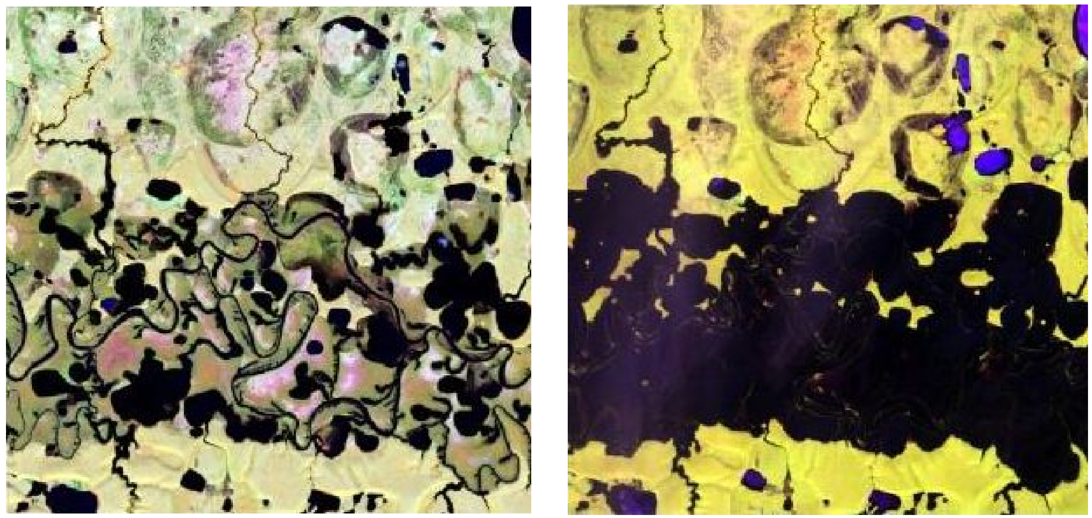
Climate change and the carbon cycle of frozen floodplains.



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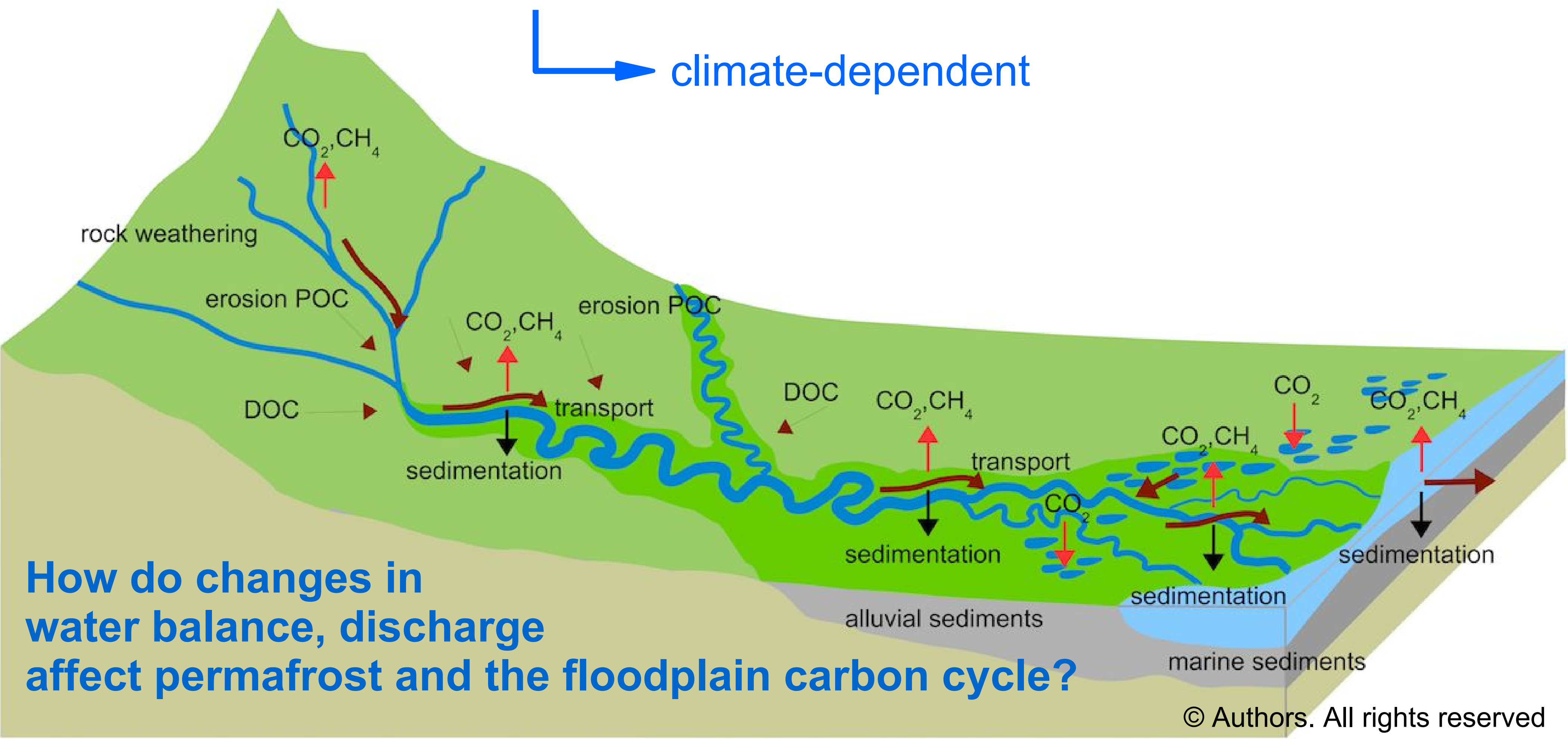
River plain carbon cycle

Transport / emission of dissolved carbon species
Erosion, transport and re-sedimentation of particulate carbon

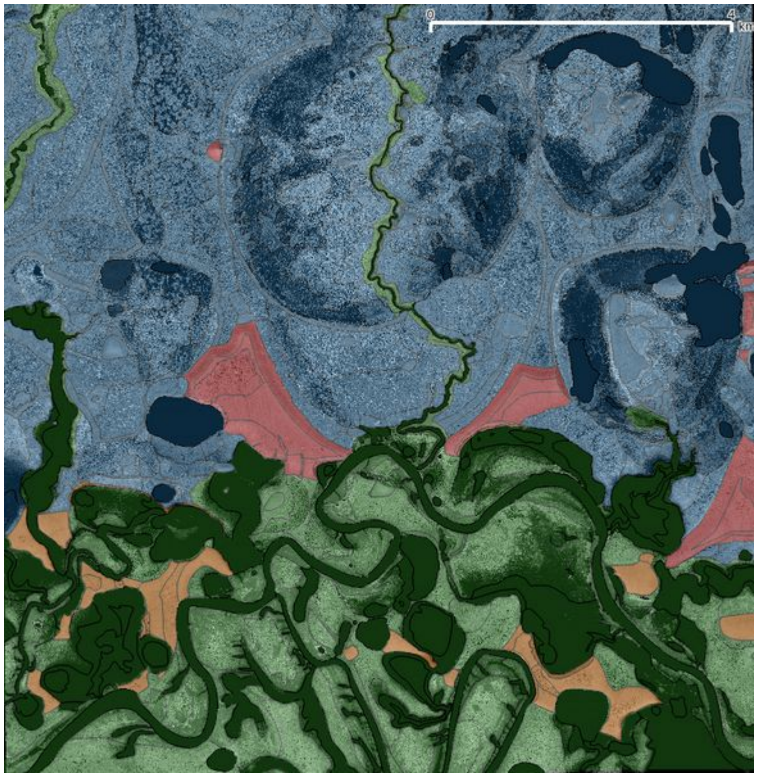
→ depends on river regime, morphology / channel mobility

→ climate-dependent



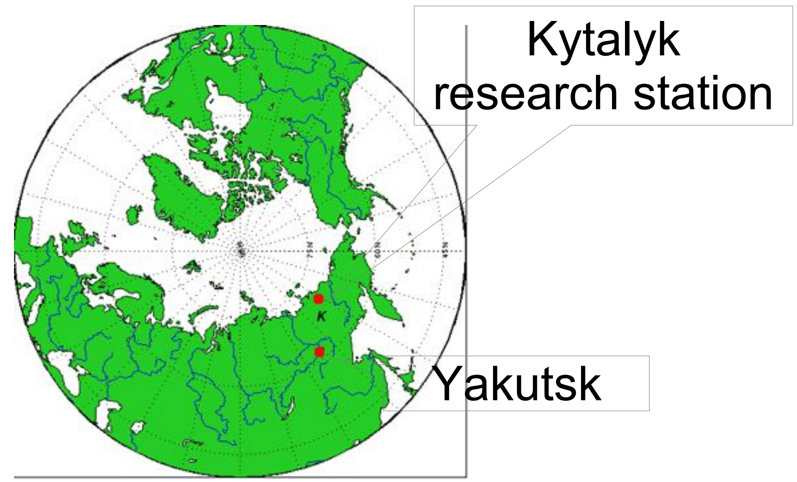
How do changes in water balance, discharge affect permafrost and the floodplain carbon cycle?

Berelegh floodplain, NE Siberia



Holocene floodplain
Drained thaw lake basins ***(alas)***
Yedoma remnants
Pleistocene(?) river terrace

4 km



Methods:

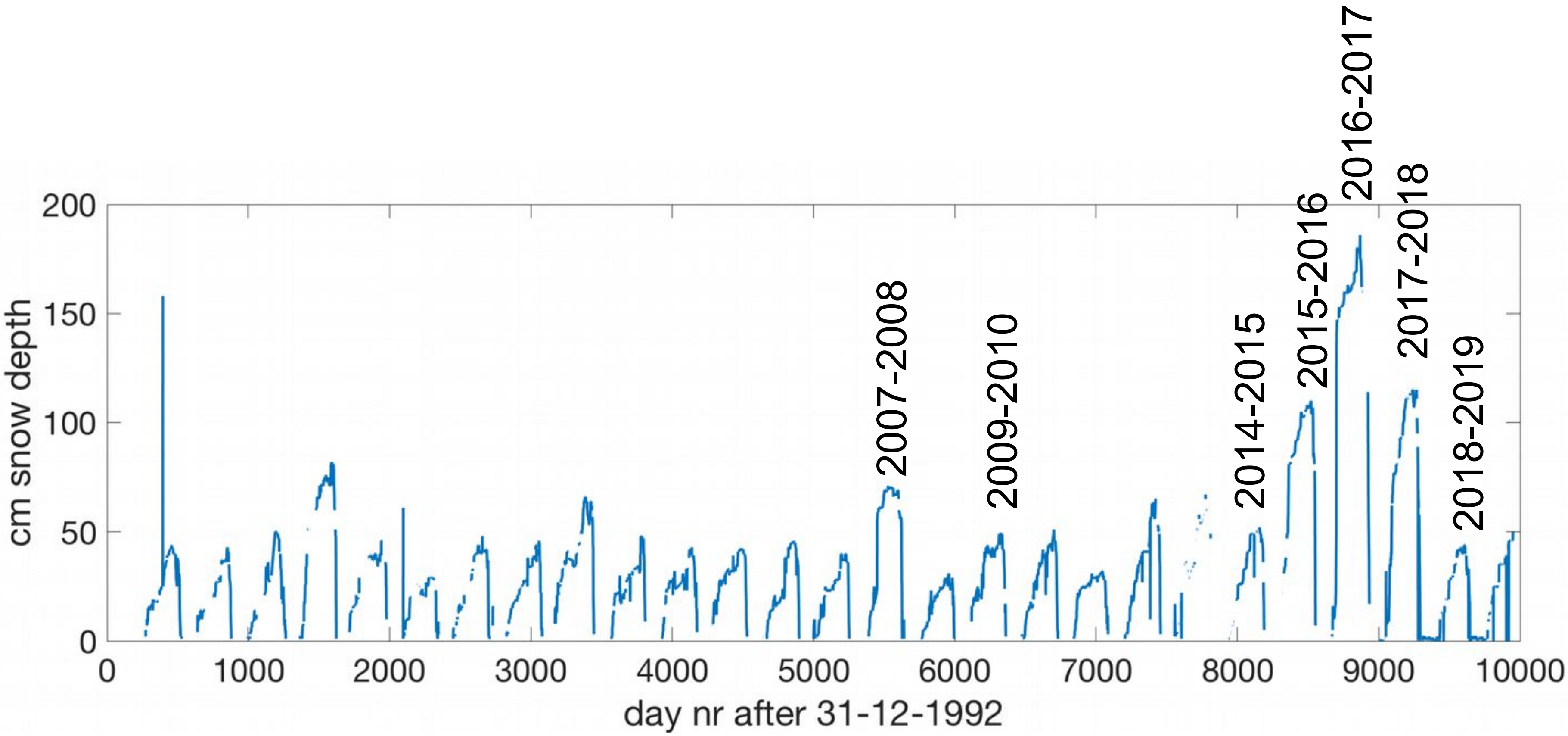
Interferometric SAR surface movement mapping

Multi-year high resolution satellite image study thaw pond development and river flooding

Geomorphological mapping

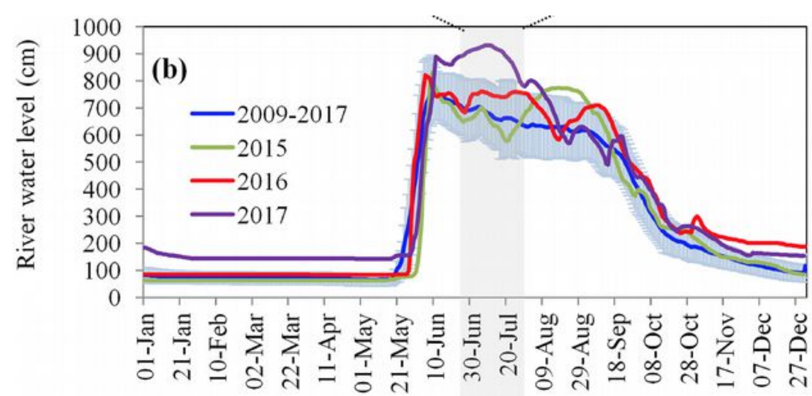
Active layer thickness data

Recent high river water and snow



2017 flood (Tei et al., 2019):

- High early flood peak early June
- Prolonged extreme flooding June and July
- Flood probability <= 1 in 49 years



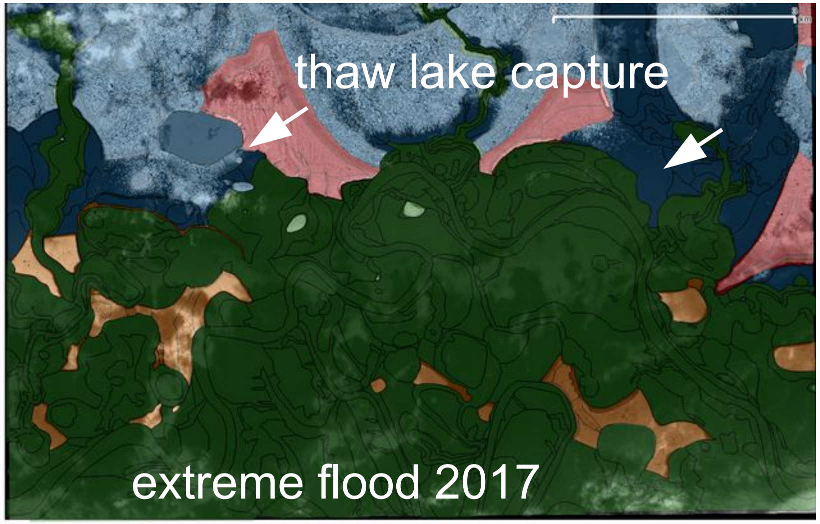
Results

1. The floodplain wetlands are

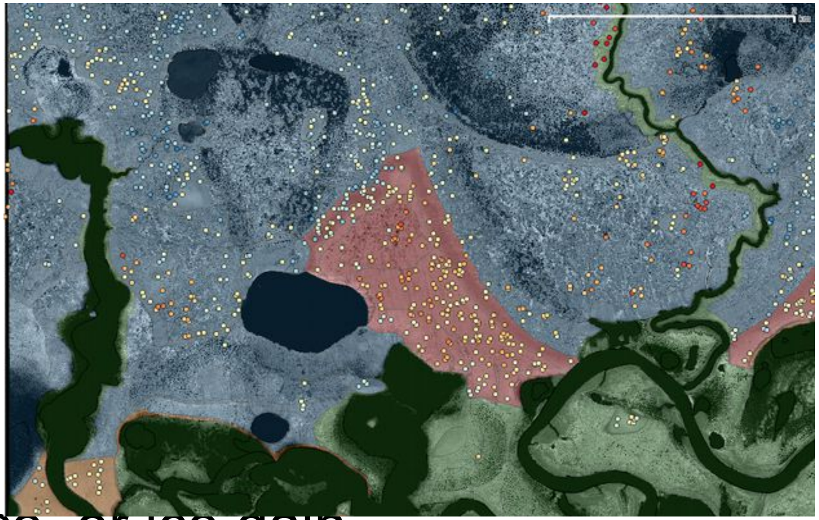
- a hotspot of CH_4 emission
- stores of carbon in sediments

2. Extreme floods expand the floodplain:

- permafrost thaw, subsidence
- capture of thaw lakes



Future projections: increased flooding of Siberian rivers (Shkolnik et al. (2016): **2-5%** increase in flood area by 2050 - 2059)



3. INSAR surface movement data:

- Subsidence in poorly-drained areas
- Well drained areas: no significant subsidence, or ice gain
- Sedimentation: on floodplain, peat accumulation in alases

See next slides also!

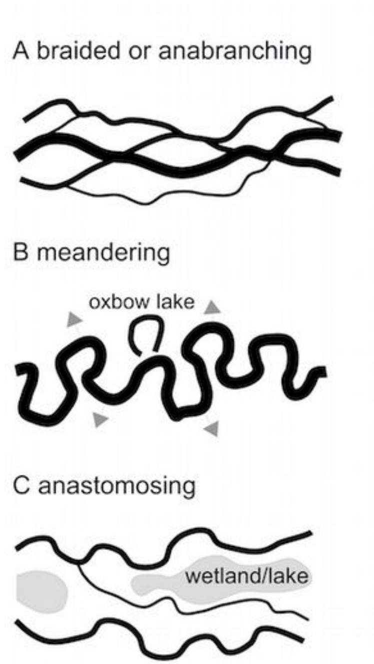
Permafrost rivers: carbon cycle diversity

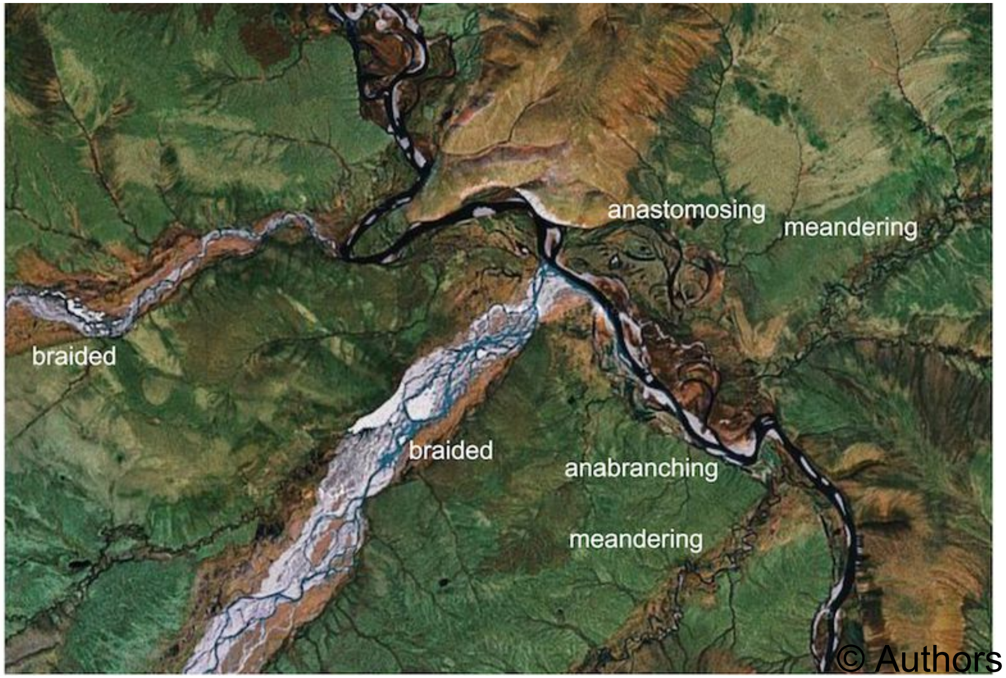
Nival or glacier-fed discharge regime, sensitive to drainage basin permafrost cover

Erosion processes linked to permafrost thaw
channel bank stability, thaw lake development

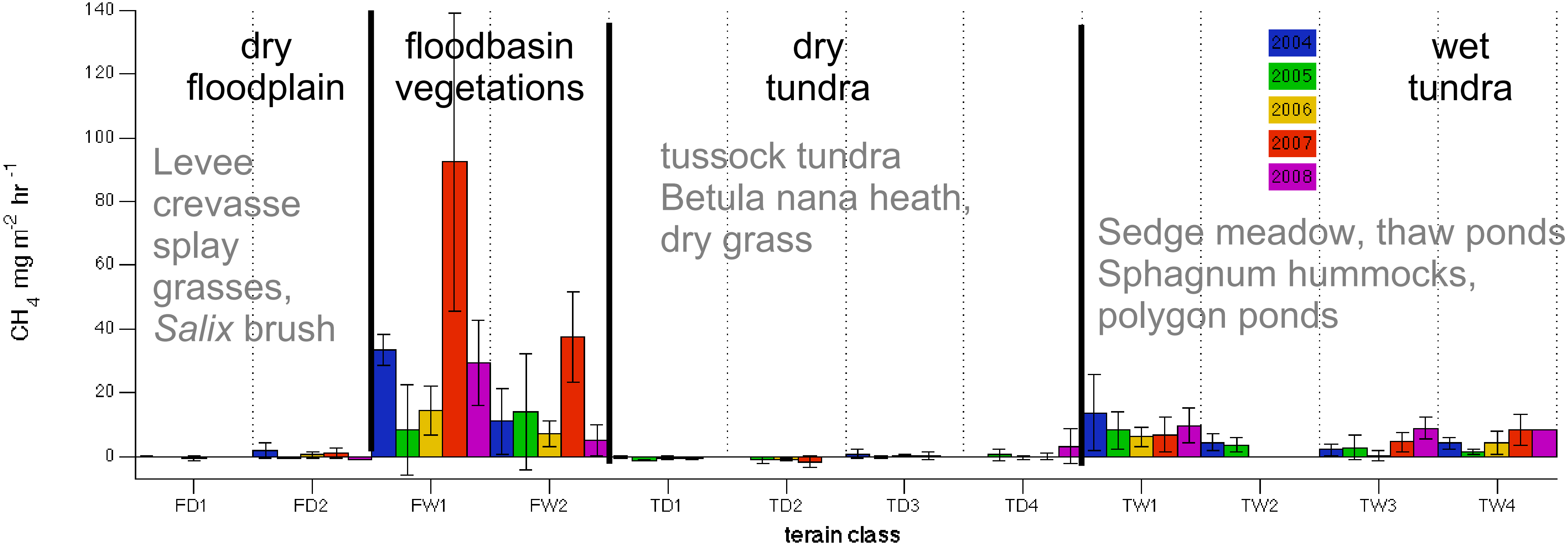
Diverse floodplain morphology affects:
carbon storage in sediments
wetland environments

Nutrient supply by floodwater





Carbon cycle significance: CH_4

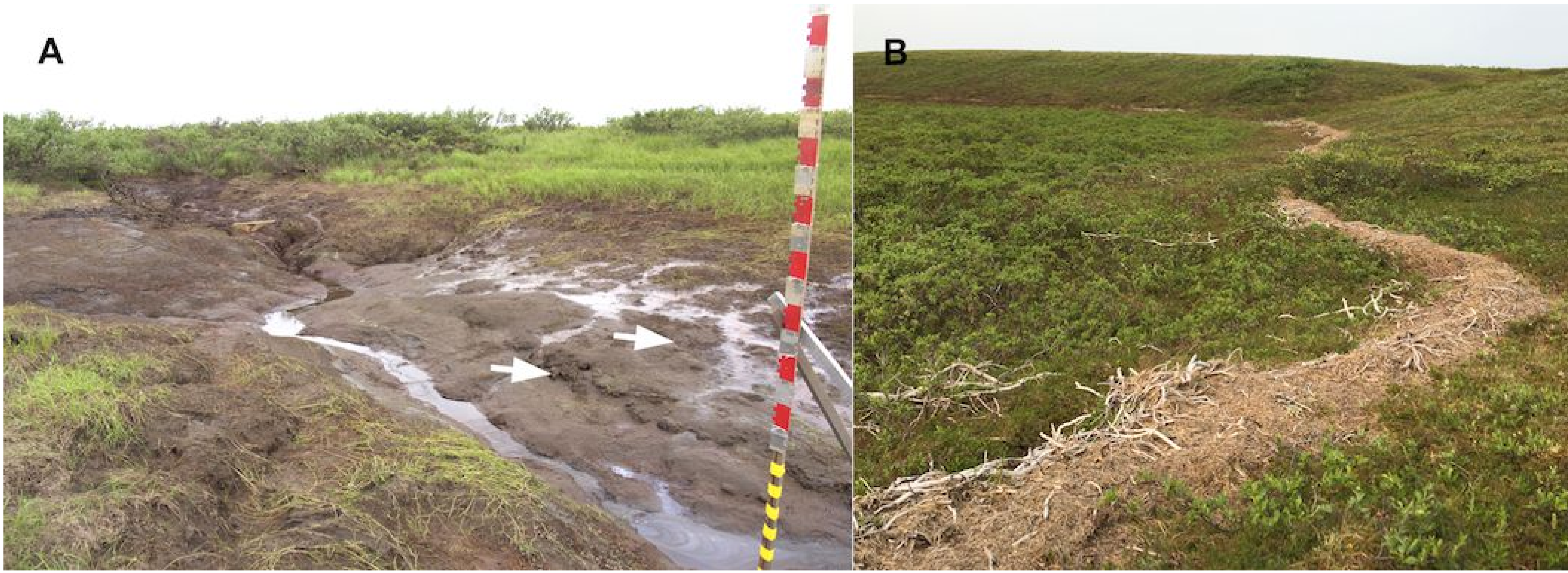


Wet floodplain vegetations:

1. Higher CH_4 fluxes than comparable sites (water level, vegetation) on oligotrophic tundra see e.g. FW2 and TW1 class above: both are sedge meadows with same vegetation composition and above-surface water table. Nutrient conditions cause higher primary production on floodplain FW2 class (Van Huissteden et al., 2005, 2009)

2. Evasion of CH_4 from river flood water in spring is an important process (Morozumi et al., 2019)

Carbon cycle significance: Organic sediment



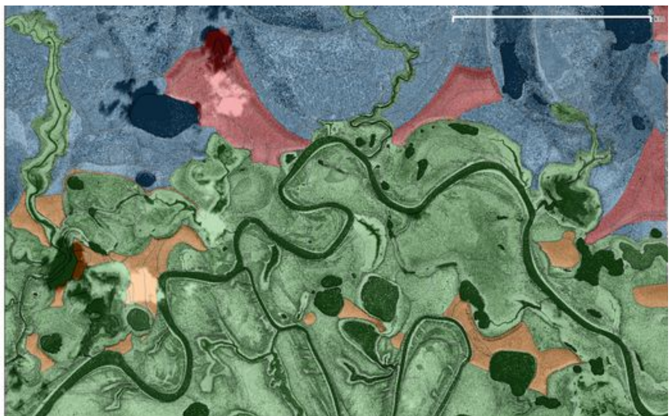
Active carbon sedimentation and burial:

- carbon in vegetation horizons in floodbasin sediment
- peat growth in floodbasin sediments
- particulate carbon deposition

Local floodbasin sedimentation rate: 0.5 ± 0.3 cm yr^{-1}

Carbon storage in floodplain sediments is poorly quantified (Hugelius et al., 2014; Van Huissteden, 2020)

River spring flood height



Low stand, end of summer (August 2010):
Thaw lakes:
If not connected with river: ± stable water level
River connected: water level follows river, drained in autumn

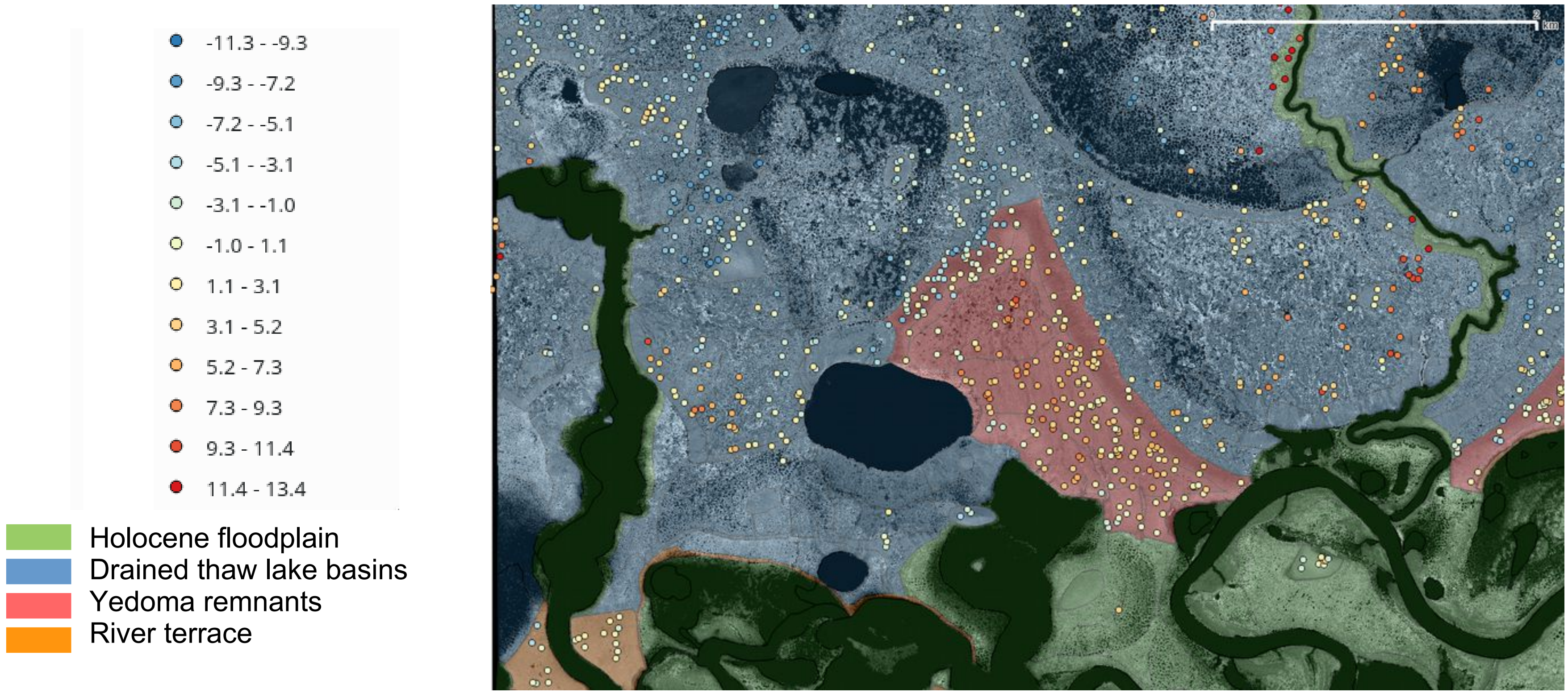
At receding, ± normal spring flood mid July 2015:
Channels are bank-full
All river-connected lakes filled
Floodbasins without lakes are partly flooded

Extreme spring flood, mid July 2017 (Tei et al., 2019)
after high winter precipitation, rain on snow, ice jams
Complete floodplain flooded except river terrace
River water invades normally non-flooded
drained thaw lake basin (DTLB) surfaces
One thaw lake invaded by river water, another nearly
(arrows)

INSAR data

Method: Persistent scatter interferometric SAR using Sentinel 1

Persistent scatterer: pixels that are not affected by surface property changes
3 year velocity rates from 2017-2019, flooding year 2017, uncertainty +-4 mm/yr



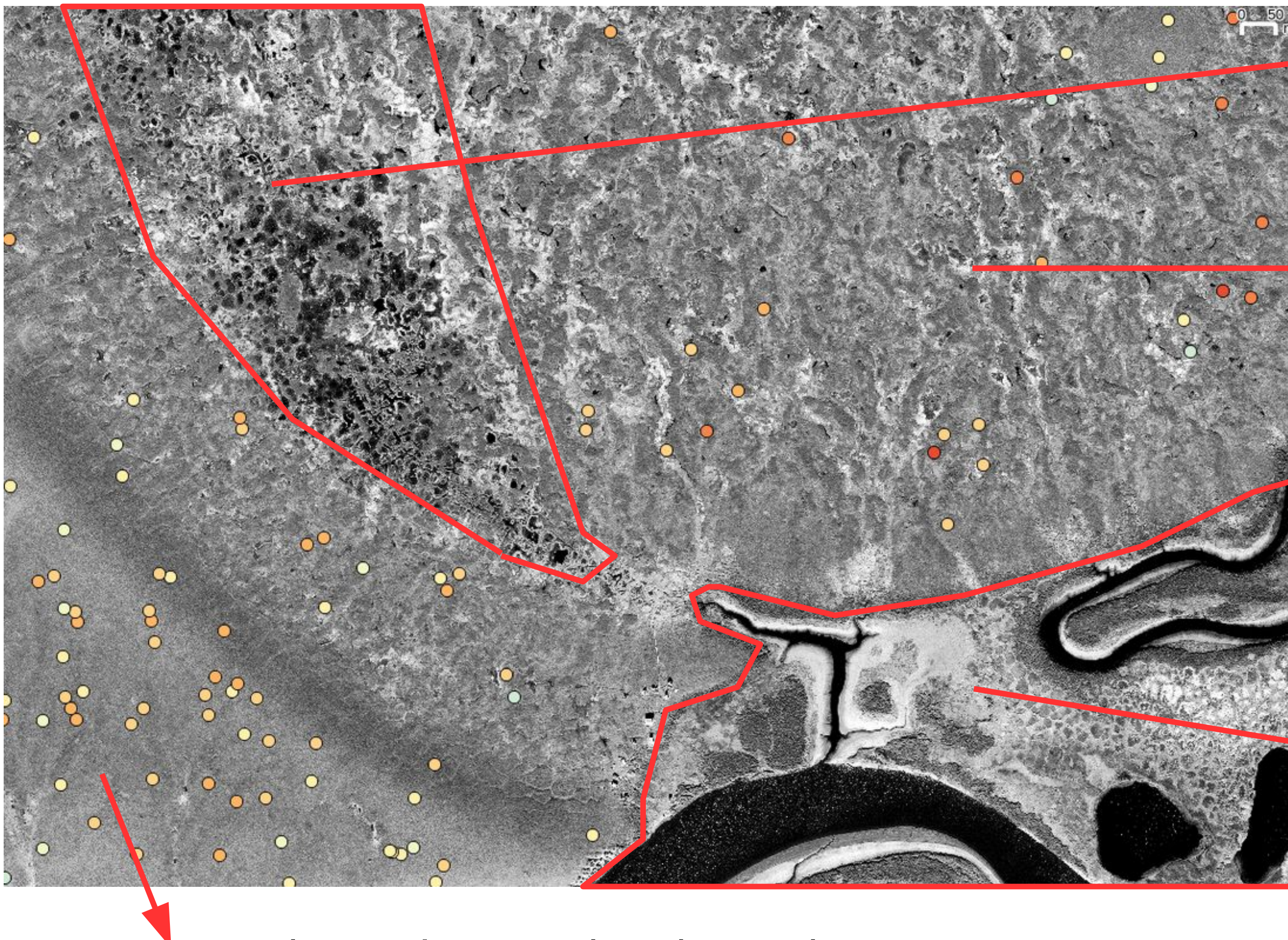
Processes affecting velocities:

- permafrost ice gain / loss (frost heave / thaw subsidence)
- slope and fluvial erosion
- sedimentation (peat growth / fluvial / colluvial deposition)
- tectonic movements (not considered here)

Data interpretation supported by geomorphological mapping and flood mapping based in high resolution Geoeye and Worldview sattellite images

Sampling bias

Cross-image requirement of coherence: ***may exclude dynamic surface types*** (vegetation change, flooding)



poorly drained areas: few points

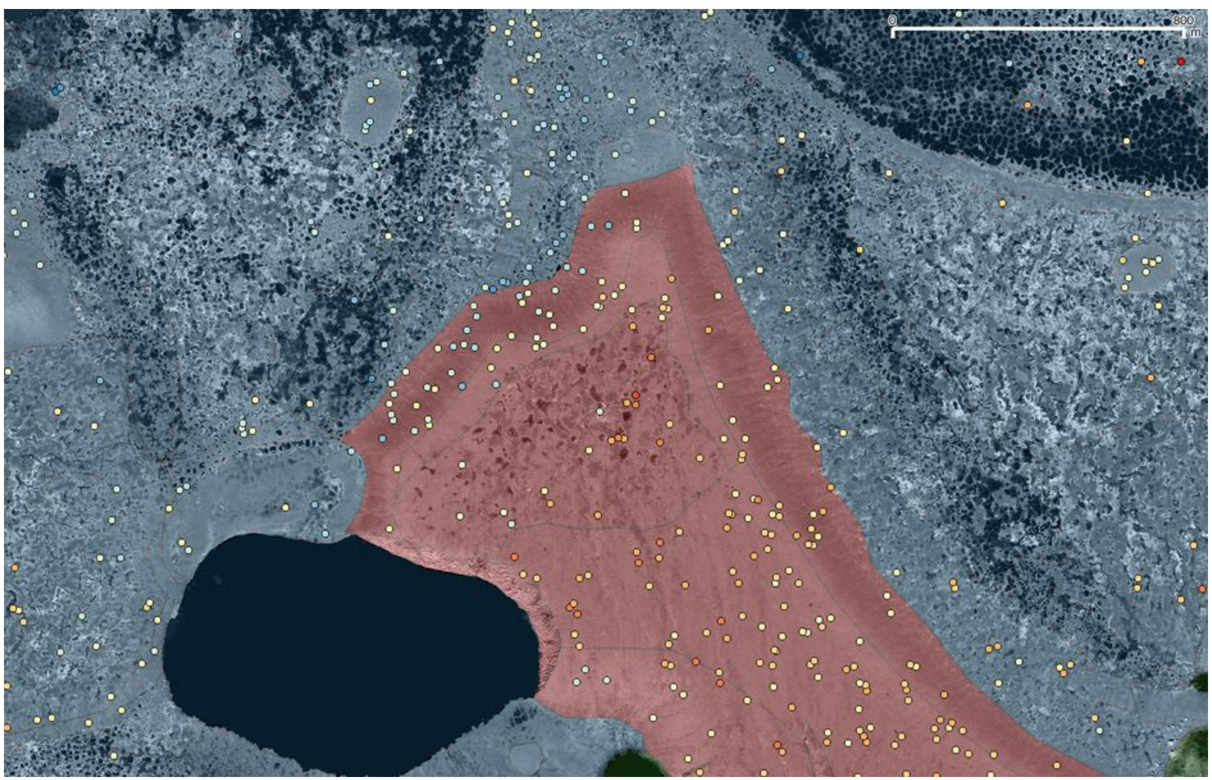
well drained thaw lake basin (alas) areas with stable vegetation: abundant points

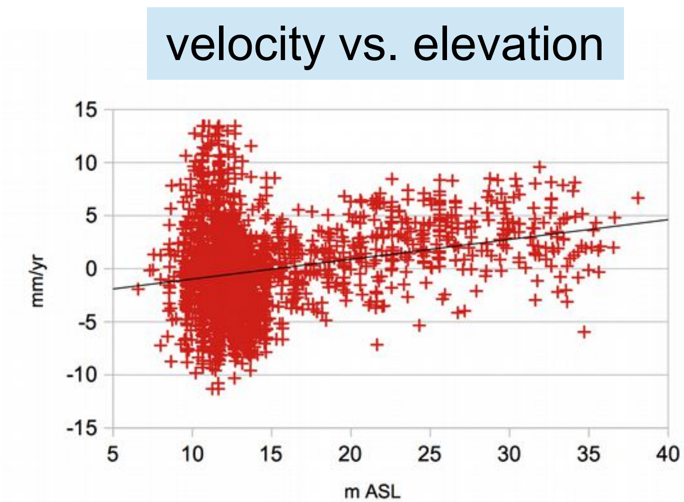
floodplain: few points

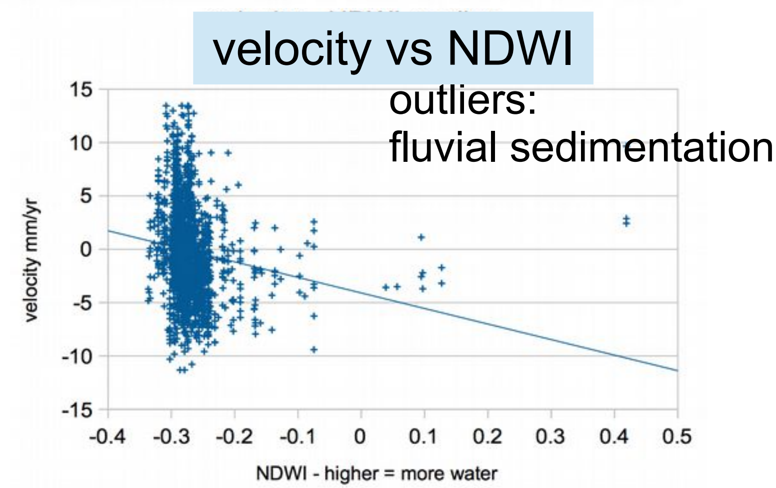
yedoma plateau: abundant points

INSAR comparison with geomorphology, high resolution images

Low-lying pond-rich thaw lake basins (alas) areas : subsiding
well-drained Yedoma and alas areas : not subsiding or heave
Higher pond density and higher NDWI water index : more subsidence ($p<0.01$)
Higher elevation : less subsidence
NDWI = normalize differential water index = (green - near infrared) / (green + near infrared)

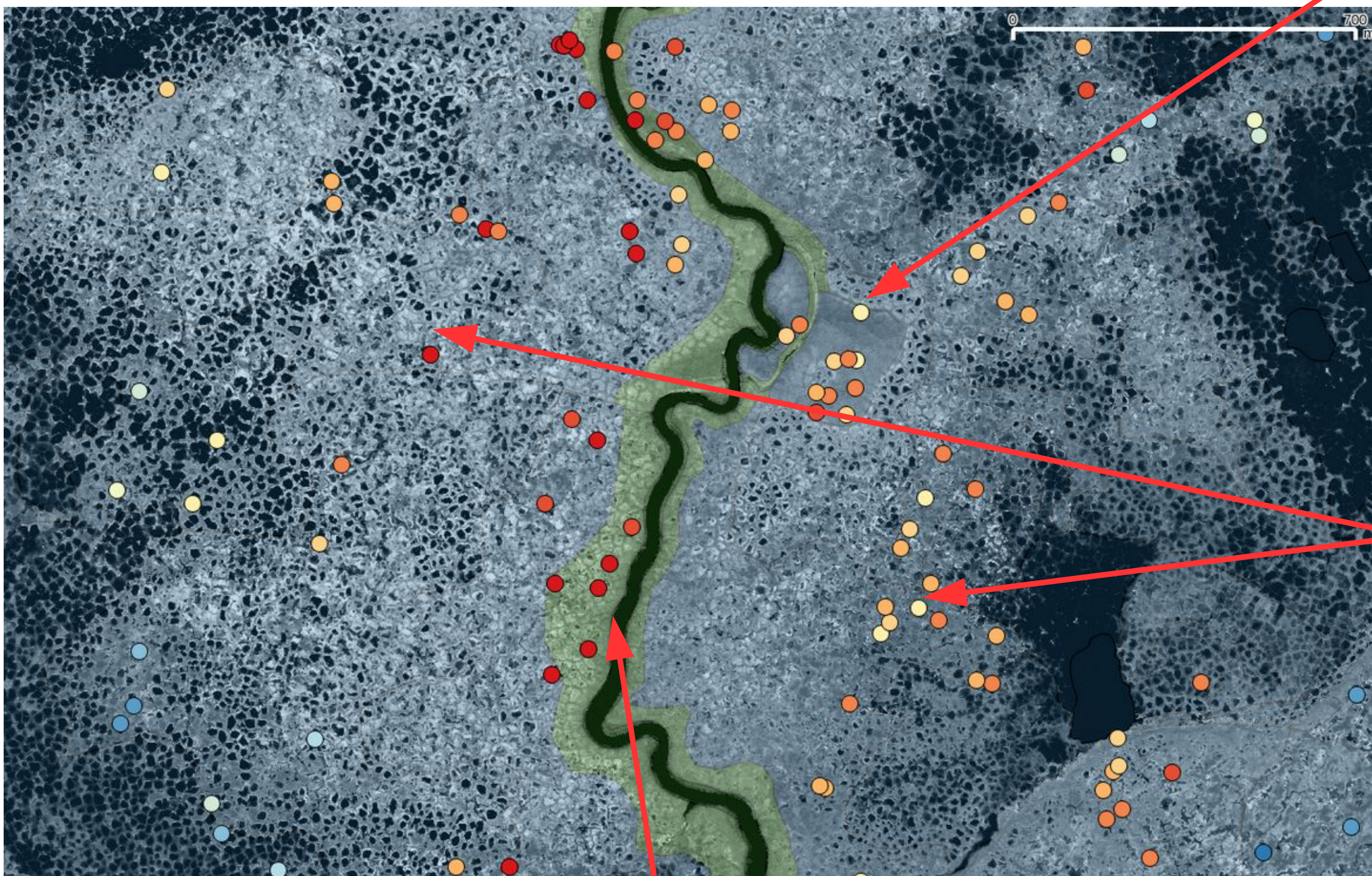






Examples drainage effect, peat growth, frost heave

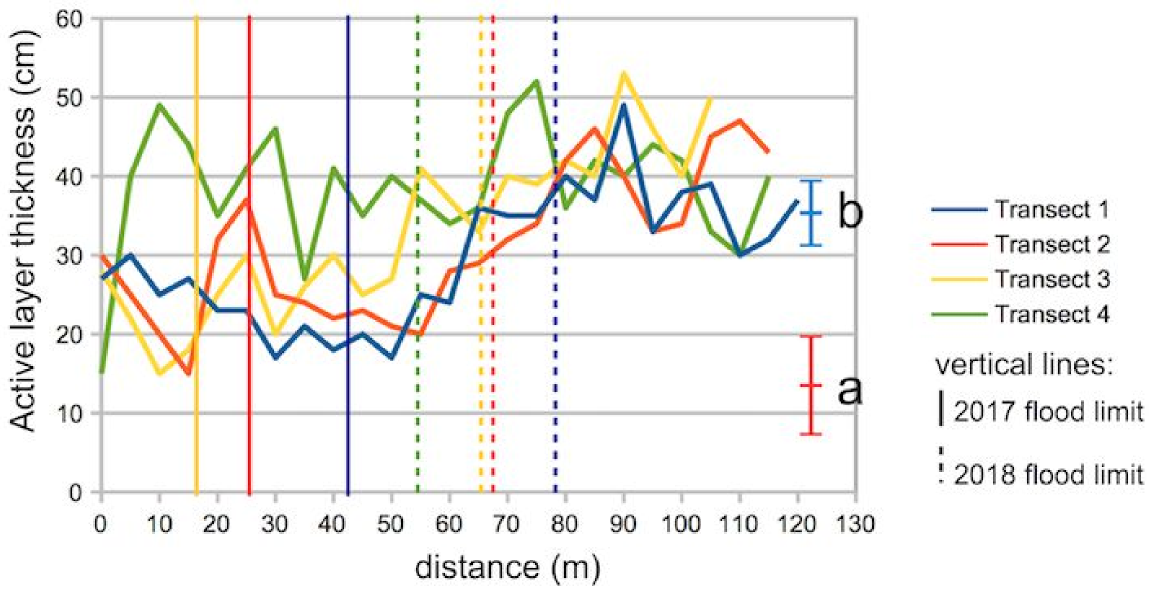
pingo complex: heave?

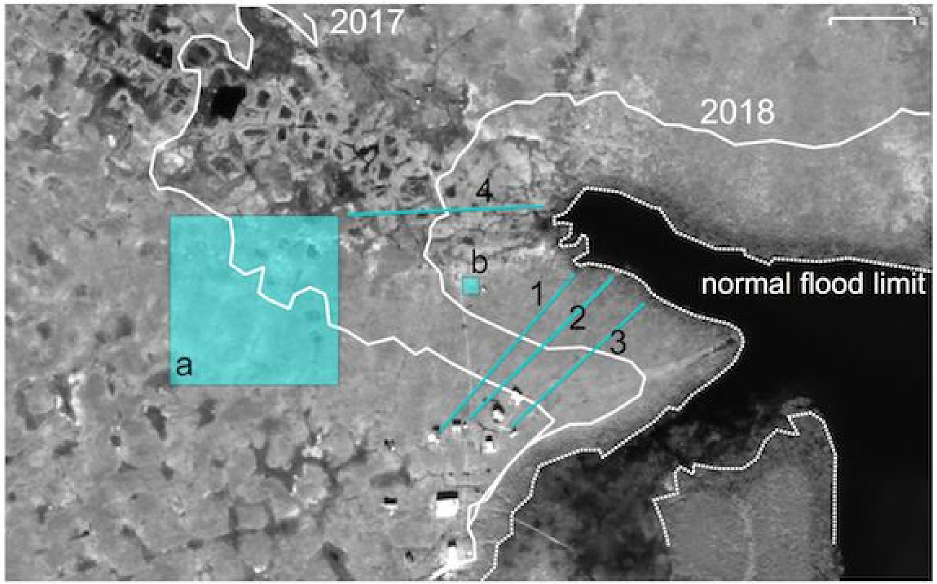


polygon areas in alas: spectral signature in satellite images indicates peat growth in ice wedge polygons

incised river channel in alas:
better drainage along banks
+ ice gain after ice loss in 2017 flood ?

Flooding affects active layer thickness





white lines: flood limits

Active layer depths in July 2018 along transects at ± right angle to 2017, 2018 flood limits

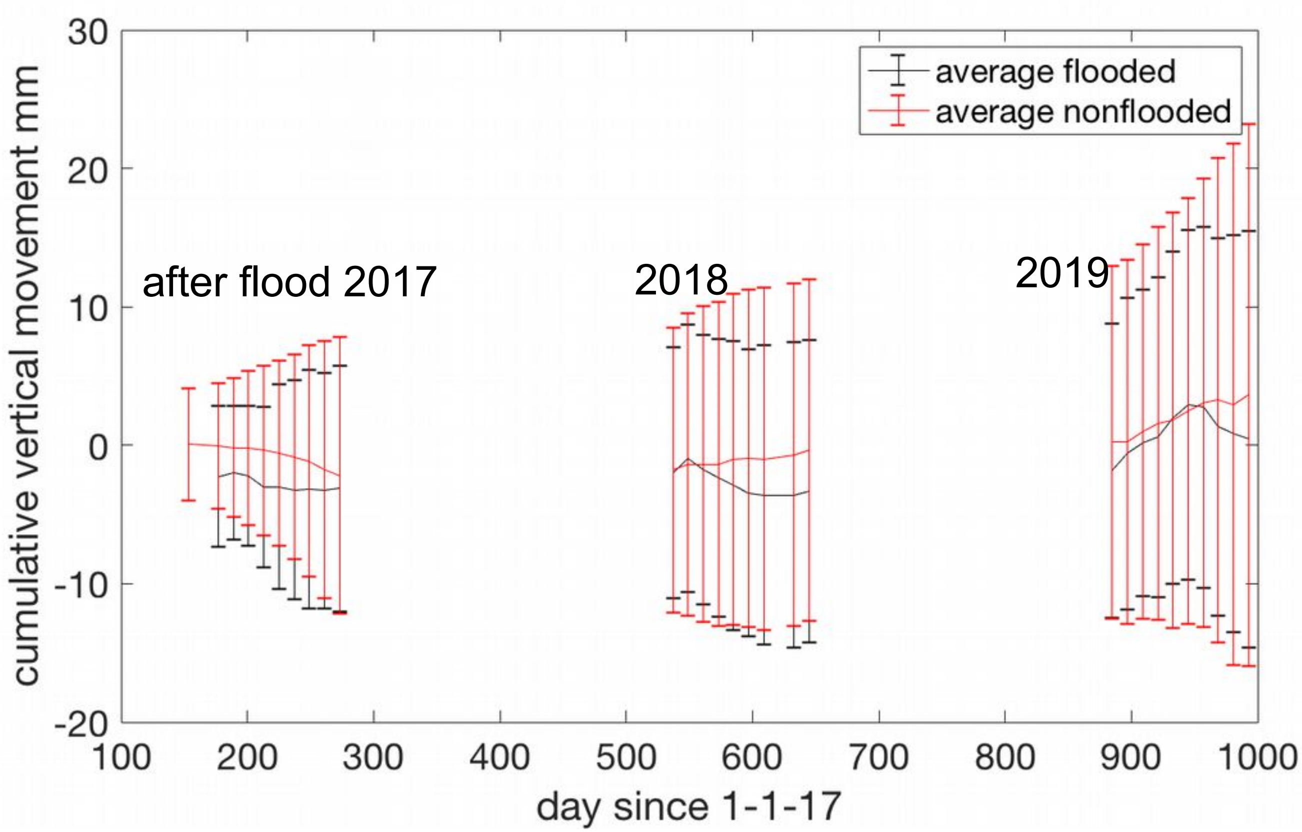
Transect 1, 2, 3 : Mesic (dry-moist) tussock tundra
increased active layer tickness in flood-affected areas

Transect 4 : Wet *Sphagnum*-dominated tundra
no clear effect of flooding

Subsidence after flooding

INSAR time series 2017-2019

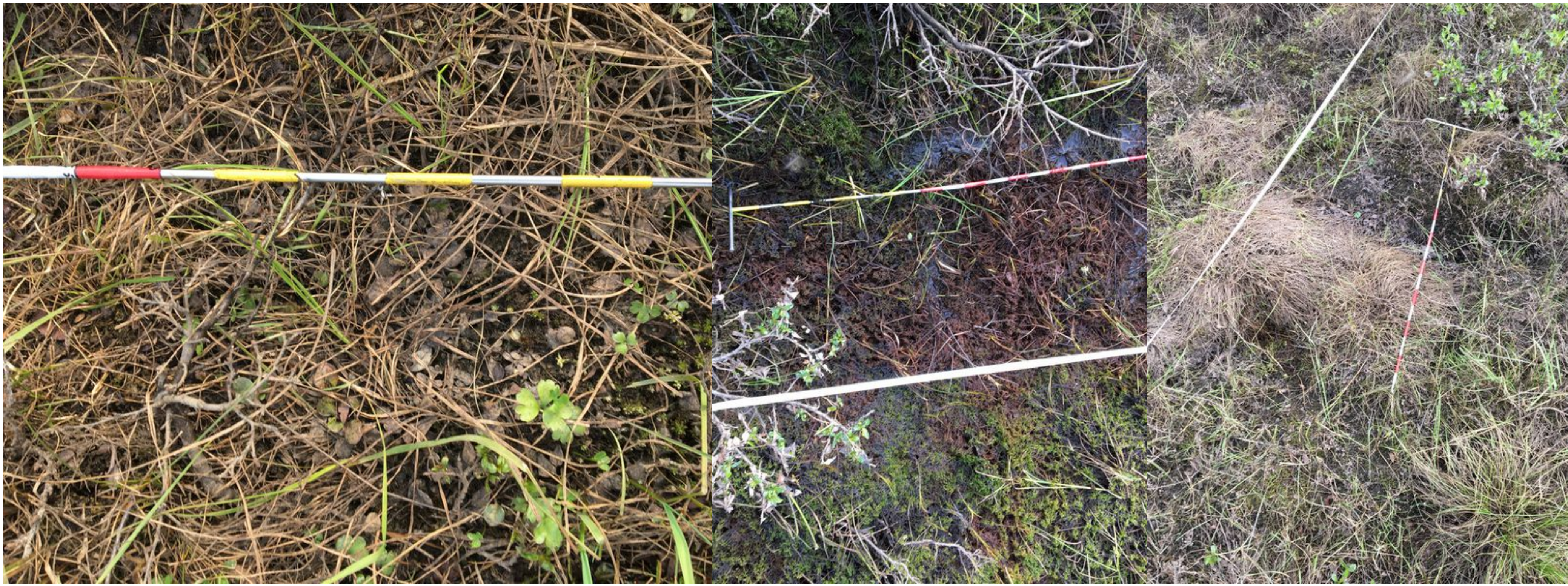
INSAR seasonal time-series surface changes in drained thaw lake basins are compared for alas point affected by the 2017 flood, and alas points that were not flooded in 2017



flooded DTLB: n = 14
non-flooded DTLB: n = 432

flooded area 2017 : early, rapid subsidence during flooding
nonflooded areas 2017 : later subsidence progressing with thaw season
effects appear to continue in 2018 (more subsidence at 2017 flooded points)
in 2019 no statistically significant difference

Flooding effects on vegetation



Flooded areas show mortality of non-flood resistant species

- Dwarf shrubs (*Betula, Vaccinium*), *Sphagnum*, *Eriophorum* tussocks
- Advantage of flood-resistant willow
- Tei et al. (2019) report forest browning

Immediate and longer-term effects of flooding on vegetation and carbon cycle need quantification!

Floodplain expansion into thaw lake basin

Visible at low water level (2010):

expanding channel + floodplain vegetation(high willow, grasses) into alas

thaw lake captured in the past by river bank erosion,
drains at river low stand

Early summer 2015 ± normal flooding:
flood water does not enter the alas at this location

2017 extreme flood

flood water enters the alas at this location and makes contact with thaw lake
subsidence + channel erosion may widen the connection of the alas to the river, and potentially drain the thaw lake

Discussion

Subsidence on poorly drained sites and floodplain:

is it driven by more surface water - ponding/flooding in wet years ?
longer INSAR time series + field observations on changes needed

Well drained sites - no subsidence, some heave:

do wet years contribute to ice accumulation at top of permafrost in wet years ?
quantification of ice content over the years necessary

Other positive surface movement:

peat accumulation (areas with *Sphagnum*)
floodplain sedimentation
colluvial deposition on lower slopes of Yedoma remnants

Extreme river flooding drives floodplain expansion by:

subsidence
thaw lake capture

What are effects on the carbon cycle, ecological changes, Arctic browning/greening?

Factors affecting the floodplain carbon cycle at a large scale:

Vegetation stress / die-back in areas affected by unusual flooding
Higher vegetation productivity on floodplain
Higher CH_4 emission in floodplain environments
Floodplain expansion creates accomodation space for carbon-rich fluvial sediment

Conclusions

1. The floodplain wetlands are
- a hotspot of CH_4 emission
- carbon storage in sediments

2. Extreme floods expand the floodplain:
- permafrost thaw, subsidence
- capture of thaw lakes

3. INSAR surface movement data show:
- Subsidence in poorly-drained areas
- Well drained: no significant subsidence, or ice gain
- Sedimentation: floodplain, peat accumulation