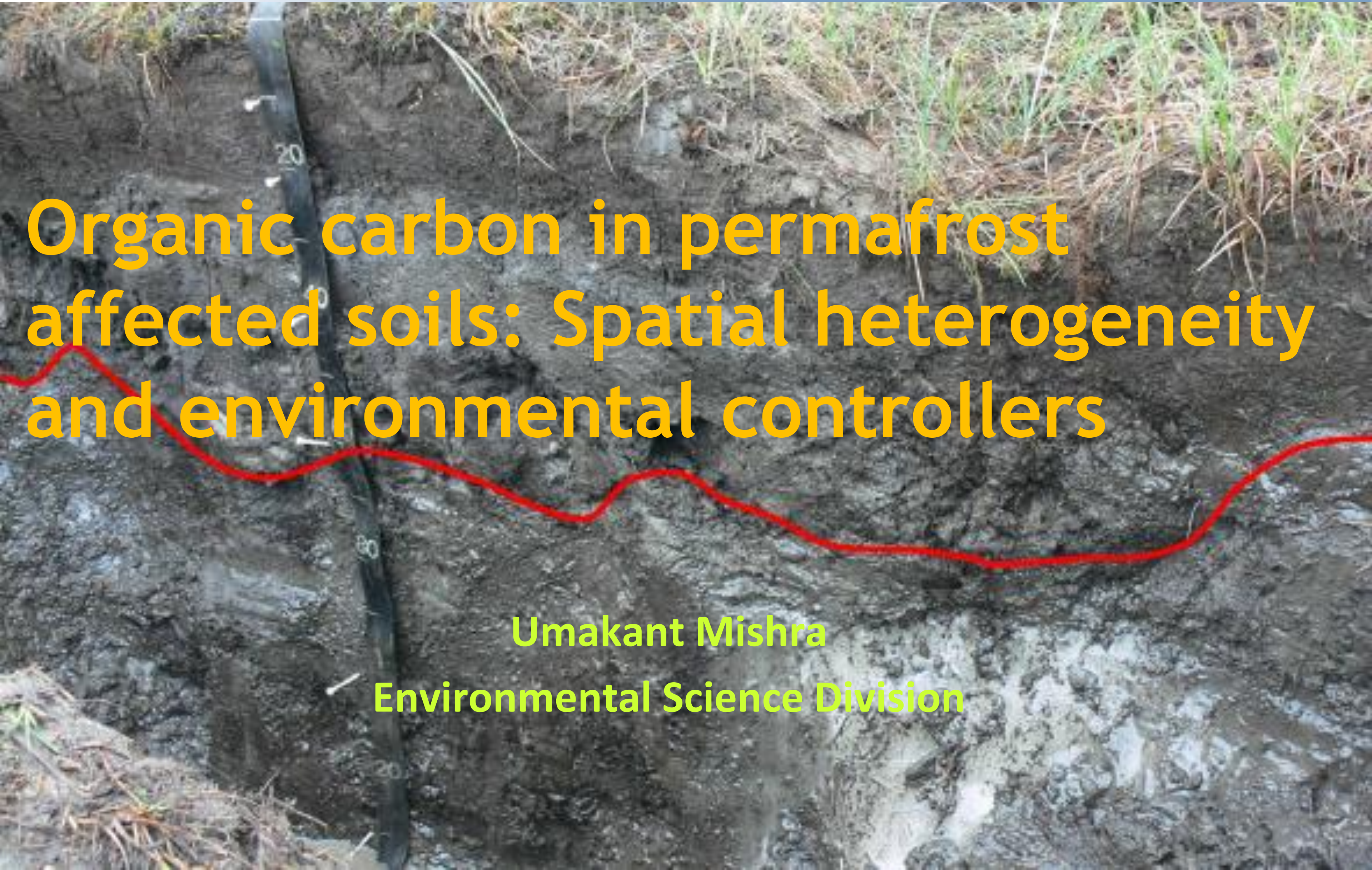
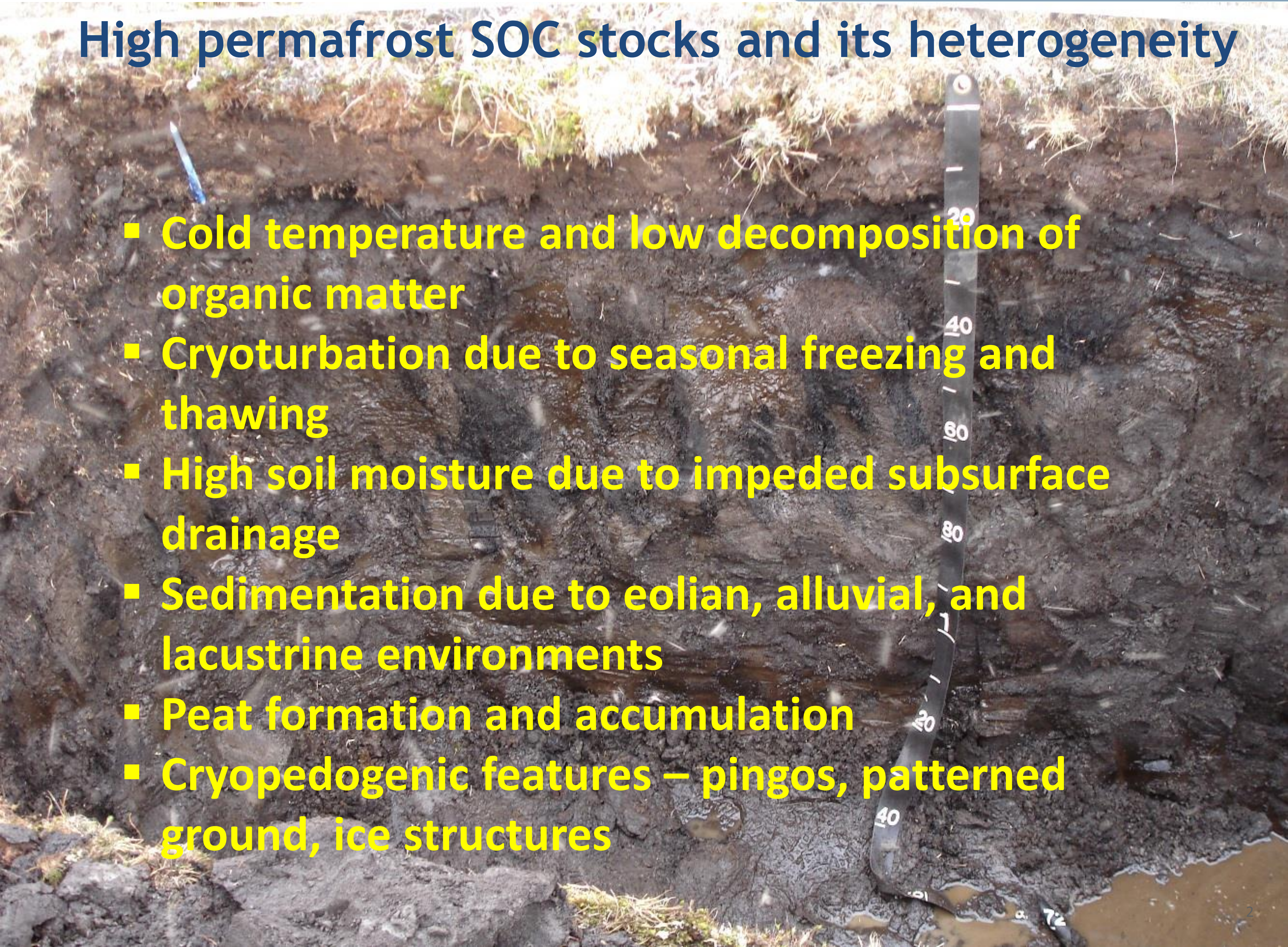


Organic carbon in permafrost affected soils: Spatial heterogeneity and environmental controllers

Umakant Mishra

Environmental Science Division

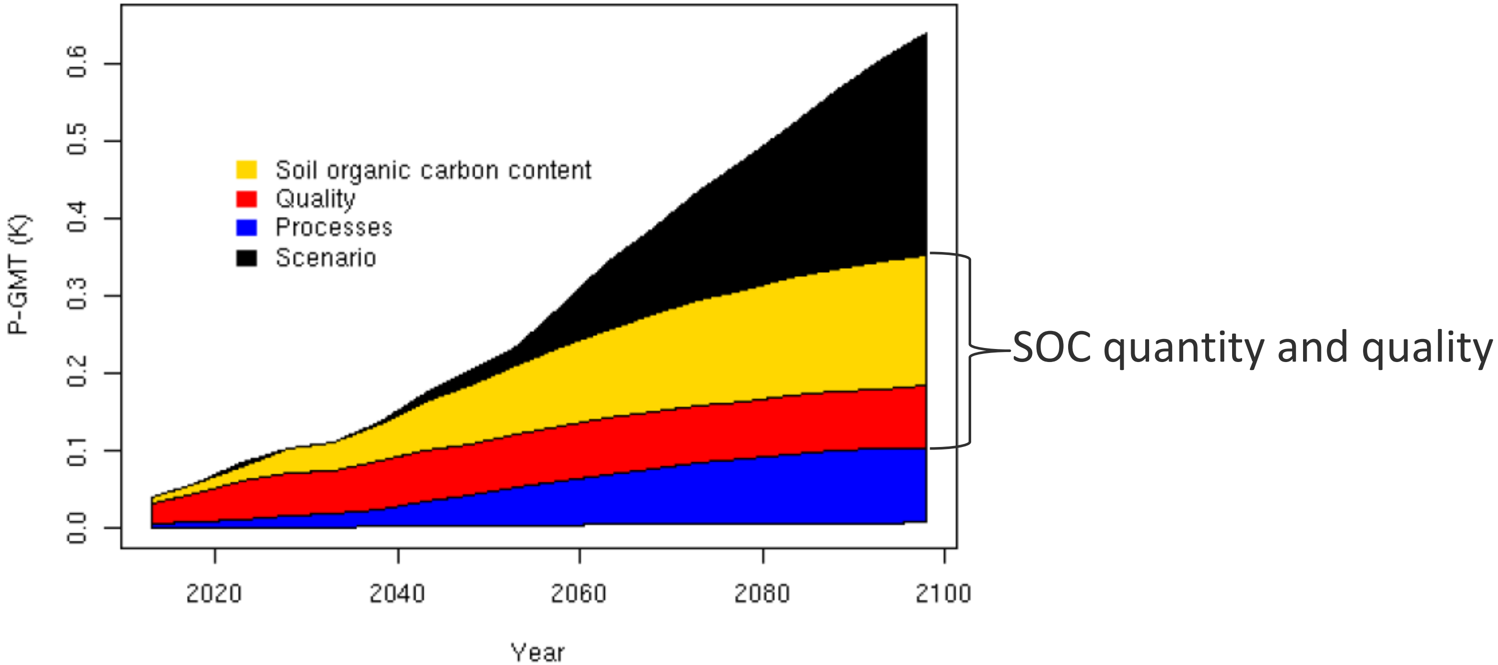
High permafrost SOC stocks and its heterogeneity



- Cold temperature and low decomposition of organic matter
- Cryoturbation due to seasonal freezing and thawing
- High soil moisture due to impeded subsurface drainage
- Sedimentation due to eolian, alluvial, and lacustrine environments
- Peat formation and accumulation
- Cryopedogenic features – pingos, patterned ground, ice structures

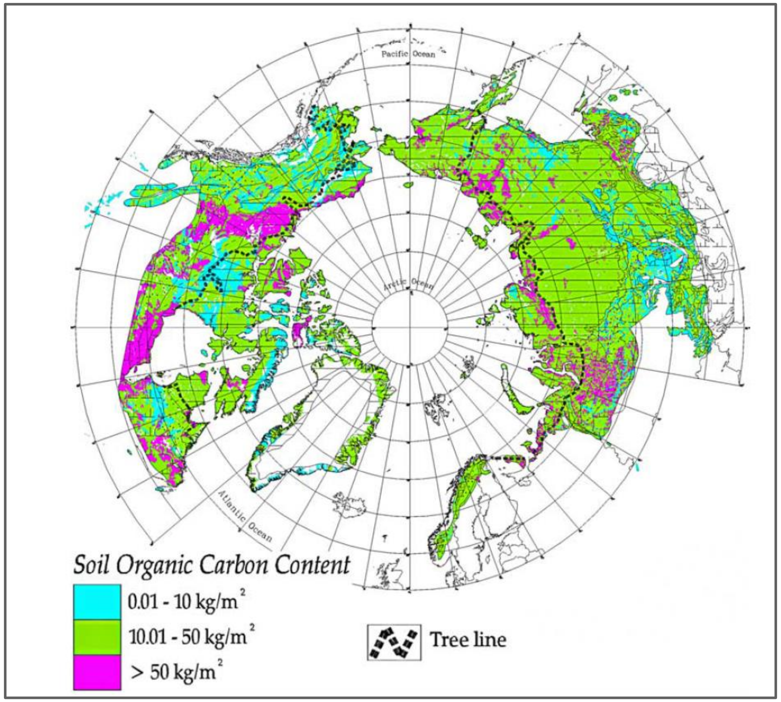
Distribution and quality of SOC determines half of the uncertainty

- **Permafrost affected soils store much of the organic carbon in terrestrial ecosystems, and remain a sensitive component of the global carbon cycle under changing climate.**
- **The spatial and vertical distribution of permafrost soil organic carbon (SOC) stocks and its quality/decomposability determine about half of the uncertainty in predicting the impact of permafrost C to the climate warming.**

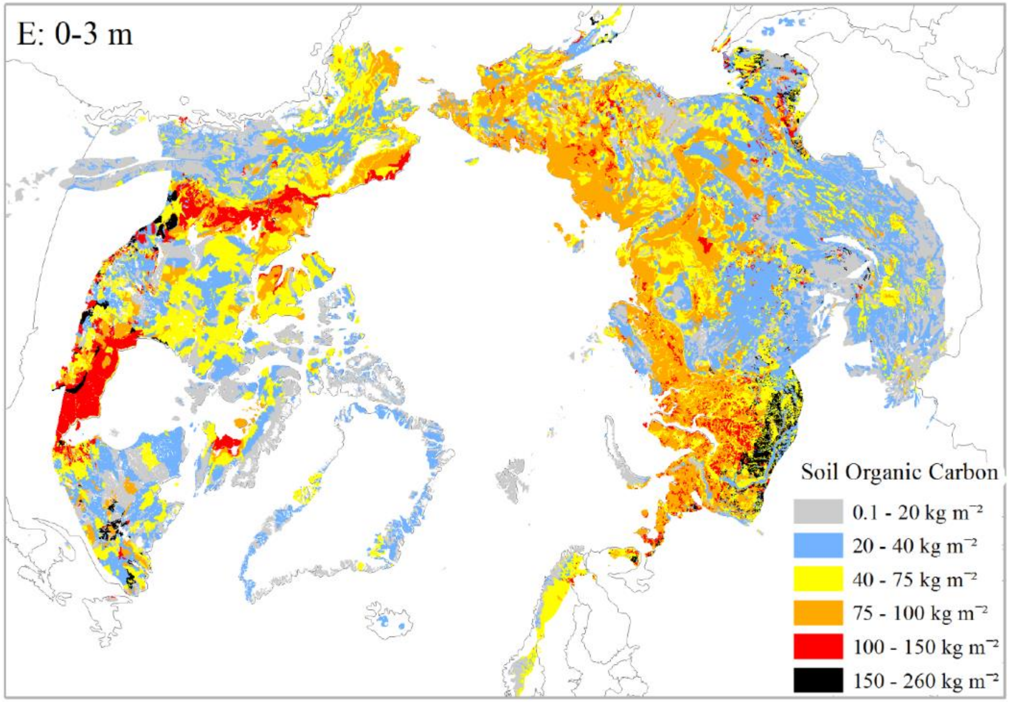


(Burke et al., 2012)

Northern circumpolar permafrost SOC stocks



(Tarnocai et al., 2009; 1672 Pg C)



(Hugelius et al., 2014; 1300 Pg C)

Earlier circumpolar studies used thematic upscaling approaches, reported large amount of SOC stocks, and identified needs of better representations of spatial heterogeneity and uncertainty in permafrost SOC stock estimates.

Study Objectives

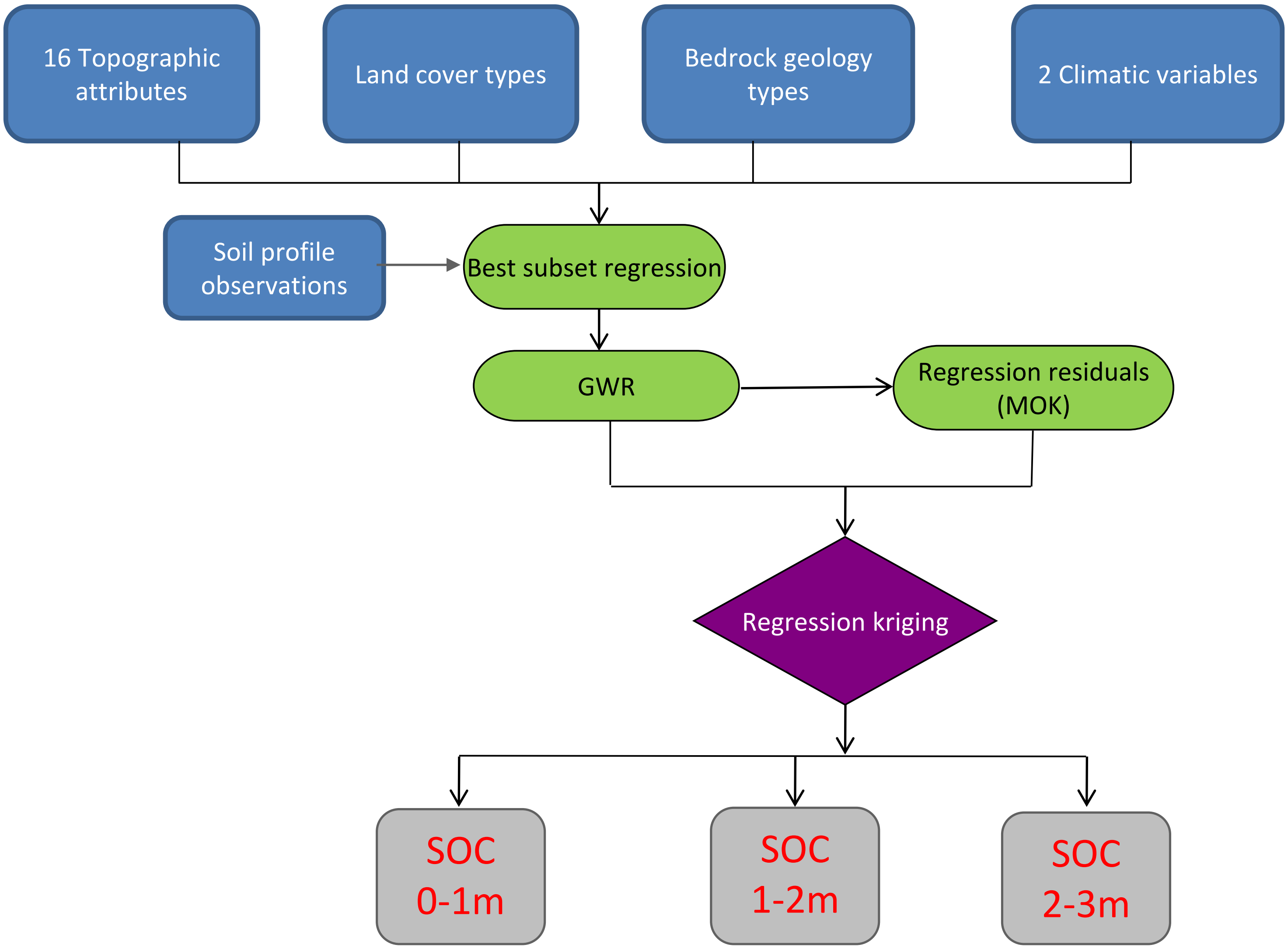
- **Develop a high-resolution harmonized global permafrost carbon stock estimates that could be used to benchmark land surface model results.**
  - **Predict the spatial and vertical heterogeneity of permafrost-affected SOC stocks and their spatial uncertainties (90% prediction intervals).**
  - **Identify dominant environmental controllers of permafrost affected SOC stocks across permafrost regions and depth intervals.**

Different approaches to predict spatial heterogeneity of SOC stocks

- **Environmental correlation between SOC and soil forming factors:**
  - ➢ **Multiple linear regressions - (Meersmans et al., 2008; Martin et al. 2011; Zhang et al., 2011)**
  - ➢ **Non-linear relations (Li et al., 2013; Sreenivas et al., 2016; Siewert et al., 2018)**
- **Spatial autocorrelation between SOC observations:**
  - ➢ **Geostatistical algorithms (Simbahan et al., 2006; Mishra et al. 2009; Cambule et al., 2013)**
- **Hybrid approach- combining environmental correlation with spatial autocorrelation**
  - ➢ **Regression kriging (Mishra et al. 2012; Martin et al., 2014; Meng, 2014)**

We used Regression-kriging approach, which uses both environmental correlation between SOC and environmental factors, and spatial autocorrelation between SOC observations.

Predicting spatial variability of SOC stocks



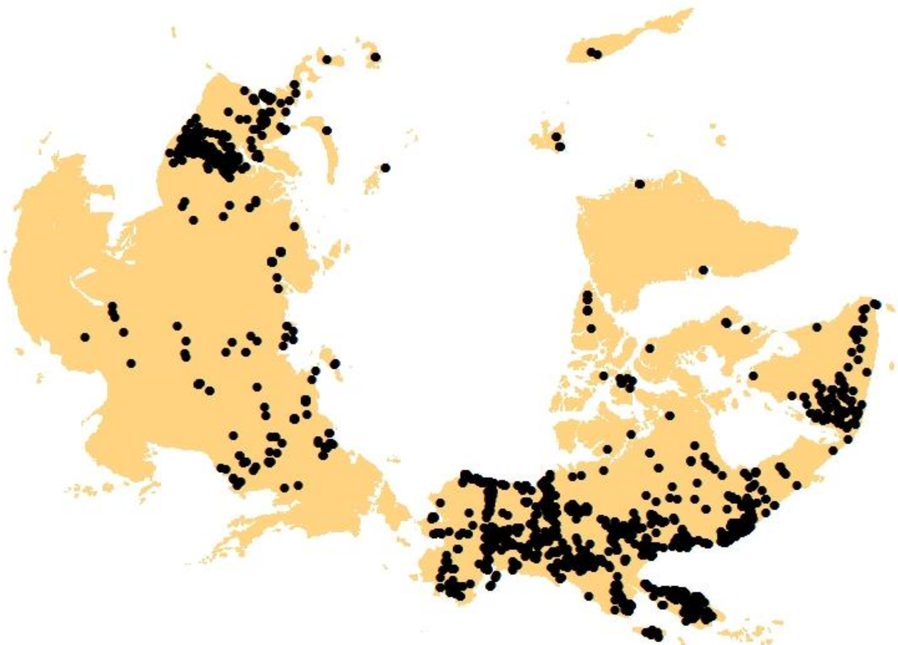
Distribution of SOC stocks across environmental factors

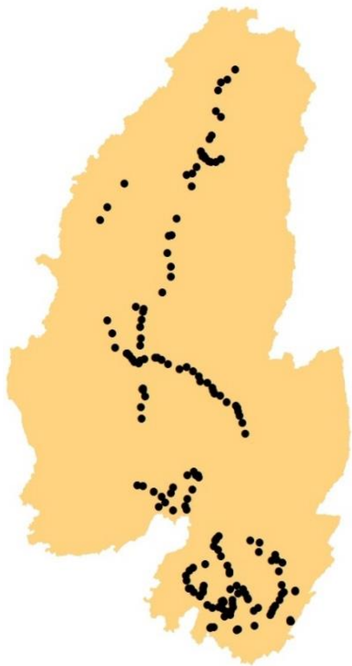
- **Topographic positions:**
  Flat surface (<2% slope angle), concave landscape (toe-slope positions), mid slope (shoulder position), and convex landscape (hill-top positions)
- **Climatic factors:**
  Different zones of average annual temperature and precipitation
- **Land cover types**

We calculated summary statistics of SOC stocks for each of the categories of environmental factors

Spatial distribution of SOC profile observations

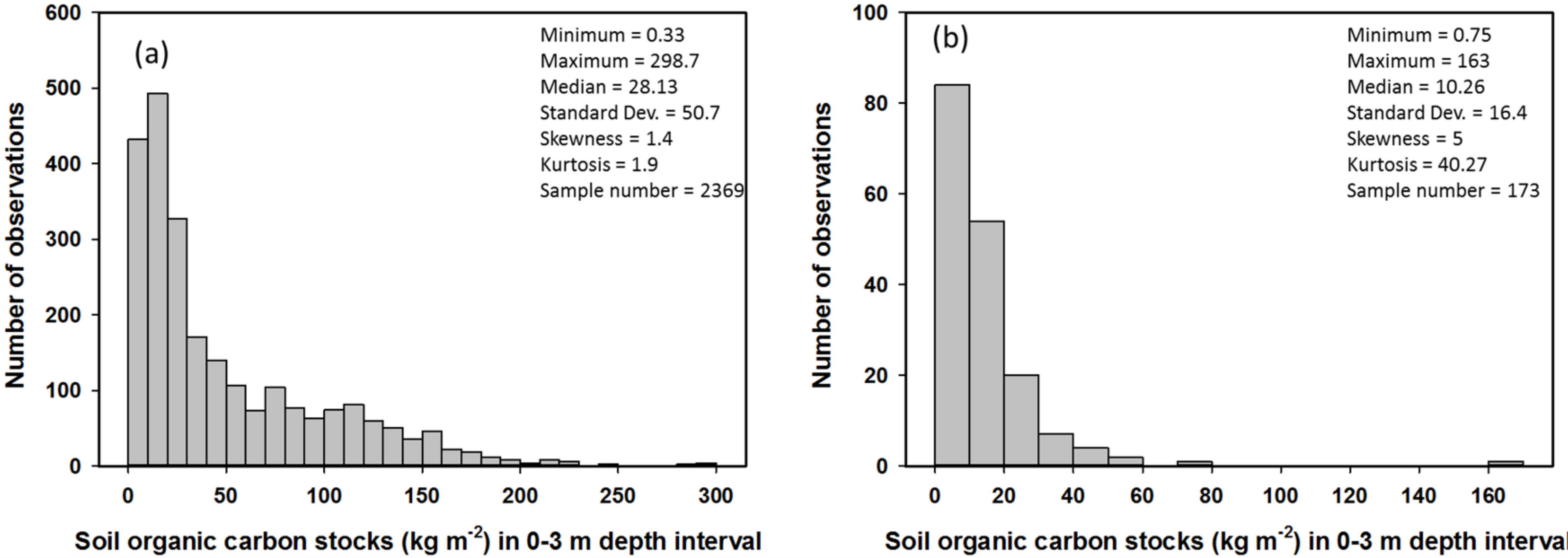
New samples from: Canada, Russia, Svalbard, Sweden





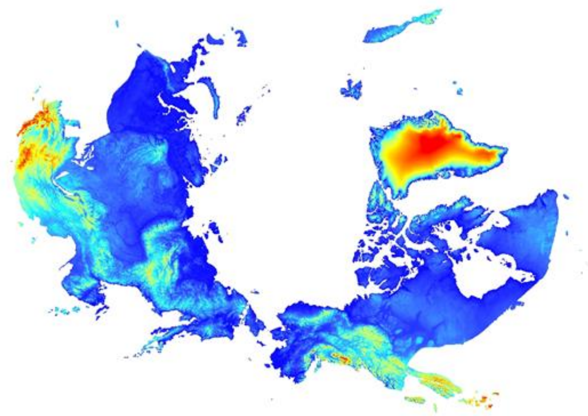
Spatial distribution of soil profile observations of SOC stocks in the northern circumpolar region (n=2369) and the Tibetan permafrost region (n=173).

Statistical distributions of the SOC stocks

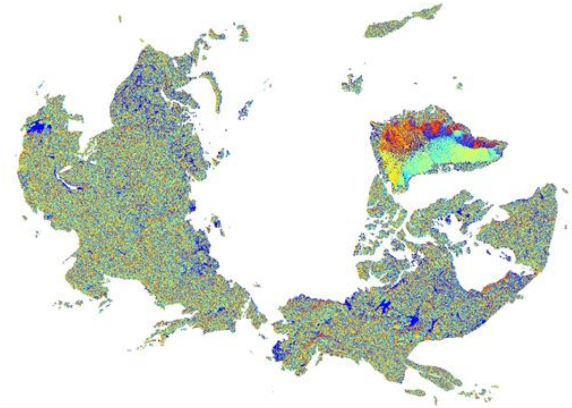


Statistical distribution of soil profile observations of SOC stocks to 3-m depth for the Northern Circumpolar region (a) and the Tibetan permafrost region (b).

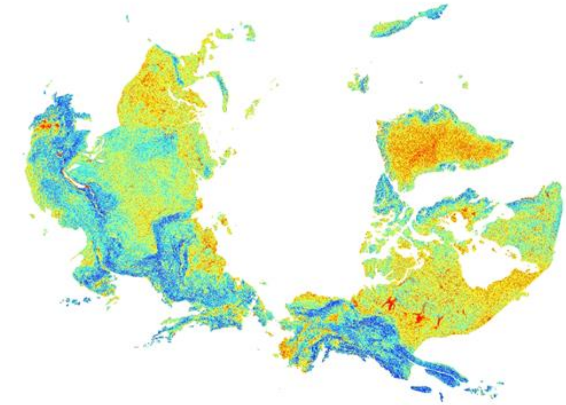
Significant environmental predictors of SOC stocks in Northern circumpolar region



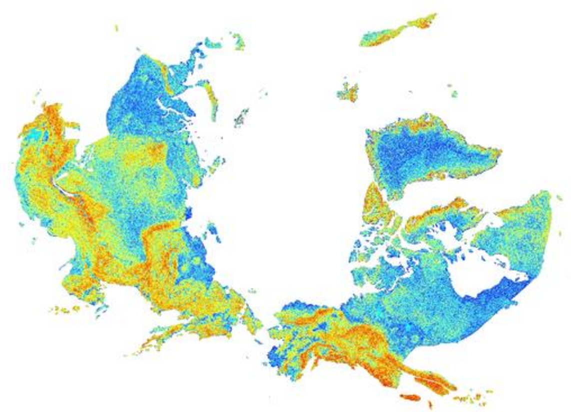
Elevation



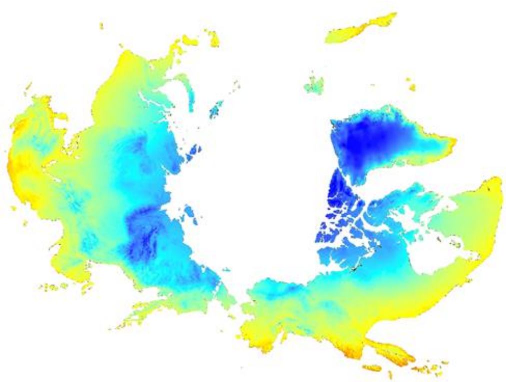
Aspect



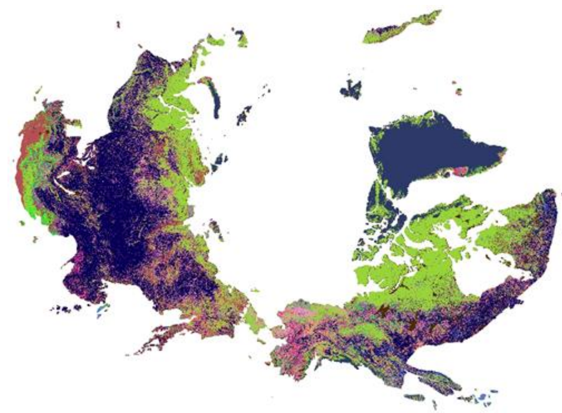
Soil wetness index



Stream power index



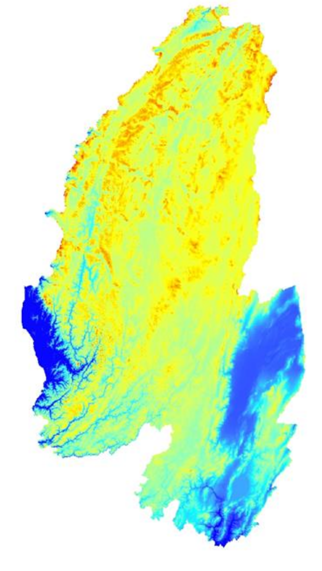
Average annual temperature



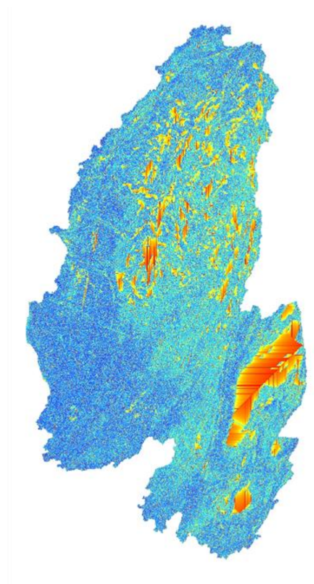
Land cover types

- **Bed rock geology types and flow accumulation were also significant predictors**

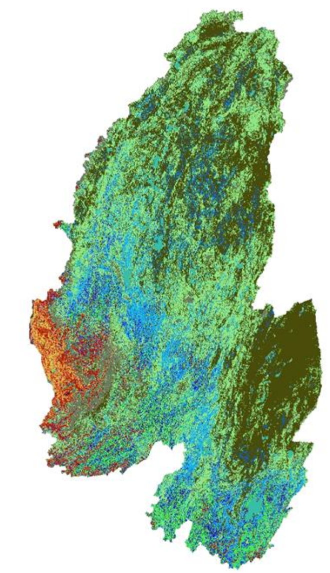
Significant environmental predictors of SOC stocks in Tibetan permafrost region



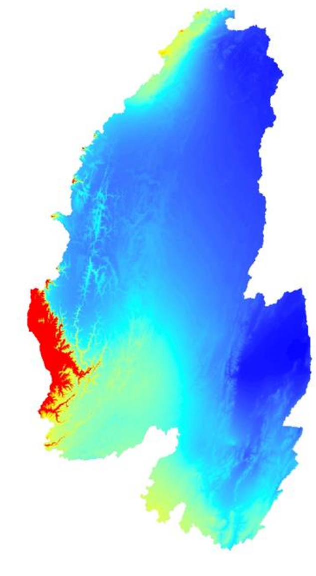
Elevation



Soil wetness index

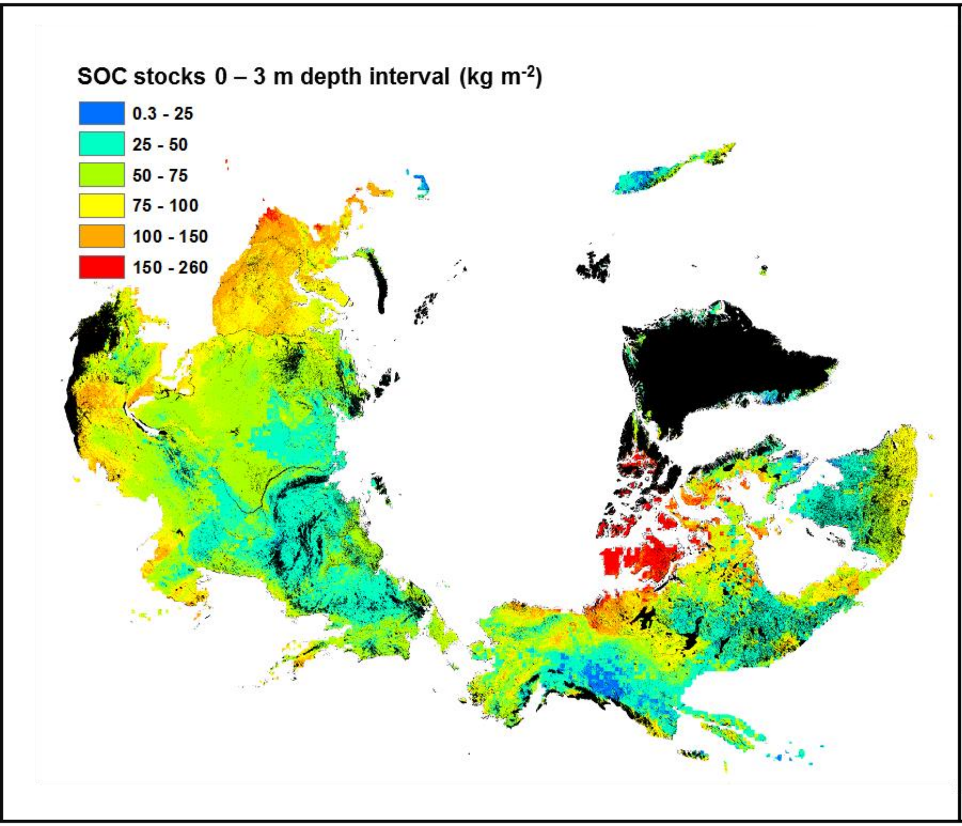


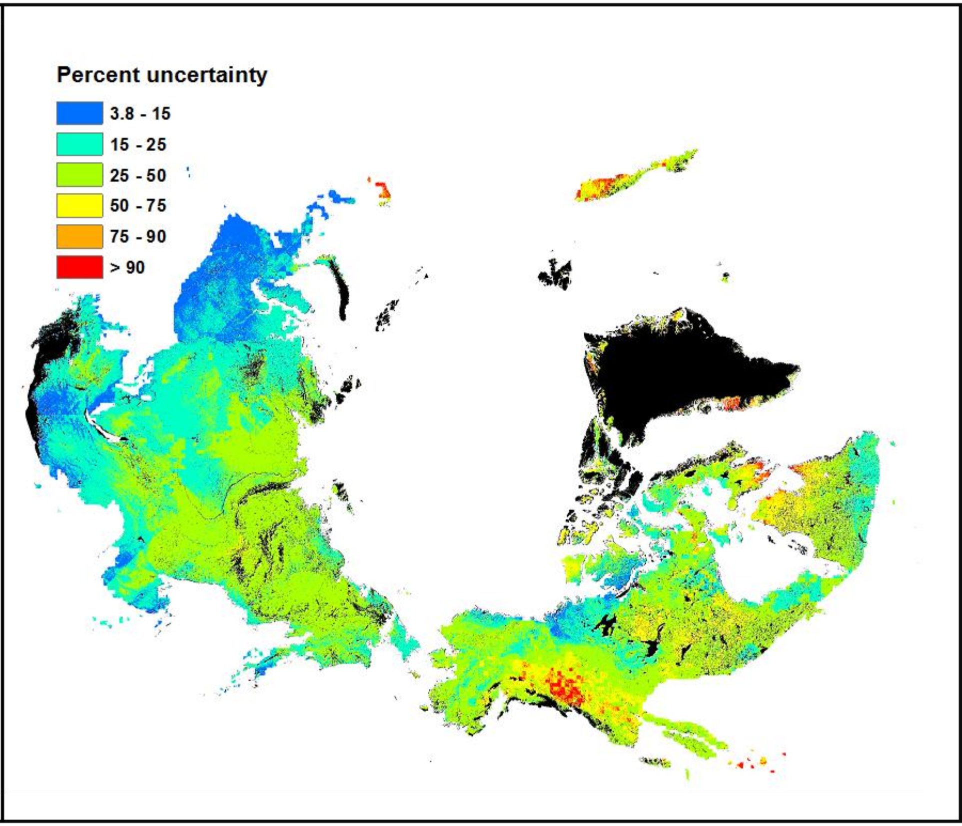
Land cover types



Precipitation

Spatial heterogeneity of predicted SOC stocks of Northern circumpolar region

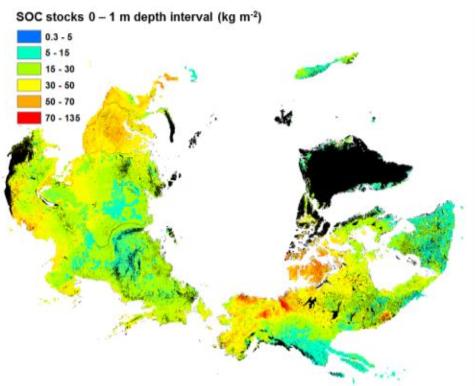


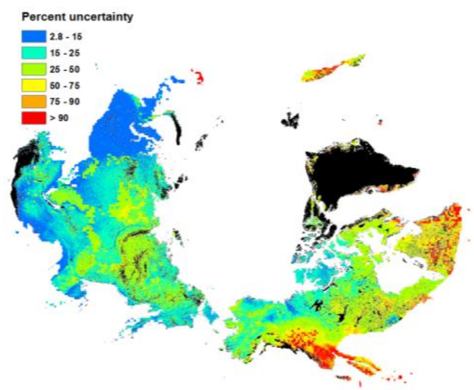


Areas in black show water surface and perennial ice, urban, and barren land with consolidated materials.

Total SOC stocks = 1210 Pg (90% CI:1070-1370)

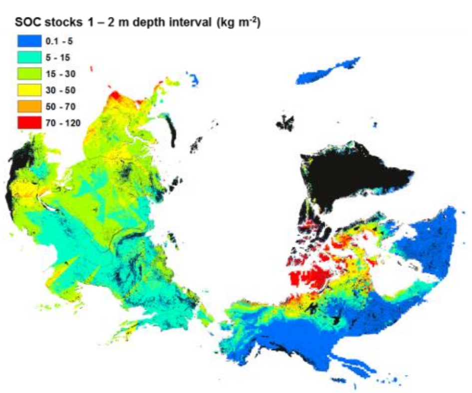
SOC stock estimates for different depth intervals

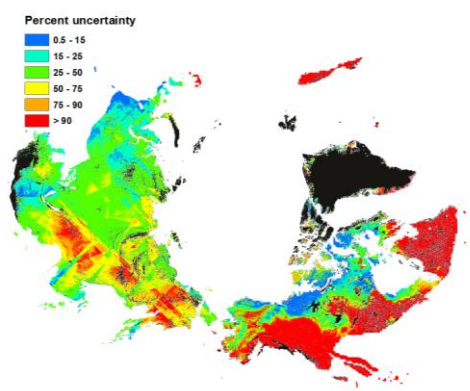




Average = 29 kg m^{-2} (90% CI: 25.5-32.5)
CV = 48%

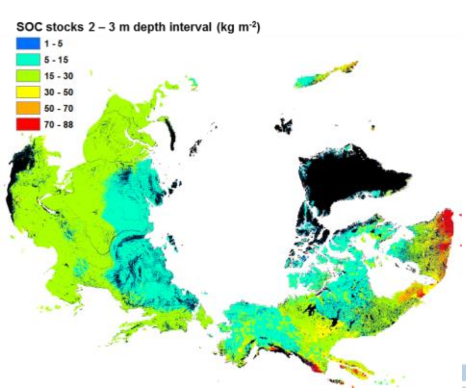
Total = 510 Pg C (90% CI: 449-572)

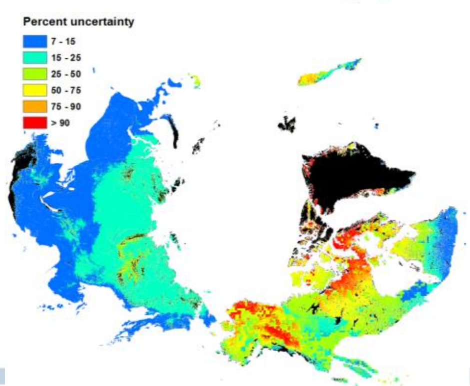




Average = 19 kg m^{-2} (90% CI: 16.5-22.0)
CV = 127%

Total = 344 Pg C (90% CI: 297-397)

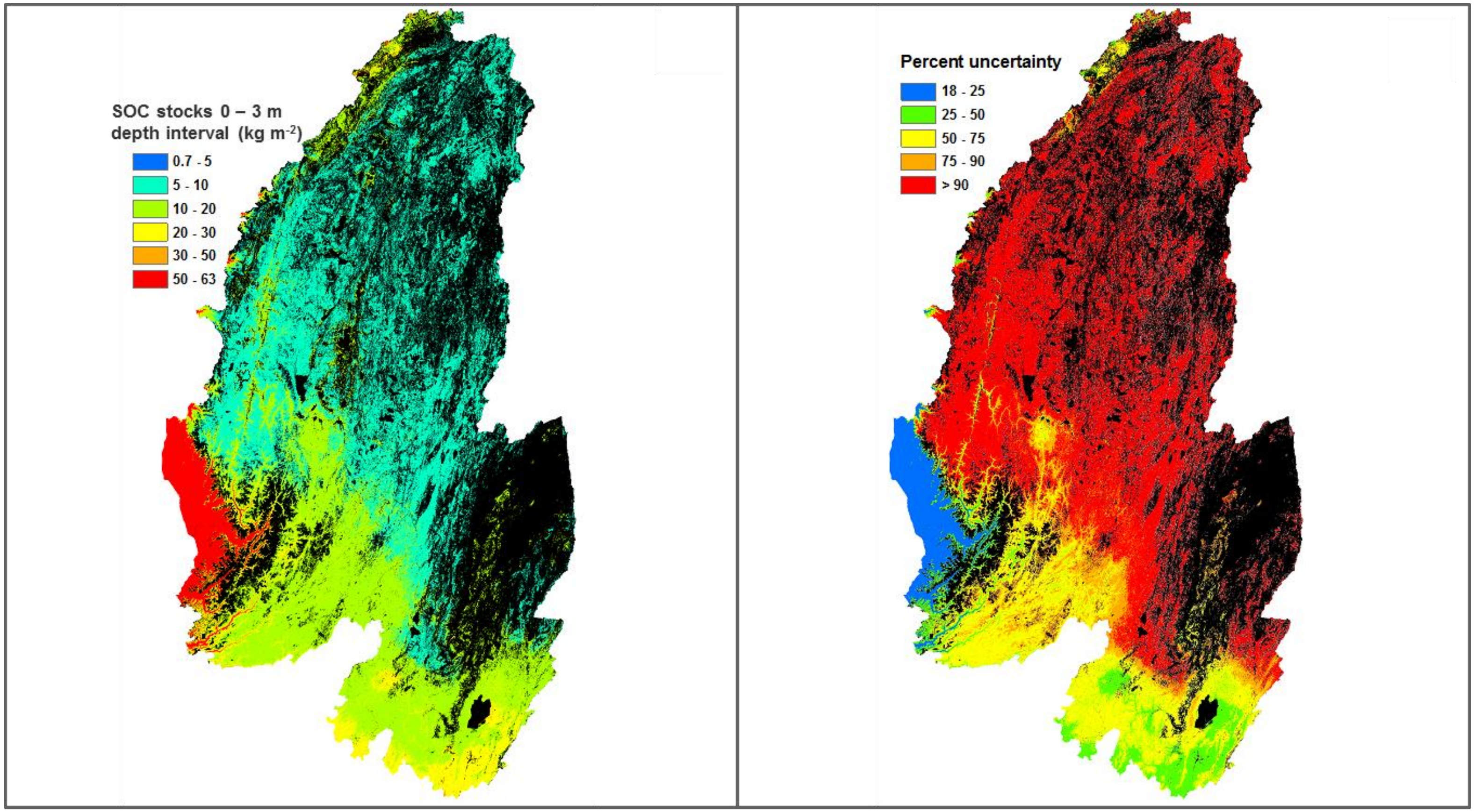




Average = 20 kg m^{-2} (90% CI: 18.0-22.0)
CV = 48%

Total = 355 Pg C (90% CI: 324-401)

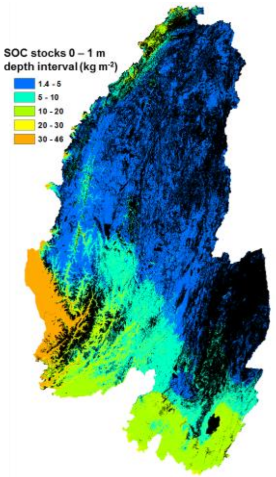
Spatial heterogeneity of predicted SOC stocks of Tibetan permafrost region

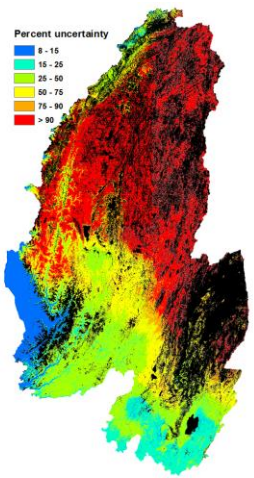


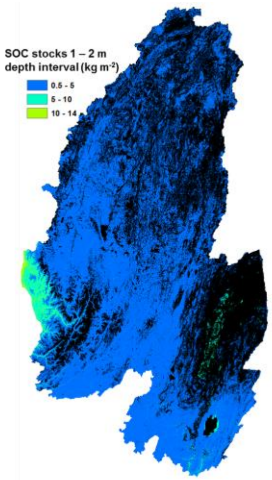
Areas in black show water surface and perennial ice, urban, and barren land with consolidated materials.

(Total = 17 Pg C, 90% CI: 11-24)

Spatial heterogeneity of predicted SOC stocks and its uncertainty in different depth intervals





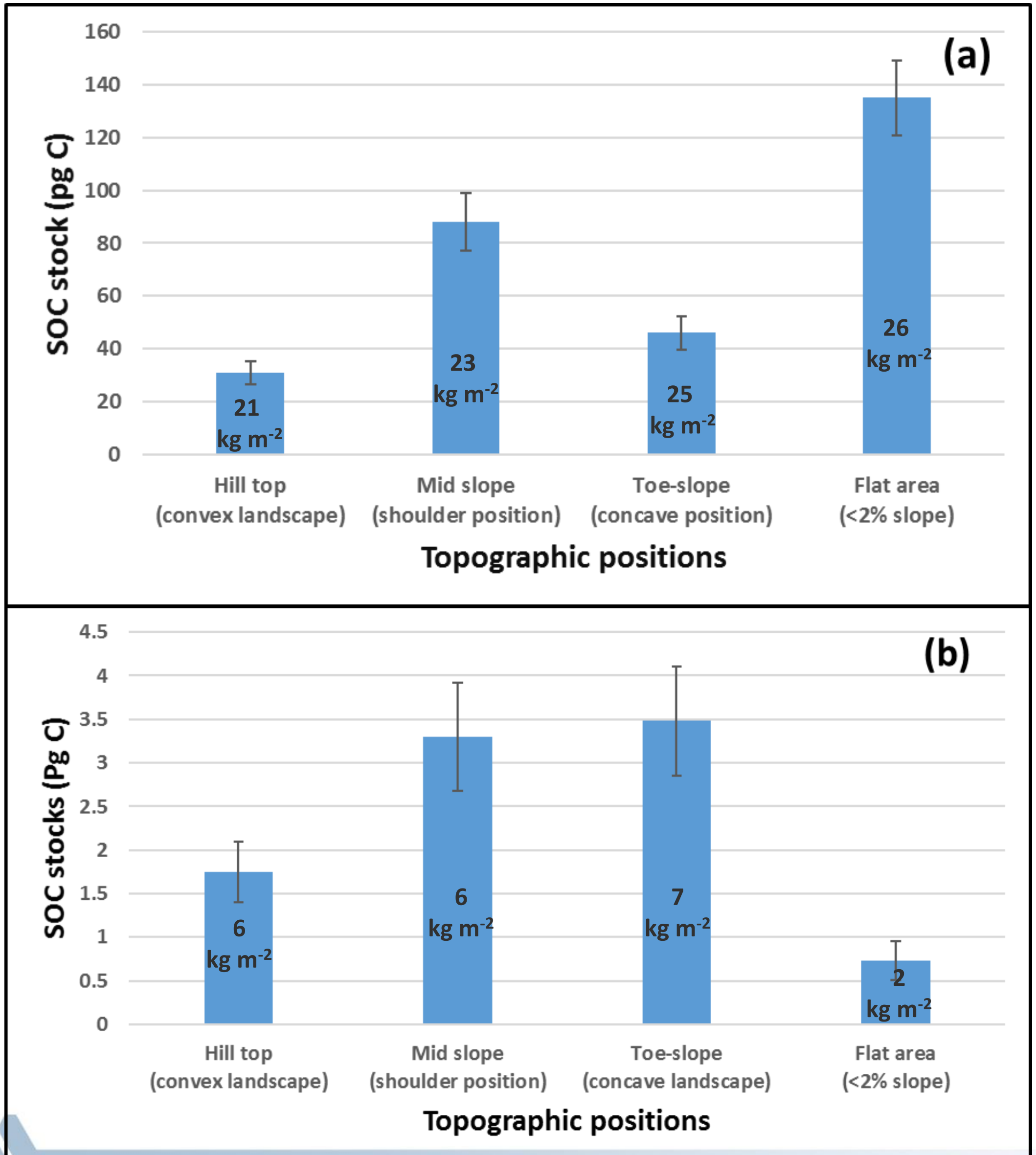


0-1m:
Average = 9 kg m^{-2}
CV = 112%
Total = 11 Pg C (90% CI: 9-13)

1-2m:
Average = 2.5 kg m^{-2}
CV = 52%
Total = 3 Pg C (90% CI: 0.5-6.3)

2-3 m:
Average = 2.6 kg m^{-2}
CV = 13%
Total = 3 Pg C (90% CI: 1.4-4.7)

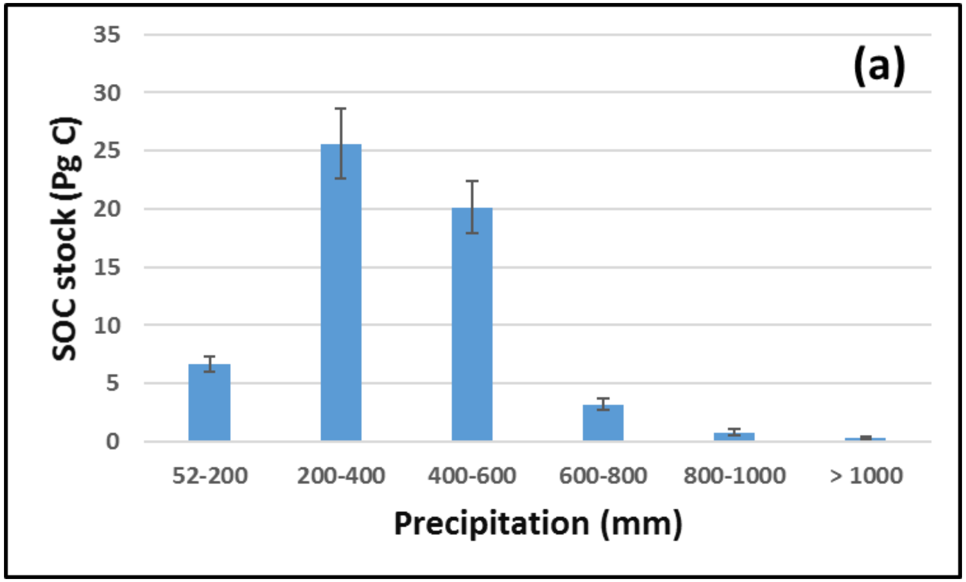
Distribution of SOC stocks across different topographic positions

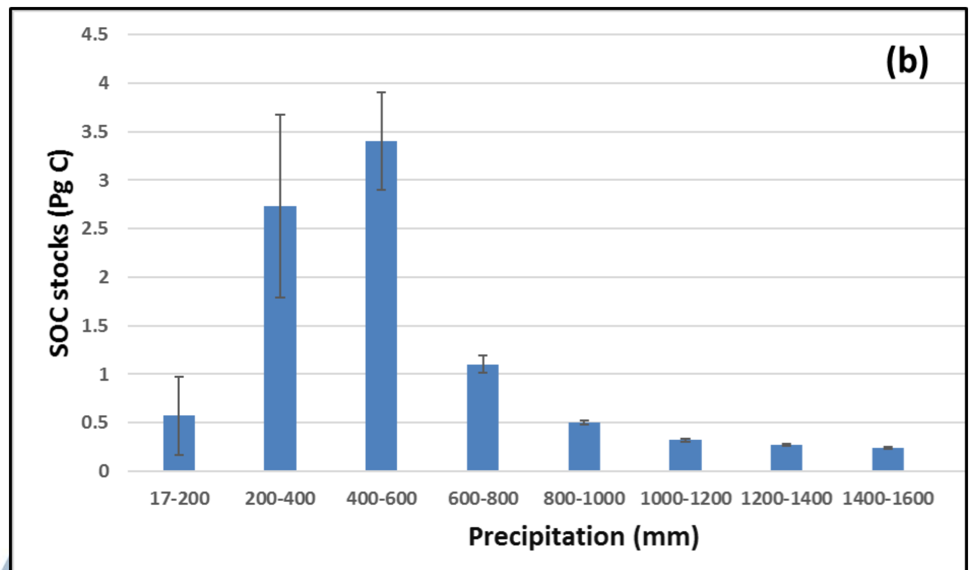


Average uncertainty:
27% in toe-slope positions in northern circumpolar region

Average uncertainty:
62% in flat positions in Tibetan permafrost region

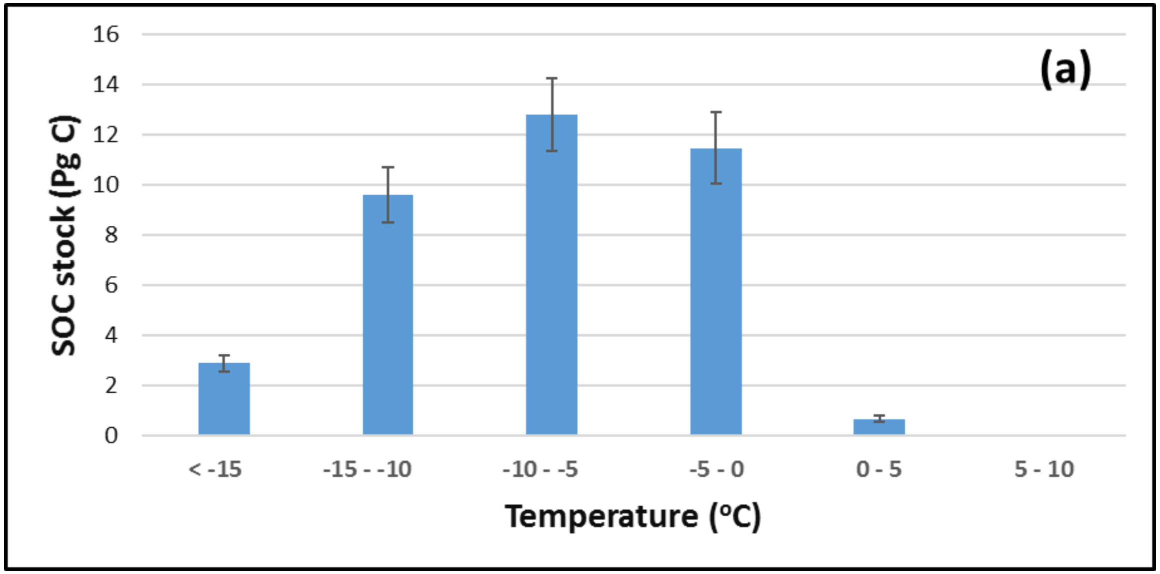
Distribution of SOC stocks across different mean annual precipitation ranges

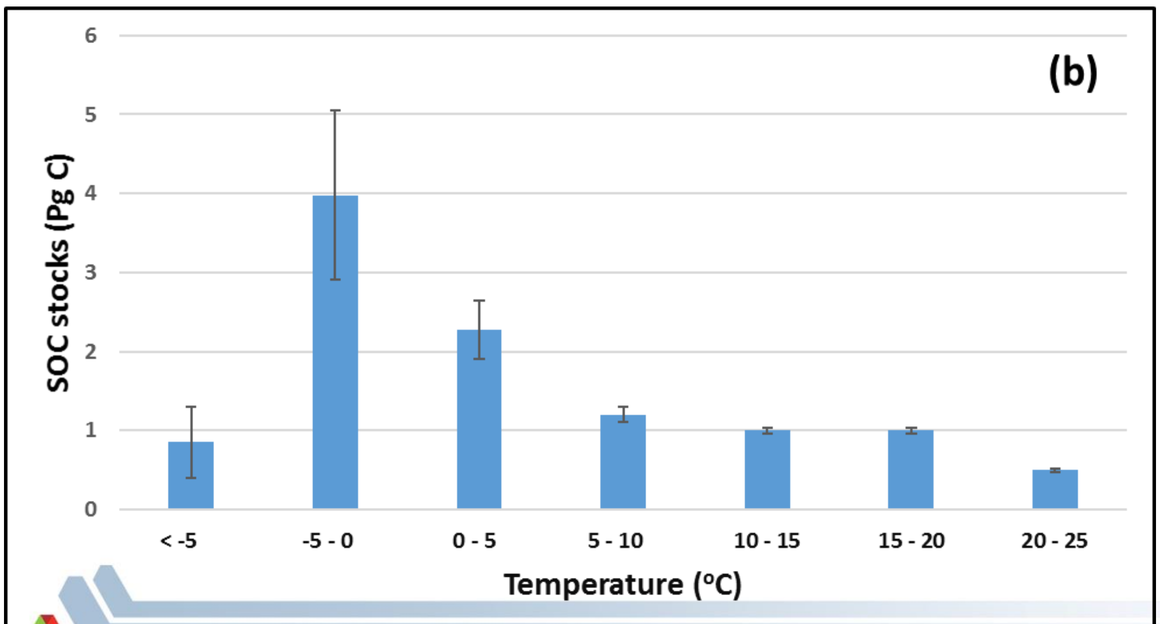




- The average SOC stock decreased linearly with precipitation in Northern circumpolar region
- The average SOC stock increased linearly with precipitation in Tibetan Permafrost region

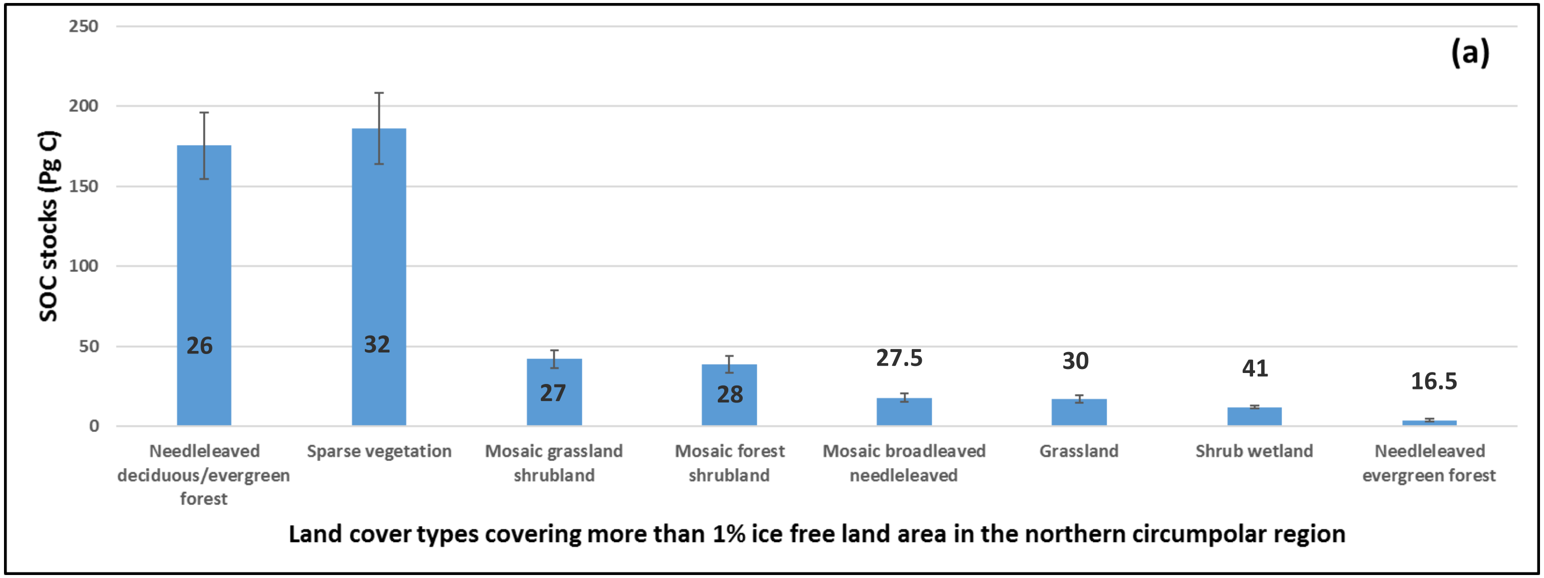
Distribution of SOC stocks across different mean annual surface air temperature ranges

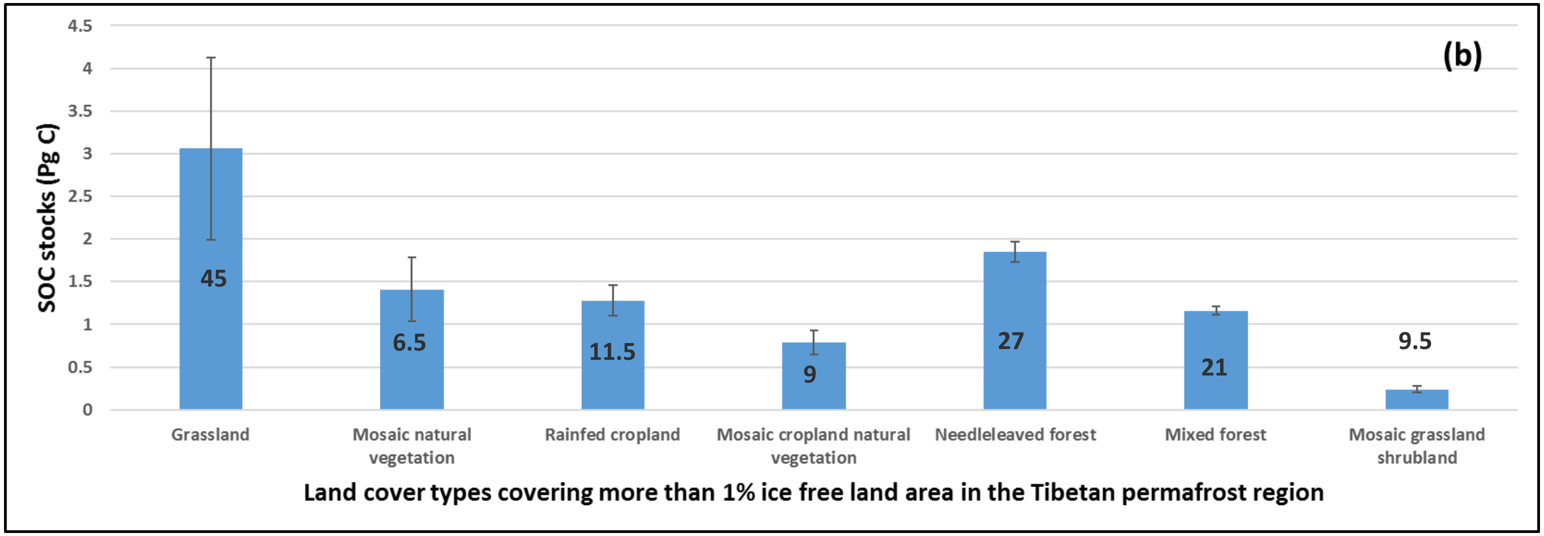




- Areas with lowest temperature and precipitation (polar desert) had lowest SOC stocks in the Northern circumpolar region
- These areas have very thin soils due to harsh climatic conditions for soil development
- The average SOC stock increased up to 0°C and then it decreased in Northern permafrost region
- The average SOC stock increased linearly with temperature in Tibet

Distribution of SOC stocks across different land cover types





Our results in comparison to earlier studies

- Our 0-3 m SOC stock estimates of Northern circumpolar region is 17.5% higher than both Tarnocai et al. (2009) and Hugelius et al. (2014)

- Our 0-3 m SOC stock estimate of Tibetan region is 13% greater than Ding et al., (2016)

- The differences between our estimates and previous studies are due to greater number of samples and different spatial prediction approach

- We used 40% more samples in total. This increase was 33%, 222%, and 52% more samples at the 0 – 1 m, 1 – 2 m, and 2 – 3 m depth intervals, respectively, than were available to Hugelius et al. (2014).

- The difference in Tibetan permafrost region was due to different spatial prediction approach we used.

Limitations of regional SOC stock studies

- **Soil profile samples come from a variety of sources which were collected using a number of sampling techniques and analytical approaches.**

- **Samples do not follow any spatial distribution and primarily located around transportation networks.**

- **Though we were able to increase sample density from 10500 km2 per sample to 7500 km^2 per sample, its extremely low for a robust geospatial study**

Summary

- Primary controllers of SOC stocks were:
  - topographic attributes, mean surface air temperature, land cover types, and bedrock geology in the Northern circumpolar region, and
  - precipitation, land cover types, and topographic attributes in the Tibetan permafrost region.

- Our results suggest a stock of 1227 Pg C in the 0-3 m depth interval of the permafrost affected soils (90% CI: 1081 - 1394 Pg C)
  - 1210 Pg C - Northern circumpolar region
  - 17 Pg C - Tibetan permafrost region

- The largest uncertainty in SOC stocks (27%) was found in the hill toe-slope positions in the circumpolar region whereas the uncertainty was highest (62%) in flat areas in the Tibetan region.

- Among climatic factors we evaluated, surface air temperature was a significant controller of SOC stocks in the circumpolar region while precipitation was a significant controller in the Tibetan region.

Future activities

- Use new samples from Russian permafrost region

- Calculate observation based estimates of SOC vulnerability based on future climatic projections.

- Benchmark spatial heterogeneity and environmental controls represented in C4MIP model projections of baseline permafrost SOC stocks.

Acknowledgement

U.S. DEPARTMENT OF ENERGY

Office of Science

PERMAFROST CARBON NETWORK

Thank you for attention!