Arctic tundra microtopographic variability: comparing remote sensing approaches for change detection analysis

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Abstract

Considering the important controls of small-scale microtopographic variability on ecosystem structure and function in arctic polygonal tundra ecosystems, it is crucial to enhance the precision of geospatial techniques and approaches for effectively tracking changes in microtopography over time. This study assesses the capacity of different remote sensing approaches to map and characterize microtopography and their associated changes in elevation. **We assess the capacity of (a) terrestrial based laser scanning (TLS), (b) aerial-based laser scanning (ALS), (c) Unoccupied Aerial Vehicle (UAV) Structure-from-Motion (SfM) and (d) satellite-derived ArcticDEM to model microtopographic variability and change at the landscape scale in polygonized tundra near Utqiaġvik, Alaska.** Point cloud densities were greatest for TLS and UAV approaches (~300 points/ m^2), followed by ALS (~15 points/ m^2). Final mean DEM RMSE values for UAV-SfM and TLS yielded an accuracy of ± 0.4 cm and ± 1.99 cm respectively, with a 95% confidence. DEM elevations acquired by the TLS and UAV-SfM approaches were highly correlated with the in-situ reference elevations, while little-to-no agreement resulted from the ALS approach and the ArcticDEM product. **Between 2018 and 2022, we observed a strong surface lowering response using fused UAV and TLS DEMs, which had a mean elevation decrease of -0.39 cm/yr. (troughs), and -0.22 cm/yr. (high-centered polygons).** This study demonstrates the suitability of UAV-SfM and TLS for enhancing the acquisition and mapping of microtopographic features in tundra ecosystems. In addition, the fusion of data across approaches (e.g., UAV-SfM & TLS) can enhance capacities to characterize microtopographic gradients, change detection and spatiotemporal coverage. This research serves as a valuable technical foundation for ongoing and planned observing of Arctic landscapes.

Methods

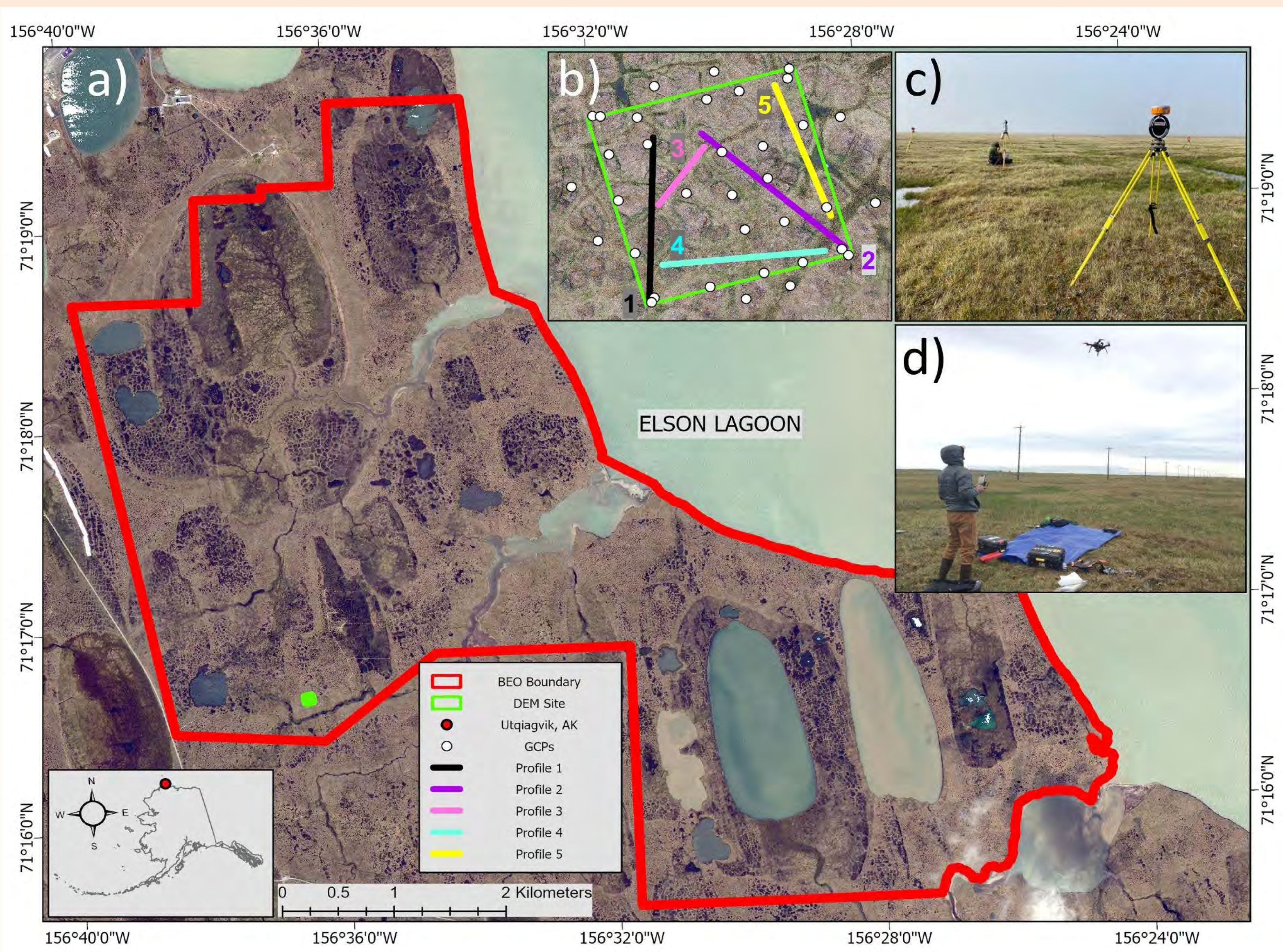

Fig. 1. The study site is located within the (a) Eben Hopson Barrow Environmental Observatory (BEO) near the city of Utqiaġvik, Alaska (base image Copyright 2010, DigitalGlobe, Inc.); (b) A UAV-SfM RGB orthomosaic outlines the study site in green (0.25 ha) and displays ground control points (GCPs) used for image alignment, georeferencing and data validations, and highlights the five profile transect lines used in this study. Field-based images show data collection for TLS (c) and UAV-SfM (d) surveys during late-July/ early-August 2018.

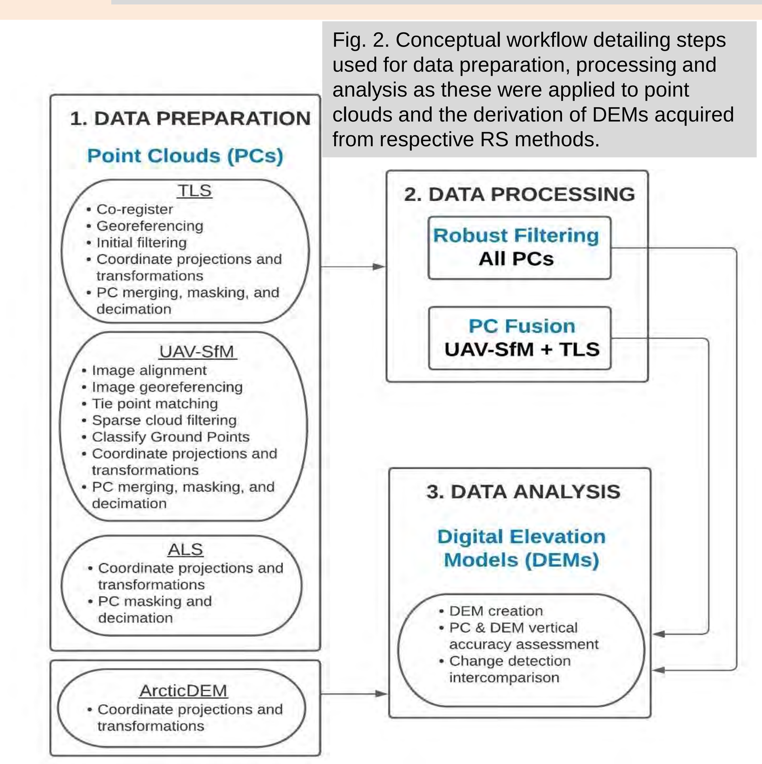

Fig. 2. Conceptual workflow detailing steps used for data preparation, processing and analysis as these were applied to point clouds and the derivation of DEMs acquired from respective RS methods.

RS Method	Year	Month	Day	# Scan positions
TLS	2012	August	20	5
	2013	August	4	4
	2018	July	31	4
	2022	August	8	5
ArcticDEM	2012	July	2	
ALS	2013	July	12	
UAV-SfM	2018	August	11	
	2022	August	8	
GCPs	2012	July	18	
	2015	August	17	
	2018	July	31	
	2022	August	8	

Table 1. Summary of sampling dates for each RS method and number of scan positions for each TLS data set.

The UAV-SfM approach shows highest accuracies when compared to reference GCP elevations.

RS Approach	Point Clouds			DEMs		
	RMSE (cm)	Vertical Accuracy (cm)	R^2	RMSE (cm)	Vertical Accuracy (cm)	R^2
TLS	1.53	2.99	0.98	1.99	3.89	0.98
UAV-SfM	0.77	1.51	0.99	0.4	0.78	0.99
Fused UAV-TLS	0.98	1.92	0.98	1.04	2.03	0.98
ArcticDEM	NA	NA	NA	30.26	59.31	0.01

Table 2. Overall mean RMSE, vertical accuracies and coefficient of determination for mean point cloud and DEM elevations compared to GCP elevations in the same years. All RMSE values were calculated between point cloud and GCP elevations and accuracies were estimated using ASPRS standards and are reported in (cm). Coefficients of determination values are reported from linear regression relationships between PC/DEM elevations and GCP elevations.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(PCz - GCPz)^2}$$

Vertical Accuracy = RMSE x 1.96

where PCZ is the ith elevation from each point cloud, GCPZ is the corresponding reference elevation, and n is the number of total points sampled.

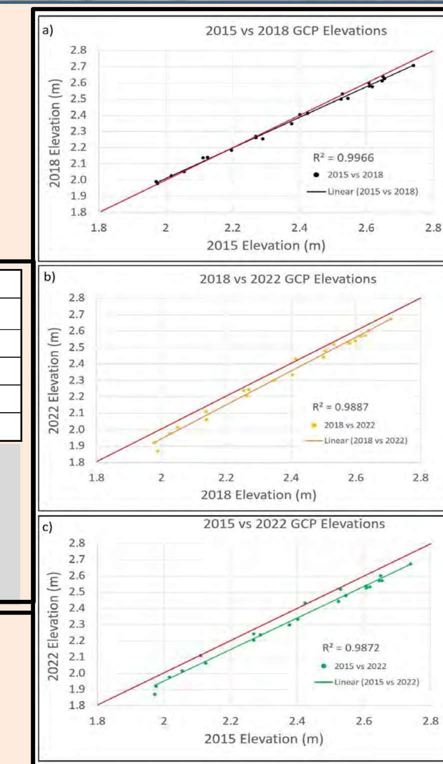

Fig. 3. Linear regression relationships and coefficient of determination between (a) 2015 and 2018, (b) 2018 and 2022 and (c) 2015 and 2022 ground control point (GCP) elevations for the 23 GCPs within the study site. The red solid line shows the 1:1 relationship.

Visual observations show high DEM variability between approaches on the same years…

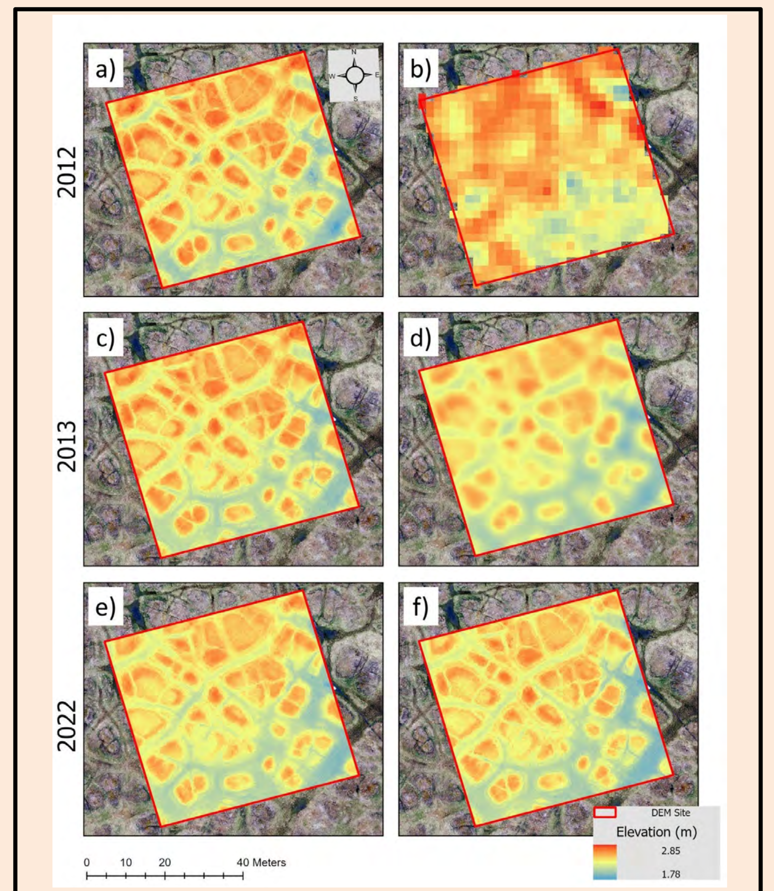

Fig. 4. High resolution DEMs of the study site highlighting collected in the same years to facilitate inter-comparison of approaches. TLS and ArcticDEM collected during 2012 are shown in (a) and (b); TLS and ALS acquired during 2013 are shown in (c) and (d); TLS and UAV-SfM collected in 2022 are shown in (e) and (f). Elevation values are shown in meters above ellipsoid height (EPSG: 26904).

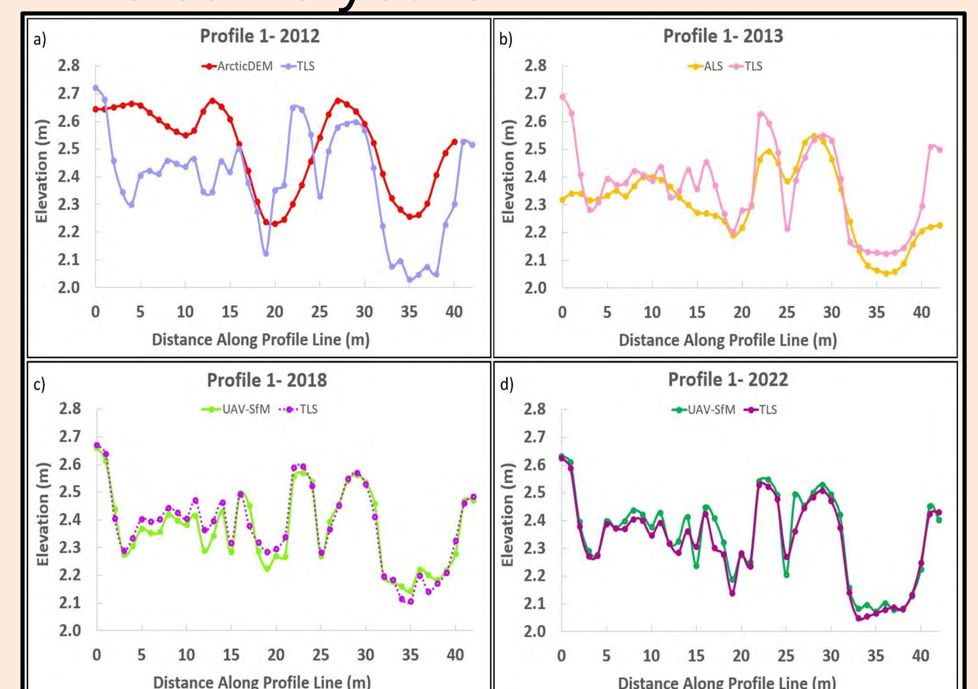

Fig. 5. Approach inter-comparison assessing microtopographic relief along profile transect 1 between TLS and ArcticDEM in 2012 (a), TLS and ALS in 2013 (b), UAV-SfM in 2018 (c) and UAV-SfM in 2022 (d). The x-axis on all plots show distance along each profile transect, while the y-axis shows elevation in meters (EPSG: 26904). The location of each profile transect is shown in Fig. 1

But higher agreement between the UAV and TLS are observed using profile lines, than between ALS/ArcticDEM and TLS.

TLS DEMs were limited in capturing low-lying troughs because of sensor viewing angle and signal absorption due to presence of standing water…

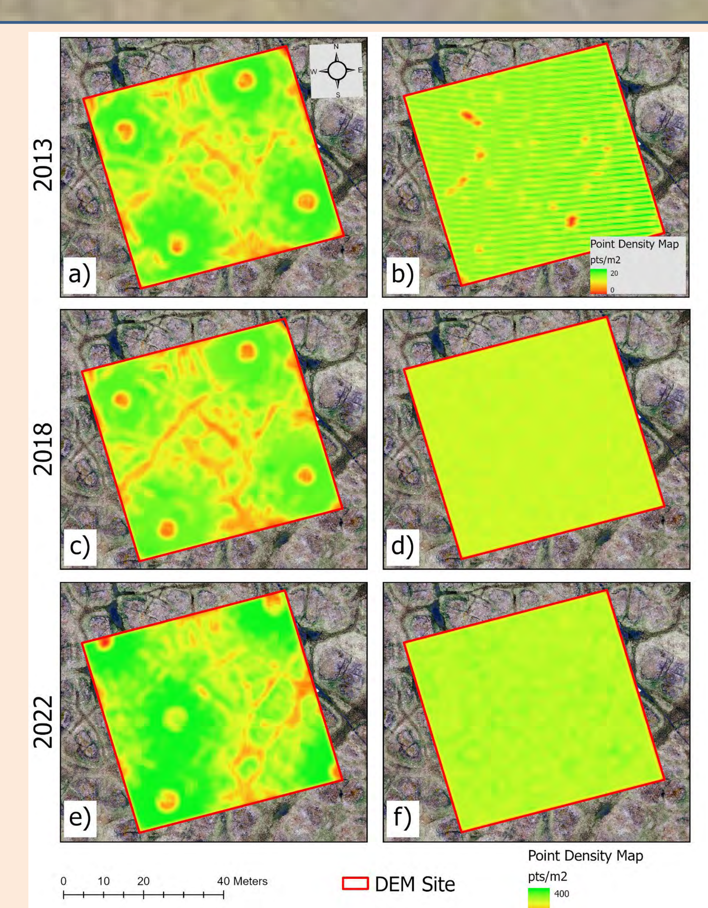

Fig. 6. High resolution point density maps (PDMs) of the study site for approaches collected in the same years to facilitate intercomparison of approaches. TLS and ALS collected during 2013 are shown in (a) and (b); TLS and UAV-SfM collected in 2018 are shown in (c) and (d); TLS and fused UAV-TLS for 2022 are displayed in (e) and (f). The units (points per m2) for the TLS and UAV-SfM map legends are displayed at the bottom of the map, while the ALS point density legend is displayed in (b). Elevation values are shown in meters above ellipsoid height (EPSG: 26904).

But point cloud data fusion and interpolation methods can help fill data gaps.

Elevation change can be estimated from multi-temporal UAV and TLS acquisitions…

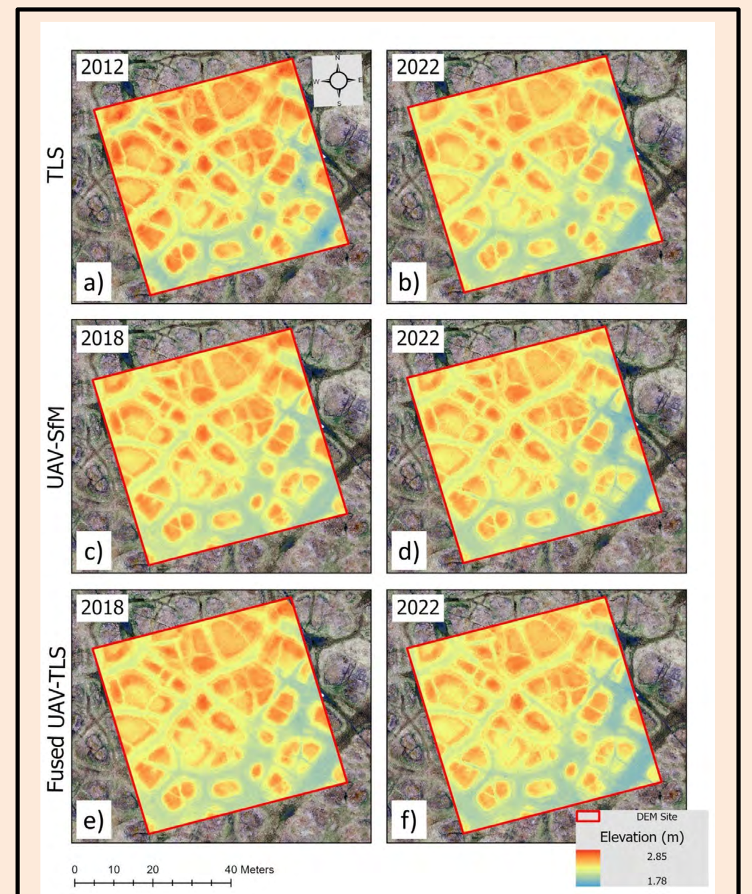

Fig. 7. High resolution DEMs of the study site highlighting temporal differences using the same approaches. TLS DEMs are highlighted in (a) 2012 and (b) 2022, UAV-SfM DEMs are shown in (c) 2018 and (d) 2022, and fused UAV-TLS DEMs are displayed in (e) 2018 and (f) 2022. Elevation values are shown in meters above ellipsoid height (EPSG: 26904).

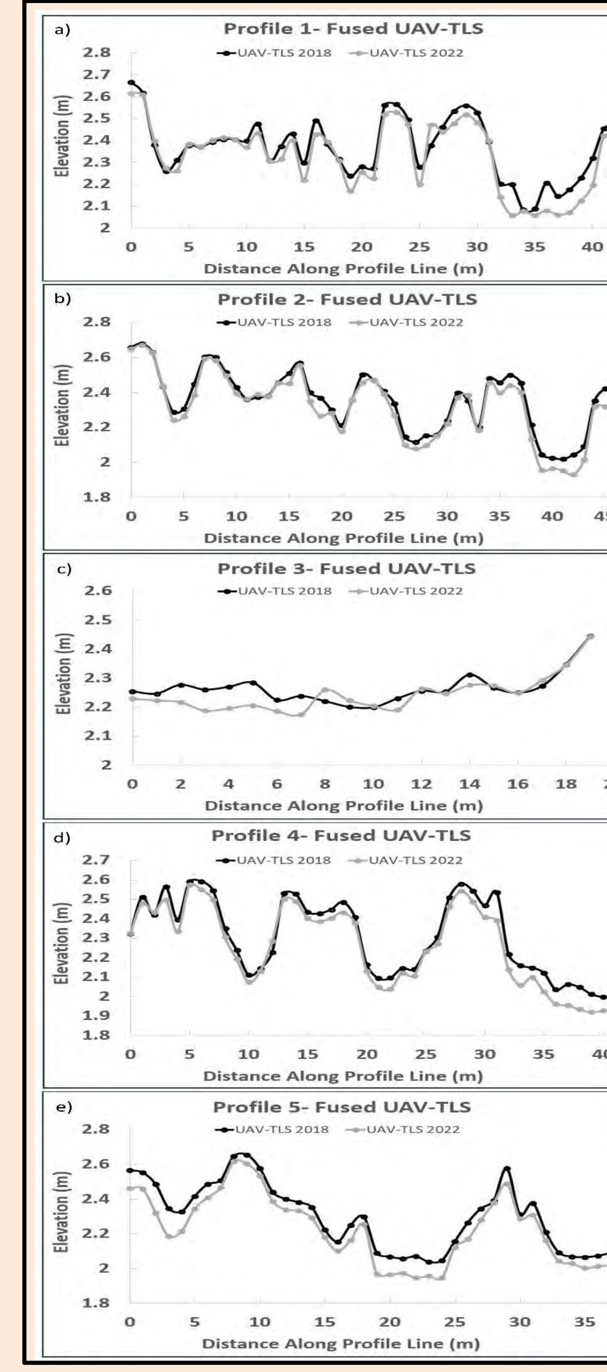

Fig. 8. Temporal inter-comparison of microtopographic relief along five profile transects derived from fused UAV-TLS DEMs in 2018 and 2022. Elevations along profile transect lines 1-5 are shown in (a) - (e). The x-axis on all plots show distance along each profile transect line, while the y-axis shows elevation in meters (EPSG: 26904).

Particularly when UAV and TLS point clouds are fused to form one gap-less DEM.

Between 2018 and 2022, DEM difference maps (DoD) showed mean elevation change was highest for the troughs (-0.39 cm/yr.) than for the high centered polygons (HCPs; -0.22 cm/yr.)

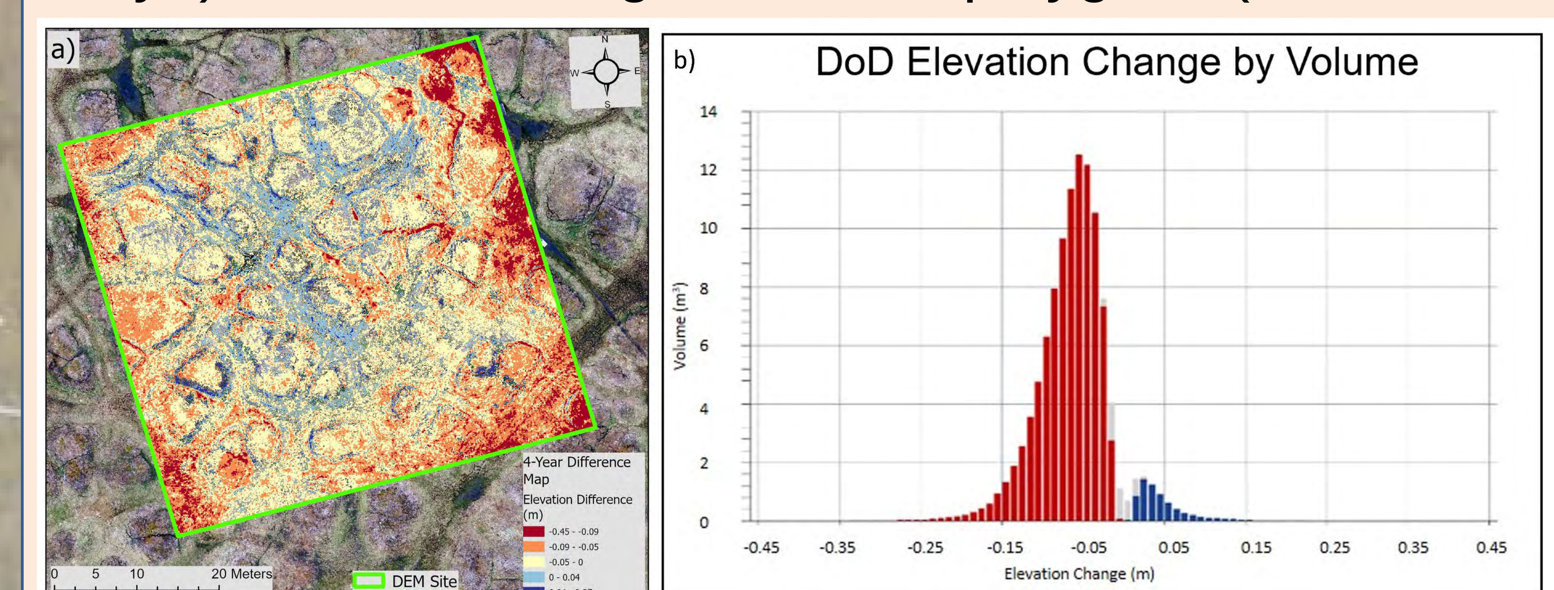

Fig. 9. DEM site outlined in green, DoD map highlighting change in elevation between 2018 and 2022 from fused UAV-TLS DEMs (a), and volumetric elevation lowering/increase estimates between 2018-2022 (b).

Conclusion and discussion

- UAV and TLS DEMs resulted with highest accuracies and lowest RMSE, when compared to ALS and ArcticDEM
- TLS PCs and DEMs resulted with lower accuracies and higher RMSE than the UAV approach
- Point cloud data fusion and interpolation methods can help fill data gaps
- UAV and TLS approaches are suitable for detecting temporal elevation change for fine-scale tundra geomorphic features
- DoD maps estimated ~94% of the total site land surface subsided, while only ~6% heaved or elevated between 2018 and 2022
- Modeling and upscaling landscape structure between drone and satellite data remains an important research priority for arctic ecosystems

Acknowledgements

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