and thus any thaw may not result in a morphological change that could be detected from aerial photographs or satellite images.

Image Processing:

The portions of aerial photographs covering the sites of interest were scanned at high resolution (1200 dpi). Ikonos satellite images were delivered in digital format. Using ERmapper image manipulation software, the images for each site were rectified and calibrated.

Images were transferred to MapInfo GIS software, in which digitizing of features was conducted. Areas and linear sizes of features were calculated. It is estimated that the overall error of positioning is on the order of 2-3 m. Careful digitizing of the same features in different images allows the measurement of areal and linear changes between the two images.

Results:

Images of the 1940's or 50's aerial photographs, as well as the satellite images are presented in Appendix B. Also in Appendix B are the digitized versions outlining thaw front interpretations.

Statistics summarizing thaw characteristics at each site are presented in the following tables. Table 2 shows the overall statistics for the sites investigated. At each site, areas were selected based upon representativeness of the overall peatland terrain. Site were selected semi-randomly, as the quality of air photo images prevented a fully random selection.

All sites are at least 50 km from the nearest weather station. To estimate mean annual air temperatures (MAAT) at each site, Environment Canada's gridded dataset for the 1961-1990 normals was used. This dataset interpolates from existing weather stations to a finer grid, yet it is unclear as to how important conditions (*e.g.* elevation) are taken into account. In particular, we feel that the interpolated MAAT for the Trout Lake site is too warm.

Overall thaw:

All sites show a significant increase in thawed area between the initial air photos and the 2000 satellite images, ranging between 33.9 and 79.2% increases (Table 2). These increases in thaw rate average about 1% per year. The greatest increase in thawed area occurred at the most northerly site, Eentsaytoo Lake, although total thawed area remained the lowest of all sites. It is possible that this site was influenced heavily by a past forest fire, although the timing of that fire is unknown. A visit to this site is planned for June 2001 in conjunction with other field work in the area.

Excluding the Eentsaytoo Lake site for the reasons mentioned above, there is a slight trend of lesser increases in thaw areas with increasing latitude. The Trout 2 site went from 16.1% unfrozen area to 24.5% of the total mapped area. Large increases were noted at both Liard sites, where thawed areas increased from 55.1 to 77.9% and 45.2 to 63.8% of the total mapped area. Increases in total thawed area were less dramatic at the Wrigley Ferry site, which increased in total thawed area from 28.5 to 38.3% over the time span from 1948 to 2000.

Lateral thaw:

Mean lateral thaw (the lateral movement of the frozen – unfrozen boundary) range from 18.6 to 7.0 m over the time period of study (Table 2). This translates into a range of 0.127 to 0.351 m per year over the 50-55 years of study. Maximum thaw rates reach over 1.0 m per year at several sites. There are also locations at the Liard site where very large peat plateaus, up to 200 x 225 m have completely thawed in the 53 years between images. Of course there are many locations that appear to be stable (not thawing), or in rare cases permafrost may be aggrading. It is thought that any real permafrost aggradation rates would be within the level of error, and thus not statistically significant. Permafrost aggradation in peatlands is a much slower process than degradation (Robinson and Moore, 2000). There does not appear to be any preferential direction or aspect for lateral thaw. Again excluding the Eensaytoo Lake site, there is a general trend of decreasing lateral thaw rates with increasing latitude.

Table 2. Overall statistics for each of the sites investigated in this study.

Site	Interpolated MAAT[1]	Area studied (km^2)	Frozen (% total) (km^2)	Unfrozen (km^2)	% increase in unfrozen area	% increase in unfrozen area per year	Mean lateral thaw rates (range) (m)[2]	Mean lateral thaw rates per year (m)
Trout 2	-2.0	0.618					10.7 (0-49)	0.214
Area 1950			0.519 (83.9)	0.099 (16.1)				
Area 2000			0.467 (75.5)	0.151 (24.5)				
% change					52.5	1.05		
Trout 4	-2.0	0.757					10.5 (0-20)	0.21
Area 1950			0.601 (79.4)	0.156 (20.6)				
Area 2000			0.531 (70.2)	0.225 (29.8)				
% change					44.2	0.88		
Liard 1	-2.7	0.615					17 (0-41)[3]	0.321
Area 1947			0.276 (44.9)	0.338 (55.1)				
Area 2000			0.136 (22.1)	0.478 (77.9)				
% change					44.1	0.83		
Liard 2	-2.7	1.321					18.6 (0-62)	0.351
Area 1947			0.723 (54.8)	0.598 (45.2)				
Area 2000			0.478 (36.2)	0.844 (63.8)				
% change					41.1	0.78		
Wrigley Ferry	-3.8	1.797					13.4 (0-69)	0.258
Area 1948			1.285 (71.5)	0.513 (28.5)				
Area 2000			1.110 (61.7)	0.687 (38.3)				
% change					33.9	0.65		
Eentsaytoo Lake	-4.3	0.214					7.0 (0-40)	0.127
Area 1945			0.190 (89.0)	0.024 (11.0)				
Area 2000			0.171 (80.0)	0.043 (20.0)				
% change					79.2	1.44		

[1] – MAAT = Mean annual air temperature. This data is based upon Environment Canada's gridded dataset for 1961-1990 normals. This dataset does not adequately account for elevation, and thus the Trout Lake site is though to be actually colder.
[2] – measurements of lateral thaw were conducted at at least 40 randomly selected locations in each study area.
[3] – complete thaw of features up to 225 x 200 m was noted yet not included in lateral thaw measurements as thaw likely proceeded both as lateral and top-down thaw.

New features:

Thaw features that are noted in the 2000 images, but do not appear to be present in the earlier air photographs, are termed new features. In most cases these features are small, but as thaw progresses they will likely become larger and start to coalesce. Table 3 summarizes some statistics for these new features, including average size and number. The dates that these new features started to form is unknown, although it is sometime between two images. New features that formed and subsequently coalesced with older features are difficult to isolate, and are included in statistics in Table 4; the expansion of older features.

New features formed at all sites and are especially prevalent at the two most southerly loactions, the Trout and Laird sites. Sites that have less permafrost to begin with have less of an area in which to form new thaw features, and a greater liklihood that new features will be quickly incorporated into older existing features.

The percent of total thaw attributed to new features is high at both the Trout 2 and Eentsaytoo Lake sites. Although the number of new features at the Liard River sites is large, the total percent of thaw is low owing to the small size of the features compared to the wholescale thawing that is ongoing.

Table 3. New features statistics

Site	Interpolated MAAT	Average size (m^2)	Median size (m^2)	n	Number per km^2	% of thaw attributed to new features
Trout 2	-2.0	413	304	18	29.1	26.3
Trout 4	-2.0	387	354	13	17.2	7.3
Liard 1	-2.7	144	124	10	16.3	1.0
Liard 2	-2.7	298	169	25	18.9	2.9
Wrigley Ferry	-3.8	619	424	9	5	3.2
Eentsaytoo Lake	-4.3	365	207	7	32.7	13.5

The Expansion of Older Features:

Individual thaw areas or features that were visible in the early air photographs, that are also noted in the 2000 satellite images are termed older features.

At all sites, the number of individual unfrozen features has decreased significantly from the early photographs to the 2000 images (Table 4), with the greatest decrease occurring at the two Liard River sites. Although this may intuitively suggest that the amount of thawed area has decreased, in fact many features have coalesced into larger, interconnected thawed features. The mean size of individual thawed features has increased at least 100% at at all sites, with increases of 271 and 849% at the two Liard River sites.

A measure of interconnectivity has been derived for these sites. This measure is area of the largest contiguous unfrozen feature divided by the total area of study. As hydrology and drainage can play a major role in the degradation and aggradation of permafrost, this statistic becomes important as a measure of the amount of hydraulically connected thawed area. A high measure of interconnectivity implies that there is a large degree of potential drainage, that is, the individual features are now largely linked and the dominance of permafrost in the landscape is diminished. Large changes in this measure of interconnectivity over time are indicative of the decreasing dominance of permafrost, and the transition to a hydrologically connected unfrozen regime. For example, at the Liard 1 site, it can certainly be said that by the year 2000, the peatland has become dominated by unfrozen peat, with permafrost becoming restricted to isolated islands. In contrast, sites other than the Liard River area are still permafrost-dominated, although the trend is certainly towards ongoing thaw, the coalescence of thaw features, the development of an integrated drainage basin, and a landscape dominated by unfrozen peatlands.

Table 4. Older features expansion statistics:

Site	Number of individual unfrozen features[1]	Measure of inter-connectivity[2]	Mean size of unfrozen features (m^2)	Median size of unfrozen features (m^2)
Trout 2				
1950	26	0.024	3828	957
2000	16	0.044	8617	5536
% change	-31	83	125	478
Trout 4				
1950	35	0.037	4217	962
2000	25	0.075	8495	1708
% change	-29	103	101	78
Liard 1				
1947	30	0.374	11644	1088
2000	4	0.717	110550	454
% change	-87	92	849	-58
Liard 2				
1947	79	0.130	7456	737
2000	31	0.478	27686	1272
% change	-61	268	271	73
Wrigley Ferry				
1948	83	0.037	6174	3675
2000	65	0.059	10478	6861
% change	-22	59	70	87
Eentsaytoo Lake				
1945	67	0.015	340	172
2000	45	0.035	922	475
% change	-32	133	171	176

[1] - includes only unfrozen features that are visible in both images, and not new features

[2] – a measure of the amount of interconnectivity between unfrozen features, expressed as the area of the largest contiguous unfrozen feature divided by the total area of study.

Other features of note:

The thawing noted at the Liard sites is perhaps the most interesting example of permafrost degradation in this region. The two sites investigated have, in the past 53 years, crossed the threshold from a permafrost-dominated peatland with disrupted drainage towards a pattern of isolated permafrost and interconnected drainage. Although thaw has certainly been noted at the other sites, they are all still dominated by permafrost and without significant interconnection of thaw features.

Drainage and water levels play an important role in peatland development and carbon storage within peatlands (Robinson and Moore, 2000). If a section of a peatland thaws without adequate drainage (*i.e.* still surrounded by permafrost), then water tables most often remain high. In this situation vegetation is dominated by aquatic *Sphagnum* species and sedges, often with high methane fluxes and moderate carbon sequestration rates. This can also occur in very recently thawed areas (collapsed margins) where drainage may be somewhat better (see top right photo of Liard River, Appendix A). Over time, older features and those with adequate intial drainage (high values of interconnectivity), vertical vegetation accumulation tends to outpace the water table, and a shrubbier surface vegetation develops, with less water-tolerant *Sphagnum* species dominating (see bottom right photo of Liard River, Appendix B). This situation, where the water table is approximately 20-40 cm below the surface, tends to be much more efficient than wetter sites at storing carbon, and also has decreased methane emission rates. It is thought that unfrozen peatlands with a depressed water table (ombrotrophic systems) will become more dominant with time, and also much more dominant with improved drainage due to ongoing permafrost melt and increased interconnectivity. This will result in an overall increase in carbon storage compared to the previously frozen state, with minimal methane fluxes.

Figure 2 provides a dramatic example of this transition to an ombrotrophic peatland at the Liard River 2 site. In the 1947 air photo (enlarged) (Figure 2a), the central portion of the thawed zone has a very light tone, likely indicating a low-lying *Sphagnum*-dominated surface. By the year 2000 (Figure 2b and c) several older sections of the unfrozen peatland have developed a darker shrub and tree-dominated surface cover. This vegetation change is likely owing to a dropping of the water table, and is noticed at several location within the region (total of approximately 6% of the unfrozen area). This pattern is not noticed at any location other than the two Liard River sites. Although permafrost was not present at the shrubby site visited during field investigations, this succession is the first step towards the redevelopment of permafrost. However, it is unlikely that the re-development of permfrost will occur given recent and predicted future climate warming.

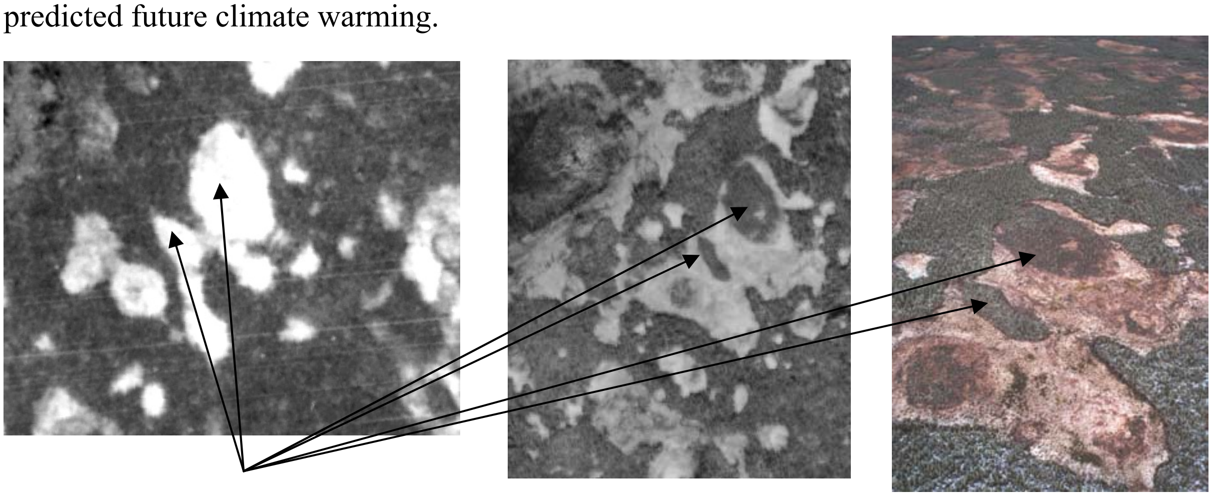

Figure 2. a) 1947 air photo, b) 2000 satellite image, and c) 2000 photograph. Shrub and tree-dominated features have developed since 1947 indicating drier conditions.

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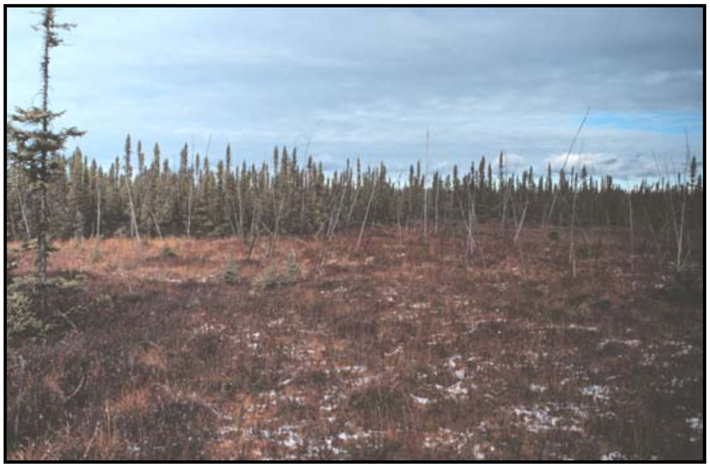
Appendix A

Photographs of sites investigated for recent permafrost thaw.

Trout Lake Site

Liard River Site



Wrigley Ferry Site

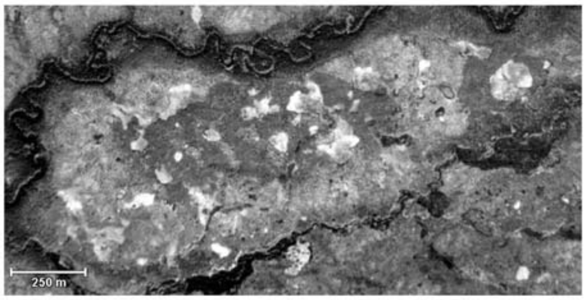
Eentsaytoo Lake Site

Appendix B

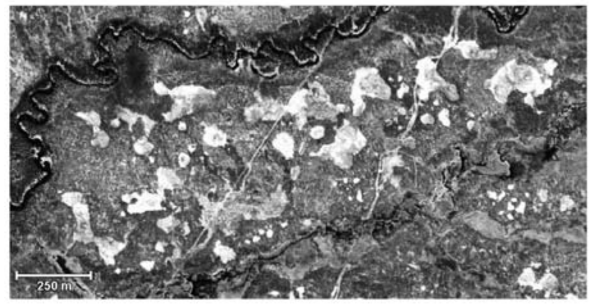
Aerial photographs, satellite images, and digitized images of thaw changes

Trout Lake Site (Site 2)

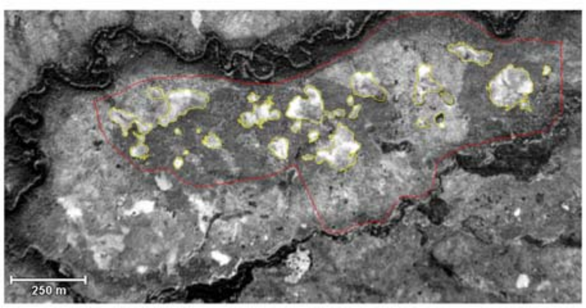
1950 air photograph



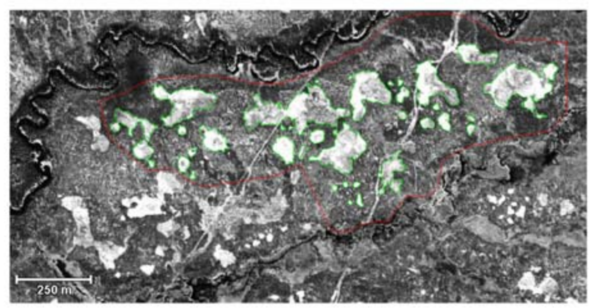
2000 Ikonos image



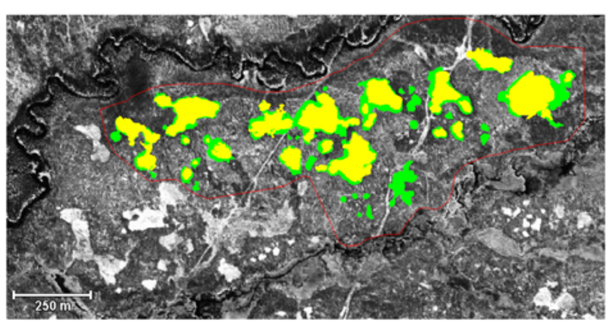
1950 air photograph with total peatland area studied (red) and thawed areas delineated (yellow)



2000 Ikonos image with total peatland area studied (red) and thawed areas delineated (green)

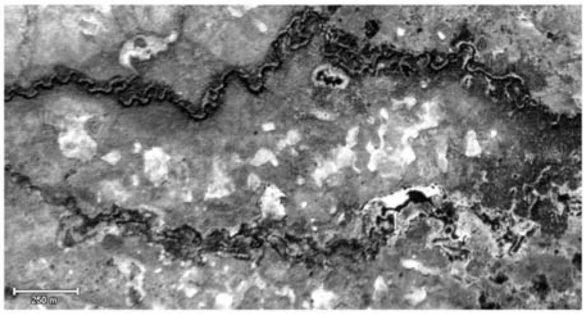


2000 Ikonos image with total peatland area studied (red), 1950 thawed area (yellow fill), and the new thaw occuring by 2000 (green fill)

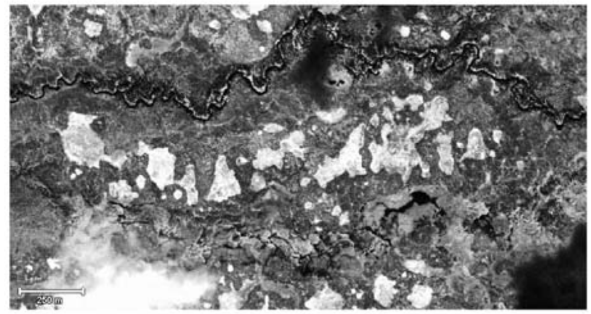


Trout Lake Site (Site 4)

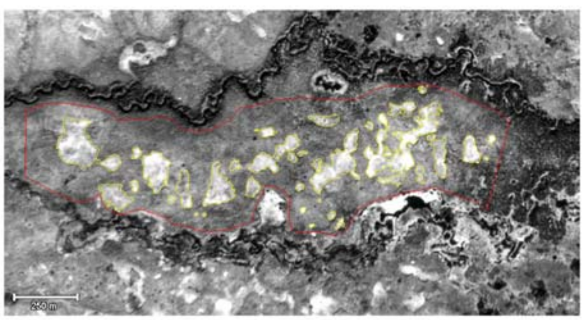
1950 air photograph



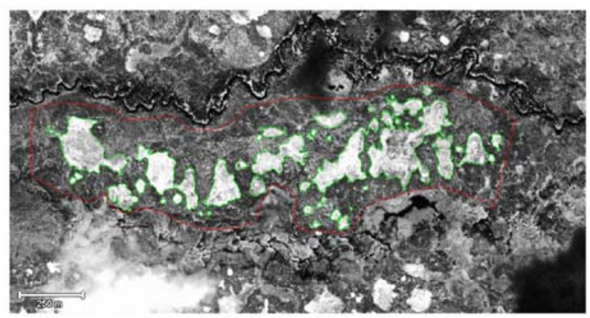
2000 Ikonos image



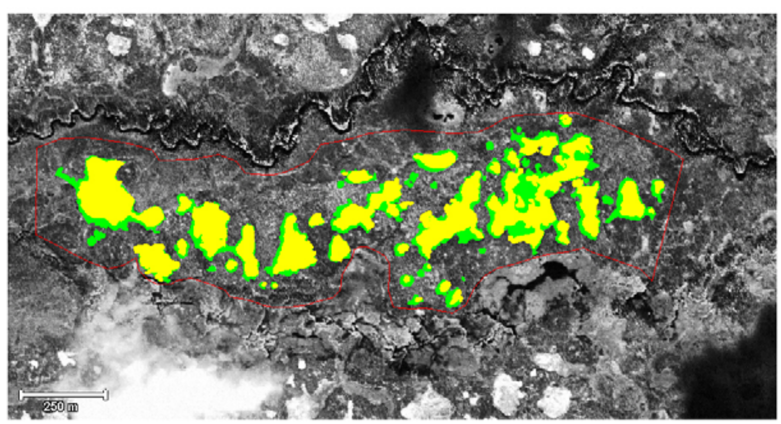
1950 air photograph with total peatland area studied (red) and thawed areas delineated (yellow)



2000 Ikonos image with total peatland area studied (red) and thawed areas delineated (green)

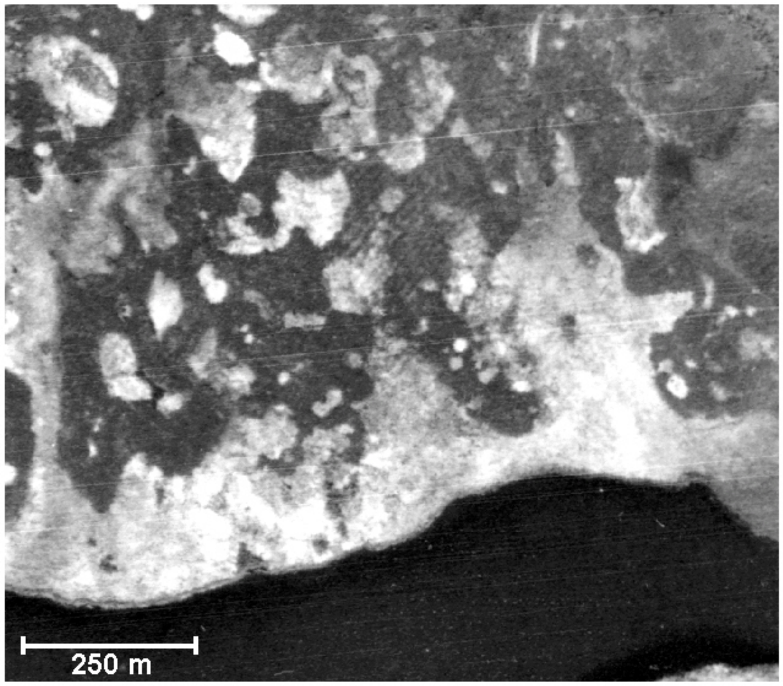


2000 Ikonos image with total peatland area studied (red), 1950 thawed area (yellow fill), and the new thaw occuring by 2000 (green fill)

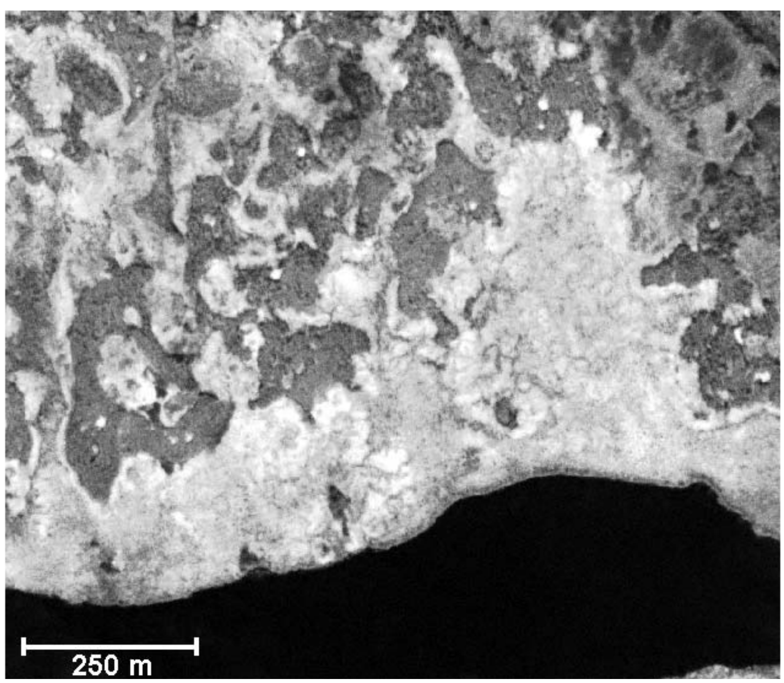


Liard River Site (Liard 1)

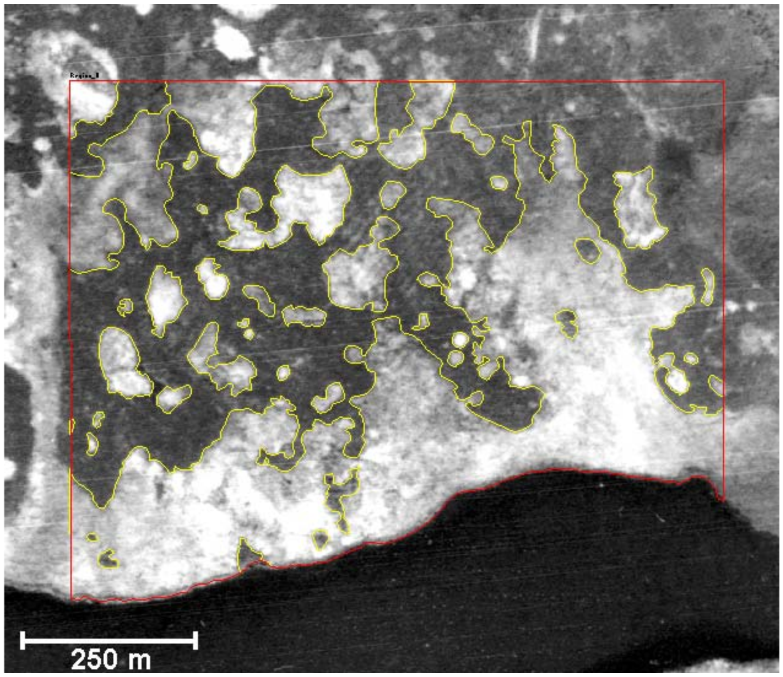
1947 air photo



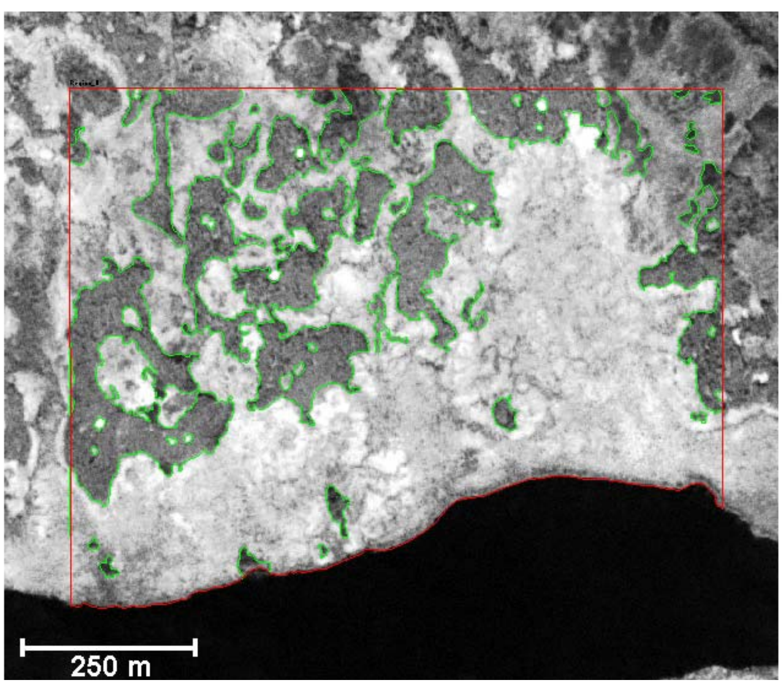
2000 Ikonos image



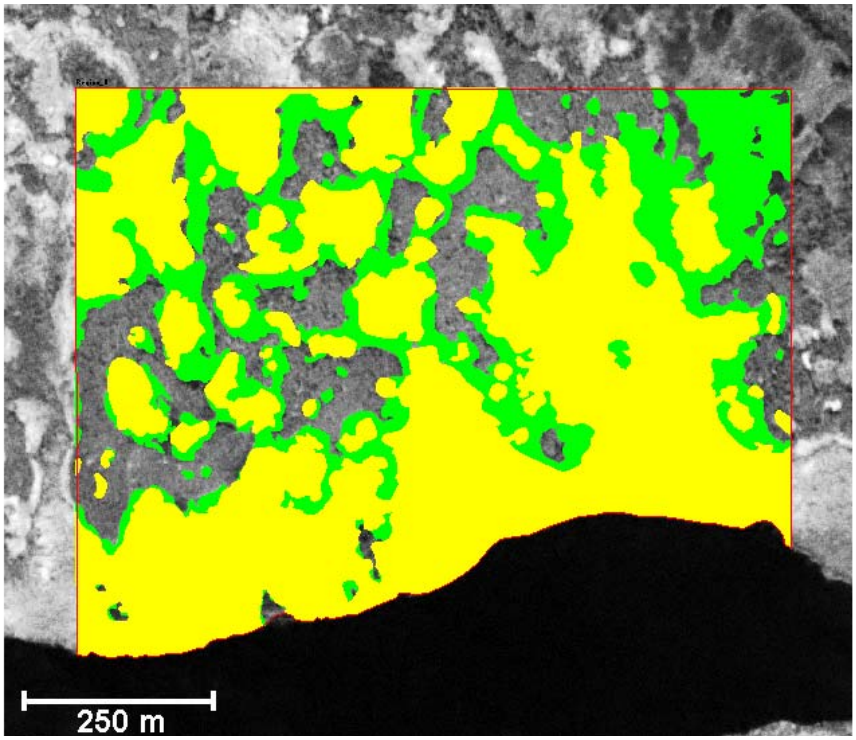
1947 air photograph with total peatland area studied (red) and peat plateau (frozen) areas delineated (yellow)



2000 satellite image with total peatland area studied (red) and peat plateau (frozen) areas delineated (green)

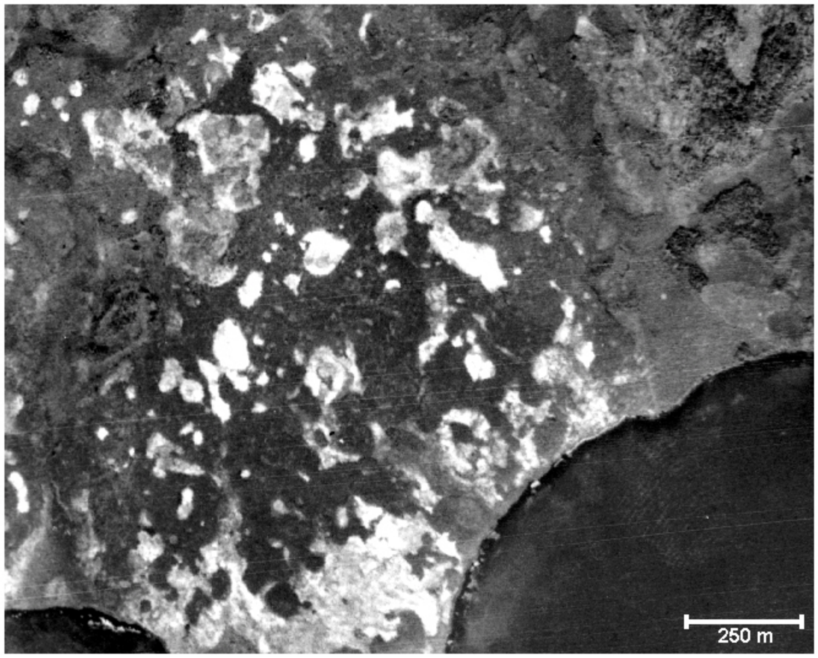


2000 Ikonos image with total peatland area studied (red), 1950 thawed area (yellow fill), and the new thaw occuring by 2000 (green fill)

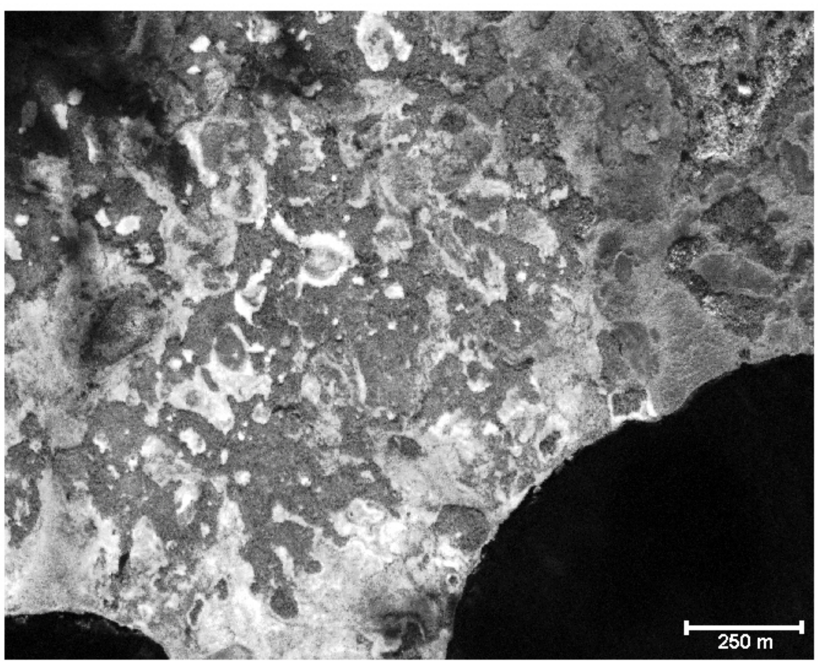


Liard River Site (Liard 2)

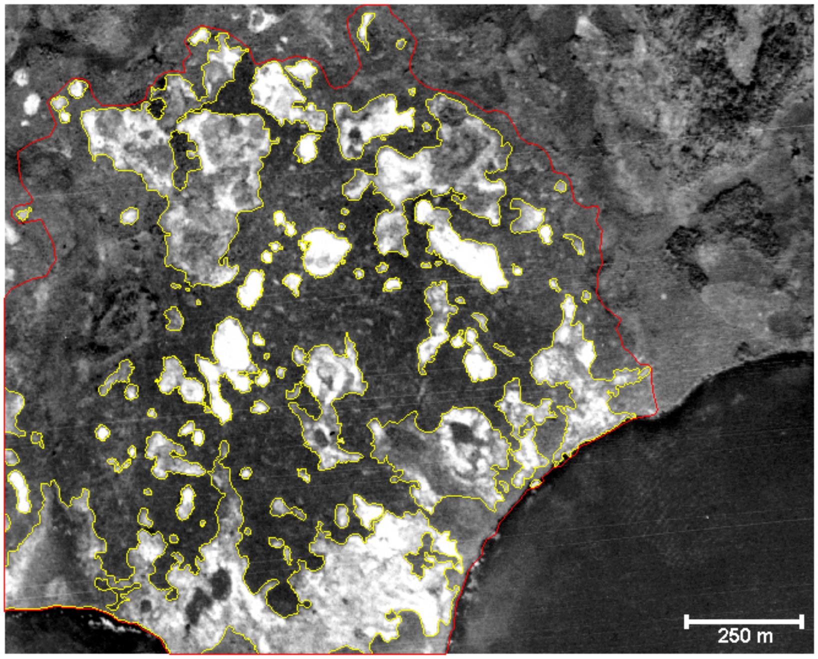
1947 air photo



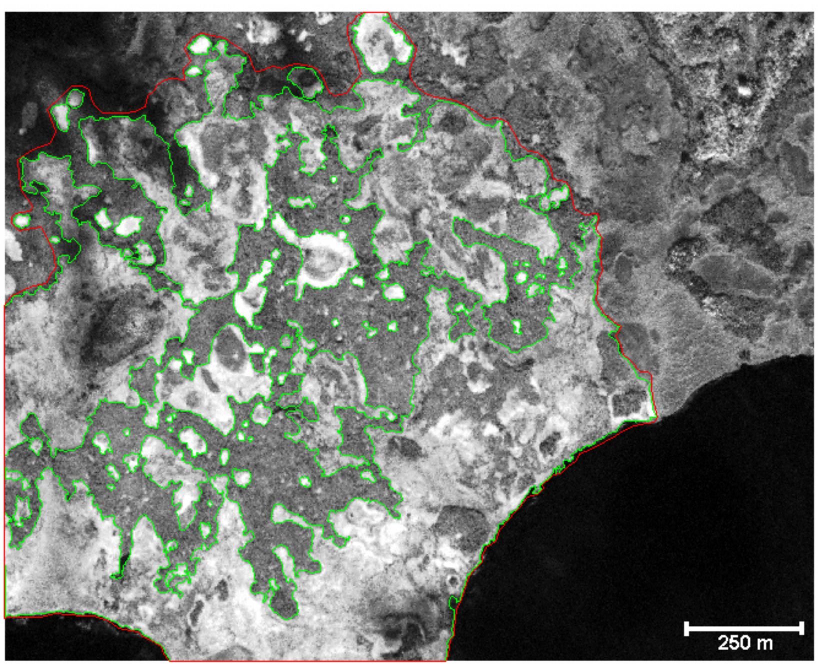
2000 Ikonos image



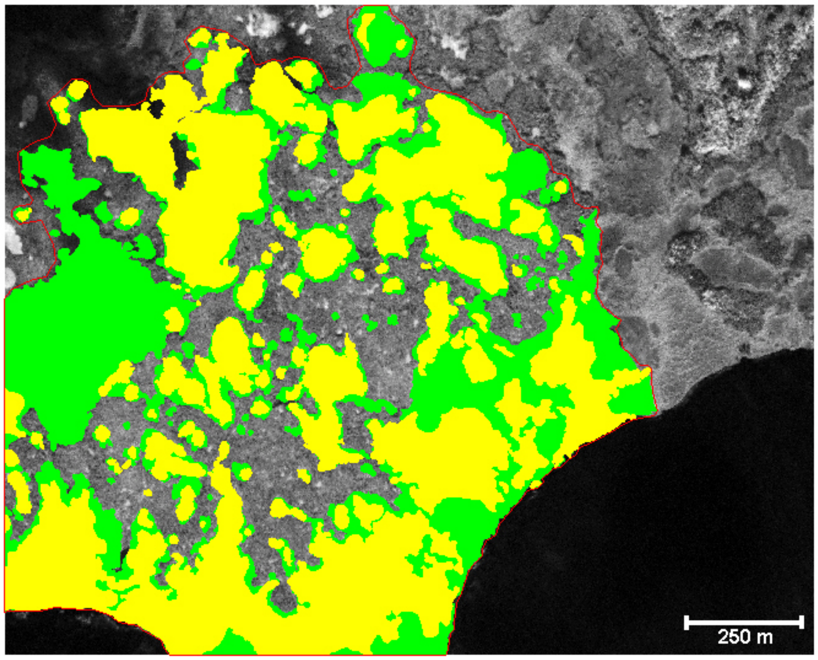
1947 air photograph with total peatland area studied (red) and peat plateau (frozen) areas delineated (yellow)



2000 satellite image with total peatland area studied (red) and peat plateau (frozen) areas delineated (green).

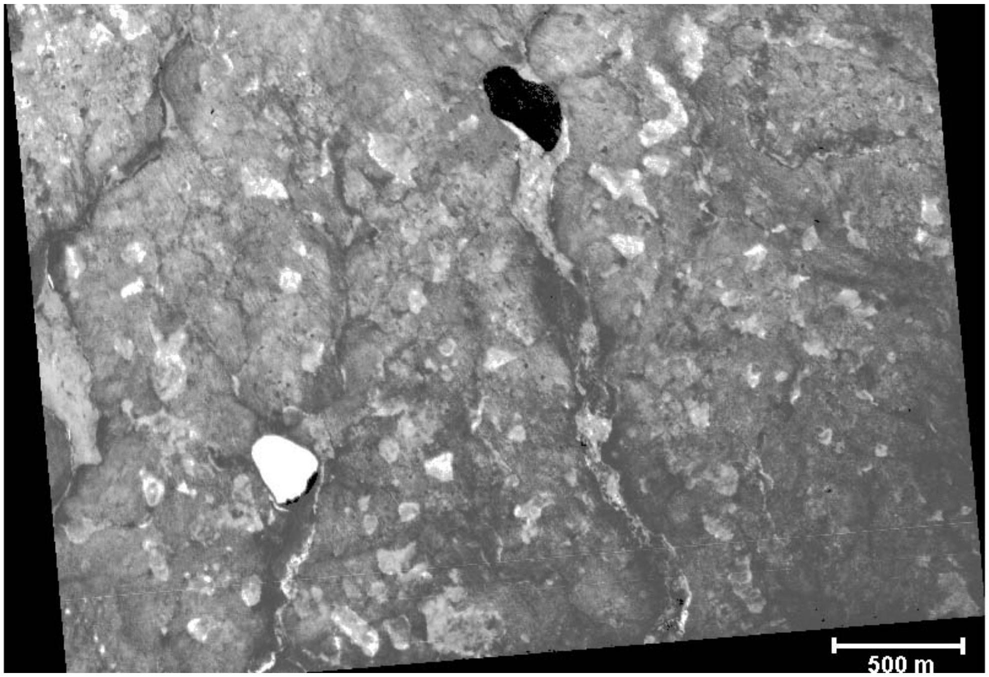


2000 Ikonos image with total peatland area studied (red), 1947 thawed area (yellow fill), and the new thaw occuring by 2000 (green fill).

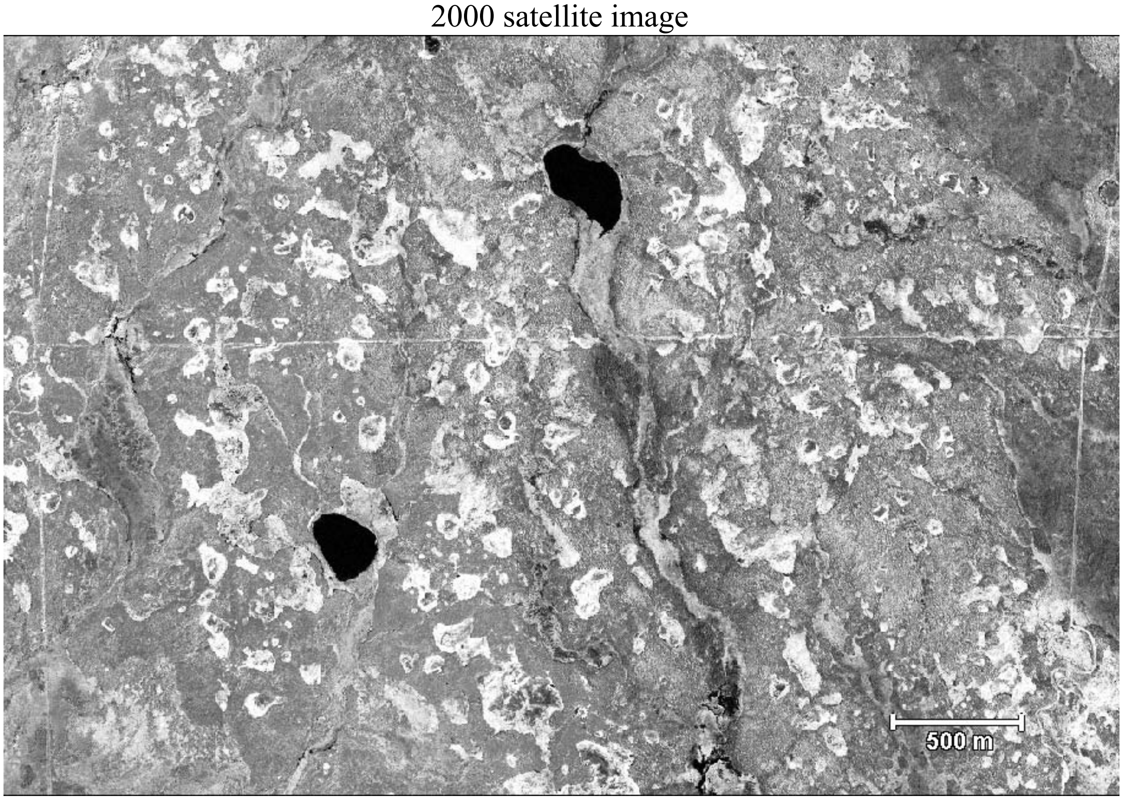


Wrigley Ferry Site

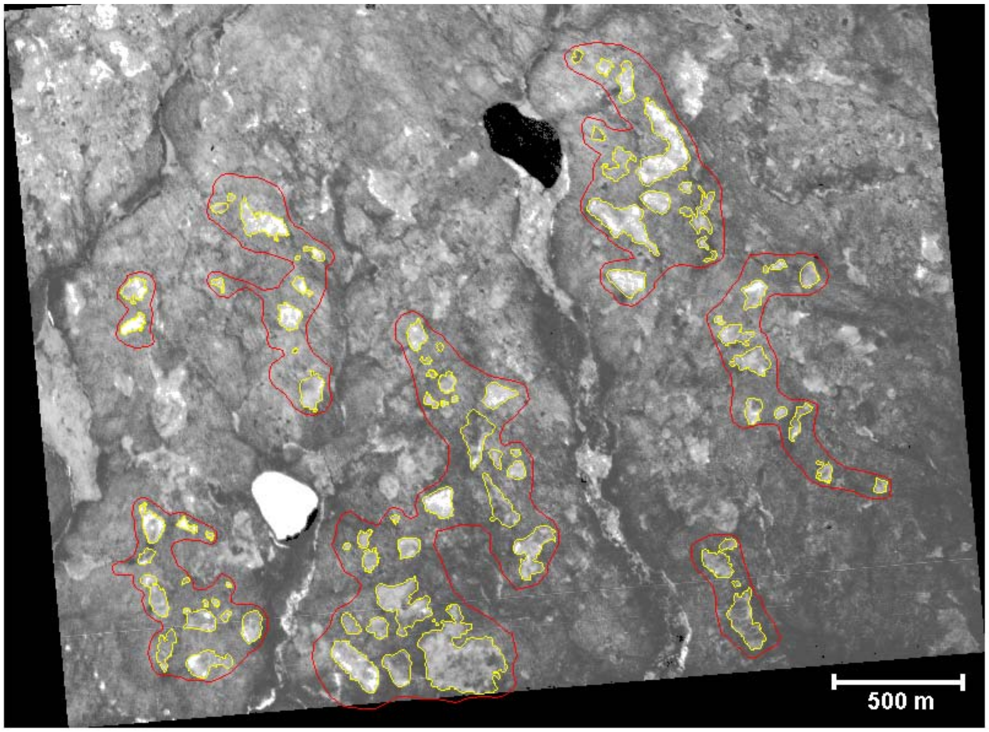
1945 air photo



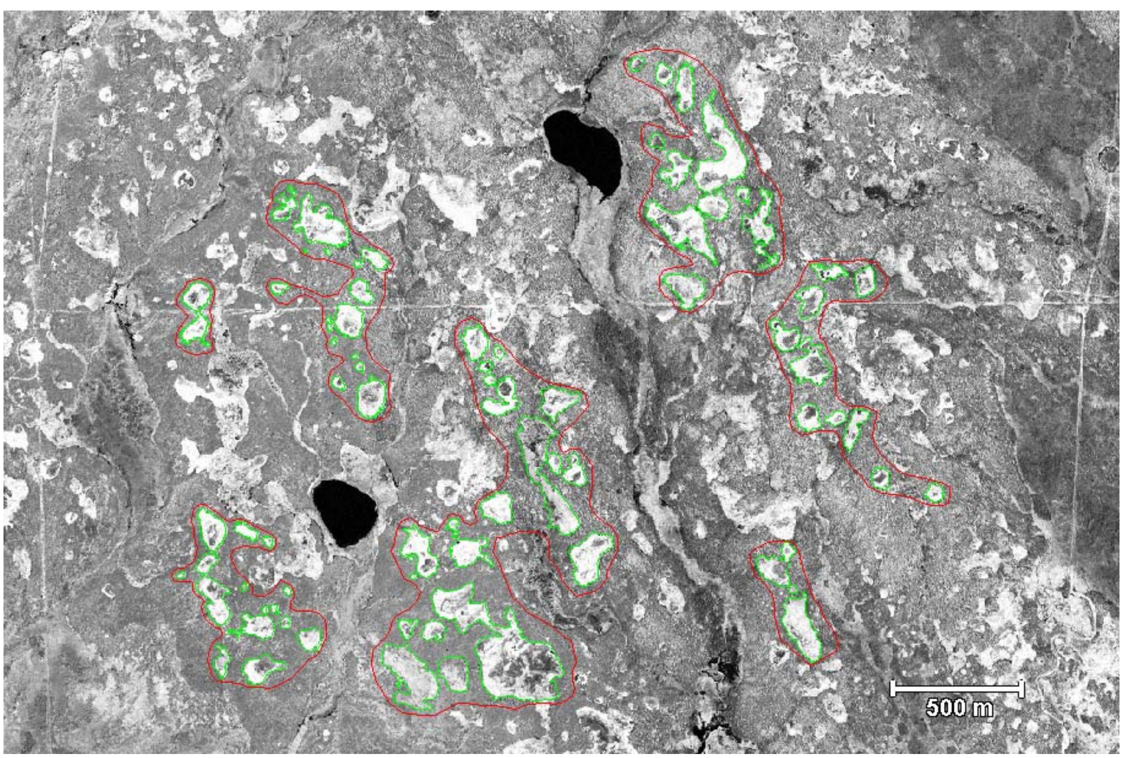
2000 satellite image



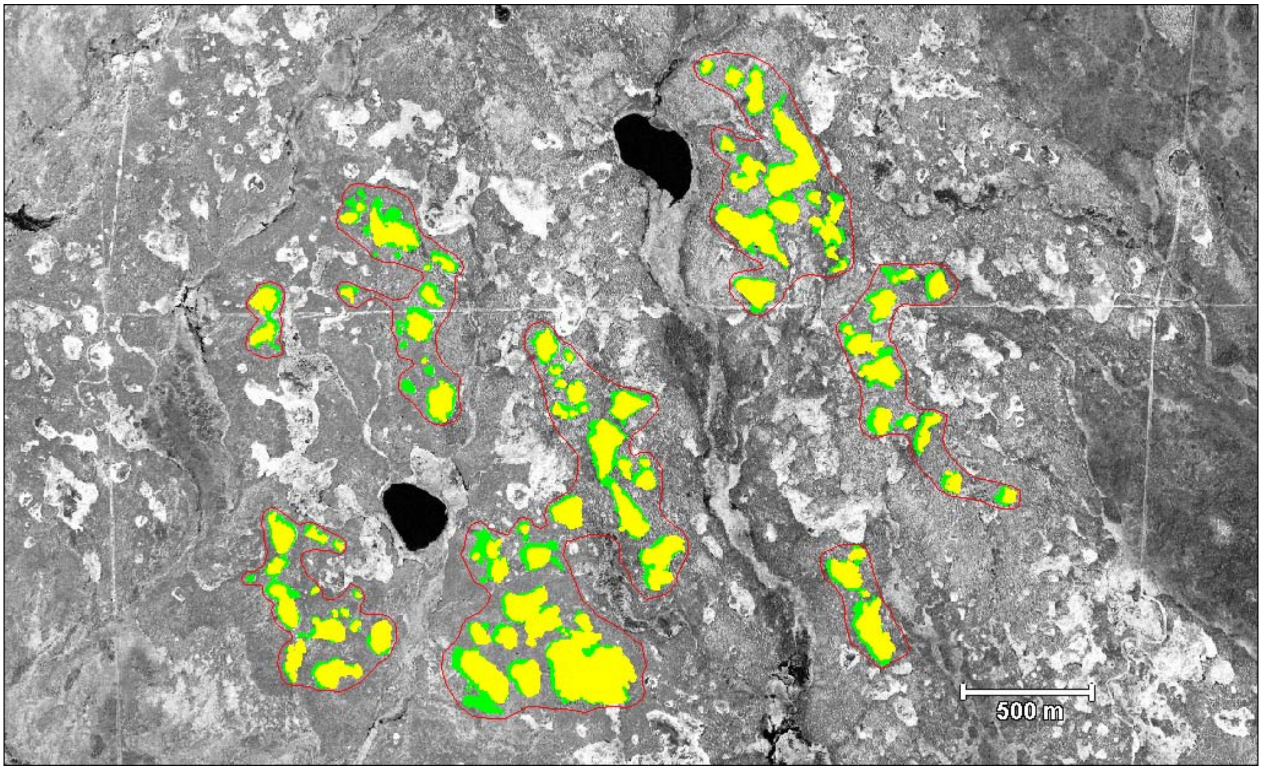
1945 air photograph with total peatland area studied (red) and peat plateau (frozen) areas delineated (yellow)



2000 satellite image with total peatland area studied (red) and peat plateau (frozen) areas delineated (green).

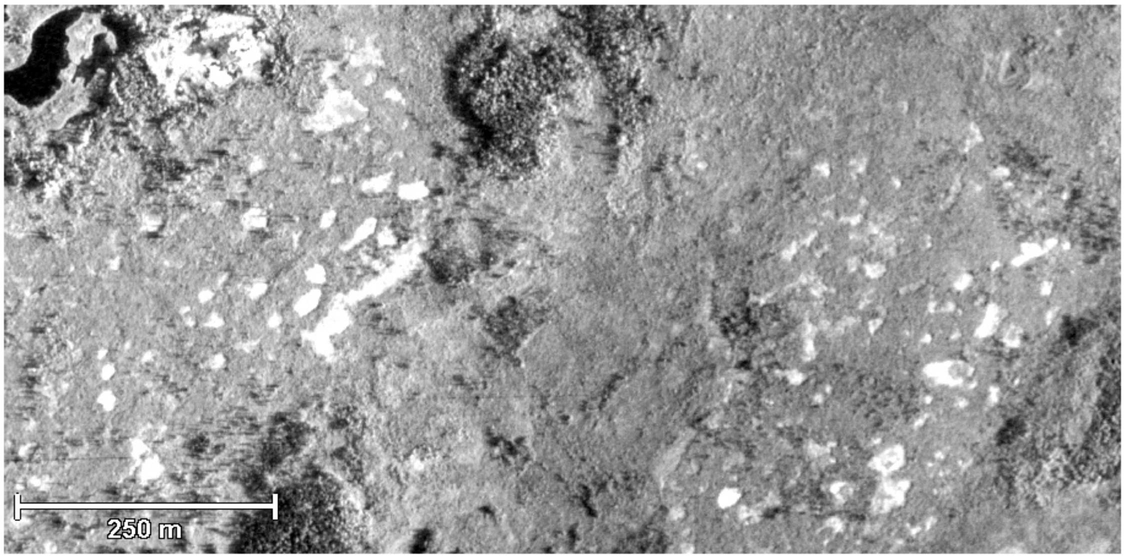


2000 Ikonos image with total peatland area studied (red), 1945 thawed area (yellow fill), and the new thaw occuring by 2000 (green fill).

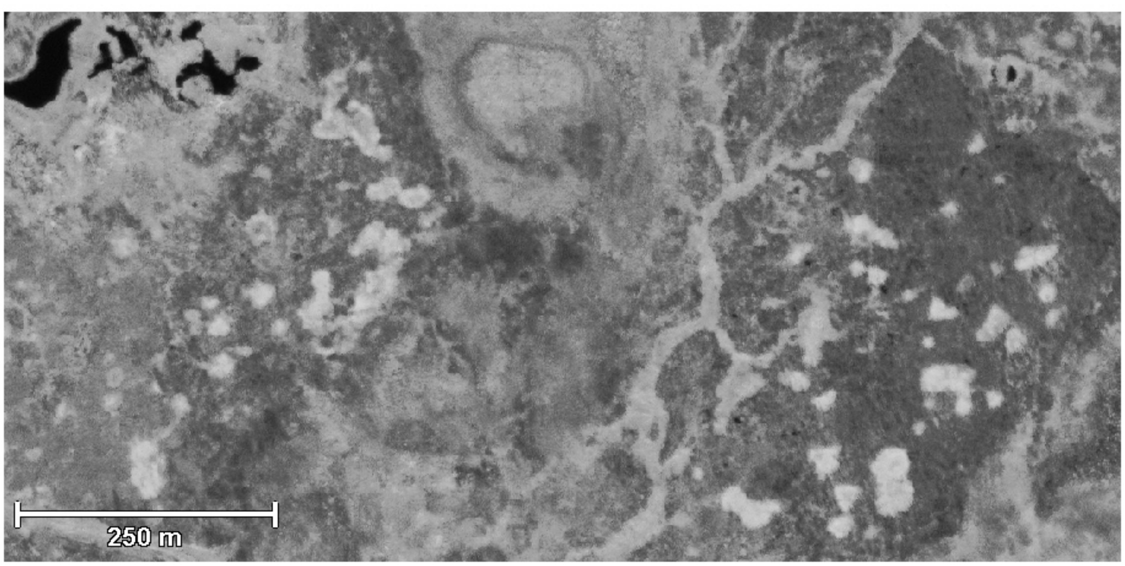


Eentsaytoo Lake Site

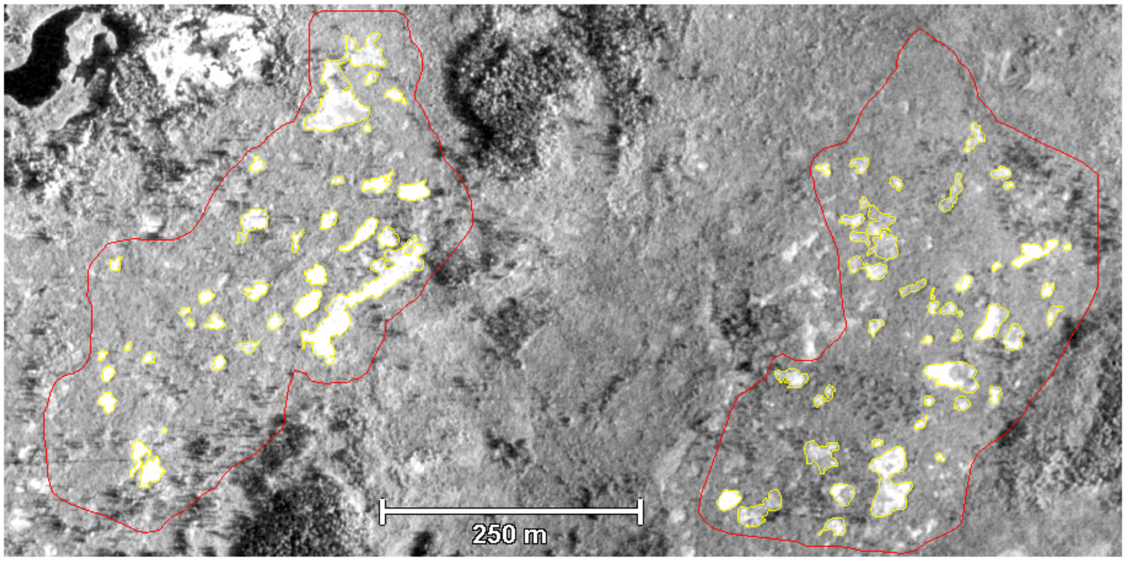
1948 air photo



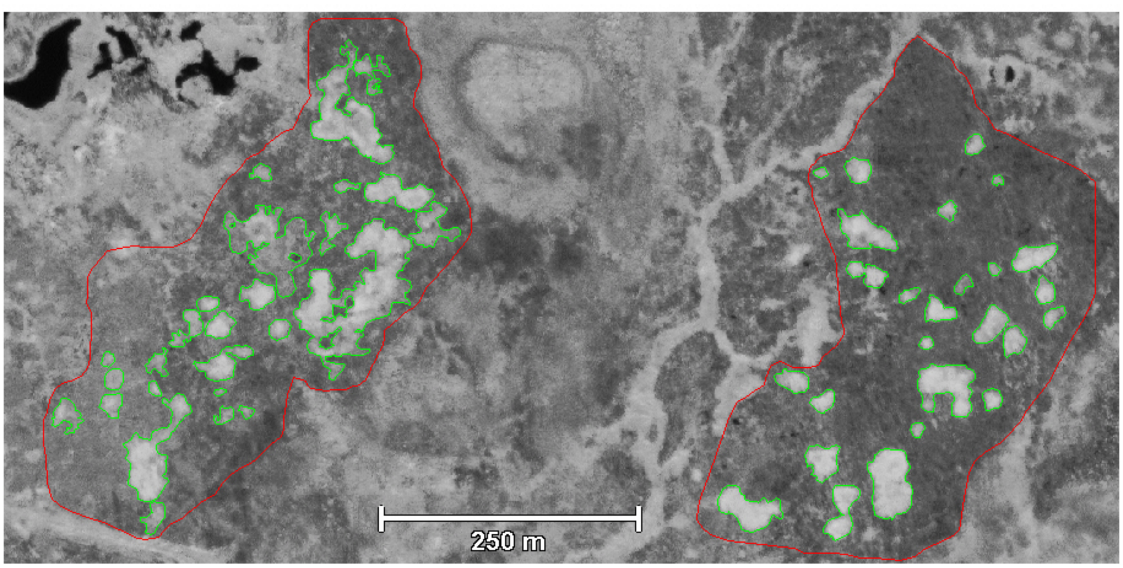
2000 Ikonos image



1948 air photo with total peatland area studied (red) and peat plateau (frozen) areas delineated (yellow).



2000 satellite image with total peatland area studied (red) and peat plateau (frozen) areas delineated (green).



2000 Ikonos image with total peatland area studied (red), 1948 thawed area (yellow fill), and the new thaw occuring by 2000 (green fill).