UNIVERSITY OF CAMBRIDGE

Remote sensing characterization of the location and dynamics of the arctic treeline

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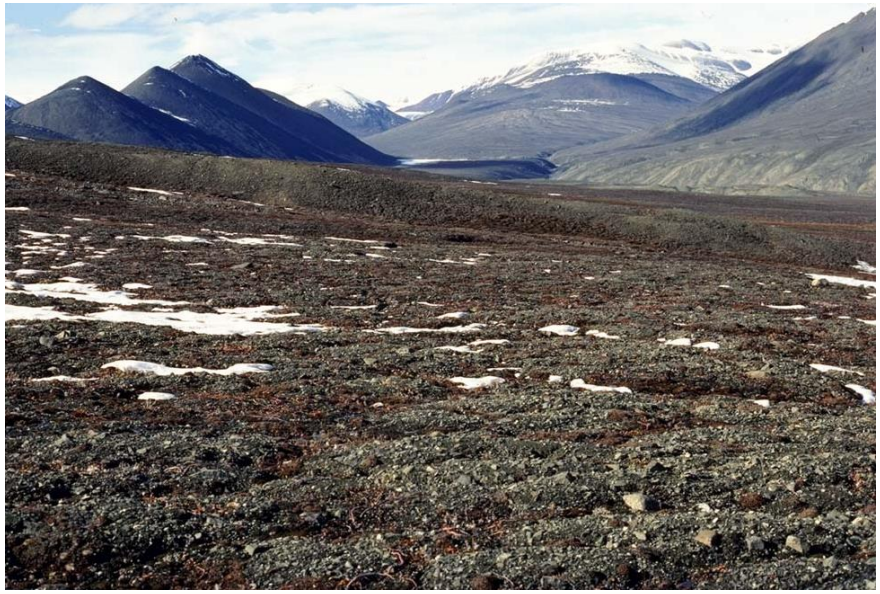
The Boreal Forest – The Arctic Tundra

- Earth's greatest vegetation **transition zone**
- ***Gradients*** in carbon flux, water flux and albedo

→***Gradients*** in tree cover/density, tree size/shape, tree growth

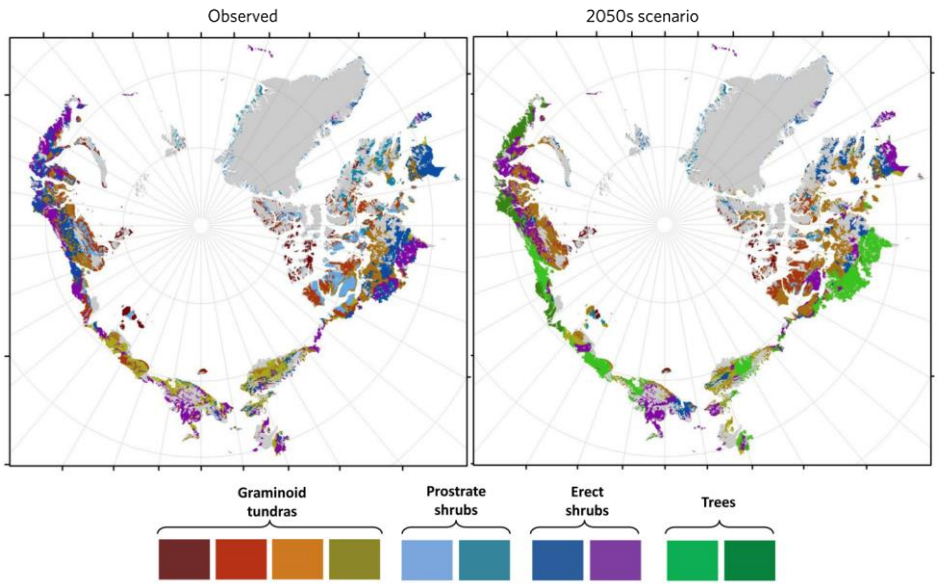
en.wikipedia.org

bio.maimi.edu



Changes in the Arctic Treeline

- **Interface positioning**
  - general trend & model predictions: ***northward shifts*** (tundra replaced by boreal forests)
- **Species composition of the taiga**



Changes in the Arctic Treeline

- **Implications**: CO_2 absorption ↑

  CH_4 emission ↓

  Albedo ↓

  Alternations of the hydrological cycle

Changes in the Arctic Treeline

- **Treeline movement:** regional differences
  - static / dynamic equilibrium (Masek 2001)
  - increase in biomass w/o moving (Payette et al., 2001)
  - northward (Gamache & Payette 2005; Esper 2004)
  - southward (Vlassova 2002; Crawford 2003; Montesano et al. 2009)
- ***Lacking***: consistent data on the location & dynamics of the treeline ***at a circumpolar scale***

Changes in the Arctic Treeline

- **Explanatory factors:**

  - local climate
  - topography
  - evolutionary history
  - soil development
  - hydrology
  - treeline configuration
  - human activities, etc.

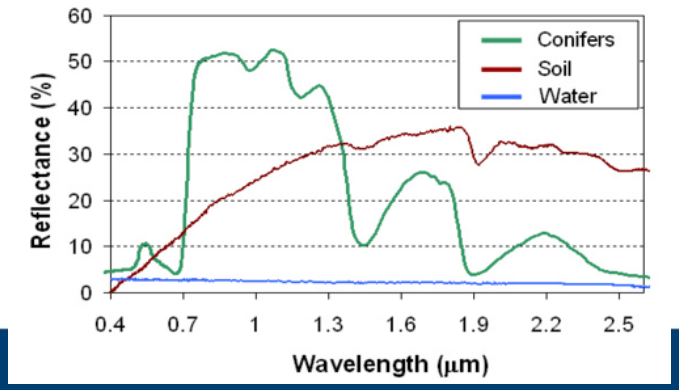
livescience.com

Objectives

- Use coarse- to moderate- resolution satellite image products to study the configuration of the **Arctic treeline** and its variation over the past few decades.

Delineation of the Arctic Treeline

- **Spectral-based detection:** gradients on vegetation parameters (e.g. VCF, NDVI)
- **Hyperspectral imagery:** vegetation spectral profiles
- **Very-high-resolution imagery:** individual tree identification



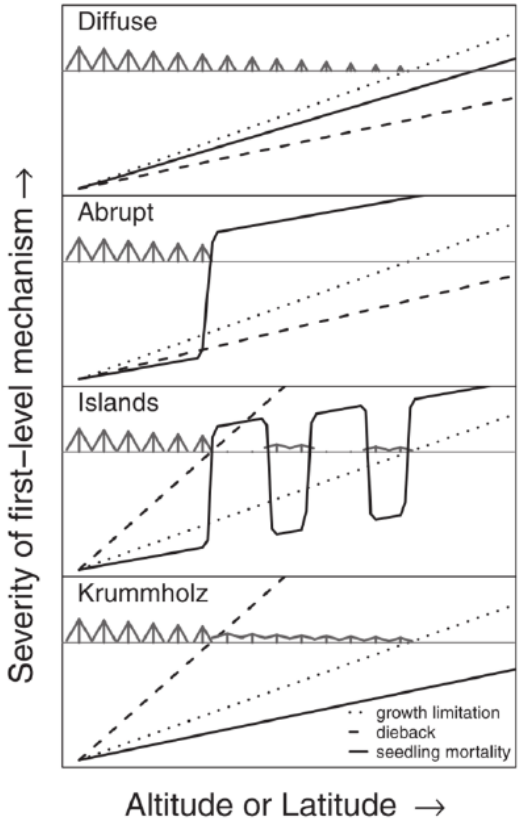
Delineation of the Arctic Treeline

- **A potentially powerful tool - Treeline forms**

  - TTE susceptibility to outside forcing ← dominant controlling factor of treeline position

  - different forms have different primary mechanisms controlling treeline positions

  → spatial pattern of forms: basis of ***spatial pattern of treeline vulnerability***



Conceptual diagram illustrating the four treeline forms and how treeline form can result from growth limitation (dotted black line), dieback (dashed black line) and mortality (solid black line).(from Harsch & Baber, 2011)

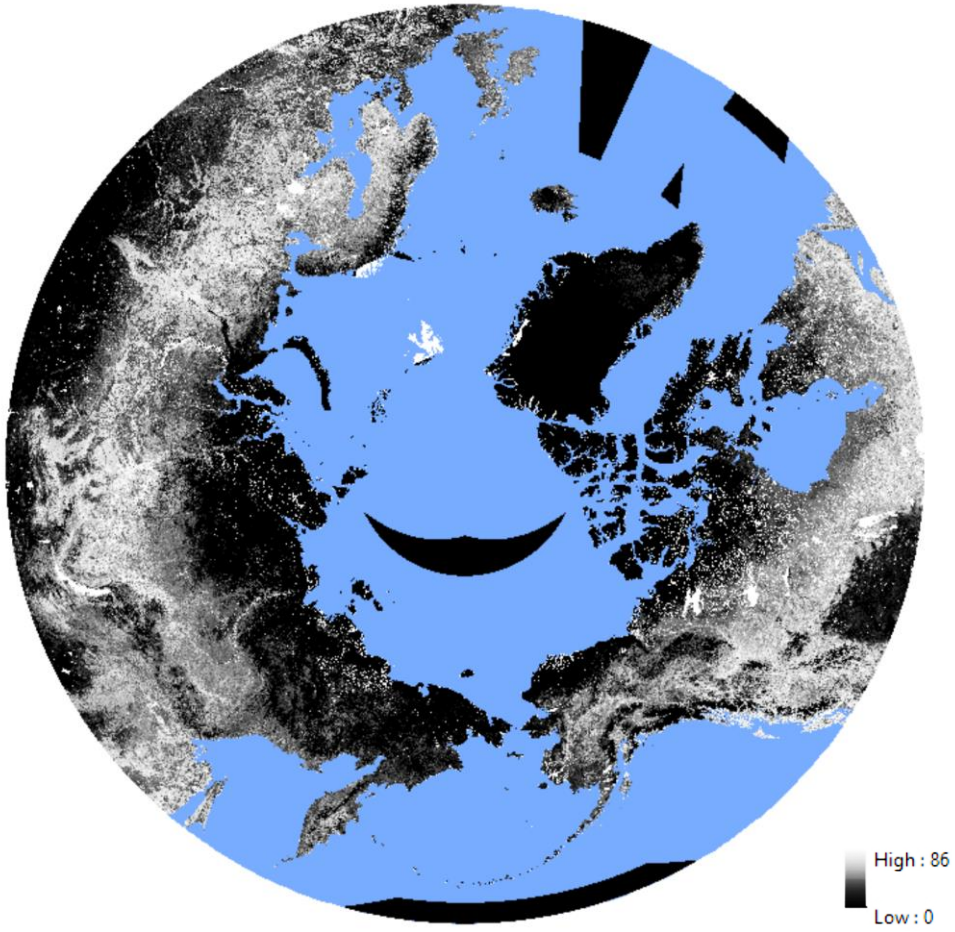
Delineation of the Arctic Treeline – Study Area

- **48N-80N**

Based on Montesano et al., 2009

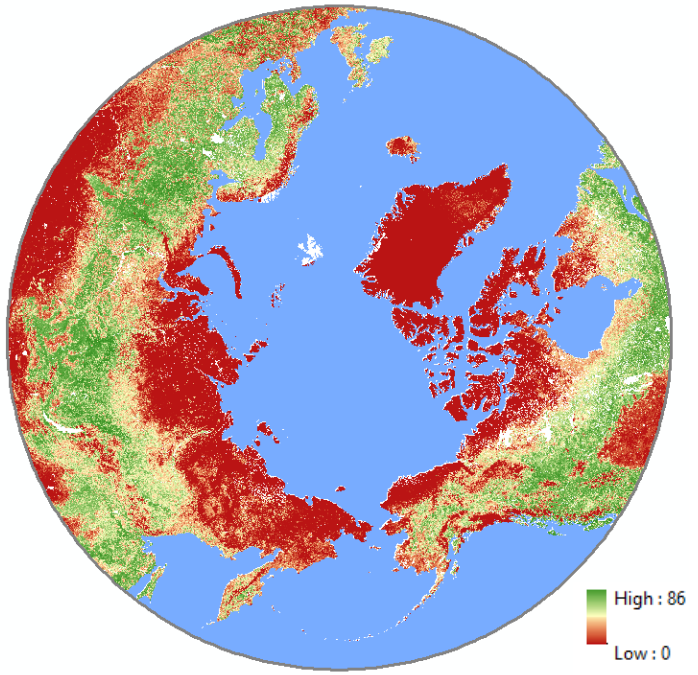
Delineation of the Arctic Treeline – Data

- **MODIS VCF**



Delineation of the Arctic Treeline – Data

- **MODIS VCF product:**
  - pixel value: proportional estimates for trees
  - from all 7 bands from MODIS Terra
  - GeoTIFF format
  - resolution 250m
  - 2000 - 2010



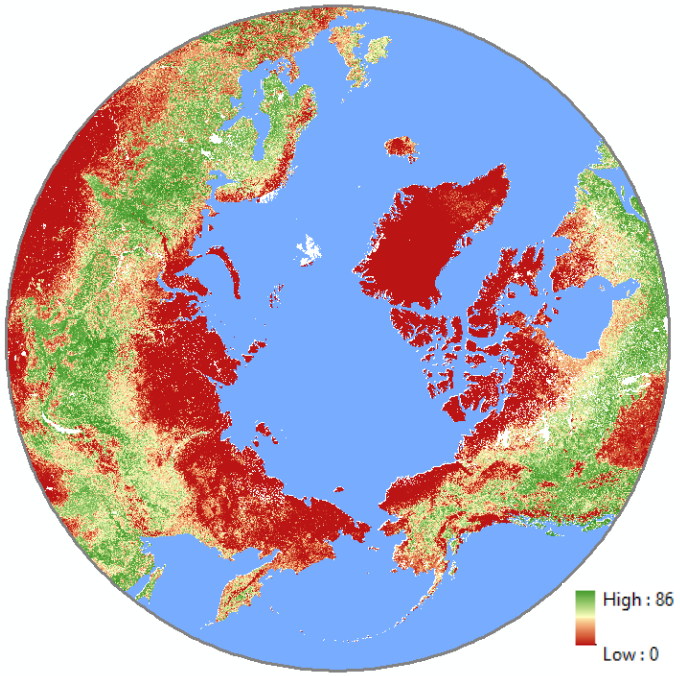
Delineation of the Arctic Treeline – Data

- **MODIS VCF product:**

  - general assessment:

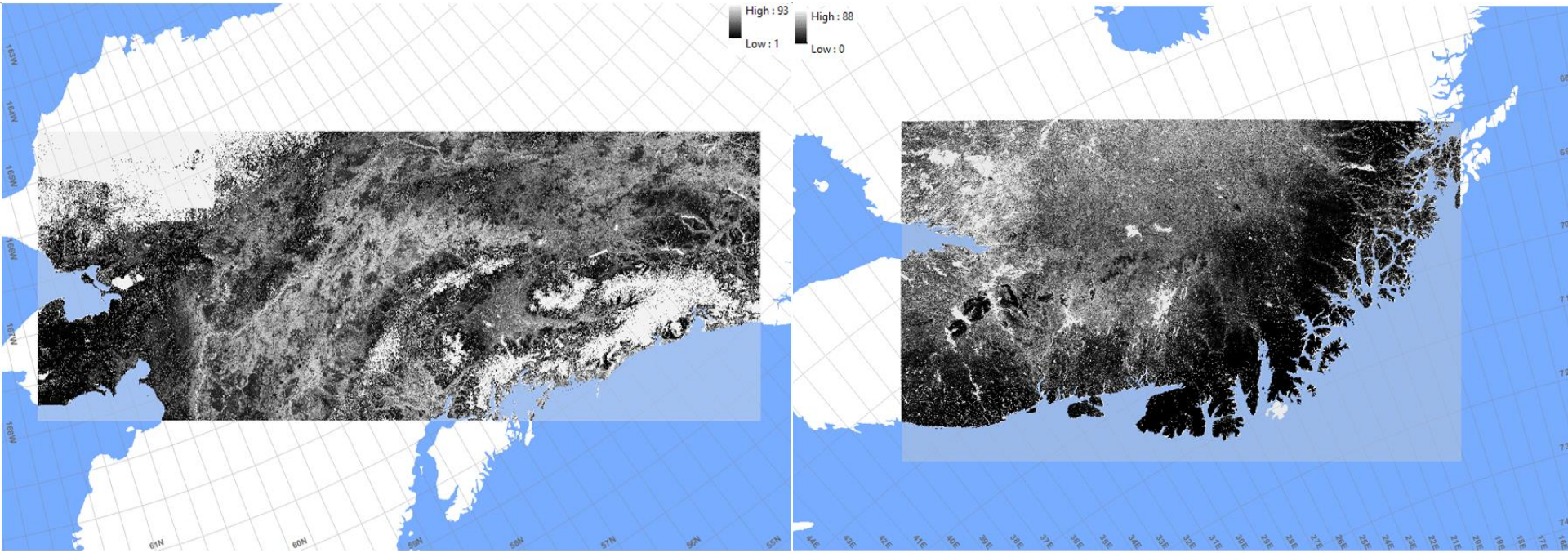
    underestimation in dense tree cover

    overestimation in lightly forested regions



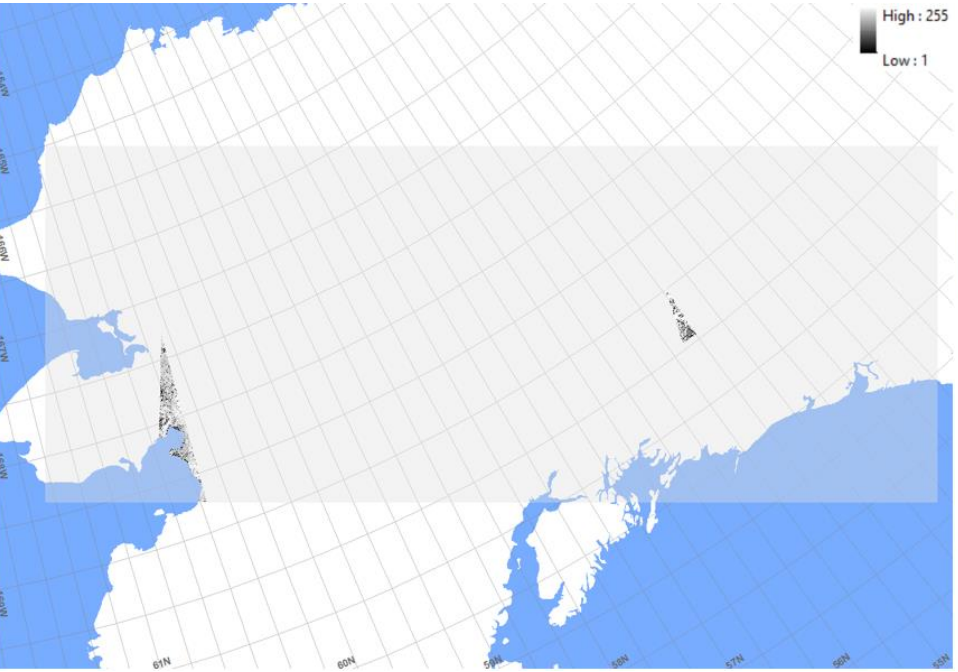
Delineation of the Arctic Treeline – Data

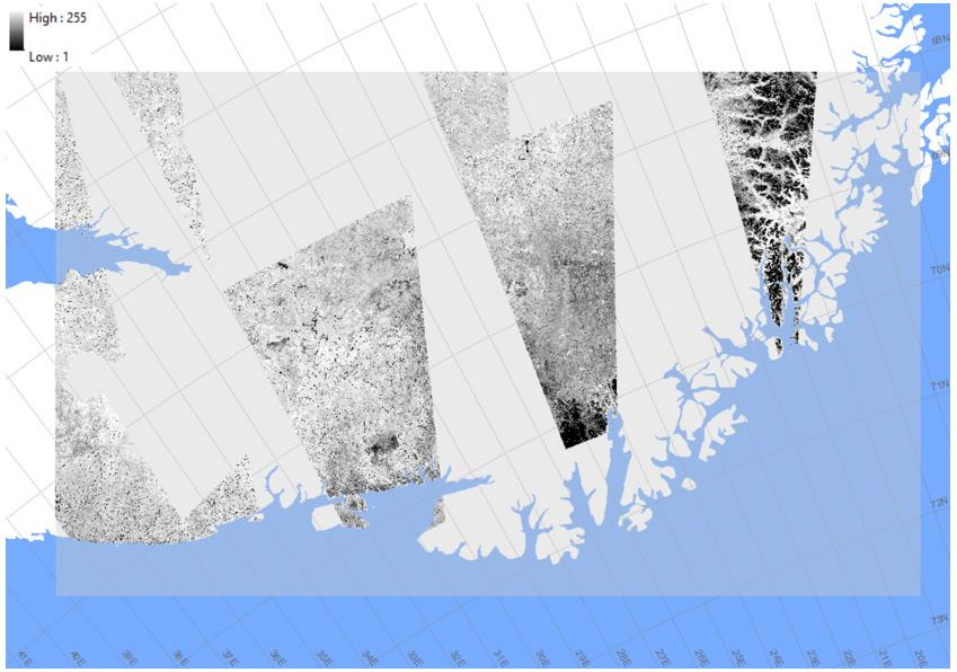
- **Landsat VCF**



Delineation of the Arctic Treeline – Data

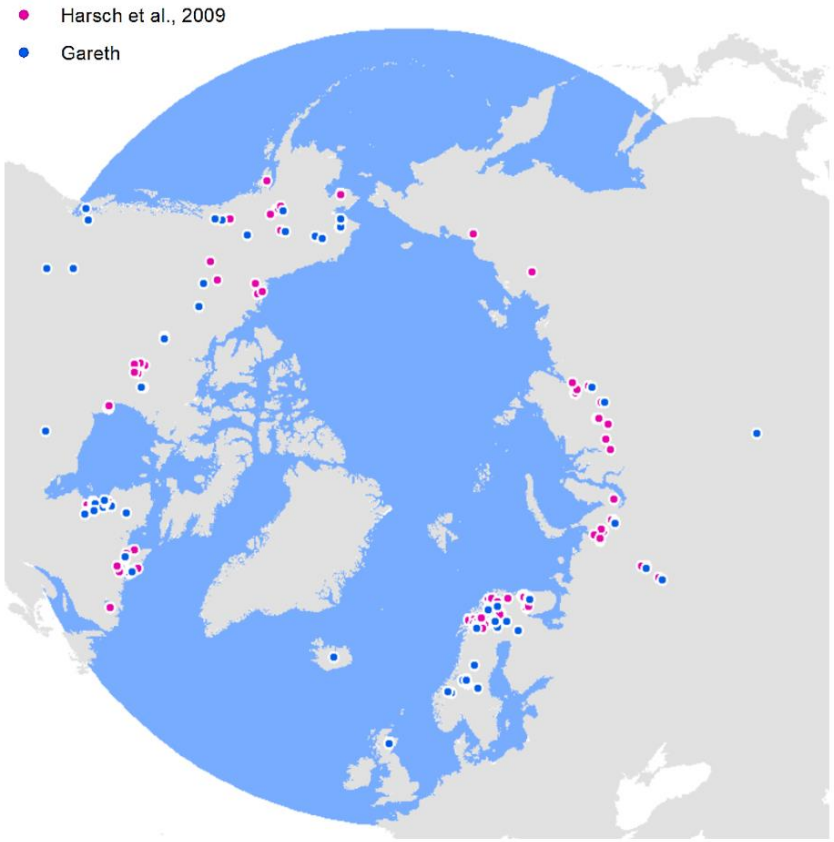
- **NDVI from Sentinel-2**



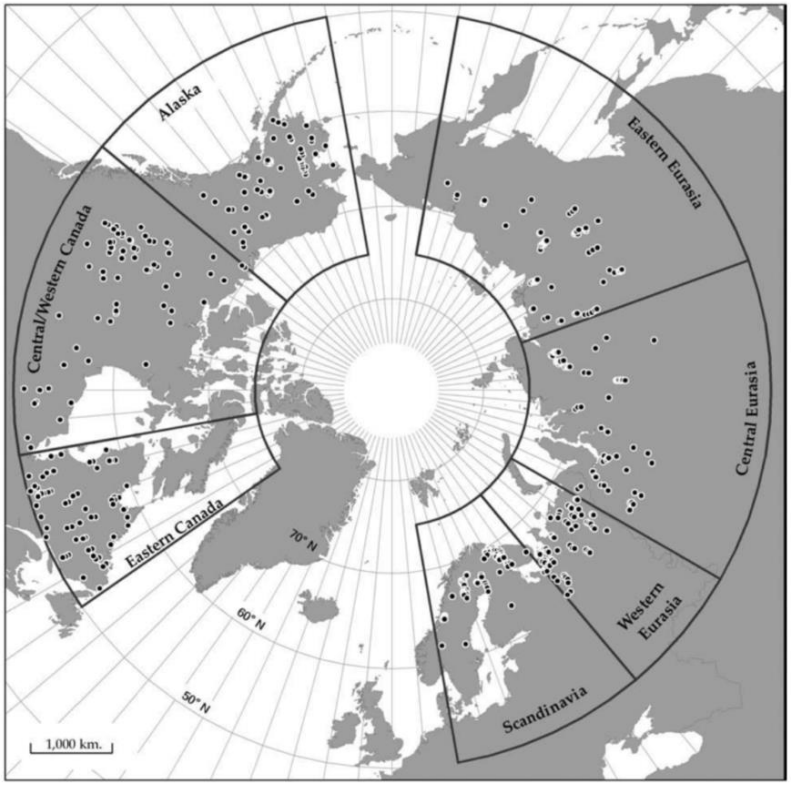


Delineation of the Arctic Treeline – Data

- **Site data: treeline points**



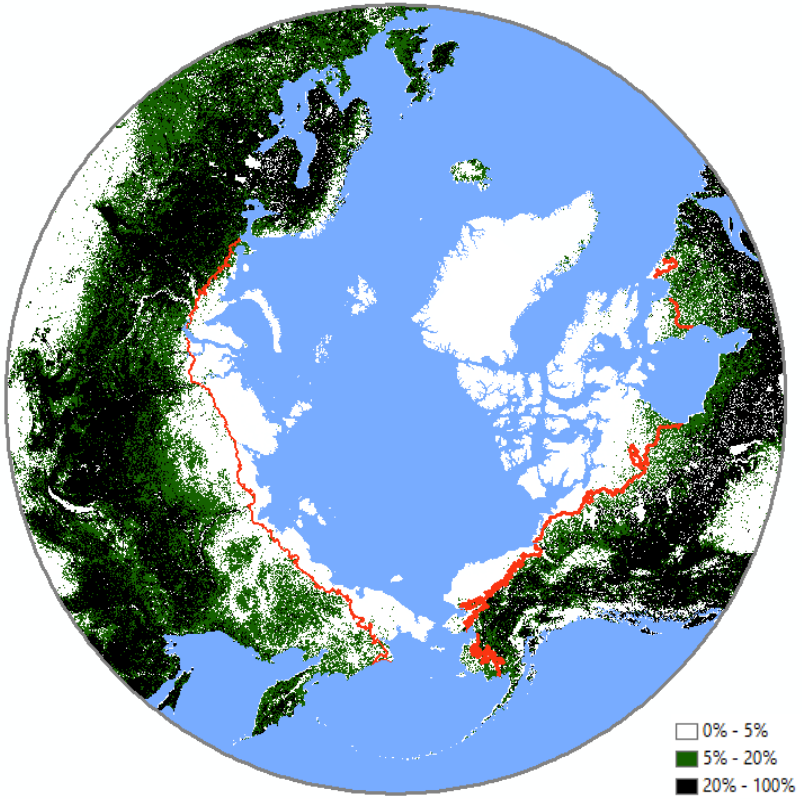
Montesano et al., 2009



Delineation of the Arctic Treeline – Experiment 0

- **Examination of the MODIS VCF dataset**

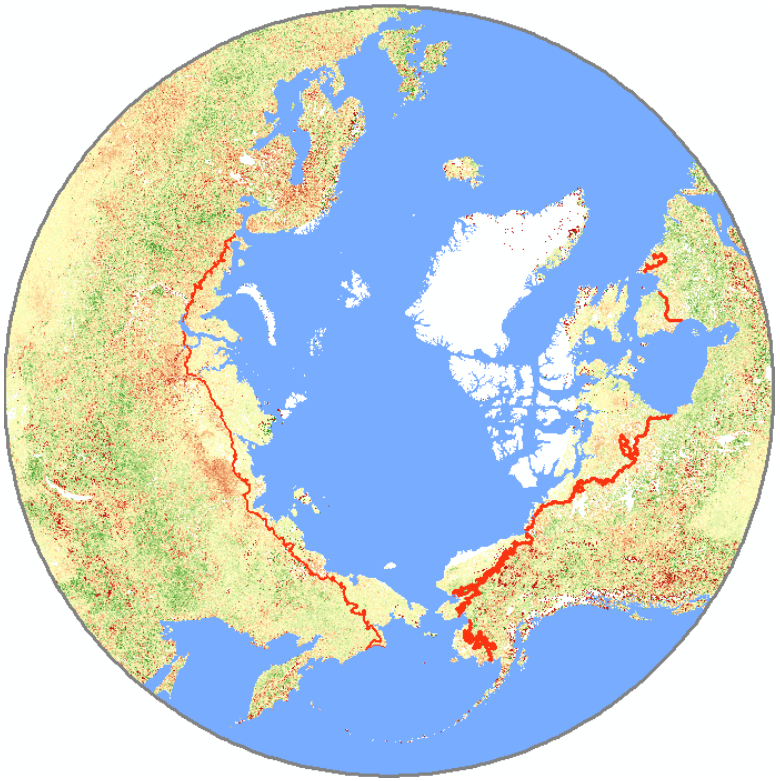
  - Avg.VCF



Delineation of the Arctic Treeline – Experiment 0

- **Examination of the MODIS VCF dataset**

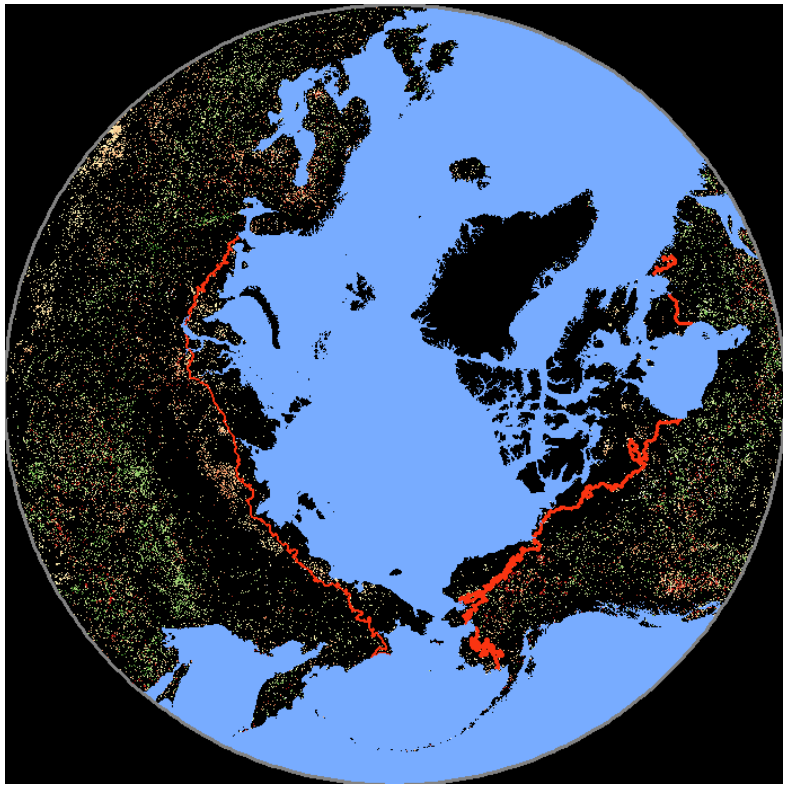
  - Linear Regression



Delineation of the Arctic Treeline – Experiment 0

- **Examination of the MODIS VCF dataset**

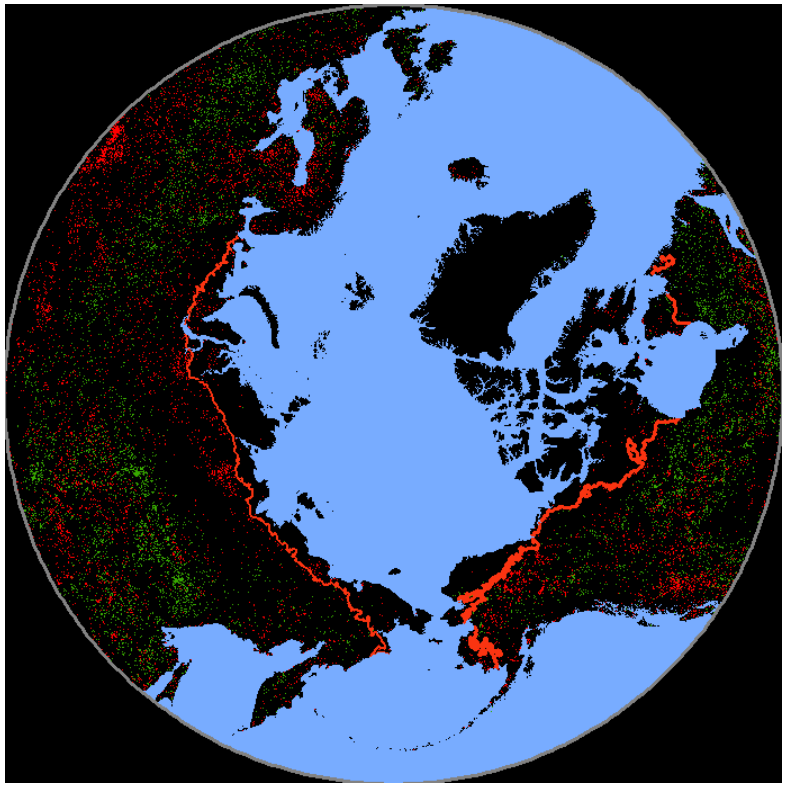
  - Linear Regression



Delineation of the Arctic Treeline – Experiment 0

- **Examination of the MODIS VCF dataset**

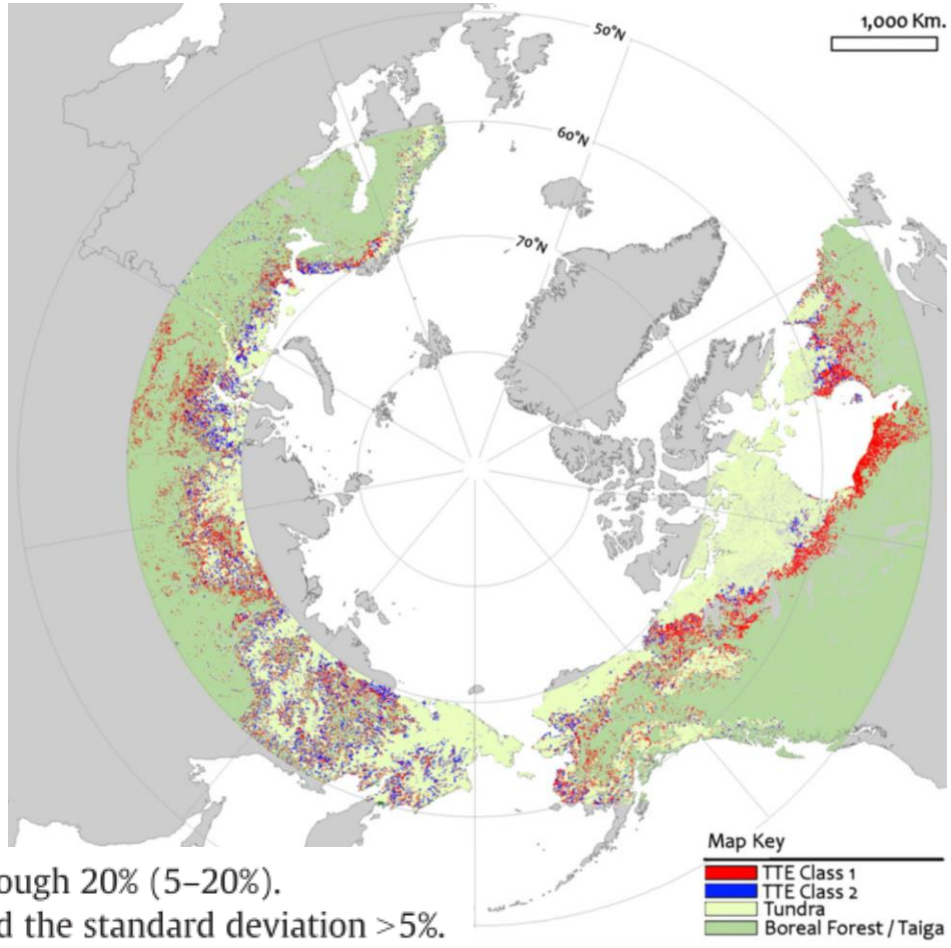
  - Mann-Kendal Test



Delineation of the Arctic Treeline – Experiment 1

- **VCF thresholding**

  - reference



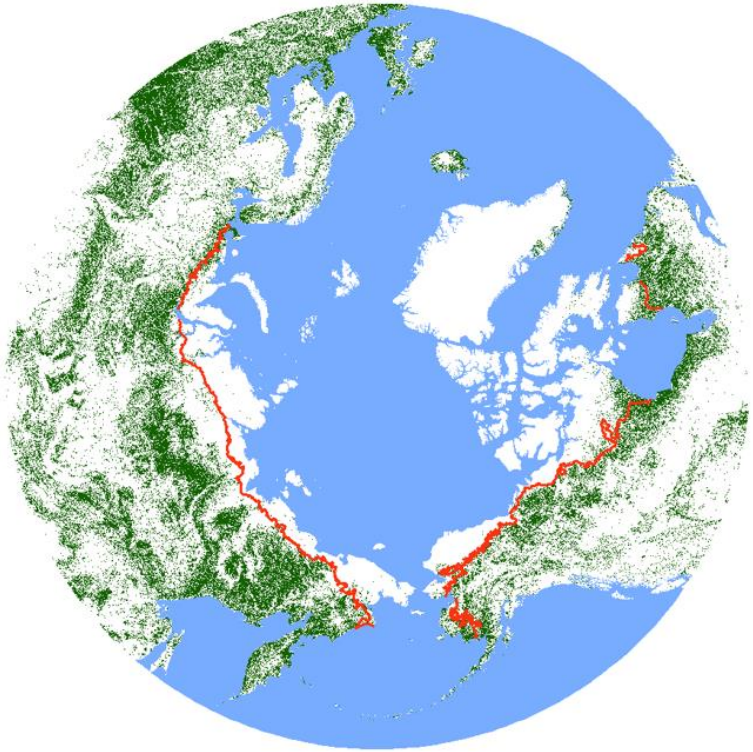
1. The mean VCF_{adj} value from 5% through 20% (5–20%).
2. The mean VCF_{adj} value was <5% and the standard deviation >5%.

Ranson et al., 2011

Delineation of the Arctic Treeline – Experiment 1

- **VCF thresholding –** using MODIS VCF

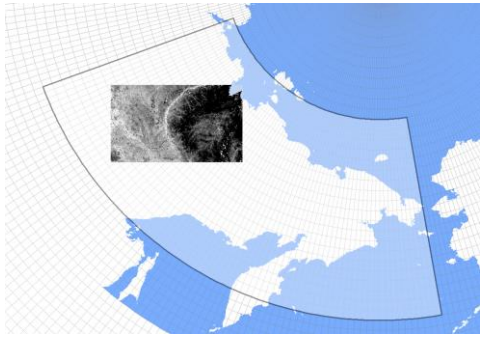
Ranson et al. (2011).

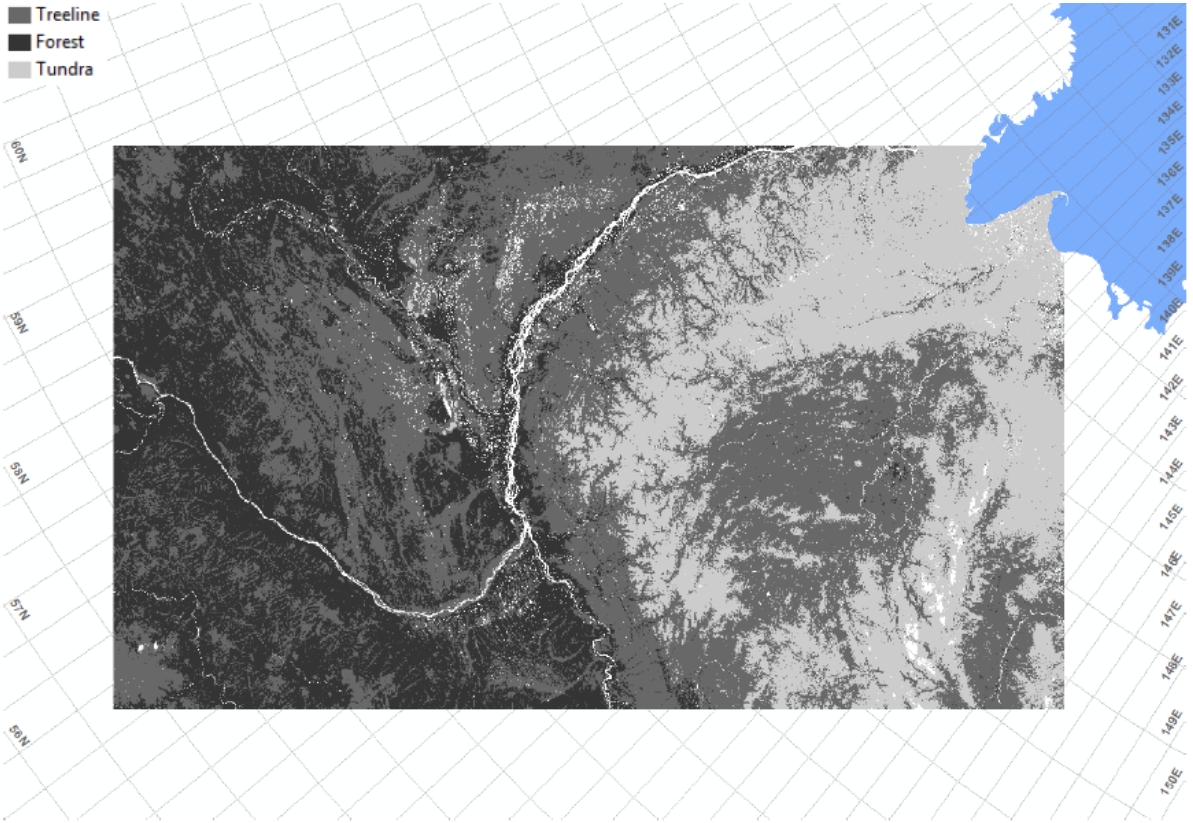


Based on MODI VCF thresholds

Delineation of the Arctic Treeline – Experiment 1

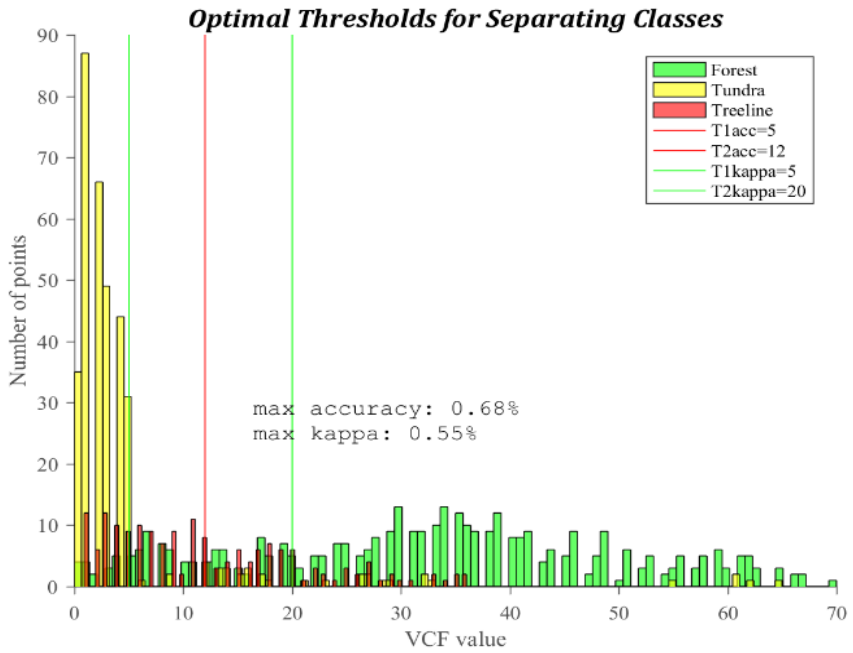
- **VCF thresholding** – zoomed in on Eastern Eurasia subset





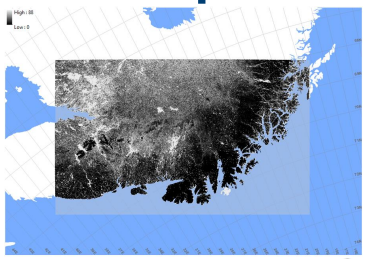
Delineation of the Arctic Treeline – Experiment 2

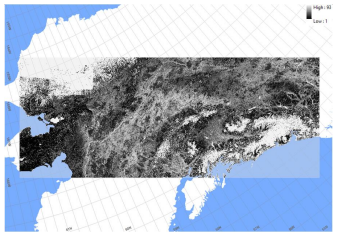
- **Adaptive VCF thresholding** – Eastern Eurasia subset

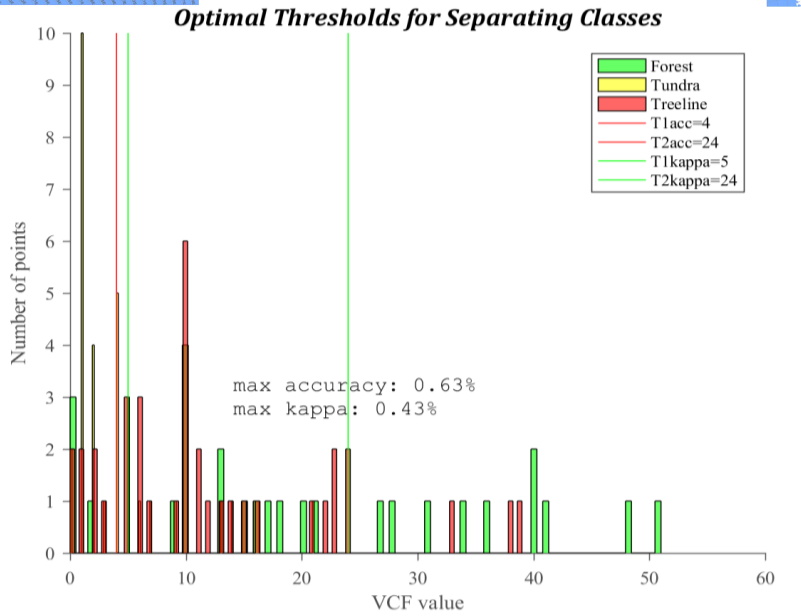


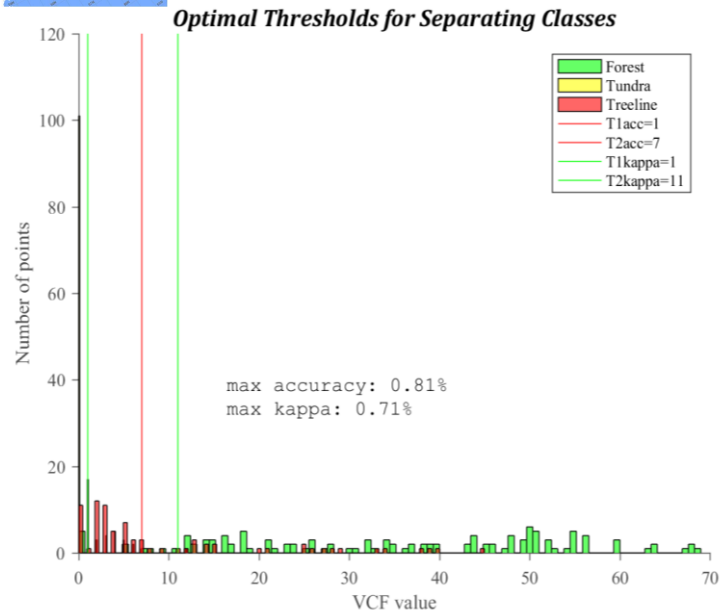
Delineation of the Arctic Treeline – Experiment 2

- **Adaptive VCF thresholding** – 2 additional subsets









Delineation of the Arctic Treeline – Experiment 3

- **Classification utilizing textures measurements**

GLCM-based textures

Autocorrelation: a measure of repeating patterns in an image.

$$\sum_i \sum_j ij P_{i,j}$$

Cluster prominence: a measure of asymmetry in an image.

$$\sum_i \sum_j (i + j - \mu_i - \mu_j)^4 P_{i,j}$$

Cluster shade: a measure of the skewness of the image.

$$\sum_i \sum_j (i + j - \mu_i - \mu_j)^3 P_{i,j}$$

Contrast: a measure of local variations in an image.

$$\sum_i \sum_j P_{i,j} (i - j)^2$$

Correlation: a measure of the linear dependency of grey levels on a point's neighbouring pixels.

$$\frac{\sum_i \sum_j ij P_{i,j} - \mu_x \mu_y}{\sigma_x \sigma_y}$$

Dissimilarity: similar to contrast – a measure of local variations.

$$\sum_i \sum_j P_{i,j} |i - j|$$

Energy: (also referred to as Uniformity or Angular second moment) a measure of orderliness, that is pixel pair repetitions, in an image.

$$\sqrt{\sum_i \sum_j {P_{i,j}}^2}$$

Entropy: the opposite of energy; a measure of the randomness (or disorder/complexity) of the image; a homogeneous image results in a low entropy value; a heterogeneous image results in a higher value.

$$\sum_i \sum_j P_{i,j} (-\ln P_{i,j})$$

Homogeneity: (also referred to as Inverse difference moment) a measure of image homogeneity – small differences in pair elements result in larger values; strongly and inversely correlated to the GLCM contrast.

$$\sum_i \sum_j \frac{P_{i,j}}{1 + (i - j)^2}$$

Maximum probability:

$$\max (P_{i,j})$$

Sum of square (variance): a measure of heterogeneity in the image. μ is the mean of $P_{i,j}$.

$$\sum_i \sum_j P_{i,j} (i - \mu)^2$$

Secondary texture measures that are derived from the above texture measures are also included in the analysis:

Difference entropy:

$$-\sum_{i=0}^{N_g - 1} P_{x-y}(i) \log P_{x-y}(i)$$

Difference variance:

$$\text{Variance of } P_{x-y}$$

Information measure of correlation 1:

$$IMC1 = \frac{HXY - HXY1}{\max (HX, HY)}$$

Information measure of correlation 2:

$$IMC2 = \sqrt{(1 - \exp (-2.0(HXY2 - HXY)))}$$

Inverse difference:

$$\sum_{i,j=0}^{N_g - 1} \frac{P_{i,j}}{1 + |i - j|}$$

Sum average:

$$\sum_{i=2}^{2N_g} i P_{x+y}(i)$$

Sum entropy:

$$-\sum_{i=2}^{2N_g} P_{x+y}(i) \log P_{x+y}(i)$$

Sum variance:

$$\sum_{i=2}^{2N_g} (i - sa)^2 P_{x+y}(i)$$

Where:

$P_{i,j}$ is the (i, j)th entry in the GLCM; μ_x, μ_y, σ_x and σ_y are the means and standard deviations of p_x and p_y;

N_g is the number of distinct grey levels in the quantized image;

Σ_i is $\Sigma_{i=1}^{N_g}$; Σ_j is $\Sigma_{j=1}^{N_g}$;

$P_{x+y}(k) = \Sigma_{i=1}^{N_g} \Sigma_{j=1}^{N_g} P_{i,j}$, ($i+j=k$; k=2,3,…,$2N_g$);

$P_{x-y}(k) = \Sigma_{i=1}^{N_g} \Sigma_{j=1}^{N_g} P_{i,j}$, ($|i-j|=k$; k=0,1,…,$N_g$-1);

$P_x(i) = \Sigma_{j=1}^{N_g} P_{i,j}$; $P_y(j) = \Sigma_{i=1}^{N_g} P_{i,j}$;

$HXY = -\Sigma_i \Sigma_j P_{i,j} \log P_{i,j}$;

$HXY1 = -\Sigma_i \Sigma_j P_{i,j} \log p_x(i) p_y(j)$;

$HXY2 = -\Sigma_i \Sigma_j p_x(i) p_y(j) \log p_x(i) p_y(j)$;

and HX and HY are entropies of p_x and p_y.

Delineation of the Arctic Treeline – Experiment 3

- **Classification utilizing textures measurements**

  appropriate **subset of textures** for different spatial subsets – testing separability

  1. Calculate average (& std dev.) of textures for all points in 3 categories
  2. ***t-tests*** performed for the 3 category pairs (after F-test), repeated for 3-57 window sizes

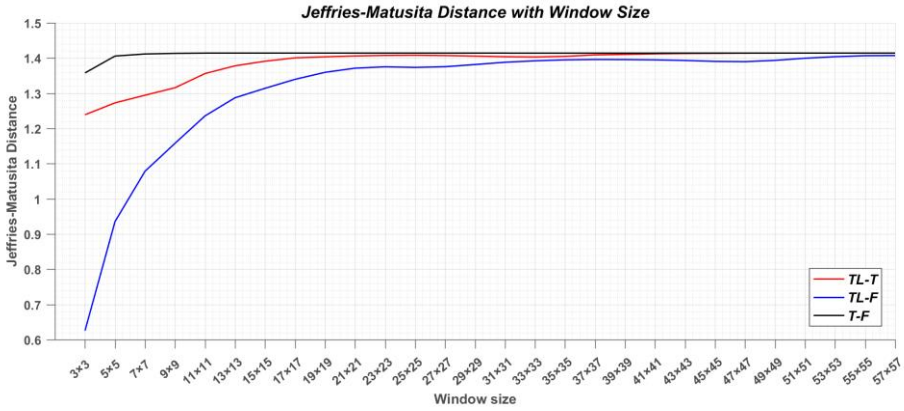
     → table of t stats. (t stats. – 3 pairs,19 textures, in 28 window sizes)
  3. texture flagged if a pair is inseparable
  4. usable texture: flagged ***no more than 3 times*** in all resulting tables
  5. e.g. final list for the Eastern Eurasia clip:

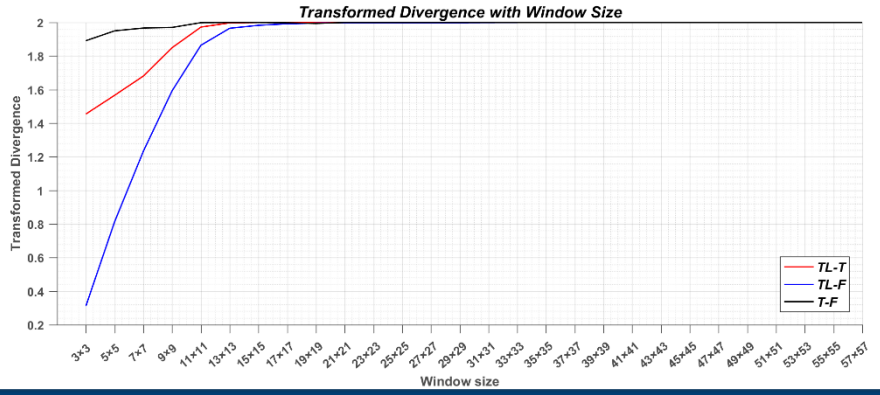
     autocorrelation, cluster prominence, difference entropy, energy, entropy, information measure of correlation 2, maximum probability, sum average, and sum entropy.

Delineation of the Arctic Treeline – Experiment 3

- **Classification utilizing textures measurements**

optimal window size



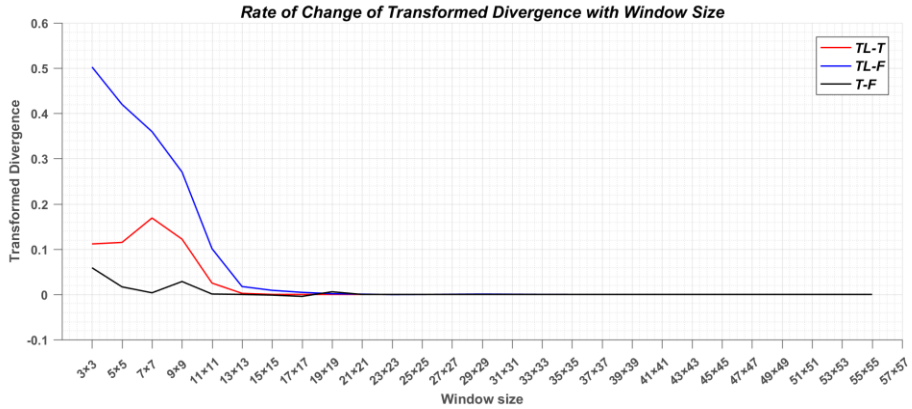


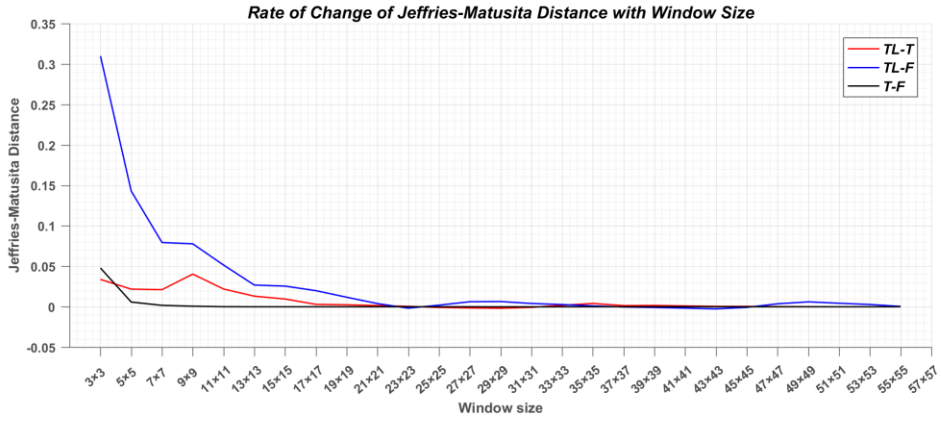
Delineation of the Arctic Treeline – Experiment 3

- **Classification utilizing textures measurements**

optimal window size

(result: 21)

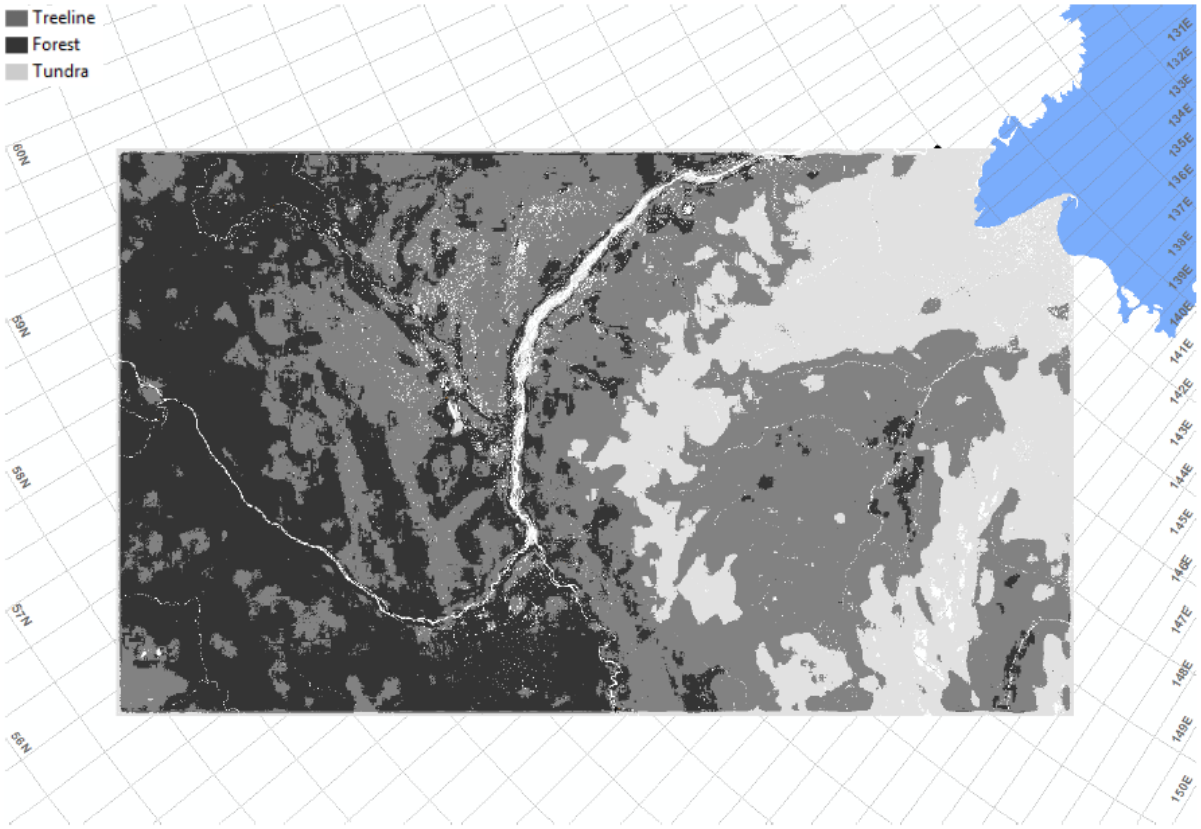




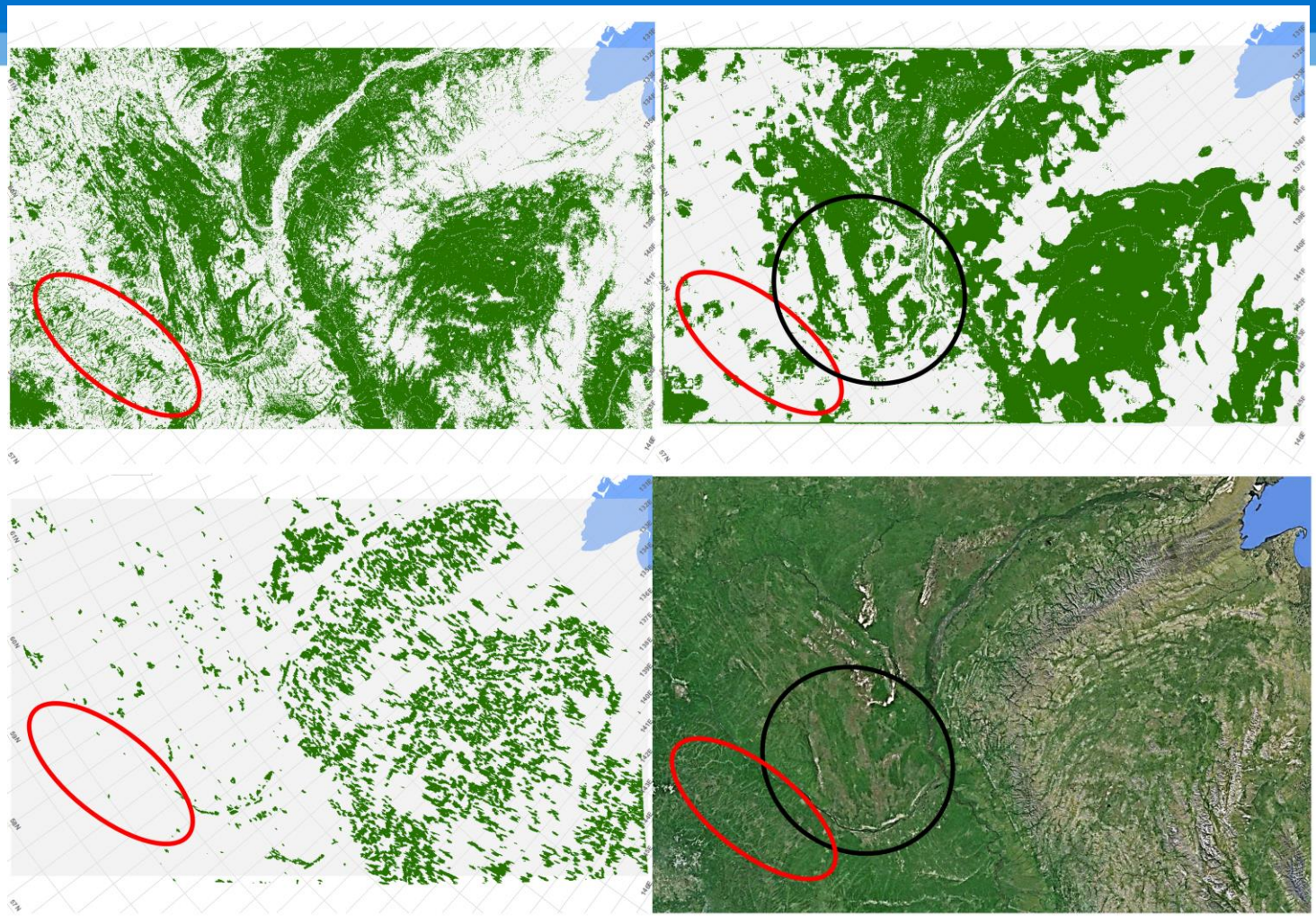
Delineation of the Arctic Treeline – Experiment 3

- **Classification utilizing textures measurements**

result



Delineation of the Arctic Treeline – Experiment 3



(Top left to bottom right) Treeline derived from the VCF thresholding, supervised classification, the study of Ranson et al., 2011, and Google Earth scene over the same area.

Delineation of the Arctic Treeline – Experiment 3

- **Classification utilizing textures measurements**

Classification accuracy and kappa coefficient of treeline delineation using the three methods.

	Overall Accuracy	Kappa Coefficient
Previous VCF Threshold	0.912	0.867
Adaptive VCF Threshold	0.912	0.867
Supervised Classification	0.918	0.876

Further experiment 1

- Further questioning of the **optimal window size** (i.e. spatial scale)

  - incorporating Landsat VCF (30m) and Sentinal-2 (20m)

  - Landsat VCF resampled at 30m intervals from 60m to 250m (+296m)

  - conducted on the Scandinavia clip (where all data are available)

Further experiment 1

Optimal window sizes derived from resampled VCF pixels of different sizes in the Scandinavia subset

Pixel size (m)	Source	Optimal Window Size (pixels)	Optimal Window Size (m)
20	Sentinel-2	17	340
30	Landsat VCF	43	1280
60	Landsat VCF (resampled)	19	1260
90	Landsat VCF (resampled)	15	1360
120	Landsat VCF (resampled)	9	1080
150	Landsat VCF (resampled)	19	2850
180	Landsat VCF (resampled)	13	2340
210	Landsat VCF (resampled)	13	2730
250	Landsat VCF (resampled)	13	3250
296	Landsat VCF (resampled)	13	3848
296	MODIS VCF	13	3848

Further experiment 2

- Using textures to further separate treeline **Forms**

  - visual inspection of treeline points w/ diff. forms (Harsch et al., 2011)

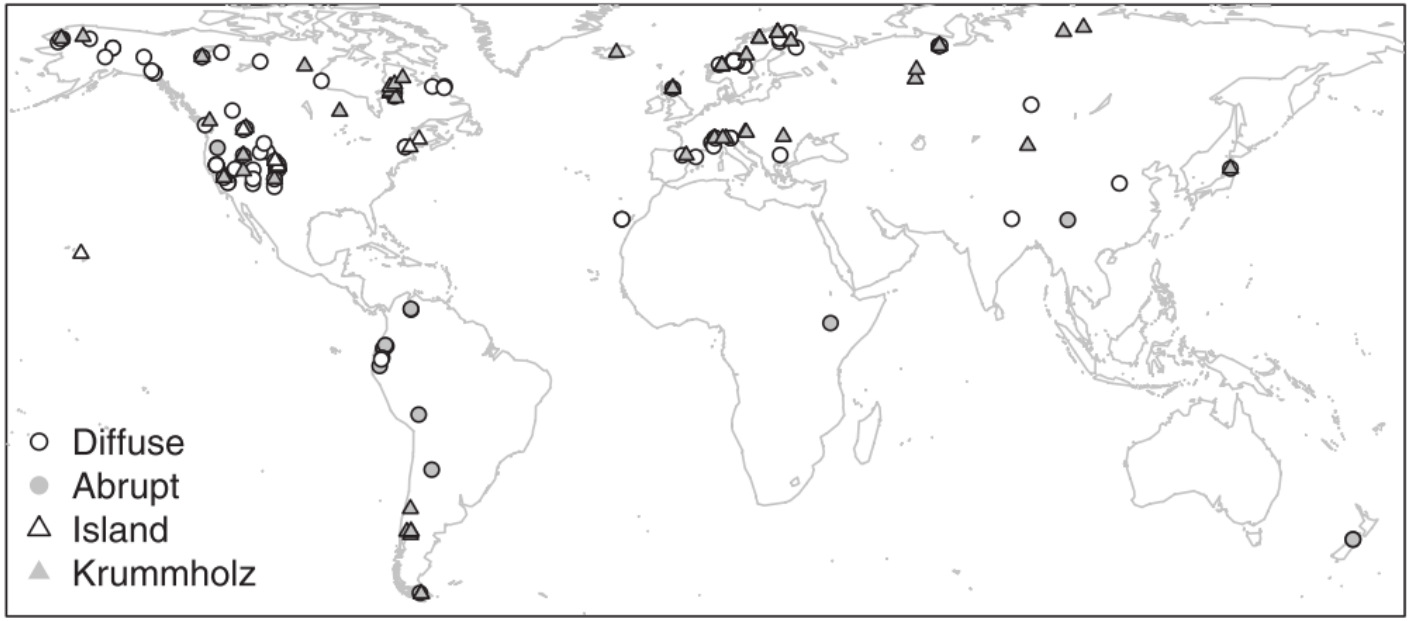
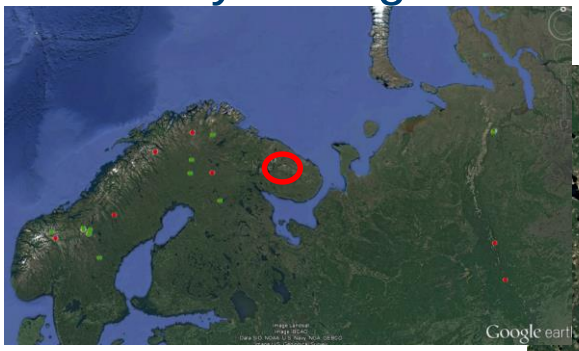


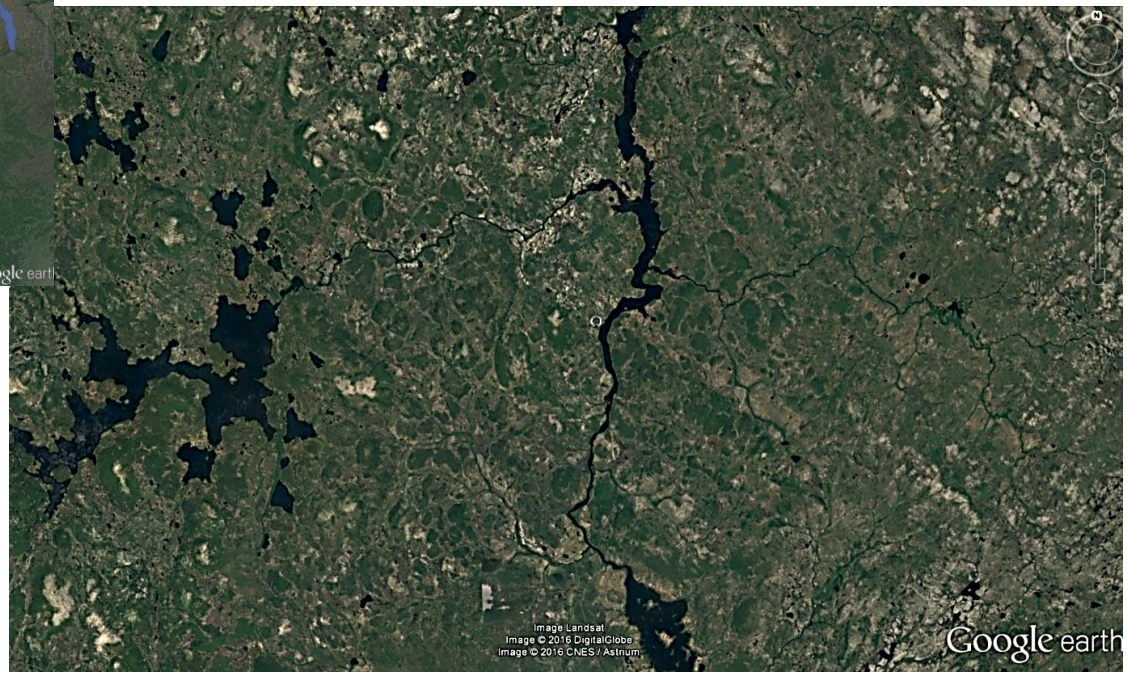
Figure 3 Location of 195 treeline sites analysed in this study grouped according to whether they are diffuse (white circles), abrupt (grey circles), island (white triangles) or krummholz (grey triangles) in form. For information on the database see Appendix S1. For references see Appendix S2.

Further experiment 2

- Using textures to further separate treeline **Forms**

  - only distinguishable form: islands





Further experiment 2

- Using textures to further separate treeline **Forms**

  - others difficult to **distinguish** / **coincide** (e.g. krummholz-island form)

    and often **interrupted** by surface features (esp. water bodies)

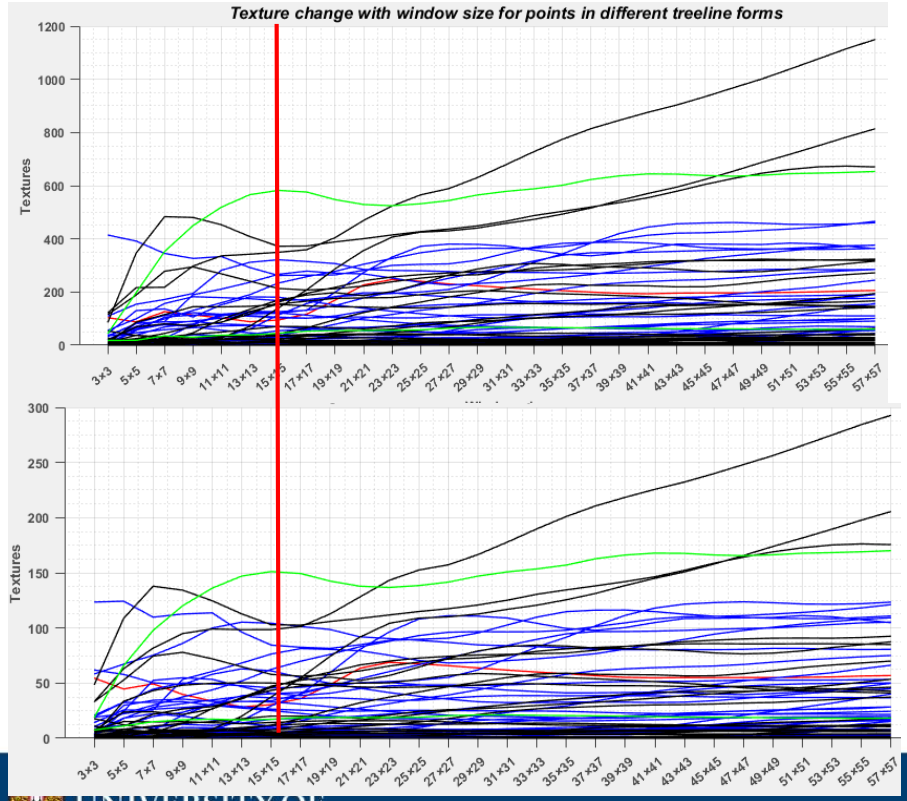
  - VCF product: limit to tree cover >5m → krummholz often not

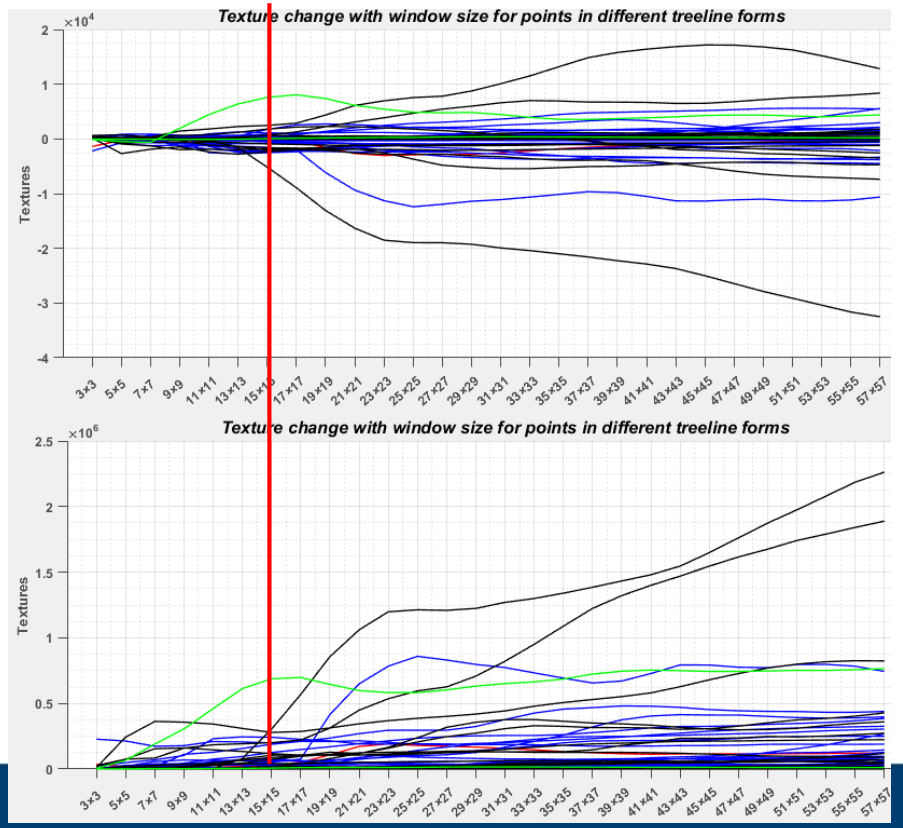
    registered

Further experiment 2

- Experimental plotting of texture value change w/ window size

  - →for some textures at some distances, **islands** separable form others





Further experiment 2

- Further separation of treeline into diff. forms: difficult
- However possible for treeline to be separated from tundra/forest, from its unique spatial arrangements taking any of the 4 forms

Future tasks

- Calibrate VCF products using **finer-resolution** imagery (e.g. Landsat and other higher-res / field-based data)
- More detailed (possibly different) treatment of latitudinal vs. altitudinal treelines (spatial scale + elevation profile)
- Possible inclusion of DEM data for better capturing altitudinal treelines

- Thanks!