Quantifying Soil Properties and Relationship to Vegetation Dynamics in Arctic Tundra using Aerial Platforms and Geophysical Monitoring

Baptiste Dafflon, John Peterson, Craig Ulrich, Rusen Oktem, Anh Phuong Tran, Haruko Wainwright, Susan Hubbard

Lawrence Berkeley National Laboratory, Berkeley CA, US

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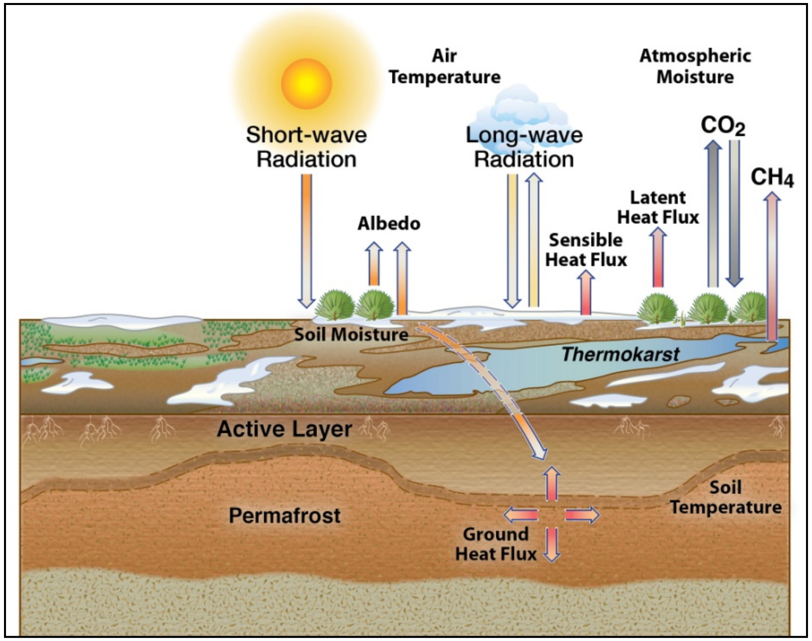
The Vulnerable Arctic System

- Large stock of organic carbon currently sequestered
- Significant permafrost could be lost by 2100
- Microbial decomposition of newly bioavailable C could lead to significant production of greenhouse gas
- Climate could alter vegetation growth, energy balance and geomorphology



Next-Generation Ecosystem Experiments (NGEE)

...improving climate model predictions through advanced understanding of coupled processes in Arctic terrestrial ecosystems

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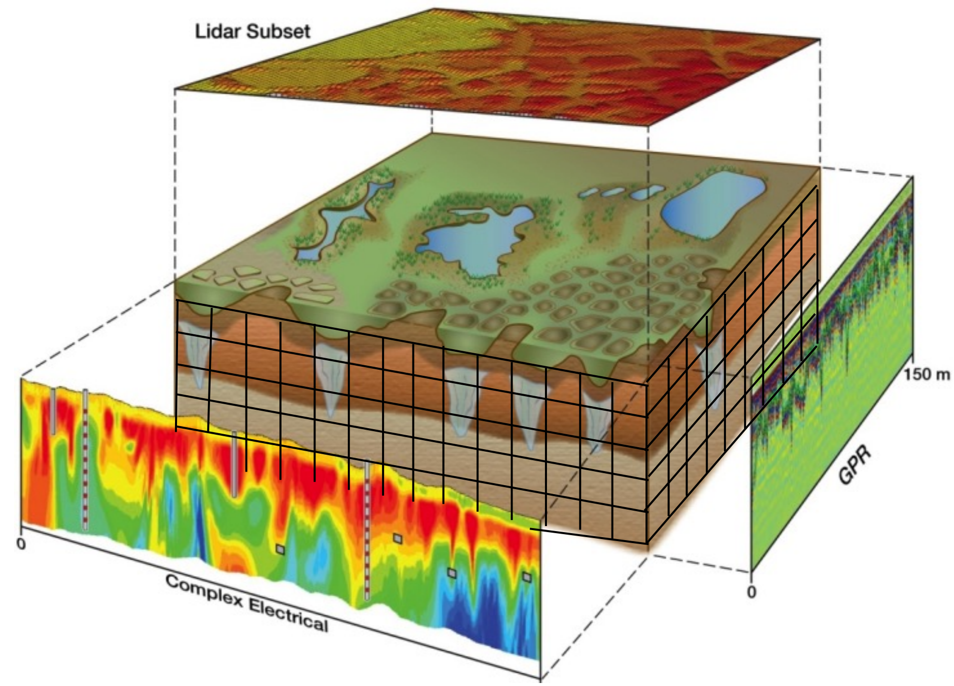
Exploring Surface – Subsurface Co-dynamics

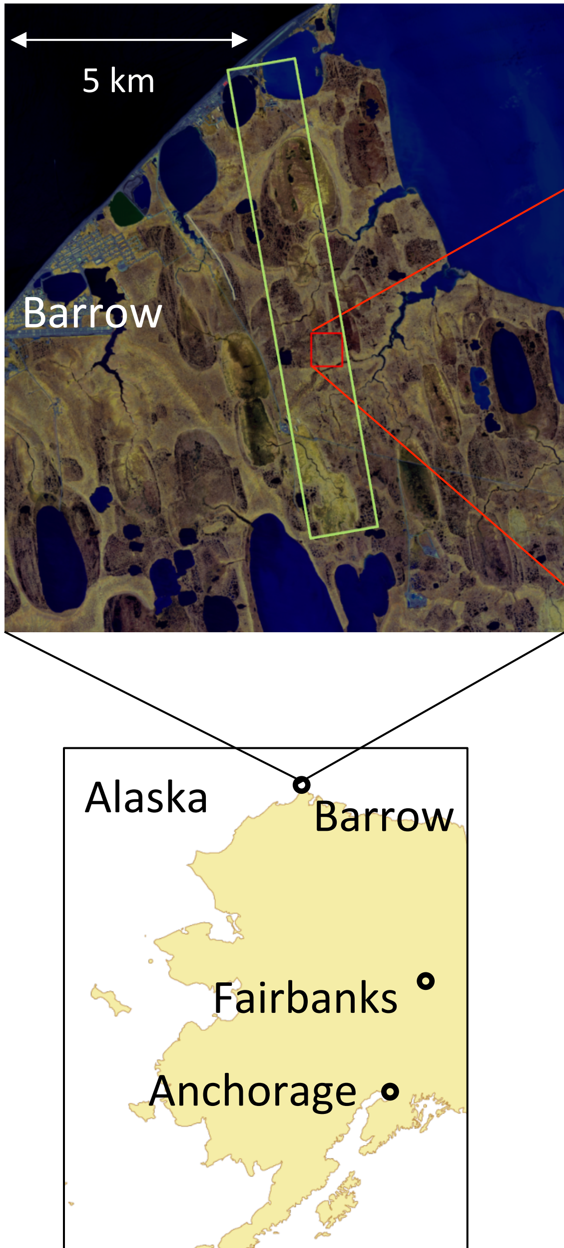
- To understand heat/water/gas fluxes and biogeochemical processes
- To define surface-subsurface properties relationships at intensive sites that can be used to estimate soil properties from remote sensing data at larger scale

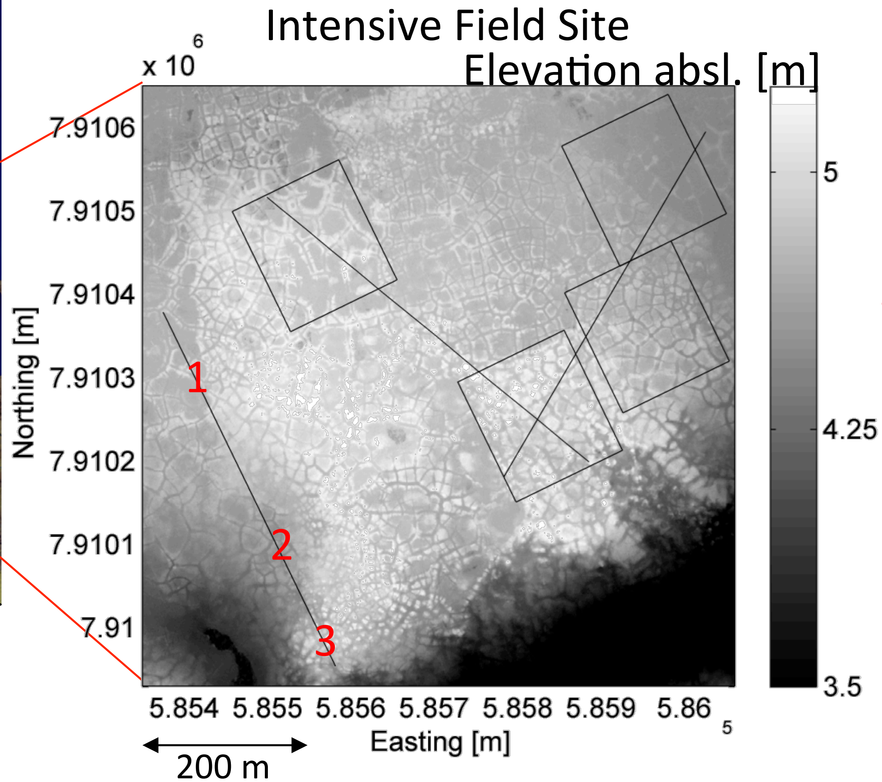


Outline :

1. **Monitor** properties and system behaviors at intensive sites using above-and-below ground imaging
2. **Investigate** co-interaction between subsurface and surface dynamics
3. **Estimate** soil properties distribution at larger scale

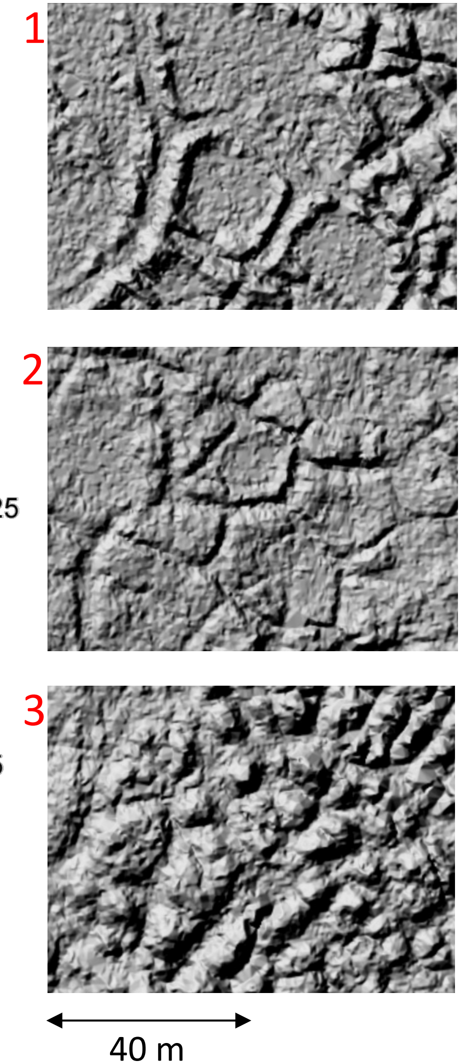
NGEE Barrow Field Site





Main geomorphological features:

- Ice-wedge polygons
- Drainage networks
- Drained thaw lake basins (DTLB)



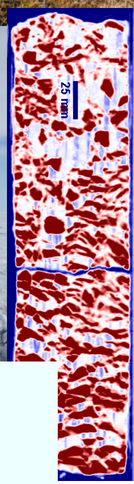
Shaded relief maps of low- to high-centered polygons

Multi-scale Subsurface Characterization

Water content
Temperature
Surface water
Vegetation
… Point-scale data

Landscape metrics
Surface water
Vegetation
… Kite-based imaging

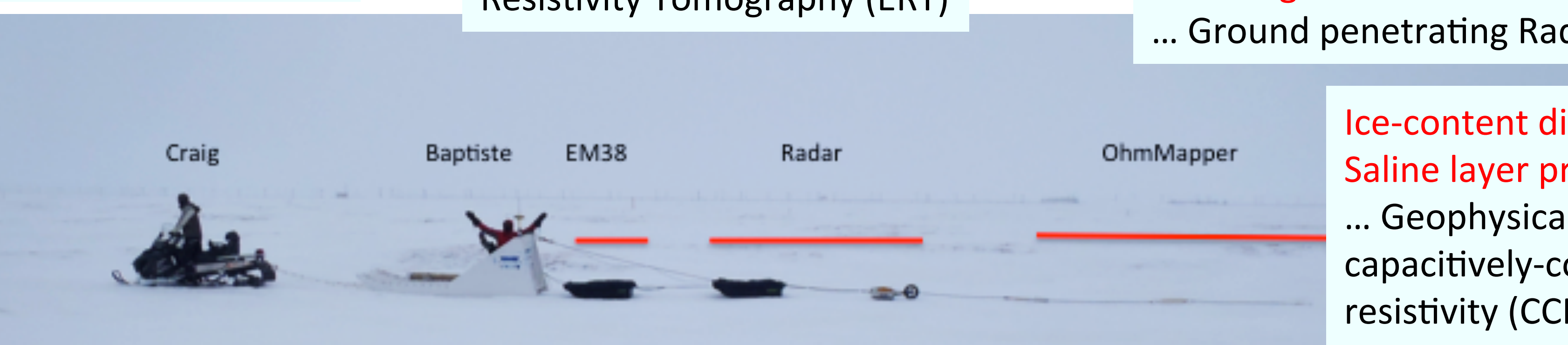
Water content in thawed layer
… Electromagnetic portable tool (EM38)



Soil properties
… Cores, CT-scan, lab analysis

Thawed layer properties
Ice-content distribution
Saline layer properties
… High-resolution Electrical Resistivity Tomography (ERT)

Thawed layer thickness and properties
Snow thickness
Ice-wedge location
… Ground penetrating Radar (GPR)

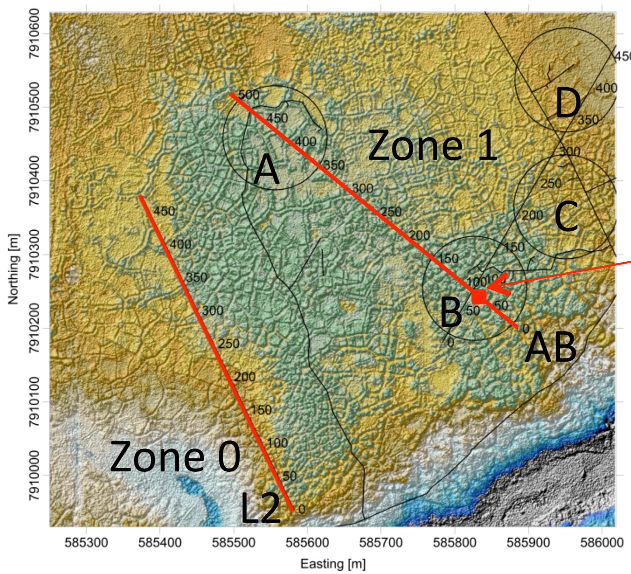


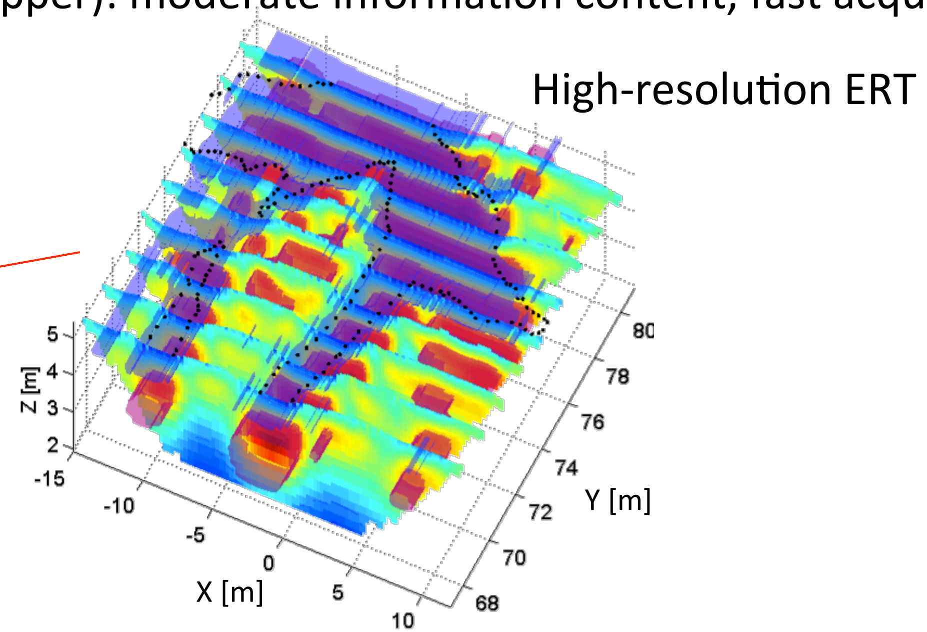
Ice-content distribution
Saline layer properties
… Geophysical train (with capacitively-coupled resistivity (CCR))

Background on Bulk Electrical Resistivity

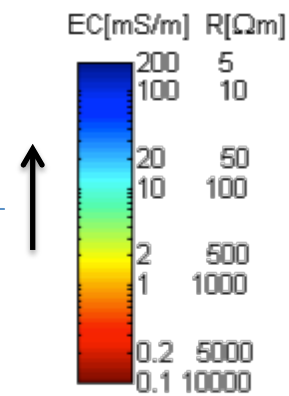
Various methods providing different spatial resolution vs coverage:

- Electrical Resistivity Tomography (ERT) : high spatial resolution, slow acquisition
- Eletromagnetic portable tool (EM38): low information content, fast acquisition
- Capacitively-coupled resistivity (OhmMapper): moderate information content, fast acquisition





More water
Higher salinity
Higher T
More clay
Lower cementation



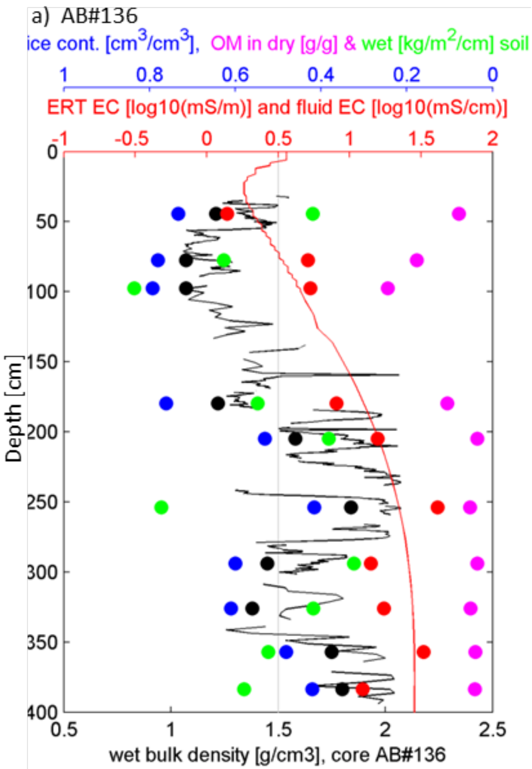
Unfrozen sediments with **high salinity**, Unfrozen **clay**

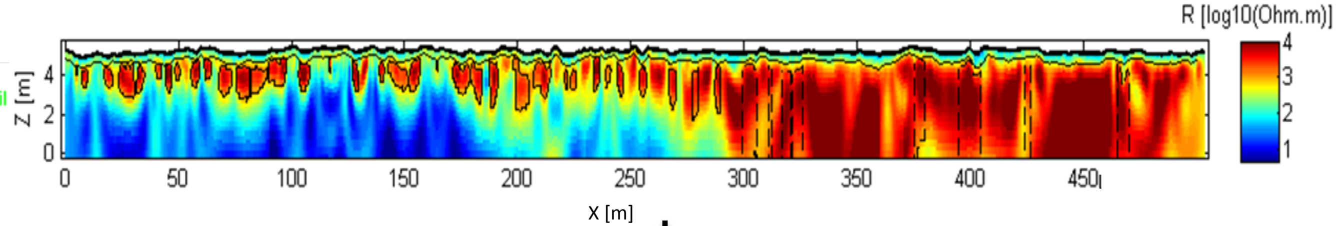
Unfrozen sediments, Frozen clay

Frozen sediments

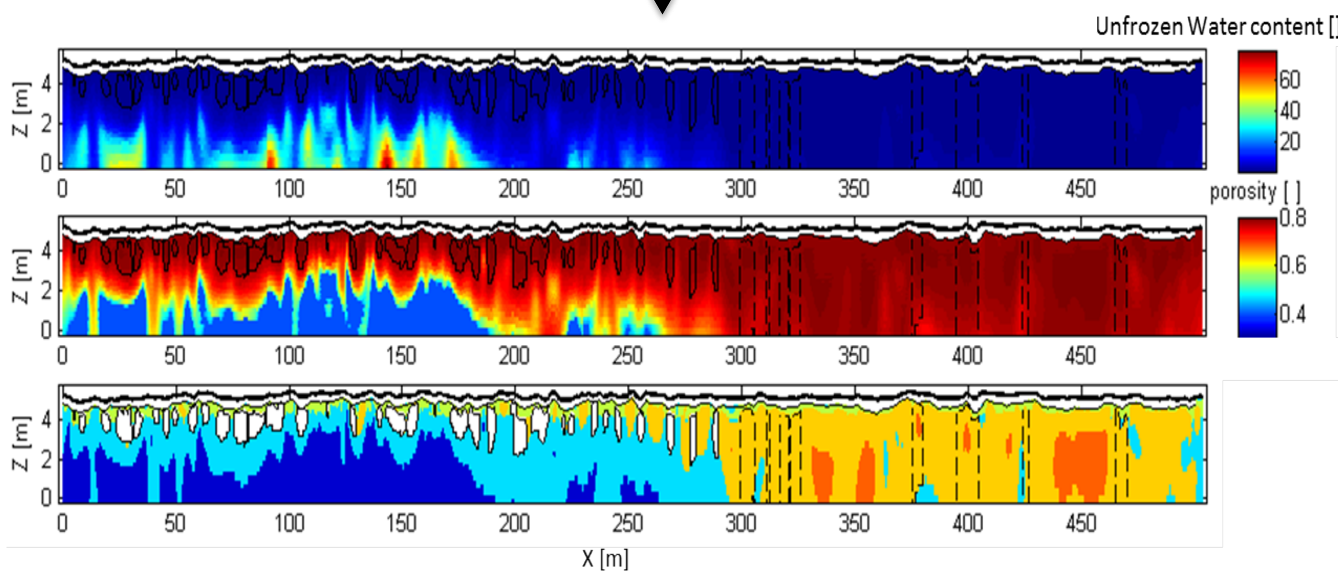
Ice, Ice-rich, Frozen sediments (no clay), **Rocks**

Estimating Soil Properties in Permafrost





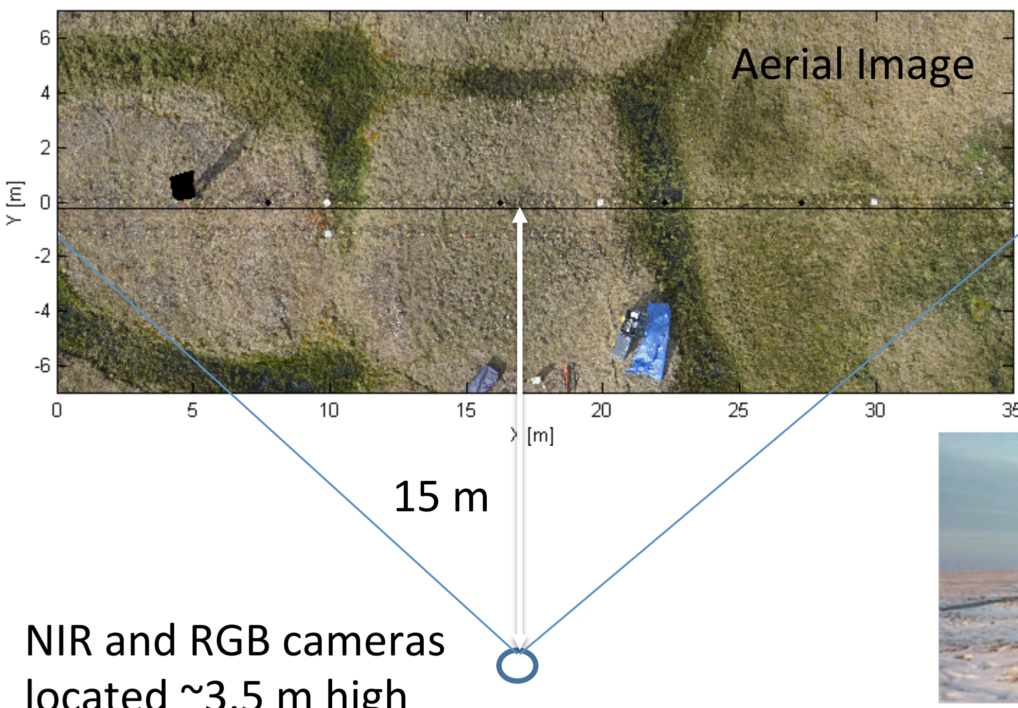
- El. Conductivity (1/R) and salinity are strongly correlated
- Relationship between fluid salinity and porosity
- ERT, Archie's law and in situ relationships can be used to estimate unfrozen water content and porosity



Dafflon et al., 2015

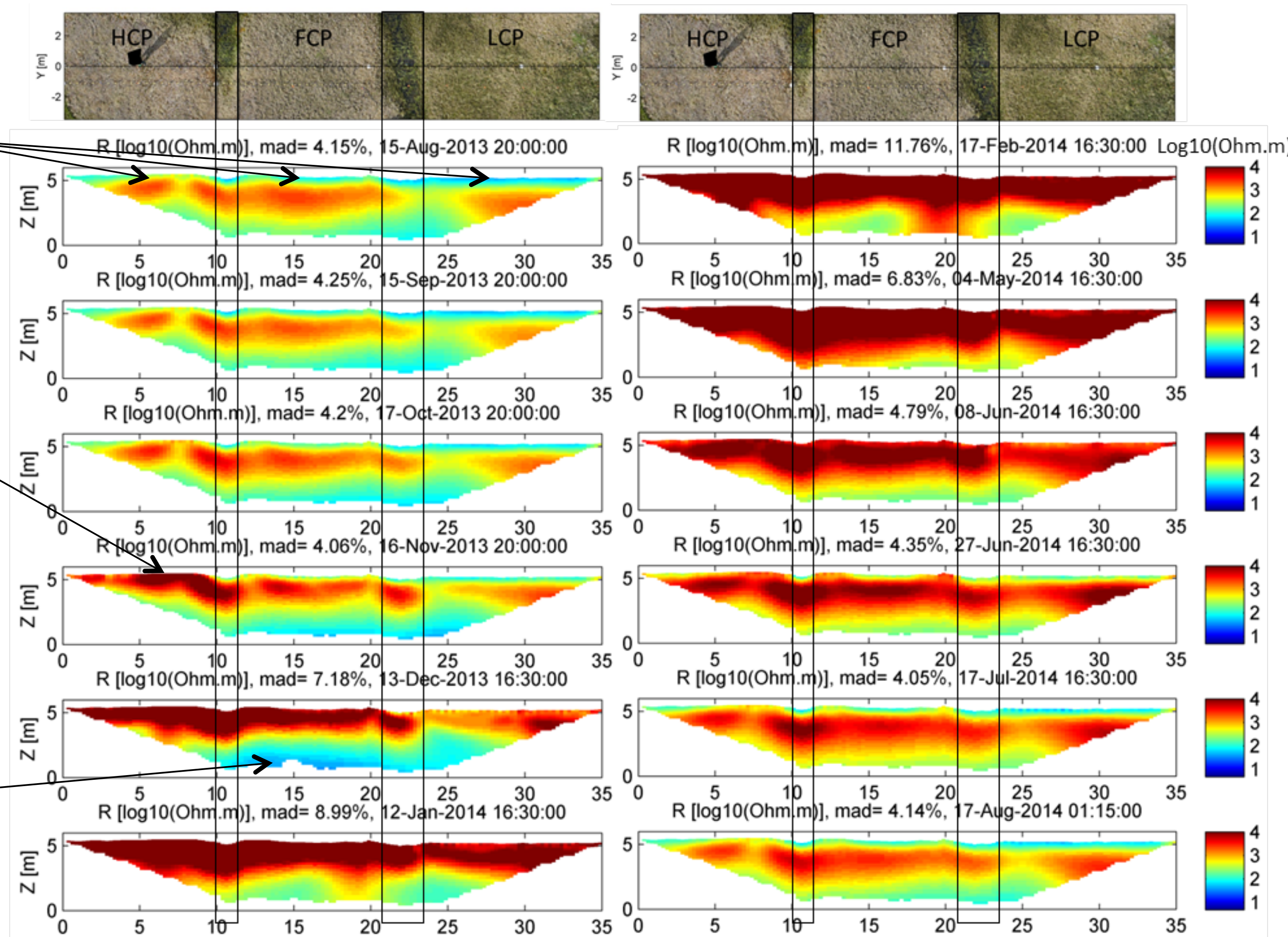
Monitoring Surface-Subsurface Co-dynamics

- Electrical Resistivity Tomography (ERT) autonomous monitoring system
  - Proxy for unfrozen water content in thaw layer
  - Influenced by ice-water fraction and salinity in permafrost
- Temperature depth profiles and TDR monitoring (6 locations)
- Pole mounted optical camera (RGB and NIR)
- Sporadic measurements of thaw layer thickness, snow thickness and topography
- TRAM and Eddy covariance tower nearby for radiation and meteorological data

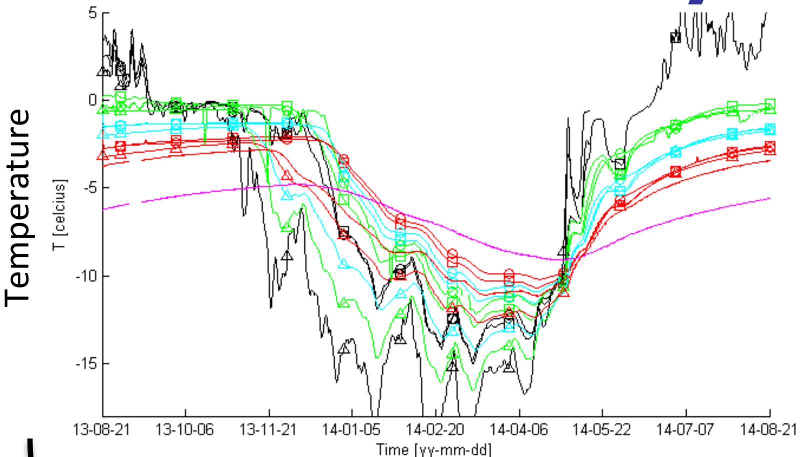


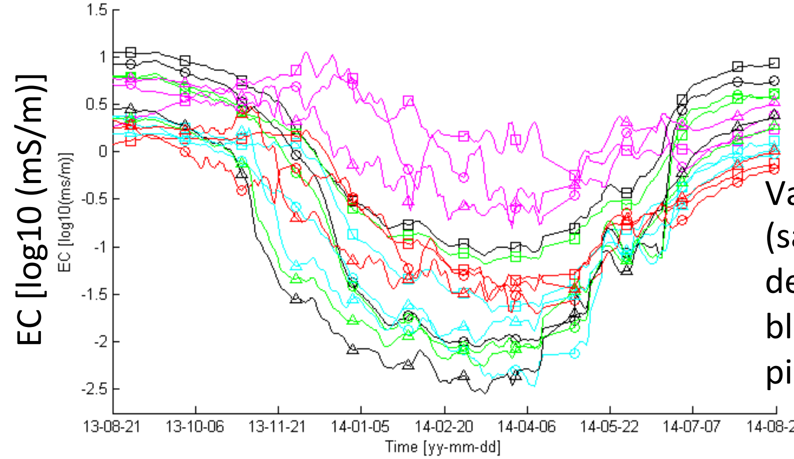
Soil and surface properties control the spatial variability in freeze-thaw process

- Dry HCP, wet FCP and fully saturated LCP thaw layer
- Freezing occurs first in HCP, then in FCP and LCP
- Highest Temperature at 3 m depth is in December (-5 C)
- High conductivity due to saline water

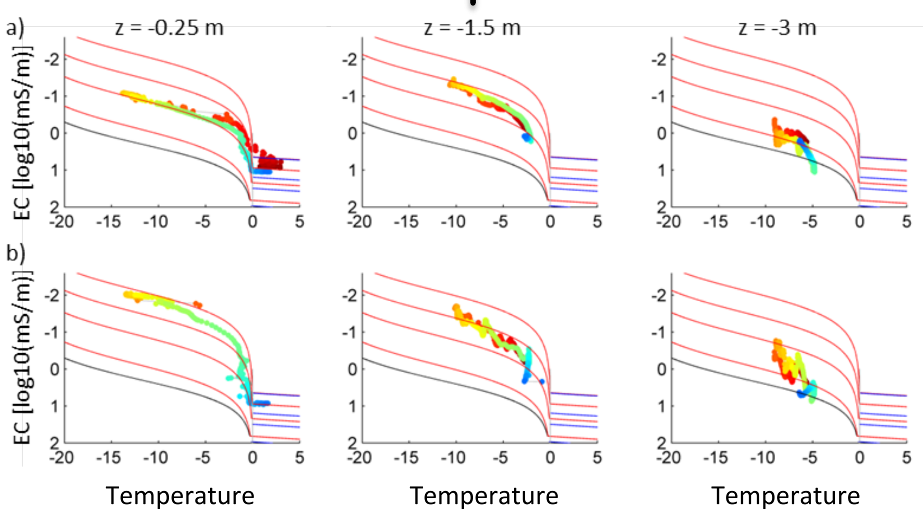


Subsurface monitoring for in situ estimate of freeze-thaw dynamics and water content





Various locations (same color) and depth (shallow-black-green-red-pink-deep)



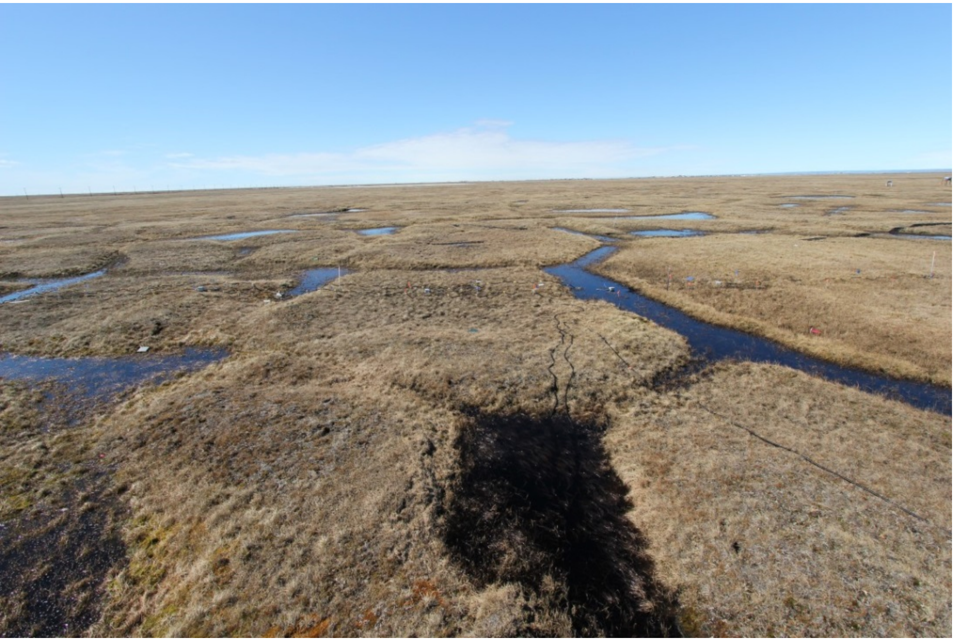
Petrophysical models

↓

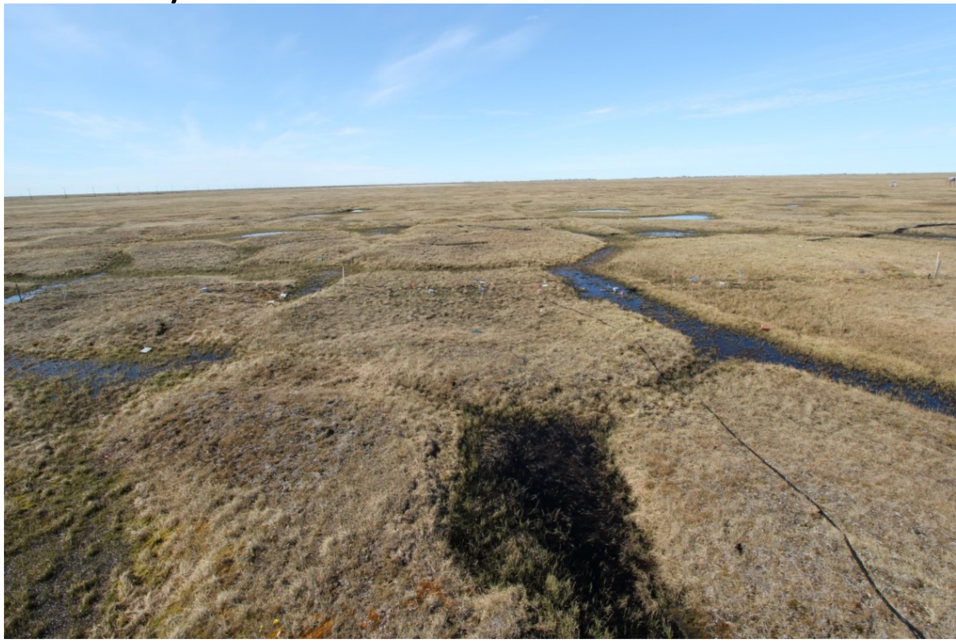
→ Advanced in situ estimation of unfrozen water content in soil which depends on temperature, soil structure, total water content and initial salinity

- Unfrozen water content at 3 m depth varies between 2 and 30% depending on salinity and temperature
- Unfrozen water content at 0.25 m depth reaches a minimum of 5% when salinity remains low

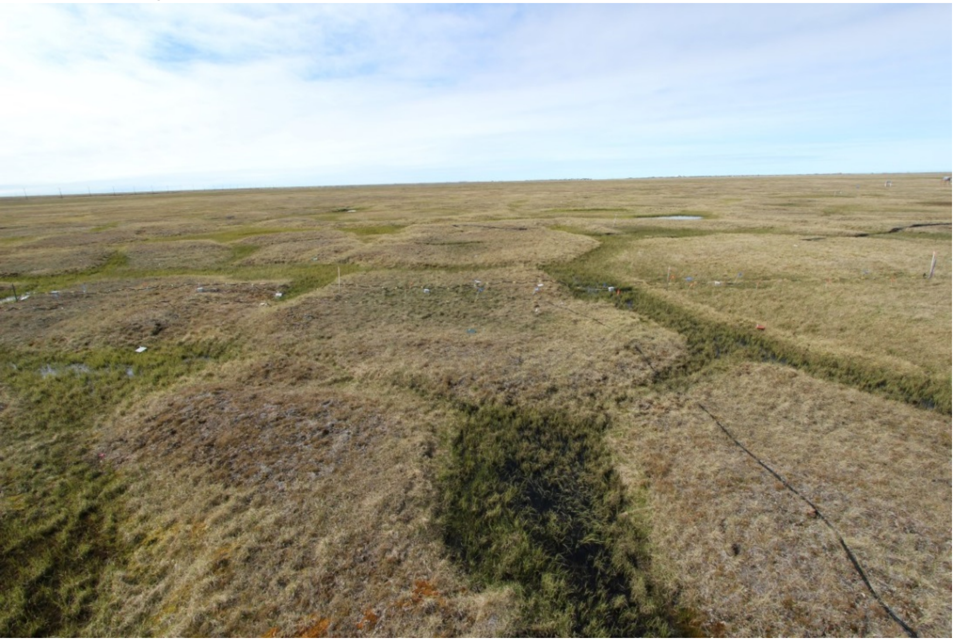
June 29



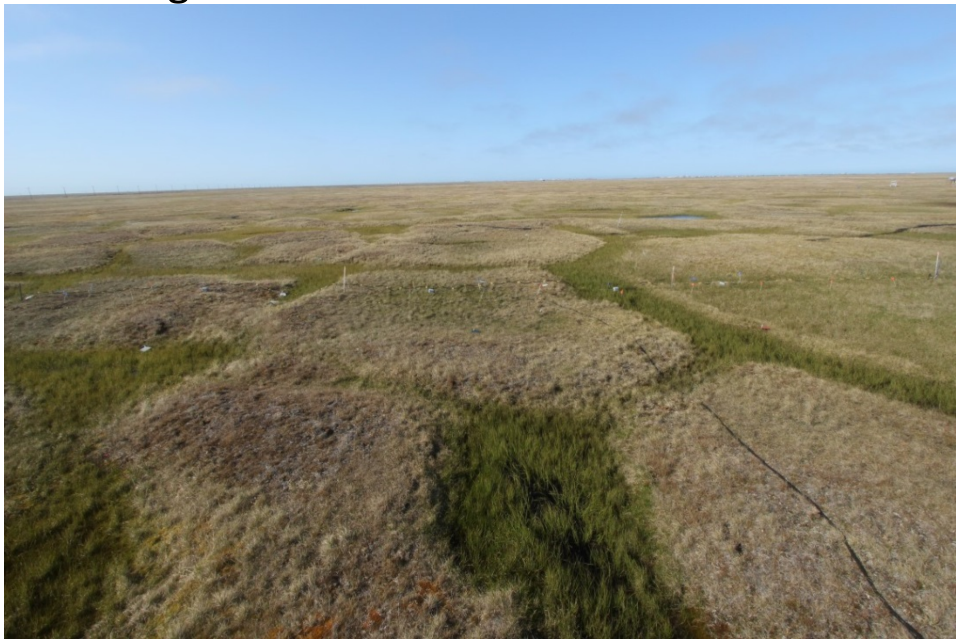
July 5



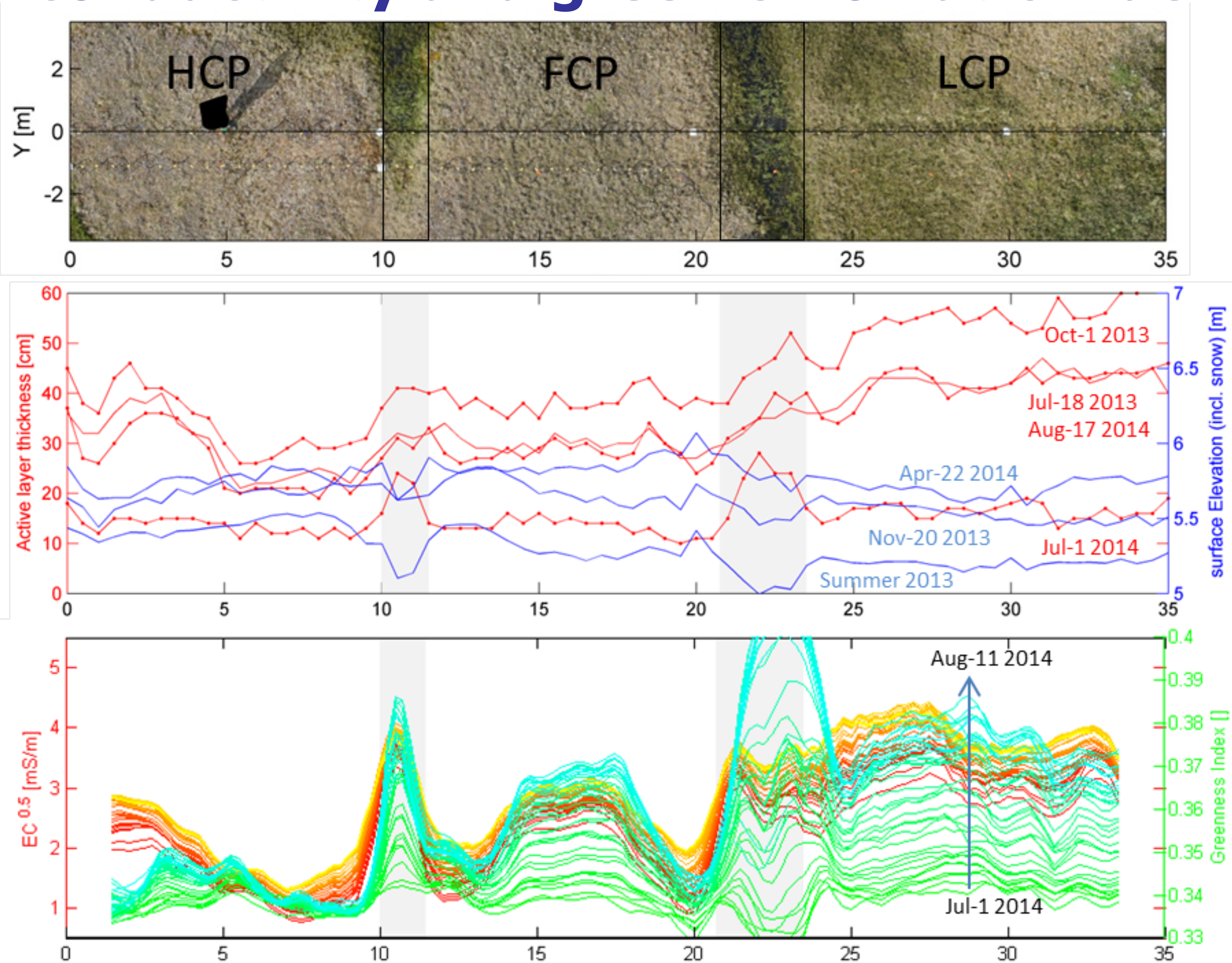
July 19



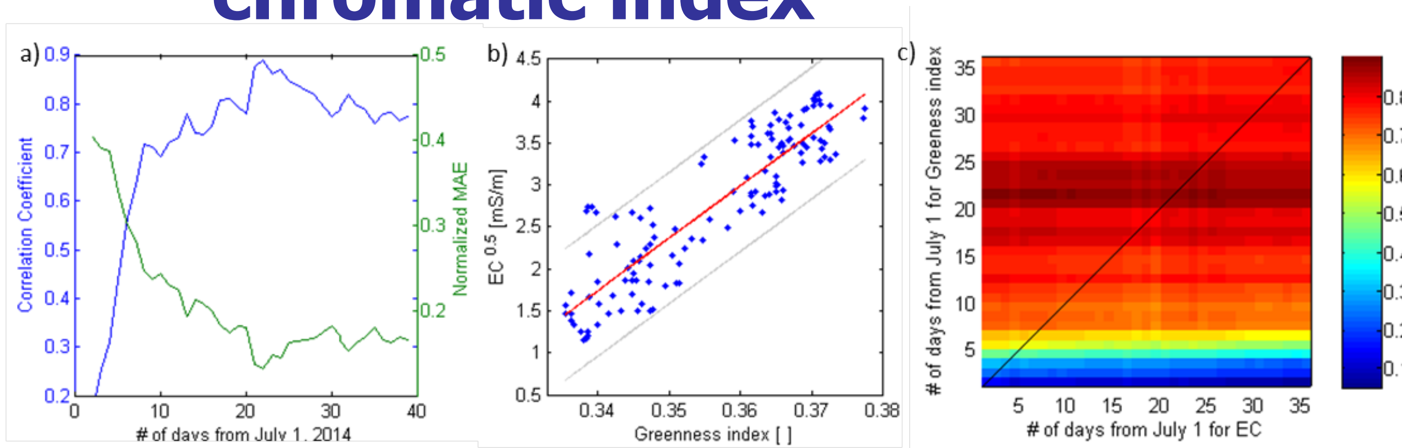
August 10

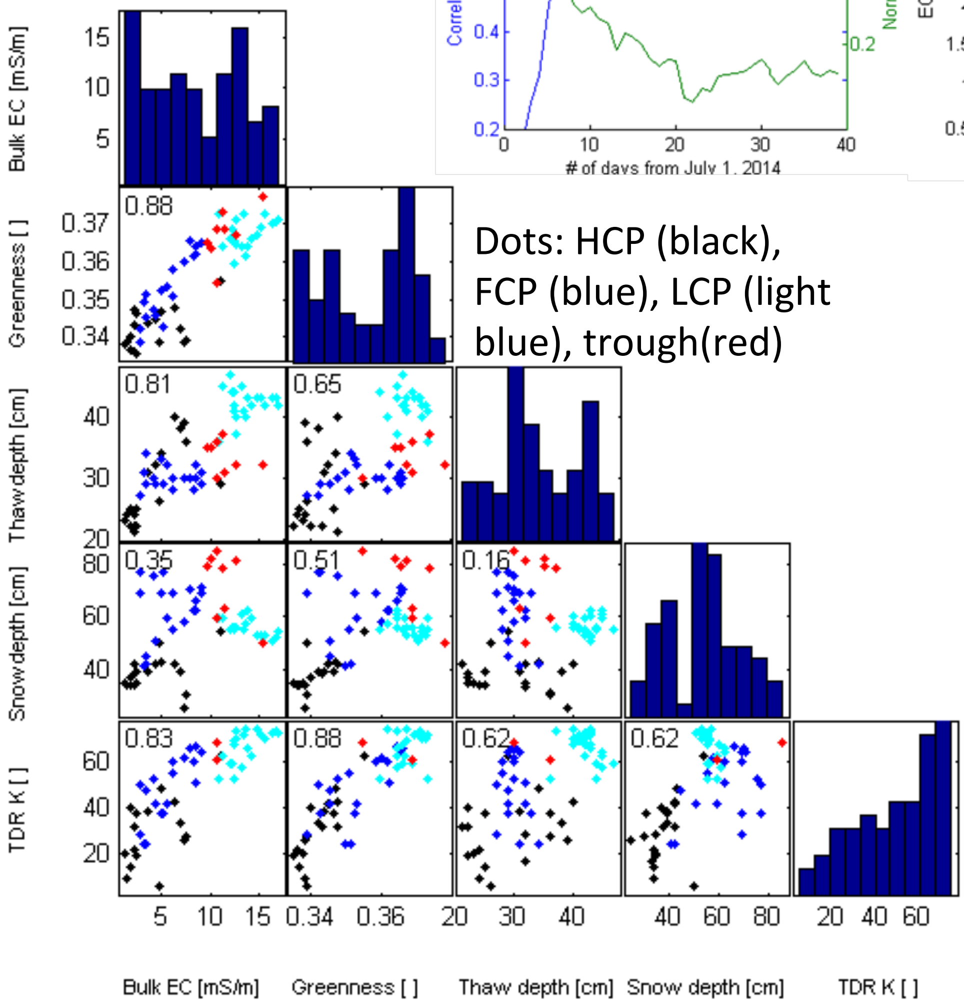


Co-variability in thaw layer thickness, electrical conductivity and green chromatic index



Links between thaw layer properties and green chromatic index

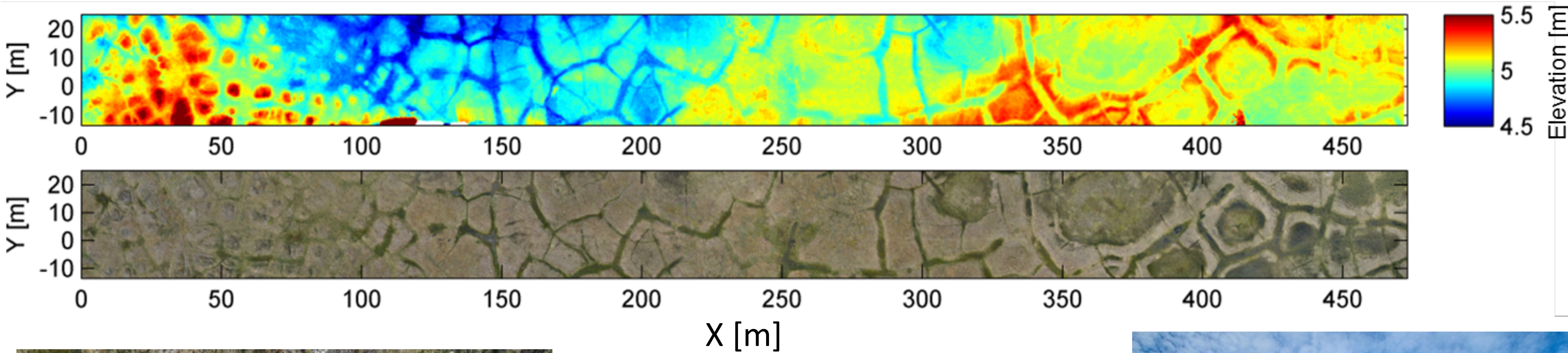




Dots: HCP (black), FCP (blue), LCP (light blue), trough(red)

- El. conductivity in thawed layer is strongly correlated (>0.88) with the greenness index at the peak of the growing season
- Greenness index is less auto-correlated over time than the bulk conductivity
- Thaw layer thickness shows strongest correlation with bulk electrical conductivity and then greenness index.
- Polygon type can be used to drive functional zonation
- Green chromatic index is more robust than NDVI for low-altitude imaging

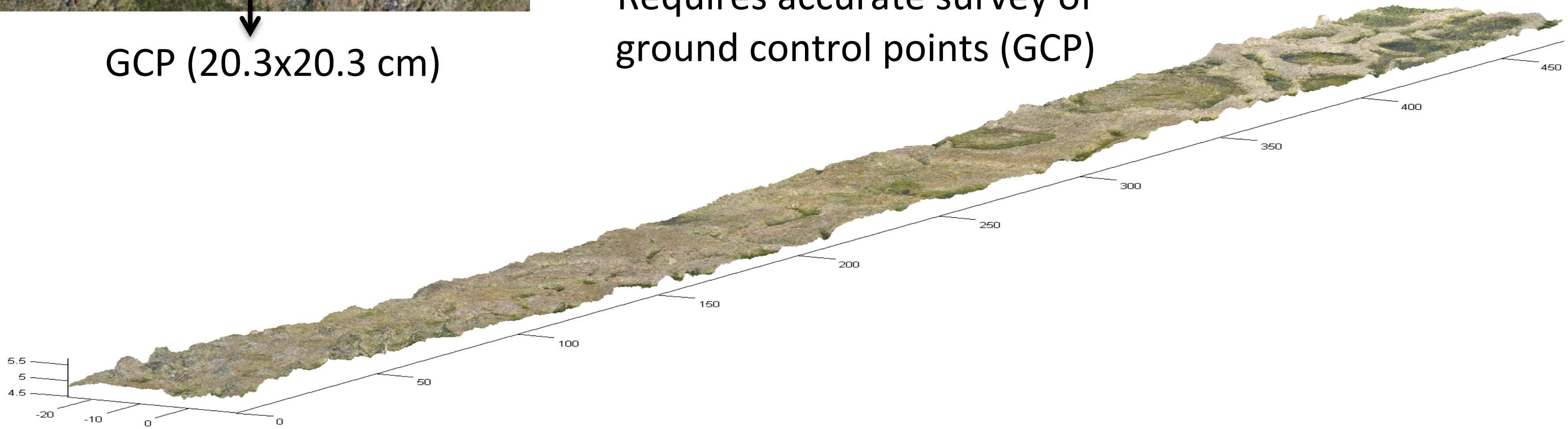
Landscape imaging at larger scale



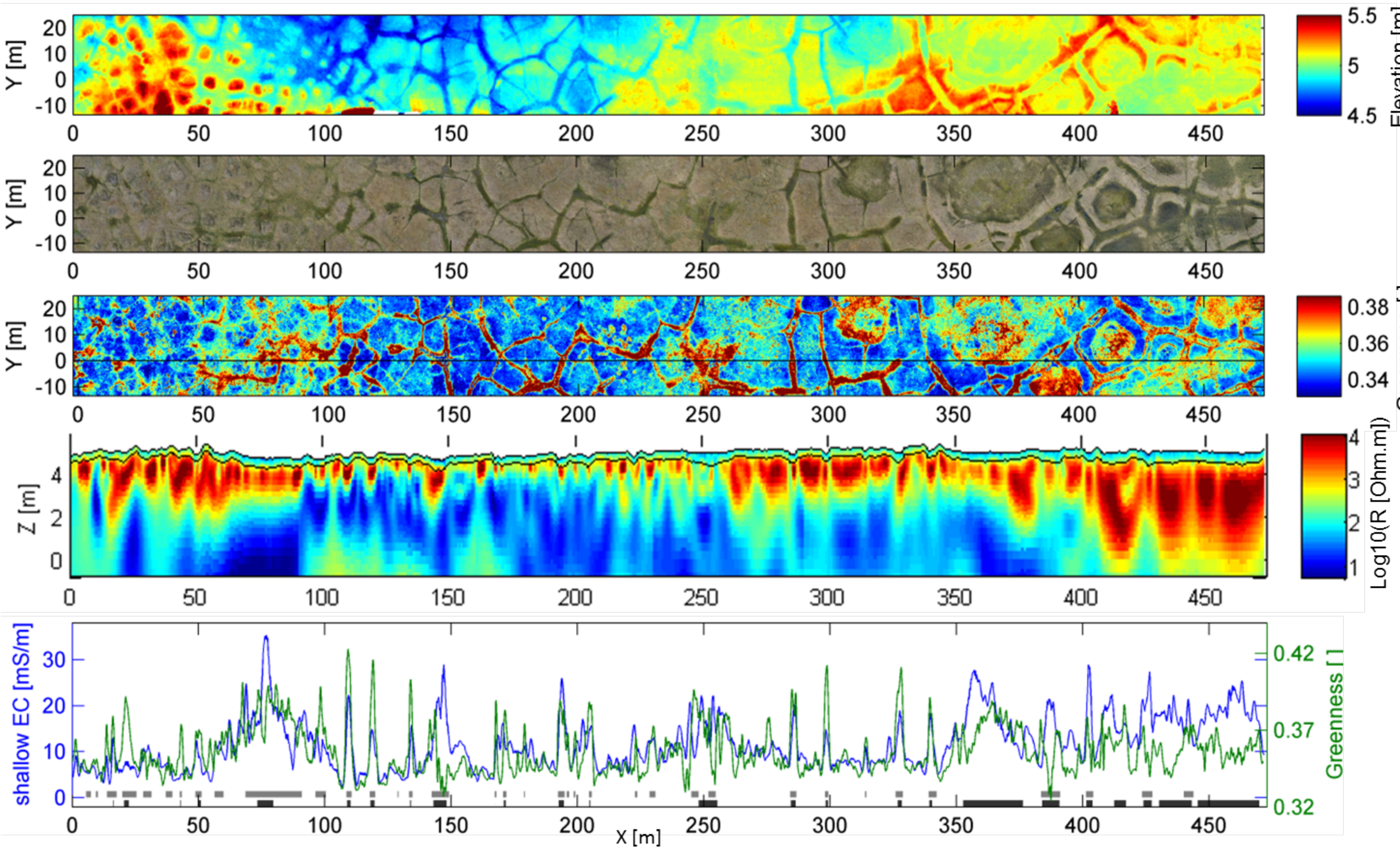
GCP (20.3x20.3 cm)

Mosaic and DEM reconstruction using optical camera and structure from motion techniques:

- Resolution < 0.05 m
- Accuracy in x-y-z < 0.1 m
- Requires accurate survey of ground control points (GCP)



From intensive site to larger spatial scales



- Soil electrical conductivity from the top 20 cm in ERT and collocated green chromatic index shows correlation coefficient >0.75 with lowest match where surface water is deep

Upscaling of Ecosystem Functioning Properties

Points: Ground truth and point-scale data (e.g., ALT, Wc, NDVI, CO_2 fluxes, core data)

Find/validate correlations to geophysics and remote sensing

Lines: Spatially continuous geophysical/aerial imaging

Define subsurface/vegetation/geomorphology functional zones

Site: Remote sensing dataset (Lidar, multi-spectral)

Property distribution in each zone

Distribute zones over large areas

<u>Two-step Approach</u>

→ Identify **meaningful zones** with respect to **ecosystem functioning**

→ **Bridge** point data and remote sensing data

Wainwright, Dafflon et al., 2015

Conclusions

- Novel **autonomous coupled above- and below-ground monitoring** approach to quantify subsurface and surface dynamics and their interactions

- **Geophysics** provide important information on subsurface properties in a spatially and temporally continuous manner; critical to **bridge gap between point and remote sensing data**

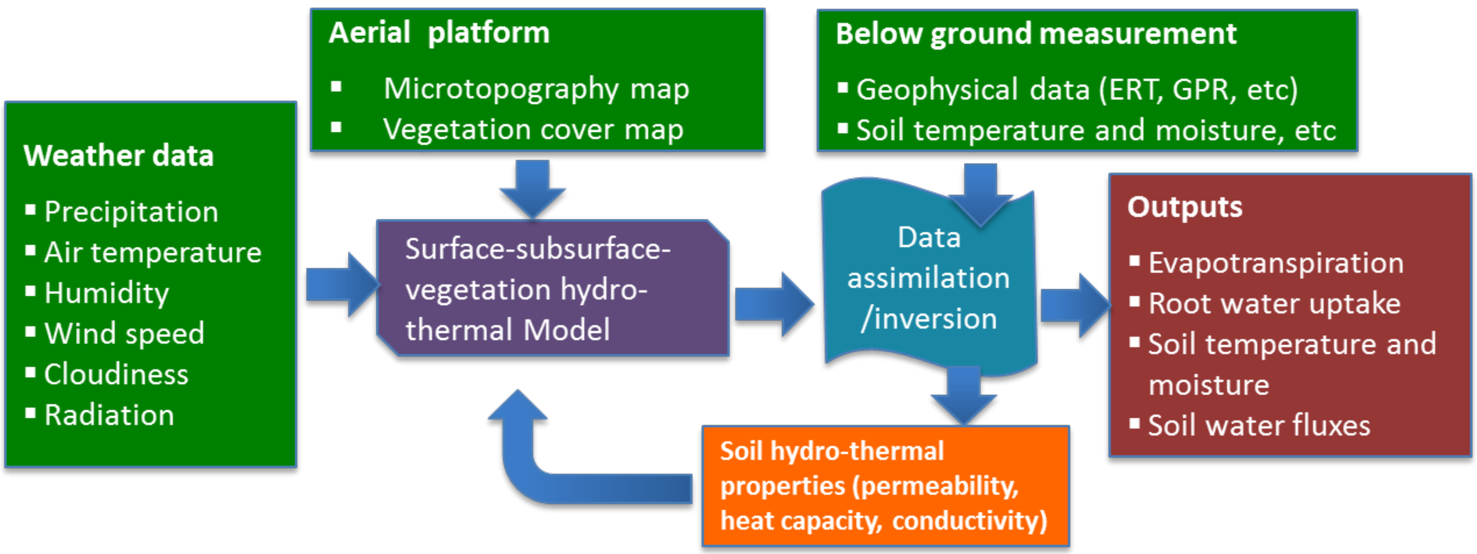
- Coupling **point-scale, geophysical and above-ground measurements** enables significant advances in estimating soil properties and freeze-thaw behavior

- **Subsurface and surface interactions** defined at intensive sites can be used with remote sensing dataset for **probabilistic mapping or functional zonation** of key ecosystem properties at larger spatial scales

Next Steps

- Optimizing sensor suite to combine direct and indirect measurements (above- and below-ground measurements) for multi-scale system characterization and understanding

- Thermal-hydrological-geophysical coupled inverse modeling to provide estimates of water and energy fluxes and hydraulic and thermal parameters needed to constrain biogeochemical models



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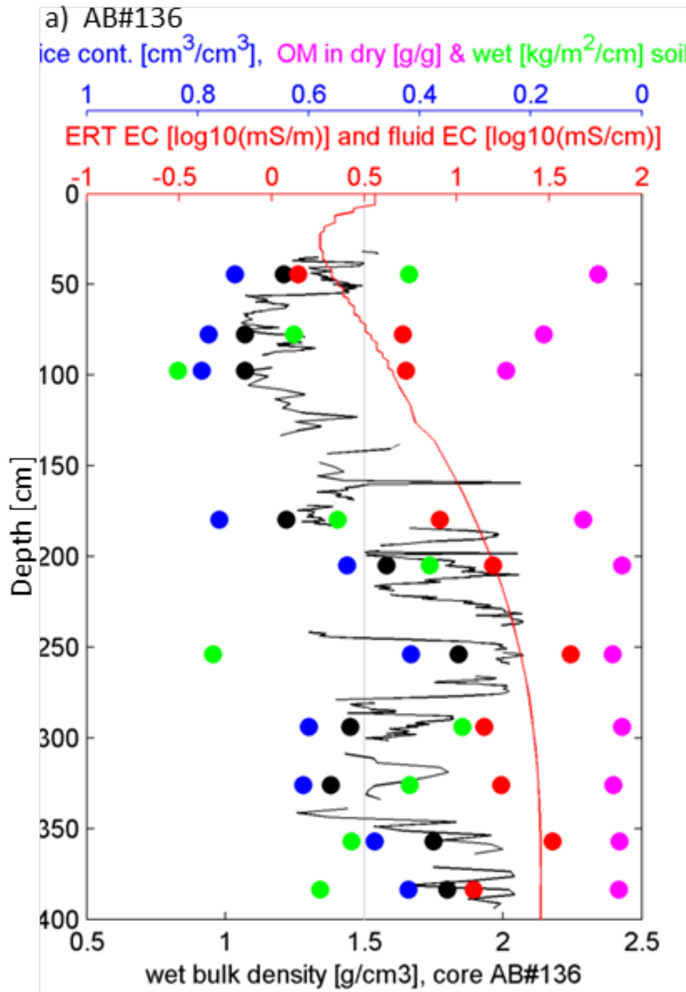


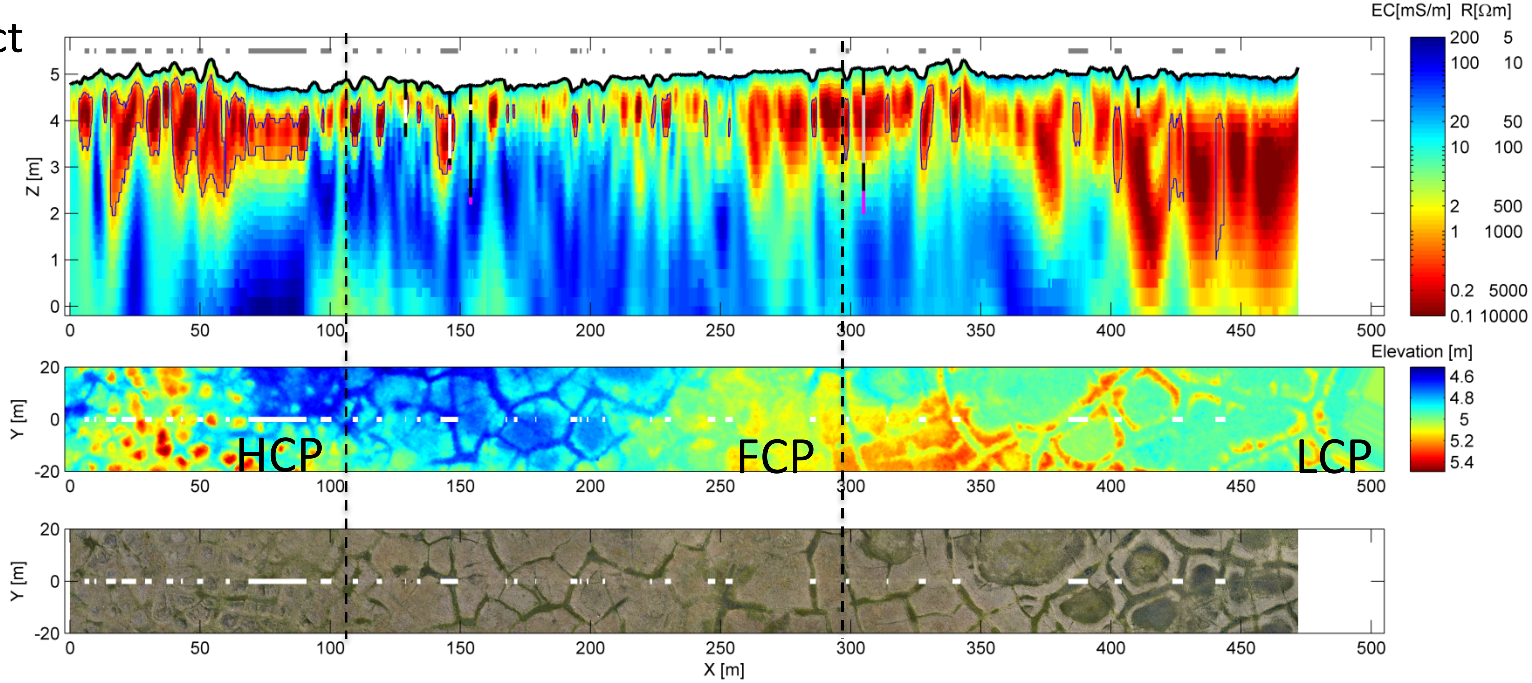
a) AB#136
ice cont. [cm3/cm3], OM in dry [g/g] & wet [kg/m2/cm] soil
1 0.8 0.6 0.4 0.2 0
ERT EC [log10(mS/m)] and fluid EC [log10(mS/cm)]
-1 -0.5 0 0.5 1 1.5 2
Depth [cm]
0 50 100 150 200 250 300 350 400
0.5 1 1.5 2 2.5
wet bulk density [g/cm3], core AB#136

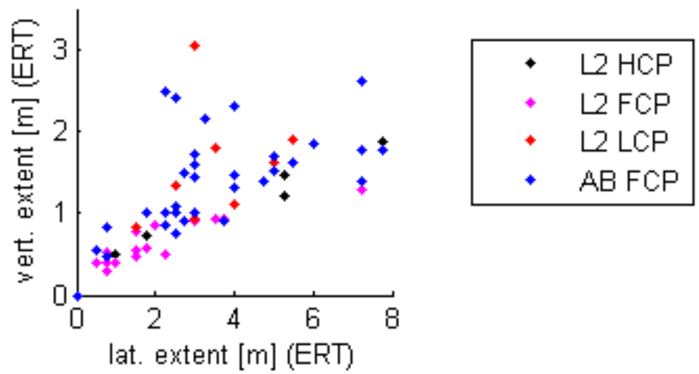
Surface-subsurface co-variability

L2 transect

"ERT" ice along:
75% of HCP interval
17% of FCP interval
19% of LCP interval

Troughs represent:
47% of HCP interval
17% of FCP interval
18% of LCP interval

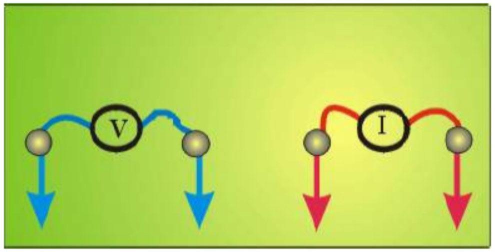




- Very large HCP "ERT" ice-wedges are a combination of multiple ones (numerous cracks)
- Ice-wedge dimension depends more on trough size (and density) than polygon type
- Collocated high-resolution data enables pattern recognition and delineation (in progress)

Electrical conductivity (EC) based methods

Electrical resistivity tomography (ERT)



Slow acquisition

Limited by contact resistance

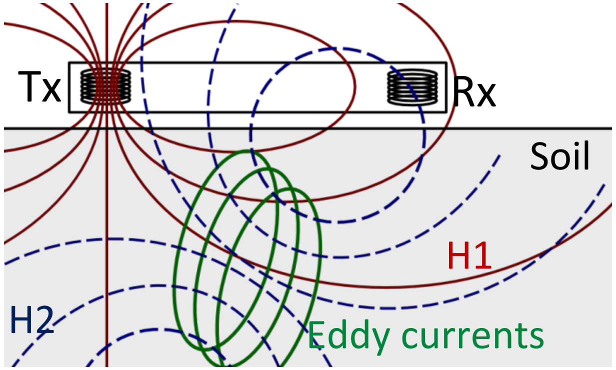
Variable depth of investigation

Limited non-uniqueness

No calibration required

⇒ High-resolution imaging at specific sites (during growing season)

Frequency Electromagnetic Induction (EMI) portable tools



Very fast acquisition

No contact required

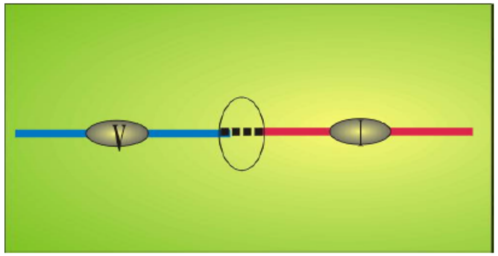
Very shallow sensitivity

Non unique solution

Calibrations issues

⇒ Potential to estimate thawed layer properties (in top 0.5 m) over large areas (during growing season)

Capacitively Coupled Resistivity (CCR) method



Fast acquisition

Limited contact required

Shallow sensitivity

Non unique solution

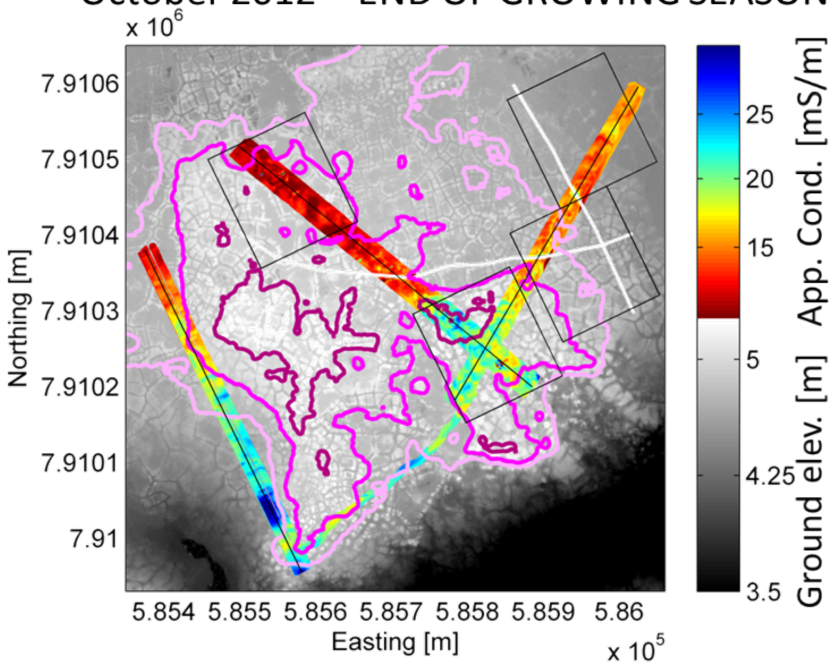
Limited calibration issue

⇒ Potential to estimate permafrost properties (in top 6 m) over large areas (in winter)

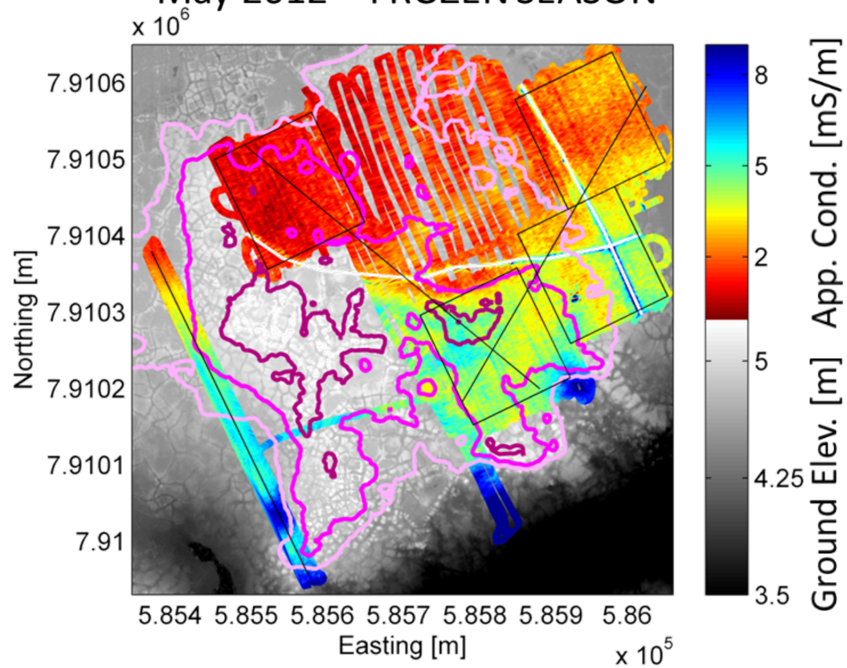
2D map of electrical conductivity distribution

EM38 map

October 2012 – END OF GROWING SEASON

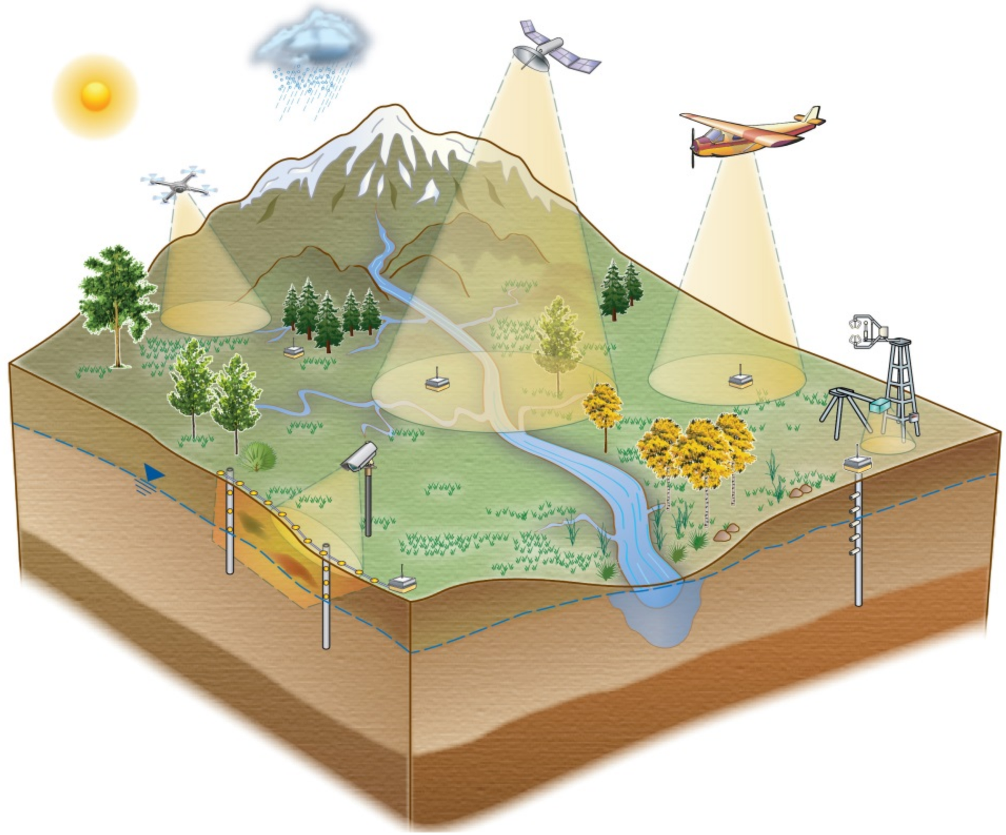


May 2012 – FROZEN SEASON



-> saline layer present at variable depth and not only correlated with topography

Technology can help multi-scale understanding



Quantifying spatiotemporal distribution of soil properties, ET, water/snow distribution, groundwater and surface flow required an adaptive and optimized monitoring strategy that enables:

- combining direct and indirect measurements (above- and below- ground measurements) for multi-scale system understanding
- Investigation of links between subsurface hydro-biogeochemical properties and remote sensing data to enable upscaling
- Ground truthing and calibration of remote sensing datasets