Role of vegetation and climate in permafrost active layer depth in arctic tundra of northern Alaska and Canada

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Abstract

The active layer is the top layer of permafrost soils that thaws during the summer season due to increased ambient temperatures and solar radiation inputs. This layer is important because almost all biological activity takes place there during the summer. The depth of active layer thaw is influenced by climatic conditions. Vegetation has also been found to have a strong impact on active layer thaw, because it can intercept incoming radiation, thereby insulating the soil from ambient conditions. In order to look at the role of vegetation and climate on active layer thaw, we measured thaw depth and the Normalized Difference Vegetation Index (NDVI; a proxy for total plant biomass) along a latitudinal temperature gradient in arctic Alaska and Canada. At each site several measurements of thaw and NDVI were taken in areas with high amounts of vegetation and areas with little to no vegetation. Results show that the warmest regions, which had the greatest levels of NDVI, had relatively shallow thaw depths, and the coldest regions, which had the lowest levels of NDVI, also had relatively shallow thaw depths. The intermediate regions, which had moderate levels of NDVI and air temperature, had the greatest depth of thaw. These results indicate that temperature and vegetation interact to control the depth of the active layer across a range of arctic ecosystems. By developing a relationship to explain thaw depth through NDVI and temperature, the possibility exists to extrapolate thaw depth over large scales via remote sensing applications.

1． Introduction

One of the most important features of permafrost-ridden regions is the active layer, which is the top layer of soil that thaws during the summer season. Almost all biological activity takes place in this section of the soil during the summer. The active layer is also an important layer in terms of hydrology because this is the only section of soil in which subsurface flow is not inhibited by freezing temperatures. The depth of the active layer is predominately controlled by ambient temperature, but is also influence by insulation layers such as snow cover and vegetation, slope, drainage, soil type, and water content (French 1988).

Arctic tundra vegetation production is strongly controlled by the regional climate, both directly and indirectly (Chapin and Shaver 1985). Studies have also showed that vegetation can influence the local physical environment (Ng and Miller 1975). For example, it has been shown that vegetation cover and organic matter can influence the depth of thaw in arctic environments (Ng and Miller 1975). Thaw depth is directly controlled by soil temperature, therefore the influences of vegetation on thaw depth must be the result of vegetation affecting the soil thermal retimes through insulation and microclimatic variations.

In arctic Alaska, summer temperature decreases as with latitude. The dominant vegetation also shifts also this latitudinal gradient (Walker 1998). Since these two properties both play a role in determining thaw depth, it may be expected that thaw depth also changes with latitude. In this study I attempt to dissect the interactions between climatic conditions and biotic factors in arctic tundra vegetation. I try to determine what factors explain variation in the vegetation biomass and thaw depth across a climatic gradient in arctic Alaska.

2. Study Sites

Six sites were selected along an arctic climate gradient that ranges from the North Slope of Alaska, USA to Banks Island, Northwest Territories, Canada (Figure 1).

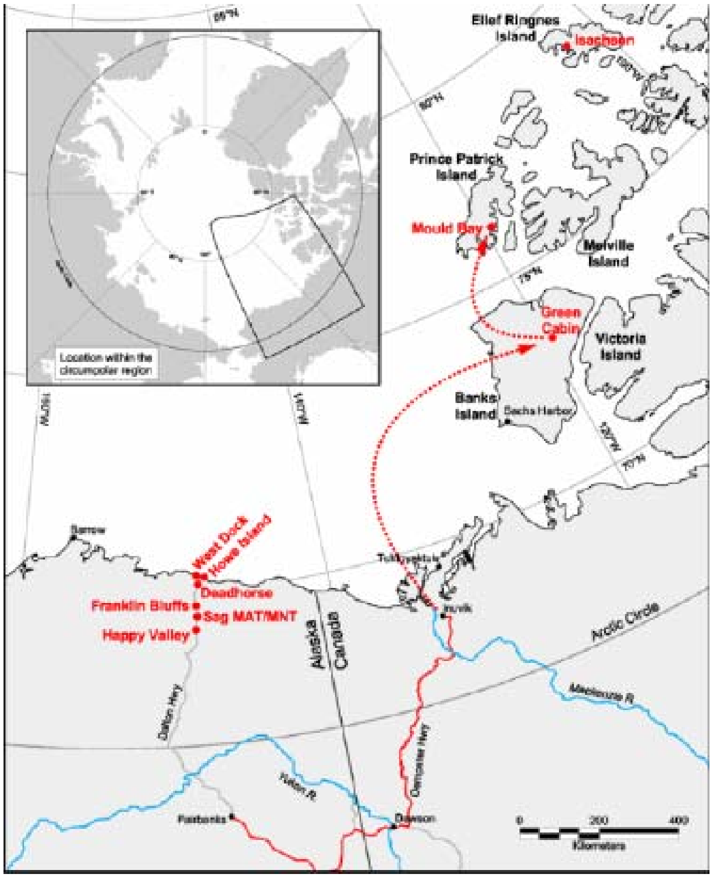

Fig. 1. Studies sites in arctic Alaska and Canada.

These sites range in latitude from N 69° 08’ 49.1” to N 73° 13’ 13.1”. The Arctic can be divided into five bioclimatic Subzones, based on climate and vegetation (Walker 1998). The sites used in this study occur in subzones C, D, and E, with two sites present in each Subzone (Table 1).

Table 1. Physical properties of the sites used in this study.

Site	Bioclimatic Subzone[1]	Coordinates		Summer Warmth Index (°C)
Green Cabin	C	N 73° 08’ 13.1”	W 119º 33’ 1.8”	18.83
Howe Island	C	N 70° 18’ 54.6”	W 147° 59' 37.0"	9.3
Franklin Bluffs	D	N 69° 40’ 29.5”	W 148° 41' 35.0"	27.01
Sagwon MNT	D	N 69° 26’ 00.3”	W° 148 40' 12.3"	28.89
Sagwon MAT	E	N 69° 25’ 32.6”	W° 148 41' 33.6"	28.89
Happy Valley	E	N 69° 08’ 49.1”	W° 148 50' 53.1"	30.2

[1] As designated by (Walker 2000)

3. Methods

At each site three sampling plots were chosen based on representative vegetation. Each plot contained two types of vegetation cover: frost boils and inter-boil areas. Frost boils represented areas of low vegetation cover. Frost boils are a type of patterned ground that lacks a border of stones (Everdingen 2002). Frost boils are generally 1 to 3 meters in diameter and have less vegetative cover than the surrounding inter-boil area (Washburn 1956, 1980). The area surrounding the frost boils, also known as the inter-boil area, represented areas of high vegetation cover.

Within each type of cover at each site, four measurements of thaw depth were taken (Fig. 2). This was done by using a metal probe. Measurements were taken during the summer of 2002 at Happy Valley, Sagwon MNT, Franklin Bluffs and Howe Island ,and during the summer of 2003 at Sagwon MAT and Green Cabin.

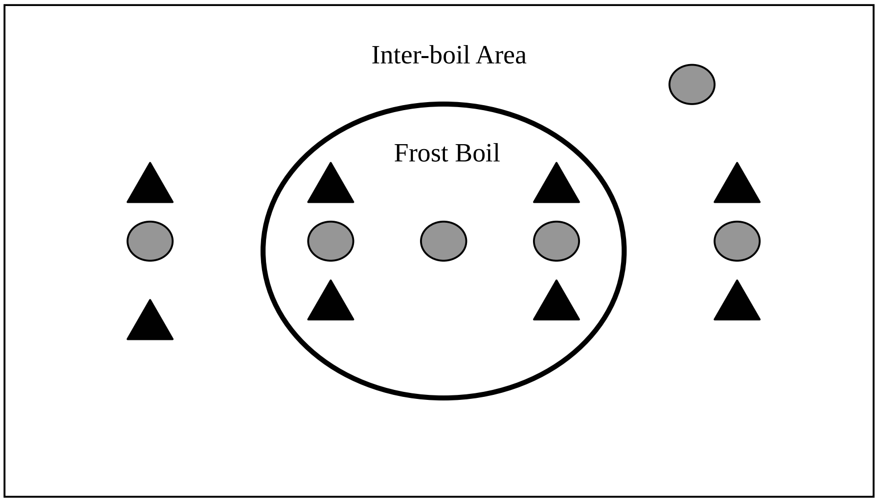

Fig. 2 Diagram of sample set-up for each plot. Gray circles represent areas where NDVI was measured with a portable spectroradiometer. Black triangles represent locations where thaw depth was measured with a metal probe.

The Normalized Difference Vegetation Index (NDVI) is a measurement of plant “greenness” (Citation ????). This index has been successfully used as a proxy of aboveground biomass in arctic ecosystems (Shippert *et al.* 1995), (Jia *et al.* 2003), Riedel *et al.* in press). NDVI was estimated with a spectroradiometer (PS-II portable field spectrometer made by Analytical Spectral Devices, Inc.) that measures the reflectance of radiation emitted from a surface over a variety of wavelengths. NDVI is calculated via the following equation

$$NDVI = (NIR - R) / (NIR + R) \quad (1)$$

where NIR = the spectral reflectance of near infrared radiation (wavelength of 0.725 to 1.1 μm), and R = the spectral reflectance of red radiation (wavelength of 0.58 to 0.68 μm). At each plot three measurements were taken at low vegetation cover and at high vegetation cover.

The summer warmth index (SWI) is the sum of monthly mean air temperatures greater than 0°C. The value gives information on the total warmth for the entire growing season. The air temperature data used to calculate SWI was obtain from temperature data loggers at each site. The values of SWI are annual averages over time periods of available data. This index is correlated to thawing degree days (Walker *et al.* in press).

4. Results & Discussion

The climate in the Arctic becomes colder and more severe with increasing latitude, as suggested by decreases in SWI (Table1). The exception is for the Green Cabin site, which has a higher SWI than Howe Island, even though it is further north. This may be due to the lack of long-term climate data available for this region. SWI for Green Cabin was calculated from three years of data, including 1998, which is one of the warmest years on record (Mann *et al.* 1998). Additionally, there are other factors that influence summer climate, including solar radiation input, wind (Chapin *et al.* 1985), and proximity to the ocean.

Based on this information, it is expected that the depth of active layer thaw would decrease with increasing latitude. The reduced solar radiation input would prevent the melting of the top layer of permafrost. However, this simple conclusion does not hold true for the entire climate gradient (Fig 3). Thaw depth increased with latitude through Subzone D, after which it begins to decrease. This leads to the conclusion that there is something else other than climate controlling thaw depth in the southern portion of the climate gradient. The depth of thaw of the active layer was also greater on frost boils than inter-boil areas (Fig. 3). The difference between the frost boils and inter-boil areas appears to be greatest in Subzones D and E, and least in Subzone C. This suggests that within the sites in Subzone D and E something other than climate is controlling thaw depth.

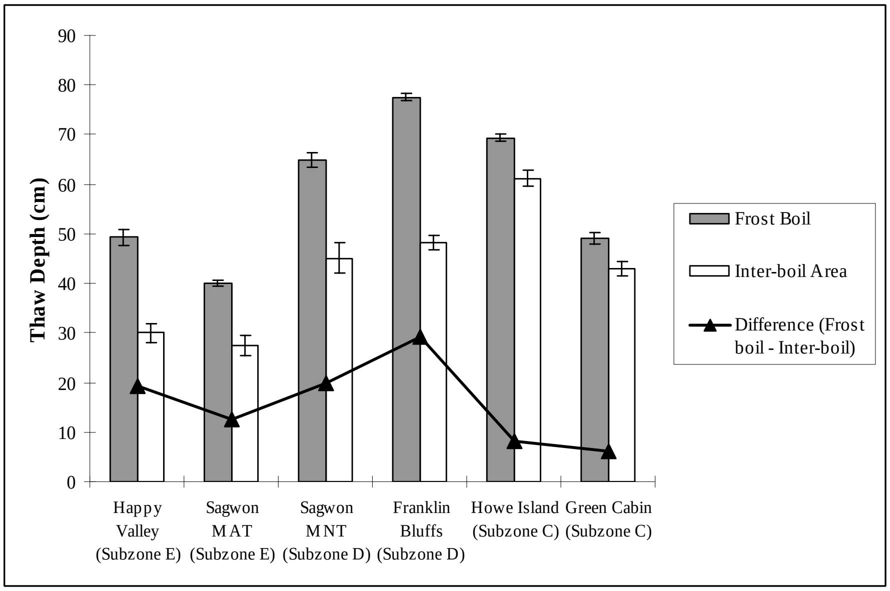

Fig. 3 Active layer thaw depth of frost boils and inter-boil areas at six study sites along an arctic climate gradient (mean ± 1 SE). The line represents the difference in thaw depth between frost boils and inter-boil areas at each site.

NDVI was lower on frost boils than in inter-boil areas (Fig. 4), which shows that the aboveground biomass on the frost boils is lower than on the inter-boil areas. This difference in vegetation is caused by higher rates of frost heave in the frost boils (Walker *et al.* in press). The differential frost heave associated with frost boils can disrupt the vegetation trying to establish on these surfaces by destroying the root systems (Jonasson *et al.* 1992). Overall the difference in NDVI between the frost boils and inter-boils is greater in the more northern sites (Subzone C). This shows that the plant communities in Subzone C (north) are disrupted more by frost heave than those in Subzone E (south).

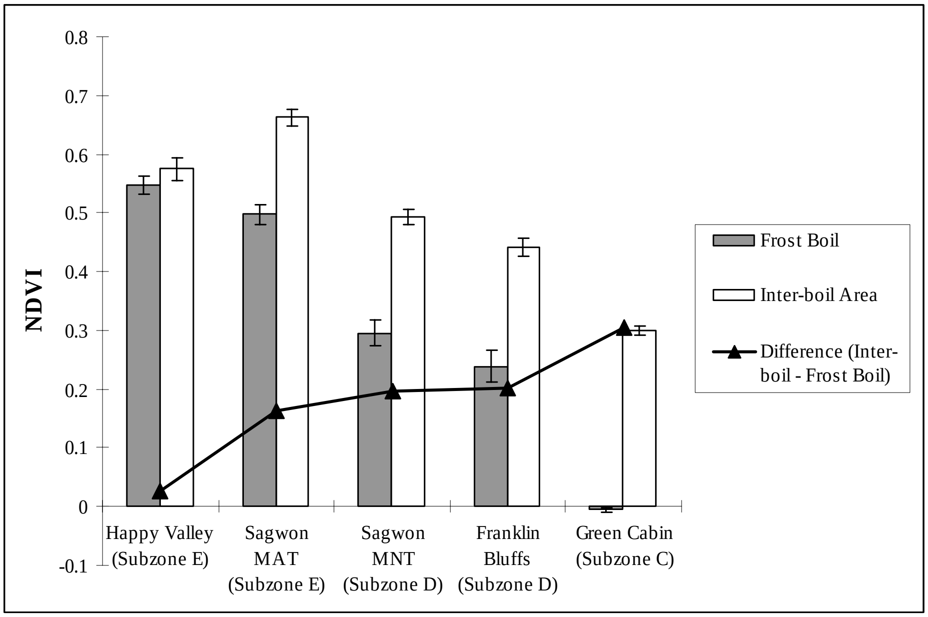

Fig. 4 NDVI of frost boils and inter-boil areas at five study sites along a climate gradient (mean ± 1 SE). The line represents the difference in NDVI between the frost boil and inter-boil at each site.

The presence of vegetation is known to have an insulating effect on active layer thaw (Ng and Miller 1975). Areas with greater vegetation cover tend to have shallower active layers. In Subzones D and E vegetation is occurring on both the frost boils and inter-boil areas. It is therefore possible that that presence of vegetation at these four sites is influencing the active layer thaw dynamics. NDVI is higher in the inter-boil areas than on the frost boils in Subzones D and E, and there is a strong difference in the thaw depth between these two locations. The difference in NDVI between frost boils and inter-boil areas in Subzone C is greatest than in the more southern subzones, but the difference in thaw in the least. This is likely due to the fact that the presence of vegetation does not have a strong influence in the more northern sites, and the climatic conditions are controlling thaw depth there.

At the site scale, there are large differences between thaw and NDVI on and off the frost boils. This further demonstrates the effect of vegetation on thaw depth (Fig. 3 and 4). In order to determine the degree of control of site-specific variation in NDVI on thaw depth, several regression analyses were performed. The initial analysis regressed thaw depth against latitude (Fig. 5).

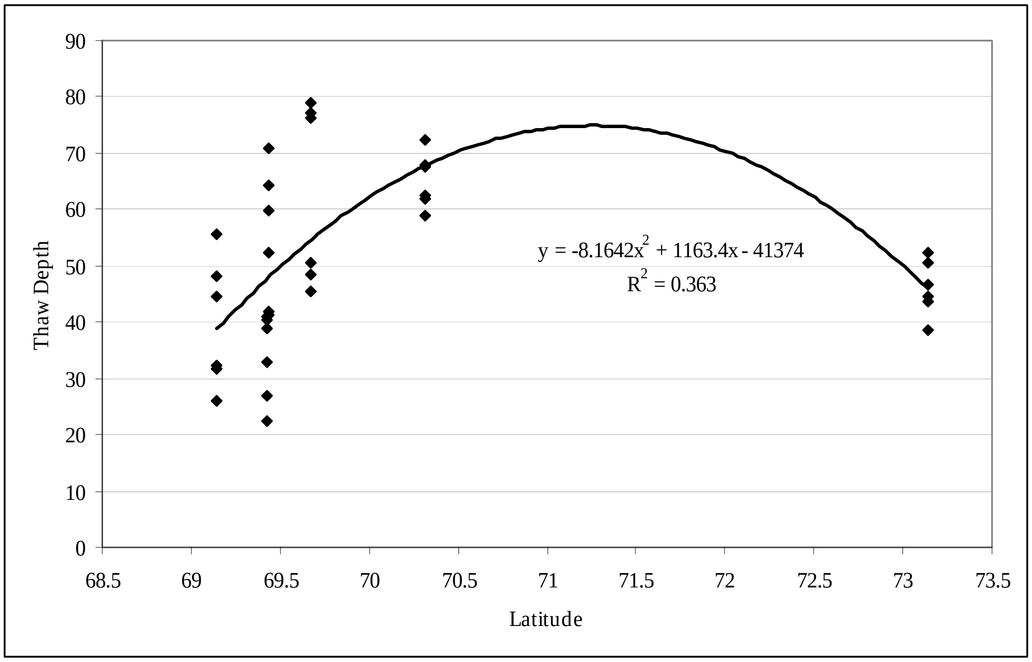

Fig. 5 The relationship between thaw depth and latitude.

This relationship explains 36% of the variance of thaw depth. By using latitude as the independent variable, we are combining the influence of both vegetation and climate, but at a regional scale. As seen in Fig. 5 there is a lot of variability in thaw depth at each site. This could be explained by the variability in the vegetation at each site. The first step in determining this involves establishing a relationship between NDVI and latitude at the regional scale (Fig. 6). Any variance seen in this graph is due to site-scale variance in vegetation.

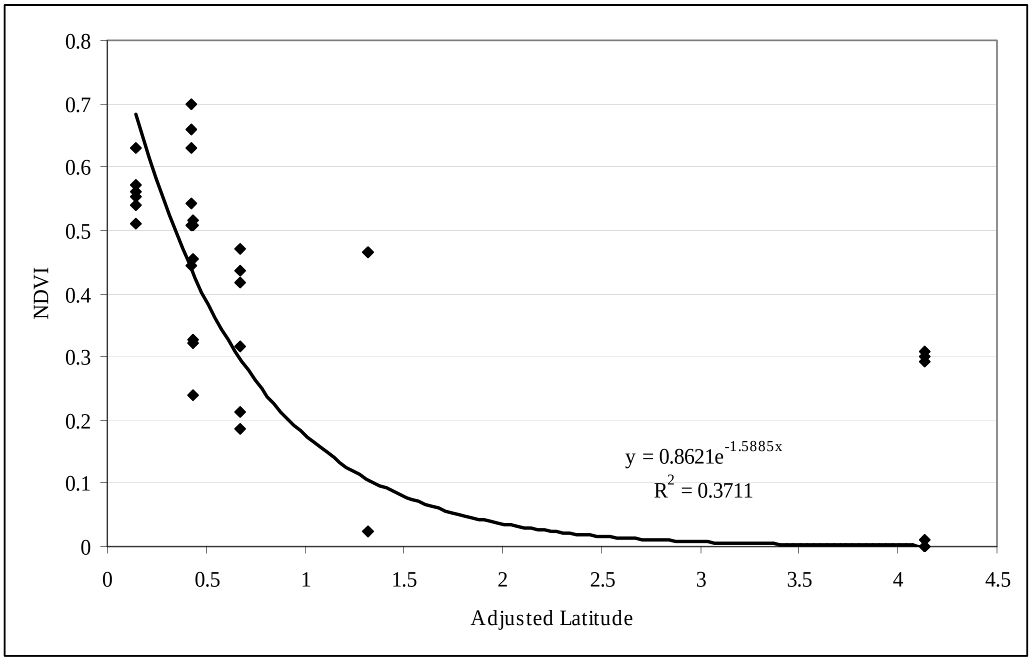

Fig. 6. The relationship between NDVI and adjusted latitude (distance of the site north from 69°N in decimal degrees).

The final step was to determine the relationship between the residual NDVI and residual thaw depth, which explains 67% of the site scale variability in thaw depth (Fig. 7). Residual NDVI and thaw depth is the amount that each site varies from the expected values base on the regressions.

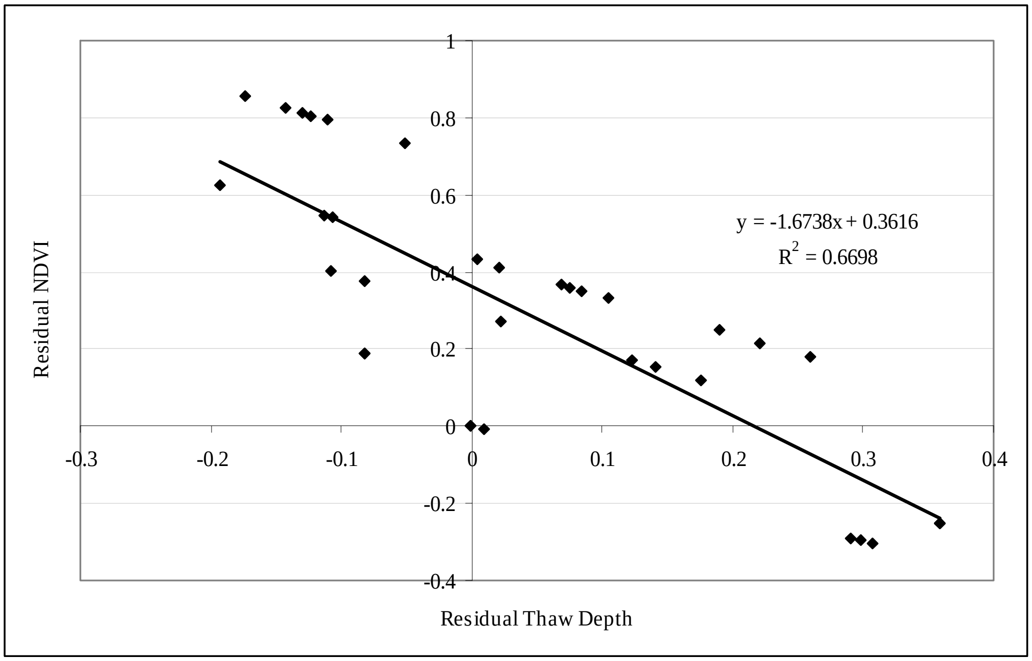

Fig. 7. The relationship between residual NDVI and residual thaw depth

The variability explained in this relationship is 67% of the variability not explained in the relationship between NDVI and latitude (Fig. 5). The combination of these two relationships, regional and site scale, accounts for 79% of the variance seen in thaw depth.

These analyses show us that vegetation plays a strong role in controlling thaw depth at various scales. Overall, the role of vegetation in controlling thaw depth declines with increasing latitude (Fig. 8). This is because vegetation decreases with latitude (Fig 6) and because the climate in the northern most reaches of the arctic are colder, resulting in shallower thaw depth.

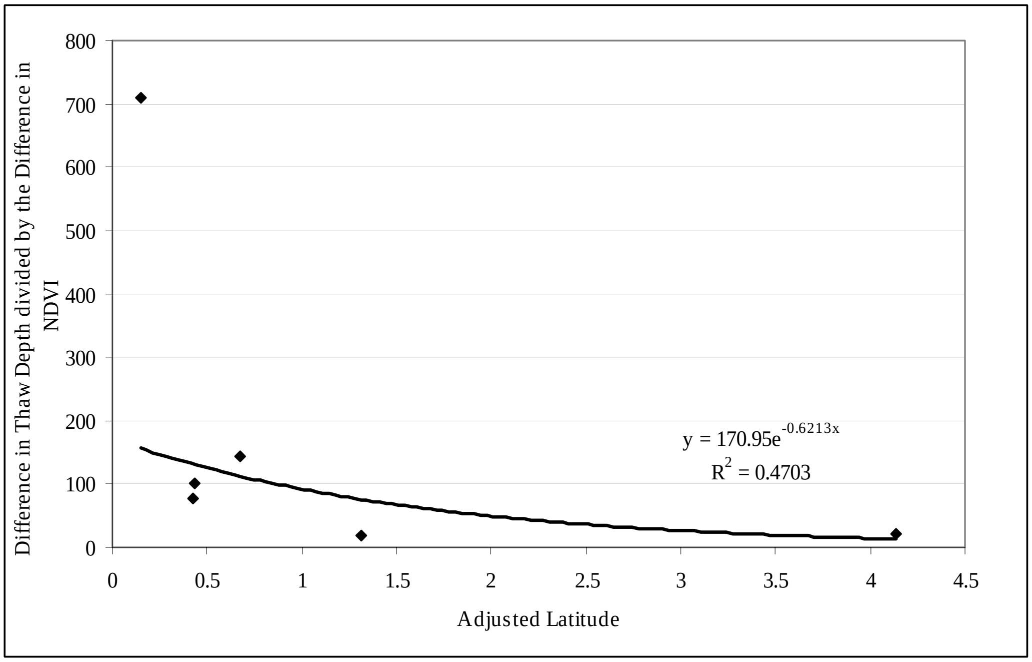

Fig. 6. The relationship between the difference in thaw depth (between frost boils and inter-boil areas) divided by the difference in NDVI (between frost boils and inter-boil areas) and adjusted latitude (distance of the site north from 69°N in decimal degrees).

5. Conclusions

It is known that vegetation cover influences active layer thaw depth. This study shows the degree to which vegetation controls thaw depth under differing climatic conditions. The results of the study imply that in the warmer permafrost-ridden areas with high vegetation cover, thaw depth is not solely controlled by climate. In the colder areas that lack vegetation, thaw depth is more strongly related to climate conditions. Efforts are currently underway to monitor the active layer thickness at sites across the entire Arctic (Note: insert CALM citation). In the event that monitoring is not taking place in a specific location, it may be possible to derive the depth of thaw using remote sensing data of air temperature and vegetation cover. Remotely sensed data exists for both of these factors. The relationships established in this paper will be strengthened by additional data, including NDVI and thaw depth from Subzones A and B in order to have a dataset for the complete Arctic climate gradient.

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