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REVIEW

Standardized monitoring of permafrost thaw: a user-friendly, multiparameter protocol[1]

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Abstract: Oimate change is destabilizing permafrost landsc.apes, affecting infrasttuctW'e, ecosystems, and human livelihoods. The rate of permafrost thaw is ronttolled by surfu.ce and subsuiface properties and processes, all of which are potentially linked with each other. However, no standardized protncolexists fur measuring permafrost thaw and related processes and properties in a linked manner. The permafrost thaw action group of the Terrestrial Multidisciplinary distributed Observatories for the Study of the Arctic Connections (T-MOSAiC) project has developed a protocol, fur use by non-specialist scientists and technicians, citizenscientists, and indigenous groups, to rollectstandardized metldata and data on permafrost thaw.The protncol introduced hereaddresses the need ID jointly measure permafrost thaw and the associated surface and subsuiface environmental conditions. The parameters measured along transects include: snow depth, thaw depth, vegetation height, soil ll!xture, and wab!r level. The metadata collection includes data on

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timing ofdata collection, geographicalcoordinates, land surface characteristics(vegetation, ground surfu.ce, water conditions), as well as photographs. Our hope is that this openly available dataset willalsobe highlyvaluable **fee** validation and parameterizationof numerical and cooceptual models, and thus to **the** broad community represented by the T-MOSAiC project.

Keywords:snow depth,vegetation height, soilcharacteristics.active layer thaw depth, permafrost monitoring protocol.

Resume: Le changement climatique destabilise Jes paysages de pergelisol, affi!ctant Jes infrastructures, Jes ecosystemes et Jes moyens de subsistance des populations. Le taux de degel du pergelisol est controle par Jes proprietes et Jes processus en surface et en subsurface, qui soot tous potentiellement lies Jes uns aux autres. Pourtant, ii n'existe pas de protorole normalise pour mesurer **le** degel du pergelisol et Jes processus et proprietes connexes de maniere liee. Le groupe d'action sur le degel du pergelisol *Terrestrial* Multidisripinary distributed *Observatories* for *the* Study*of the* Arctic *Connections (f-MOSAiq* a elabore un protocole destine a etre utilise par des scientifiques et des techniciens non specialises, des scientifiques citoyens et des groupes autochtones, pour collecter des rnetadonnees et des donnees normalisees sur **le** degeldu pergelisol. Le protorole presente id repond a la necessite de mesurer ronjointement le degeldu pergelisol et Jes conditions envirmnementales associees en surface et en subsurface. I.es pararnettes mesures le Jong des transects sont : l'epaisseur de la neige, l'epaisseur du degel, la hauteur de la vegetation. la texture du sol et le niveau de l'eau. La collection de metadonnees comprend des donnees sur le moment de la rollecte des donnees, Jes coordonnees geographiques, Jes caracteristiquesde la surface emergee (vegetation. surfu.ce du sol, conditions de l'eau), ainsi que des photographies. Les auteurs esperent que ce jeu de donnees librement accessible sera egalement ttes utile pour la validation et le parametrage de modeles nurneriques et conceptuels, et done pour la vaste communaute representee par le projet T-MOSAiC. [Traduit par la Redaction!

MotS<les : hauteur de neige, hauteur devegetation, caracteri.stiques du sol, profondeur de degel de la couche active, protocole de surveillance du pergelisol

Background and general introduction

Northern landscapes and infrastructure are affected by the thaw of permafrost, especially in regions of ic rich permafrost, because thawing can lead to surface subsidence and slope instability. Permafrost thaw has profound implications for Arctic ecosystems and their inhabitants, through changes to surface drainage and water resources (Osterkamp et al. 2009; Kokelj and Jorgenson 2013), vegetation and wildlife habitats (Sturm et al. 2001b; Jorgenson et al. 2010), and through the positive feedback to global warming via the emission of greenhouse gases (Burke et al. 2017; Burke et al. 2017; Hugelius et al. 2020; Turetsky et al. 2020

There is an urgent need for standardized monitoring of permafrost conditions. The impacts of permafrost thaw on ecosystems are expected to increase with climate warming, changes in precipitation, and increasing surface disturbance (Kokelj and Jorgenson 2013; Rasmussen et al. 2018). For 2020, the Arctic Report Card highlights the highest recorded surface air temperatures, record lows of June snow cover, opposing trends of tundra greenness, and extreme wildfires (Arctic Program 2020 Permafrost temperature and active layer thickness are increasing, but there is considerable spatial variability in the magnitude of the change, owing to local variations in snow, vegetation, and soil characteristics (Romanovsky et al. 2020). These local variabilities are critical fur the evaluation of permafrost thaw. Not onlydo the rate and nature of permafrost thaw depend on factors such as snow depth, the thickness of the organic layer, and vegetation height, but permafrost thaw will in turn influence these variables (Vincent et al. 2017). For example, increases over time in the density and height of shrubs have been reported from tundra regions across

Table 1. Summaryof existing protocols i>rthe parameters presented in this papei:

Spheres	Existing protocols,o,ganaation
Snow	Essential Climate Variables products and requirements for snow,The Global Climate Obsemng Sy.;tem(GCOS) flbe Global Oimate Observing Sy.;tem 2016a) **Estimating the snowwater equivalent from snowdepthdata, lntemational Commission for Snow** and Ice Hydrology (ICSH)*(Jonas* and Marks 2016) **The international c)asg.flcation forseasonal snowon the ground. International Association of** Cr)ospheric Sciences (IACS)(Fien et al. 2009) European Snow Booklet.WSLln.stirute for Snowand Avalanche Research SLF(Haberkorn 2019) Chapter S: Snowand Ice, International Tundra Experiment (IfEX) Manual,Danish PolarCenter (Molau 1996)
Permafrost	GlobalTerrestrial Nen,ork for Pennafrost. International Pennafrost Association (IPA) (Streletskiy et al. 2017b) Methods for measuring active-la)"r tbicla,ess:A handbookon periglacial field methods; IPA: Circumpolar J\<:li-,, layer Monitoring Nen,ork (CALM()Nelson and Hinkel 2004) Essential climate variables(ECVs} productsand requirements for permafrost. GCOS (The Global Climate Obse,ving System 2016b) Active layer monitoring standard protocoL Arctic Development and Adaptation *to* Permafrost in 'lransition (ADAPI)(Arctic Development and Adaptation *to* Permafrost in 'lransition) Chapter 6: Active layer protocoL(ITEX) manual(Nelson et al 1996) **Assessment of the status of the de\\!lopment of the standards for theTerrestrial Essential Climate** Variables, Pennafrost (Smith and Brown 2009)
Veget11ion	Chapter n: Community baseline measurements. ITEX manual (Molau and Edlund 1996) Veget11ion standard description protocol, ADAPT(Grogan et al. n.d) **New handbook for standardised measureme.nt of plant ftmctional traits rldwide** (Pt!rez.Harguindeguy et al 2013)
Water	Guide *to* Hydrological Parametea - Volume 1.World Meteorological O,ganiution (World Meteorological Organization 2008) Soil moisturecontent. CALM(Circumpolar Actm> layer Monitoring Network)
Soil	Sampling protocols for pennafrost<>ll,cted soils (Ping et al. 2013) Soil s yfieldsandaboratory methods, U.S. Department of Agriculture. Natural Resources Conservation Service (Soil Su,vey St1ff20l4) Active layer sampling standard protocol for /N detennination,ADAPT(Arctic De-,,lopment and **Adaptation to Perrn.afrost inTransitionc_,** Planningand making a soil survey. Food and Agriculture Organization of the United Nations (Food and Agriculture Organization of the United Nations) Terrestrial instrument system(llS) soil pitsampling protocoLThe National Ecological Obse,vatory Nen,ork(NEON) flbe National llcological Obse,vatory Network 2021) The United NationsTerminology Database.United Nations(United Nations 20t2j

Note: The pa.rame.ten a.regrouped into five spheres: mow. pe.rma.frost.vegetation, water. and soilCitable references aregiven in the table: some pro fexampleADAPT.CALM) provide ixotomlson1ine filrwbkhwe JXOvidelinksin the re.fere.nce sectionof *this* piper.
•https:/)'www.<l'll.ulavalajadapt/f<O'"a>Js/adapLp .

the Arctic, and locally, shrub expansion may also be driven by permafrost degradation (Sturm et al. 2001b). Shrub growth can in turn reduce (Blok et al. 2010) or promote (Wilcox et al. 2019) permafrost thaw, depending on how shrub height affects snow accumulation and snow melt.The hydrological conditions in ice-rich permafrost lowlands determine the thawing of permafrost; inundated and wetter areas favour degradation, whereas drainage and drier soil conditions favour stabilization (Nitzbon et al. 2020).

No common protocol exists that simultaneouslyconsiders both permafrost thaw and the key environmental variables that affect permafrost thaw. A number of protocols have already been created by specialized research communities (Table 1), but each is dedicated to only a small subset of parameters. Collocated and consistent measurements of multiple variables are needed to explain changes in permafrost conditions, and therefore to upscale or to make future projections of future permafrost thaw.In addition, particular parameters are required as inputs for numerical and conceptual models (including Earth system

models and specialized permafrost models, such as CryoGrid; Nitzbon et al. 2020).The focus of our study was to design such a multiparameter protocol.

Here we developed simple protocols and an associated mobile app that will enable a wide range of non users to make high uality, standardized, and accessible measurements. Our protocols address the need for consistent collection and integration of data from across the permafrost region to: (i) better monitor and understand permafrost thaw; (ii) establish a baseline against which future change can be measured; and (iii) support the integration of field measurements within pan-Arcticgeospatial datasets developed through remote sensing analyses or modelling. The app guides the user through the observation process, ensures that the observations are consistent and well documented, and transfers the observations to an accessible database.

Wedeveloped the protocol in the Terrestrial Multidisciplinary distributed Observatories for the Study of the Arctic Connections (T-MOSAiC) action group on permafrost thaw. T-MOSAiC is an International Arctic Science Committee (IASC) pan-Arctic, land-based programme that extends the activities of the sea-based programme Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC; https:/Jmosaic-expedition.orgn. Originally T-MOSAiCwas planned to run concomitantly with MOSAiC to achieve simultaneous measurements of biogenic, hydrological, and atmospheric fluxes by extending the work to the lands surrounding the Arctic Ocean. Because the COVID pandemic limited travel to field sites, T-MOSAiC was extended to the end of 2021. Intense monitoring is proposed for 2021 to kick-start a longer term observational program to monitor the progression of thaw in permafrost and other associated environmental changes.

In this paper, we detail the rationale behind the protocol and choice of measurements; the detailed protocol is available in Appendix A.

Protocol overview - choice of parameters and scale issue

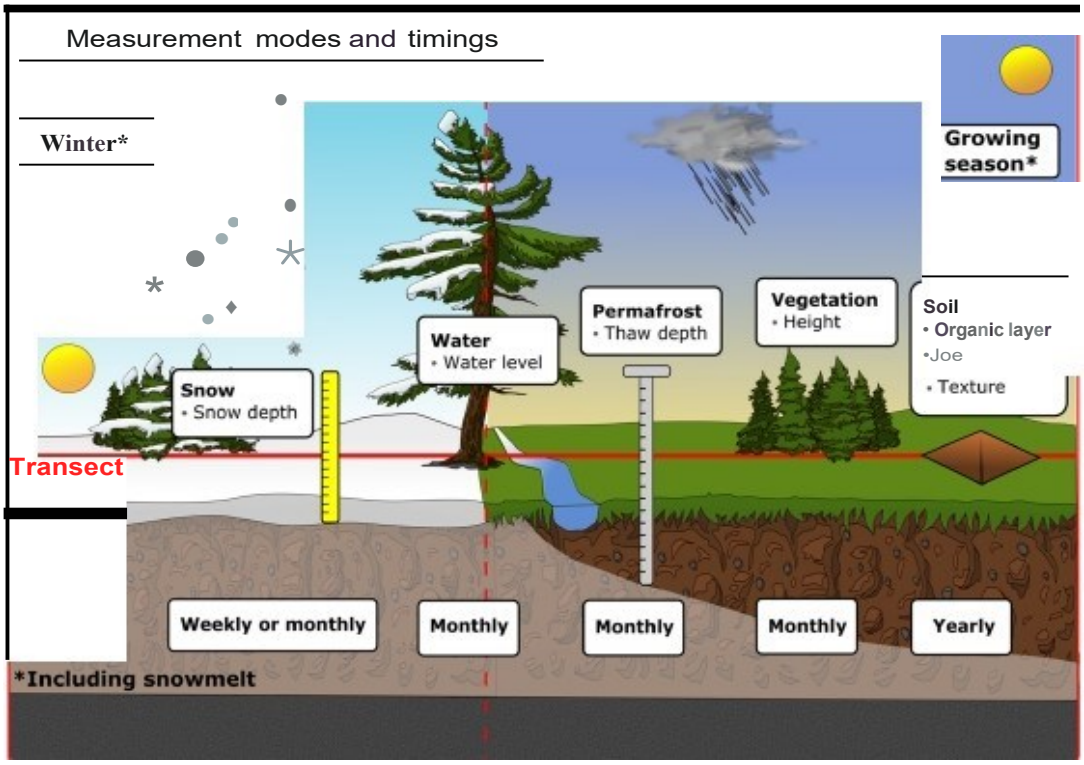
Protocols for everyone

The protocol's primary target group is not the permafrost experts, but persons with limited prior field experience. The users comprise professionals and students from a wide range of backgrounds, including ecology, hydrology, and geology. In epth expertise in permafrost ecosystems is not required. Citizen scientists form the protocol's secondary target audience, ideally underguidance from an experienced user. For instance, a high-school class could continually monitor the permafrost conditions with support from a biology teacher.

The protocol is geared towards nonspecialists in three ways. First, no specialized knowledge or skills are needed. The measurements are simple, and an app has been developed to guide the user through the measurement process. In addition, videos are provided to illustrate key steps.The app also takes care of data handling, ensuring data quality and usability by enforcing the compilation of required metadata and homoge.nizing datatransmission, and storage. Second, no specialized equipment is needed.The protocol only requires simple tools, namely a ruler, camera, tape measure, shovel, and a steel rod. Finally, the protocol has been streamlined so as not to take up too much of the nonspecialist's time.

Appendix A provides further details of the app for data collection, as well as instruc• tional videos. One was recorded at a permafrost site in northern Norway in autumn 2020 by fine-art students. Another one was recorded at the permafrost long-termobservatory site Bayelva on Svalbard, Norway, in spring 2021 by the permafrost thaw action group and the Alfred Wegener Institute Helmholtz Center fur Polar and Marine Research (AWi).

Fig.1. Spheres with the associated parameters. measureme.ntmodes. andobse.rvation timingalong one transect overone seasonal cycle.



Par.uneters

Wegrouped the parameters for which we provide protocols into 5 spheres as follows:

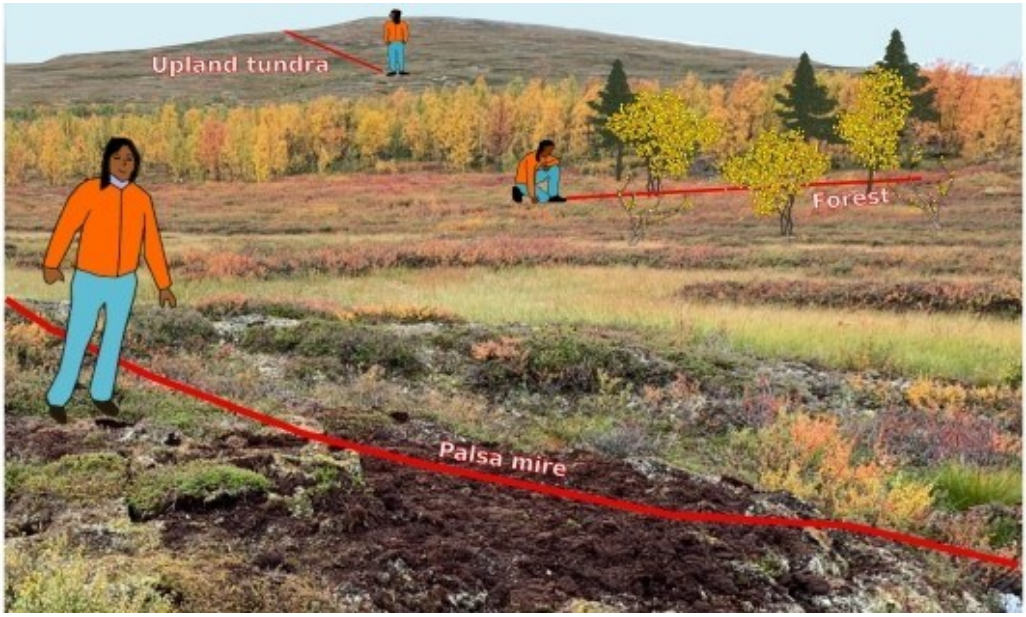
1. Snow: snow depth;
2. Permafrost: thaw depth;
3. Vegetation: vegetation height;
4. Water: water level;
5. Soil: organic layer depth, soil texture, ground ice.

We chose the specific measurement parameters (Fig. 1) to cover the major controls of permafrost thaw with simple measurements that are accessible to non-experts, and in doing so we inevitably cannot include some commonly used parameters, such as soil temperature, owing to their need for specialized equipment.

Figure1 gives an overview of the spheres we incorporate, the measurements described in this protocol, and their seasonality. Measurements start during the winter on snow, and are continued at the same transect points through the seasons of snowmelt, vegetation growth, deepening of the thawed layer, and development of a water level in summer. Measurements of soil properties, such as organic layer thickness and soil texture, are only doneonce along the transect - ideally during the later part of the season when the thawed layer has reached its maximum.

Our five parameters in these spheres can vary dramatically across the landscape, for example, snow depth on palsas is much shallower than on an adjacent mire (Martin et al. 2019). In addition, all these spheres interact with each other, and the landscape variability

Fig. 2. Eumple of landscape variability covering palsa mire.forest.and upland nmdra(Ukoras: Finrunark. **northern Norway). lypically. one 10 m long transect cannot coverall thecharacteristic features as shown in this figure. If ti.mingand capacities allow. several transects canbe est.abI.isbed. If the.re is already an est.abUshed transect at this site it canbe used.**



is sometimes driven by dynamic feedbacks between these parameters, which can amplify small variations into major sources of heterogeneity. For example, a small variation in surfuce elevation can lead to a positive feedback in which snow and water accumulate in the depression, warming the ground and leading to thaw and potential ground subsidence (if the permafrost is ice-rich), resulting in further accumulation of snow and water, and increasing permafrost thaw at this location (Kokelj and Jorgenson 2013; Nit2bon et al. 2020). Some features vary at the metre-scale, including microtopography such as hummocks, and vegetation. Others will vary on the scale of hundreds of metres, such as differences between valley bottoms and hillslopes. This protocol accounts for these issues of parameter interconnectivity and variability by using transects, with measurements of multiple parameters from diflerent spheres conducted on the same transect.

Where to measure?

The protocol design aims to ensure that measurements capture the variability within a landscape. Because the overarching goal is to understand permafrost thaw on a pan-Arctic scale, we must consider the issues in scaling between a measurement at a single point to regional modelsfsatellitedata pixels (10s to a few100s of metres to kilometres) and global models (10s to 100s of kilometres

Toensure representation of variability within a landscape, and taking into account the target audience and time constraints in the field, we chose the scale of the measurements as a 10-30 m Jong transect to allow "typical microtopographic reatures" to be resolved by

sampling every 1 m. This means that the minimum effort (one10 m long transect) can resolve a key aspect of variability and requires very little investment of time. Examples of typical microtopography captured by the sampling strategy include tundra polygons and peat plateausfpalsas, which are typical landforms in pennafrost areas.

Time permitting, larger-scale variability will be captured with further transects in the local area, taking account of the landscape features that are present. For example, at the Jskoras site in northern Norway (Fig. 2), separate transects would ideally cover the palsa mire, the forest, and the nearby upland tundra. Furthermore, larger-scale topographic features, such as the slopes and the bottom of a valley, could be captured through multiple transects. In the protocol we urge the users to consider the landscape variability in and around their site, and to select "representative" locations for their transect (see the protocol described in Appendix A).

Details oflhe spheres' parameters

The five measurement spheres are described below. Here we give details on the scientific importance of each sphere and its interactions with permafrost thaw, as well as the rationale behind the choice of parameter to measure and the chosen measurement technique.

Snow

Backgro\lld

Snow cover exerts a fundamental control on the thermal and hydrological regime of permafrost. It acts as an insulator thanks to its low thermal conductivity, reducing heat loss in winter (2hang 2005; Grunberg et al. 2020).The typeofvegetation cover can significantly influence the insulating power of snow because plants affect the distribution of snow and its depth (Domine et al. 2018). In spring, snow strongly reflects the solar radiation (i.e., a high albedo) (Stiegler et al. 2016).The duration and extent of the snowcover in spring regulate the soil temperature and meltwater supply (Boike et al. 2003). Snow masses in Arctic regions are highly diverse and determined by regional conditions. Tre.nd analyses point out an increase of snowmasses in Siberian regionswhere others are likely to decrease (Callaghan et al. 2011; Pulliainen et al.2020

We focus here on snow depth, as the thermal resistance of the snowpack is in the first order a function of snow depth(Zhang et al. 1996). Crumley et al. (2020) show the usefulness of snow depth measurements for a citizen science approach for a different application. Snow depth is spatially variable due to land-cover characteristics (topography, vegetation) and wind-induced redistribution. For example, the snow cover on plains can experience drift (Sturm et al. 2001a; Parr et al. 2020), whereas local depressions, or an abundance of shrubs, trap snow (Wilcox et al. 2019). Critical observation times are the onset of snow accu• mutation at the beginning of the winter season, absolute maximum during winter, and maximum height just before spring melt. We recommend regular observations with a frequency of at least once per month, ideally once per week.

Measurement

Snow depth is the full height of a snowpack measured perpendicular to the underlying ground (Haberkorn 2019). Snow depth captures evolution of the snow cover over time with minimal effort but maximum information.

It is measured mechanically using either a simple ruler to record the depth or, if available, a snow rod with the measuring units already on the probe.Those tools are easy to obtain and user friendly. Snow depth measurements can be difficult if the snowpack is very hard or if the soil below the snow is very soft.In the first case, the probe may not reach

the ground (e.g., if thereis a hard refrozen crust within the snowpack or in the presence of a basal ice layer). In the second case, the probe may penetrate the ground (e.g., unfrozen peat, deepgrass, or moss hummock). The vegetation (e.g., bushes) within the snowpack can alsoinfluence the measurement.

Pennafrost

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Thawdepth is the onlyvariable for characterizingpermafrost conditions that isincluded in the T-MOSAiC protocol. It is defined as the distance between the ground surfuce and the frost table (Brown et al. 2000). Thaw depth increases over **the** summer period, as the thaw front penetrates deeper into theground.The most critical time for measuring thaw depth is at the end of the thaw season, when thaw depth is at or near its annual maximum (Brown et al. 2000). This timing typically ranges from mid-August to mid-September in the arctic and subarctic regions (Brown et al. 2000

Thaw depth is an important variable fur characterizing changing permafrost conditions because increasing air temperatures andground warming often cause the maximum thaw depth to increasevia thawingat the top of the permafrost (Brown et al. 2000 However, two additional factors have to be considered when using maximum thaw depth as an indicator of permafrost response to climate conditions. Firstly, the maximum annual thaw depth varies from year to year in response to interrelated variables such as soil moisture, vegetation, and snow (e.g., Walker et al. 2003; Shiklomanov et al. 2010; Grunberg et al. 2020). Secondly, the thawing of ice-rich permafrost primarily induces subsidence rather than increases in thaw depth (Osterkamp et al. 2009; O'Neill et al. 2019). Hence, a comprehensive quantification of permafrost thaw necessitates observations of subsidence (Streletskiy et al. 2017a). While direct observations of subsidence are not included in the protocol because of the lack of simple methods for measuring it, the measurements of vegetation and inundation (wetness) can indicate subsidence induced by the thaw of ice-rich permafrost (Kokelj andJorgenson (2013).

Measurement

Multiple methods exist for measuring thaw depth in the field (Smith and Brown 2009 Mechanical probing is arguably the most popular method because it does not require sophisticated equipment (Brown et al. 2000), and for this same reason it is the method adopted for the T-MOSAiC protocol.

Thaw depth is measured by inserting a pointed metal rod (usually 1.0-1.5 min length) into thesoil down to the point of resistance against the frost table at each point along the transect.The depth that the rodhasbeeninserted into theground can then bedetermined usinga measuring tape, or fromgraduated marks on the rod itself.

The measurements need to account for the substantial small-scale spatial variability in thaw depth. Toensure unbiased sampling and to facilitate comparisons over time, the measurement should be made in immediate proximity to the marked transect point. If standingwater should make it too difficult to measure at the point, the measurement should be marked as "Water".

Mechanical probingworks best in organic and gravel-poor mineral soils that are ice bonded when frozen (Brown et al. 2000). The app guides the user through challenges that mayarise for substrates that are less amenable to probing.The most commonly encountered limitations are:

- probing may be impossible in bedrock or gravel;
- it can be difficult to distinguish between subswface stones and frozen substrate, for instance in soils that contain gravel;
- in locations of deep thaw, the thaw depth may exceed the length of the rod;
- the unusual mechanical properties of saline marine sediments or plastically frozen days present a challenge to frost probing.

Vegetation

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Vegetation is an important component in influencing the surface energy balance and the thermal and hydrological regime of permafrost. At the same time it can also react to changes in the environment (Myers-Smith et al. 2011). Different vegetation types can have contrasting effects on permafrost ecosystems. Forests are usually considered to efficiently insulate the underlying permafrost (Chang et al. 2015) by altering the thermal regime, by intercepting snow, and promoting the accumulation of an organic surface layer (Bonan and Shugart 1989; Stuenzi et al. 2021). Low stature tundra vegetation can similarly alter thermal and hydrological conditions through differences in albedo between vegetation types (Juszak et al. 2016; Aartsma et al. 2020), as well as the effect of vegetation height on snow conditions, including snow depth, snowmelt, and the physical properties of snow (Domine et al. 2018; Wilcox et al. 2019). From a permafrost-thaw perspective, we consider the presence and the height of vegetation as **the** most important parameters for including vegetation in permafrost modelling. Vegetation height is commonly measured from the soil surface to the highest point of the vegetation. As multiple measurements are made within each quadrat, thiswill thenprovide representativeaverage vegetation heights along the transect (similarly with height measurements of multiple trees).

Measurement

The measurement ofvegetation height can provide a good estimate of the type of vegetation regime present, and requires little knowledge about actual plant species or plant functional types. Height measurements should be carried out in 1 m x1 m quadrats (Molau and Edlund 1996) at each point along a 10-30 m transect. This transect should be established before taking any measurements at the site. Optionally, if the site is located in forest, a minimum ofl0 individual trees in a 15 m x 15 m plot should also be measured (Perez-Harguindeguy et al. 2013; Kruse et al. 2019). Most measurements therefore require a ruler or tape measure only, but in tallforests it might be necessary to give training in height estimation beforehand

Water

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Permafrost has a primary influence on the movement of water through a landscape, and water, in turn, impacts the ground thermal regime and the rate of permafrost thaw (Riseborough et al. 2008; Woo 2012). The liquid water and ice content of a soil exerts a fundamental control on its thermal diffusivity, and thereby the transport of heat between the active layer and permafrost (Edlefsen and Anderson 1943; Kurylyk and Watanabe 2013). Furthermore, the water content influences the thawing and freezing rates of the ground becauseof the latent heat associated with melting or freezing (Outcalt et al. 1990 In addition to influencing the rate of thaw, surface and groundwater are also indicators of thaw of ice-rich permafrost, which can lead to impoundment in depressions (Jorgenson et al. 2010). Observations of wetness are thus critical for predicting and monitoring perma• frost thaw (Jorgenson et al. 2010; Chadburn et al. 2015; Rasmussen et al. 2018

Measurement

From a permafrost thaw perspective, we consider the spatial and temporal distribution of soil wetness indicated by the height of the water table the most important hydrological variable to record. Water table observations are most easily done in combination with measurement of thaw depthor soil pit, as it can be carried out with the same equipment and along the same transect. Acquiring observations of both wetness and thaw depth at the same locations and times helps in later interpreting the relationship between water level and soil thaw. Following our protocol, the height of the water table relative to the ground surface level is noted in the hole (using the frost probe, shovel, or your hands) as: "above the ground surface", "within 10 cm below the ground surface", or "more than 10 cm below the ground surfuce". This very simple classification, carried out at points along transects, provides valuable information for characterizingsoil wetness which can be used by permafrost modellers.

Soil

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Soil properties playa crucial role in the energy andwater balanceof permafrost systems, by affecting the exchange of heat and water between the atmosphere and the subsurface, and thus the rate of permafrost thaw (Shur and Jorgenson 2007; Chadburn et al. 2015; Walvoord and Kurylyk 2016 Permafrost-affected soil comprises a mixture of"various media includingorganic matter, mineral particles ranging from gravel and sand to clay, as well as ice and unfrozen water. Organic matter insulates the permafrost from the air, the magni• tudeof"the insulation dependingon the organic layer thidcness and organic matter content (Romanovsky et al. 2020). Soil texture also influences ground ice contents of permafrost, and together they control physical, thermal, and mechanical properties of"permafrostand its behavior at thaw (French and Shur 2010; Jorgenson et al. 2010). Gravel or coarse sand show markedly different thermal and hydraulic properties compared with finei-grained soils (Shur and Jorgenson 2007 Soil texture also affects porosity, which determines the maximum amount of"water that can be contained in a soil layer. Ice content and the form of the ice (such as ice lenses or massive ice) can affect energy transfer directly, as well as induce frost heave or subsidence of the ground surface in response to the formation or melting of the ice (Osterkamp et al. 2009; Kokelj and Jorgenson 2013; Romanovsky et al. 2020).

Measurement

Soil properties are documented as a one-time observation from a single measurement **point** near the transect.To characterize **the**soil profile(pedon), a soil pit is established dose to the transect but set to the side to minimize disturbance.The pit should be approximately 1 m wide and 1m deep, or untilonecan no longer digdue to frozen ground.The scale ofl m was chosen to allow a clear soil profile to be revealed and the small-scale variability in soil properties to be accounted for.The best time is at the end of thegrowingseason when thaw depth is greatest. If digging a pit is not allowed or possible, estimating the surface layer usinga hand-held soil augerfdrill is recommended.

The observations comprise a photograph of the dear profile and a description of"visible characteristics, such as depth oforganic layer, contents of"ice and rocks, colour of"the soil, and soil texture. For nonspecialists, we provide a simple hands-on flow chart within the the myThaw app that helps identification of soil texture (i.e., clay, silt, sand, gravel) adapting the protocol of the mySoil app (British Geological Survey 2021). Overall, the soil measurements are designed so that they do not require any specialist equipment or

laboratory analysis. To restore the site, the pit must be refilled and the organic mat reassembled.

Metadata, data quality,and storage

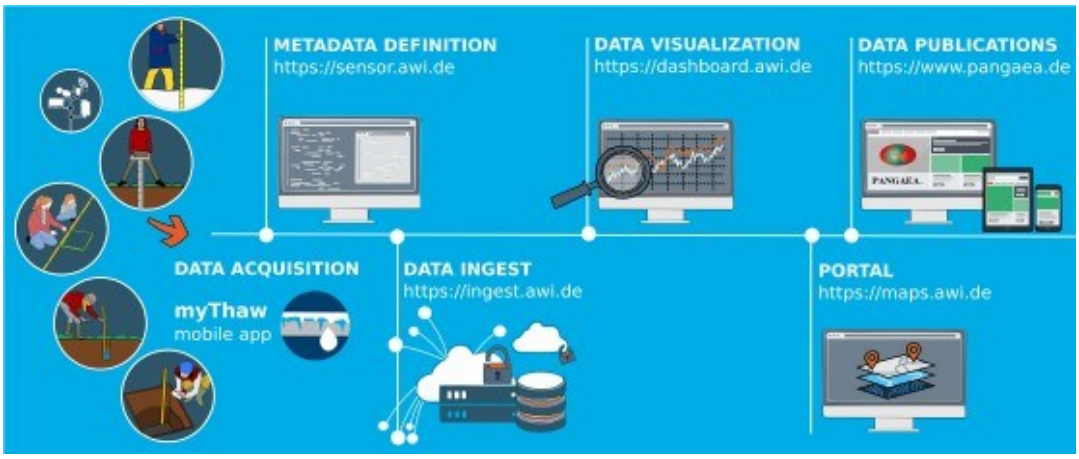
Metadata provide essential information about the quality, use, and genesis of the information being collected. Our metadata protocol complies with the standards of the OpenGeospatial Consortium (OGC)(Open Geospatial Omsortium 2021), and thus facilitates interoperability.Specifically, everything related to data processing and data management follows Observation to Archive (02A; Koppe et al. 2015; Gerchow et al. 2017), and in tum all instrumentation aspects of 02A follow sensorMl specification (OGC2014

The protocol requests basic information about the site location, including latitude, longitude, elevation, and the location of the nearest weather station. This information is crucial fur both mapping and modelling, and therefore adds greatly to the usability of the data collected. Land surface models require various forcing data, which can be obtained either from the nearest weather station, or in some cases from gridded products by using the nearest grid cell to the site.We then request an overview of the site characteristics as seen eye, including whether the site is rocky, what type of soils are there, and howwet it is. For example, it may be a very wet or dry site, or it may be mixed, and these overview assessments, while providing similar information to the spheres themselves, will give an overview of the siteas awhole.This also provides further information regarding how representative the transect measurements are.While vegetation height is covered in its own sphere, the dominant type of vegetation merits inclusion as metadata because it is a key indicator of the type of site. Basic information about any water features, such as ponds and rivers, as well as natural and anthropogenic disturl>ances are recorded because these willalso affect the site, impacting the hydrology and permafrost thaw. Photos are required in the four cardinal directions in a standardiz.ed manner that provides a sense of scale, to give an overview of the site and clarify descriptions. An additional photo shows the placement of the transect.

The protocols are designed to ensure that the data and metadata meet scientific standards. We aim to provide quality-assured and data management over the whole data life cycle. Data should be findable, accessible, interoperable, and reusable according to the FAIR principles (Findability, Accessibility, Interoperability, Reusability; Wilkinson et al. 2016). Hence, measurement data and metadata need to be provided accurately and completely, have a persistent and unique identifier, and deposited in a trusted repository. It must follow the semantics of a standardiz.ed, controlled vocabulary to have broadly applicable language fur machine access and processing. We apply the 02A dataflow framework, which includes the comprehensive description and management of alldata with metadata, central data storage, and controlled data access (Koppe et al. 2015; Gerchow et al. 2017). Through a standardized procedure, data uploads can be monitored in near-real time, and their spatial distribution visualiz.ed.The data can be accessed instantly as-is via the near-real time database (Alfred Wegener Institute 2021) while quality controlled and thematically curated datasets will be published in the PANGAEA long-term repositories (Pangea 2021), thus giving credit to the data provider in a data publication (Schafer et al. 2020). A map-based search and visualization of the data with download link fur the data(example: thaw depth) is planned. Data will becollected usinga mobile app directly in the field. Data uplink occurs on-the-fly or whenever the data collector can upload it to an AWi server and will beautomatically ingested into the02A process chain (Fig. 3).

For quality control, a first quality check is done automatically using the 02A system, such as removing unphysical data (for example, negative snow depths) or implausible coordinates and times. This is managed by setting the measurement properties in

Fig. 3. mustration showing theworldlowofthedaracollection (my'lhaw app)and 02A (Alfred WegenerlnstiMe 2021) **process cha.in towards archiving into a repository. Data are collected offline and ingested into 02A in "delayed mode· (as soon as internet access is available) using full met.adat.aannot.ation. A dashboard is used for** visualiution of the dataonce they are uploaded Daracan be visuali7.ed spatially on the Portal. Final publications wee place in the repositories. Figureadapted after Koppe *et* al. {2015



sensor.awi.de. Before archiving the dataset in PANGAEA, an additional thorough manual data check will be done.

Description of lhe mobile my1baw app for data collection

The mobile app myThaw is freely available to everybody (Appendix A). The app allows the collected data to be exported to a central data storage for data analysis and reporting. One of the advantages of apps is the possibility of gathering data offline or while on-the-go. The oflline form allows researchers to collect and store data while in the field and upload it once an internet connection is available (for example, at the field station As nearly all researchers and citiz.ens today own a smartphone or tablet, we see advantages in usinga mobile overa field notebook or report-based archives.The app is designed fur use in cold climates and is user friendly, with help/guidelines and "pop-up window" options when necessruy. Because our protocol asks for measurements at multiple moments across time and spheres, at new and recurring locations (i.e., long term measurements at the same sites), the app can identify the recurring location, thus eliminating the need to re1!llter the metadata.The app will be available under the CC BY 4.0 licence. Further maintenance and development, such as security updates and, if necessary, debugging, are planned for the future. In summruy, we provide a method fur secure and collaborative data entry, resulting in faster data analyses, visualization, access, and storage.

Next steps for lhe data: conclusions and outlook

The database thatwe will develop using this protocol and app will cover permafrost state and land-surface conditions. The value of this is not only in analysing the trends and relationships in this dataset alone, which can be used for model validation and parameterisation, but it can also be analysed in combination with otherdatasets, for example atmospheric conditions, permafrost types, and remote sensing data including vegetation maps and topography (Nitze et al. 2018; Raynolds et al. 2019

Further developments could also link our protocol to water, soils, and sediment sampling. For example, the action group called Standardized methods across Permafrost

Landscapes: fromArctic Soils to Hydrosystems (SPIASH) is currently workingon a standardiz.ed protocol for sampling mineral and organic components in soils, sediments, and water across permafrost landscapes (Bouchard et al. 2020

We present a set of simple protocols for observing permafrost thaw and associated environmental conditions. The protocols cover permafrost, snow, vegetation, water, and soil. They are unique in that they:

- are for eveiyone: no knowledge or sophisticated equipment is needed;
- encompass multiple critical parameters, so that the drivers and controls of permafrost thaw can be quantified;
- come with an app that guides the user through the measurement process and guarantees data quality, consistency and accessibilily.

The protocols address the urgent need for high uality field observations of permafrost conditions and interlinked ecosystem parameters.The observations will be critical for understanding and predicting permafrost thaw and for establishing a baseline for quantifying future change.The consistency and accessibility of the observations is crucial for data-driven analyses. The dataset will serve to enhance and validate Earth system models and remote sensing methods that are indispensable for monitoring and projecting permafrost thaw across the Arctic.

The current protocol has already been implemented by some INTERACT sites and data will be collected in 2021.The next steps include sharing it with a widergroup of scientists and the public, for example to colleagues, the Permafrost Young Researchers Network, Cryolist server, and sharing on social media.The protocol should be distributed to researchers and citizen scientists to obtain data on snow, vegetation, soil, and thaw depth at locations around the Arctic. Future work will include a linked higher level protocol that includes measurements, for example ofground subsidence and soil temperatures for which more advanced instruments, techniques, and expertise are required. More widely, similar integrated protocols that address cartxm and nutrient cycling would also be of great value in monitoring the permafrost landscape. This will require coordination with recent calls for standardized monitoring initiatives of other aspects of Arctic environments, including the need for standardized protocols for Arctic freshwater initiatives (Heino et al. 2020) or for SPIASH (Bouchard et al. 2020).

Beyond these community-led initiatives, national infrastructure funding for permanent monitoring sites is needed to understand long term permafrost thaw.

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Author contributions

J.B., S.C., and S.Z. conceived the idea and conceptualization for the protocol and paper. The original draft and outline of the paper and protocol were prepared by J.B., S.Z., S.C., and JM. The individual sections with details of the spheres in the paper and protocol were contributed by the fullowing: Snow,J.M. and MS.; Permafrost, S.Z.,J.B., E.J.W., D.S., and S.S.; Vegetation, IA. and SM.S.; Water, Y.S. and A.L.; Soil, J.B., S.C., and H.L.; Metadata, S.C., LC., N.S., and S.W.; Data collection, transrer, and storage, J.B. and NA. All of the other sections were written byJ.B., S.C., and S.Z.The figures were drawn by JM. with input fromJ.B., S.C., S.Z., and N.S.; J.B., S.C., S.Z., andJM. organized the writing and contributions from the co-authors. Review and editing of the various versions of the paper were provided by J.B., S.Z., S.C.,J.B., J.M., S.B., LA, and N.S.; NA set up the 02A data flow with inputs from J.B.The video tutorial from Iskoras was organized by IA. and H.L.The video tutorial from Bayelva was organized byJ.B. andJM. All of the co-authors approved the final version of the manuscript.

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Appendix A

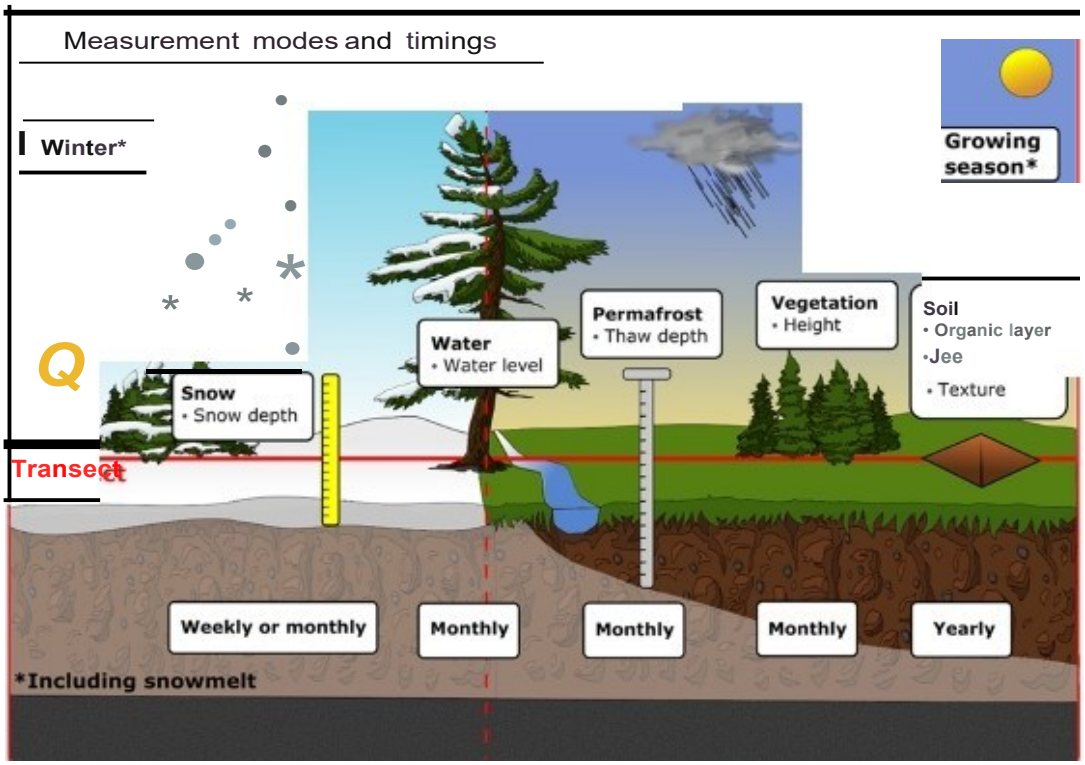
Protocol: **T-MOSAiC** pennafrost **1haw**

We provide a user-friendly application (app) named my'fhaw for smartphones, tablets and personal computers along with this protocol, which you can use to enter your data and upload it to the T-MOSAiC permafrost thaw database. The app will guide u through the measurement.

Download the myThaw app here:
https://play.google.comfstore/appsfdetails?id=de.awi.permafrost

https:/fapps.apple.comfappfmythawfid1578278222

Fig.Al. An overviewof the measurements to t.a.lce along one transect tM?rone seasonal cycle.



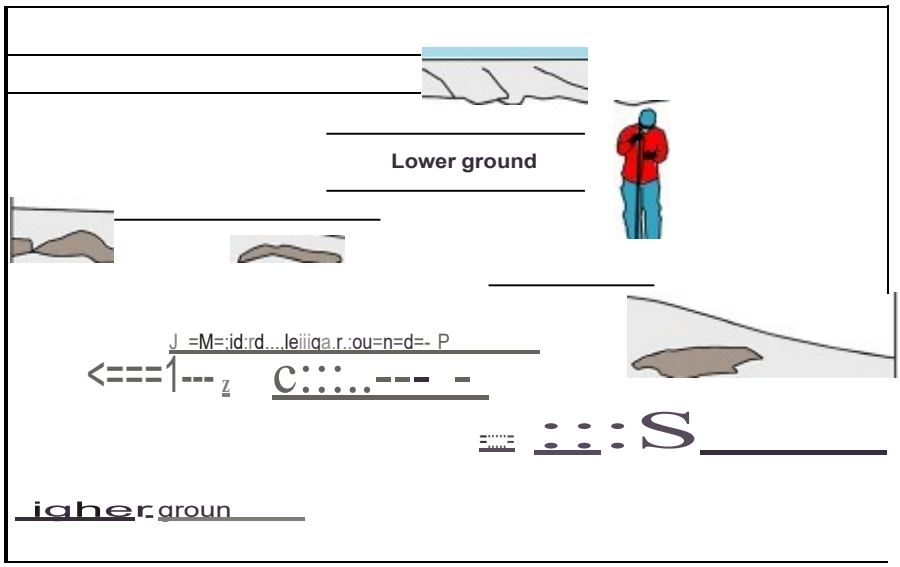
Video tutorials here:
Jskoras, N01Way, September 2020: https://youtu.be/zTskSNWmkdk
Bayelva, Svalbard, N01Way, Man:h 2021: https://youtu.beJG5dbh6Pix8o

Equipment needed(all measurements are in metric (SJ) nnits)

- Your smartphone or any other device with the myfhawapp installed
- Alternatively, a weatherproof nob!book and pencil(donot use a regular pen, the ink smears); you can enter the data from the field in the app lab!r.
- Foldable ruler (1or 2 m long) and tape measure (30 m long).
- Pointed metal rod (frost probe), aronnd1 cm thick, about1 or 2 m long; if not graduated, additional measuring tape.
- Smaller poles to leave at the site to mark the beginning and end of the transect.
- Camera or mobile phone with a camera
- A spade or shovel for digging. A hand sawor bread knife can also beveiy useful for this.

The measurement frequency will of course depend on your capacities. Please see our recommendations on themeasurement intervals as a "best case" scenario!We appreciate any measurements - if you can't take measurements as often as recommended, yourdata will still bevaluable.

Fig. A2. An example of howyou could labelyour transect photo.



Section 0. How ID locate your measurements

The overall aim of this project is to map and monitor permafrost thawat as many sites as possible around the Arctic. Before taking any measurements, you need to select a location for the transect. All of the measurements that are taken at more than one point (eveiything except the soil pit, Section on *Permafrost - thaw* depth), should be measured along a single transect thatyoucan return to each time u take measurements (Fig. Al). We recommend that the transect has a minimum of 10 measurement points spaced 1 m apart (a 10 m tran• sect), but preferably 30 measurement points spaced 1 m apart (a 30 m transect). Choose a transect by considering accessibility and representativeness: a place which is "typical for the siteJlandscape" and orient the transect to encompass the variability present at the site. Please takea photoof thetransect, and if at all possible annotate this photowith numbered measurement points. *It*is *important W be very careful when* taking mrosurements *or* walking *near your* tmnsect, *W avoid damaging the plants,* soil, *and* snow. The more often measurements are taken the more disturbance on the site might appear over time.

Note that youmust keep the numbering of the measurement points consistent when entering data in the app. lf u cannot obtain a measurement at any point, just leave the appropriate box empty.

Optionally, indicate any additional information on the photo that youcan- such as higher/middle{lower ground (see Fig. A2). You can set up more than one transect if you want to, and assign a number to each one.

Actions: Mark the beginning and end of each transect with a poleor similar (Fig. A3). In presenceof rockyground or a basal ice layer it may be necessary to use drilling equipment. To prevent microplastic pollution, pleasedo not use plastic tape or flags.

- Record the GPS coordinates of the middle of the transect usingyourphone. Alternatively, you could also use e.g., Google Maps on your smartphone by holding ur finger in ur current location to drop a pin, and then swiping up to see the coordinates of the dropped pin.
- Make sure you do not walk in your transect, especially in winter, for snow depth measurements.

Fig. A3. Measuring snowdepthon the transect during winter. This illustrates whata transect might look lilce.

Metadata

When to fill out: All information needs to be provided once for each transect, and updated once peryear if there is anychange.

1. Date of measurements•:
2. Name of the site:
3. Plot ID(if there is more than one study location or transect at your site):
4. Latitude of your site (a decimal number between-90 degrees to 90 degrees):
   Longitude of your site(between -180 to 180):
5. Elevation of your site (metres above sea level):
6. Are you aware of any nearest official or national weather service station
   ()Yes || No
   If Yes, answer the following:
   Name/ID of station and name of monitoring network:
   Distance to this weather station (if known, in m):
   Latitude of this weather station (between-90 and 90):
   Longitude of this weather station (between -180 to 180):
7. Are thereclimate data available at the site itself? ( ) Yes () No
   lfYes, answer the fullowing:
   Distance from your transect to closest climate measurement location (m) :
   Latitude of climate measurement location:
   Longitude of climate measurement location:
   Elevation of the climate measurement location:
   Variables measured (tick all that apply)
   || Air temperature
   ||Wind speed
   (I Air pressure

- ☐ Humidity
- ☐ Shortwave radiation
- ☐ Longwave radiation
- ☐ Rainfill
- ☐ Snowfall
- ☐ Snow depth

8. How do you access your site?
9. How far to the nearest road (mj ?

What doyousee at the site (30mx30 marea)?

10. Ground surface (the layer below the vegetation)
    - ☐ Rock
    - ☐ Soil

    lfyou ticked "soil" *in the previous question, tick* all *that apply:*
        - ☐ Peat
        - ☐ Gravel
        - ☐ Sand
        - ☐ Silt
        - ☐ aay
        - ☐ Unknown

11. How wet is the ground?
    - ☐ Wet (water above the smface)
    - ☐ Moist (soils are damp)
    - ☐ Dry
    - ☐ Unknown

12. Water features (tick all that apply):
    - ☐ Wetland
    - ☐ Lake
    - ☐ Wet depressions
    - ☐ Riverfcreek
    - ☐ Water tracks
    - ☐ None
    - ☐ Unknown
    - ☐ Other:_____

13. Are there trees at the site?
    - ☐ Yes
    - ☐ No

14a. Most dominant vegetation at the site:

You can use the flowchart to identify it (Fig. A4). Tick one checkbox.

- ☐ Grasses/sedges
- ☐ Forbs
- ☐ Deciduous Shrubs (e.g., *Vaccinium* sp.)
- ☐ Evergreen Shrubs (e.g., crowberry, *Empetrum* sp.)
- ☐ Moss
- ☐ Lichen
- ☐ Trees: Deciduous needle (e.g., larch)
- ☐ Trees: Evergreen needle (e.g., spruce)
- ☐ Trees: Broadleaf (e.g., birch)
- ☐ There is no vegetation

Fig.A4. Flowchart -,,geration.

14b. Indicate any other vegetation types that are present at the site:

- ( ) Grasses/sedges
- ( ) Forbs
- ( ) Deciduous Shrubs (e.g., Vacdnium sp.)
- ( ) Evergreen Shrubs (e.g., crowbeny (Empetrum sp.,
- ( ) Moss
- ( ) Lichen
- ( ) Trees: Deciduous needle (e.g., larch)
- ( ) Trees: Evergreen needle (e.g., spruce)
- ( ) Trees: Broadleaf (e.g., birch)
- ( ) There is no vegetation

In the wider area as far as you can see.

15. Disturbance

- ( ) No disturbance
- () Natural disturl>ance (example: burned area, slumps)
- () Disturl>ance by humans (example: pipeline, storage area, reservoir)
- ()Unknown

If there *is disturbance, please describe it (for example, what type, how far from the site, how* big):

16. Overview photos of the site
With your phone at highest resolution available (or another camera e.g., SO mm lens, if no cell phone):

- One photo of the site (landscape or portrait) as close as possible, showing the location (e.g., snow pit, measurement spot, etc.)
- A set of four pictures from next to the site, one looking to the North, one to the East, one to the South, and one to the West.

These should be in landscape mode with about 10% of the photo above the horizon; in one of the shots it would begood to have a person standing about 20 m away (for scale) and looking away from the camera (to avoid privacy issues). Otherwise use a scale bar, shovel, or any other object with a distinct siz.e to indicate the scale.

Section 1: Snow- snow depth[cm[

Where to measure: 10-30 m transect: This should be established before taking any measurements at the site. See Section O (Fig. A3), above, for details of how to select and mark the transect.

When to measure: Start preparing the transect before the first snowfall by marking its beginning and end (see Fig. A3). Take a photograph of the site with the transect. Start the snow depth measurements with the first day of snowfall (beginning of snow season) until the end of the melting season (less than half of the ground area covered by snow). To capture the change of snow depth over time, measure ideally once per week, or alternatively every second week. Monthly measurements are still valuable.

Instrument stick and tape measure, or graded avalanche probe.

Time: 1,-3 minutes per measurement.

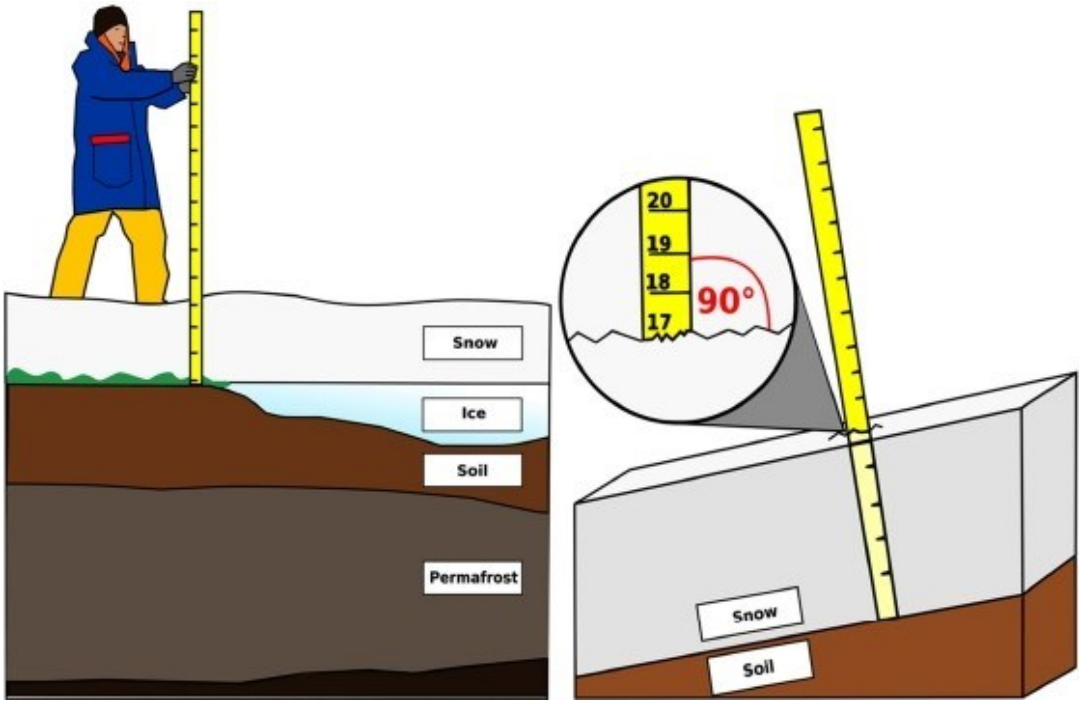
Scale: 10-30 m transect, one measurement every metre.

Method: Snow depth measurements are made during the snow season with a pole and tape measure or, if available,with agraded avalanche probe.Put the pole through the snowpack at right angles to the snow surface until it reaches ground and record the snow surface depth (precision about 1 cm; Fig. AS).

Actions:

- Put the pole or the avalanche probe straight (90° to surface) through the snowpack.
- Make sure the pole reaches theground(not just stuck on an ice layer or crust)-you mayneed to apply more pressure thanyou think or less pressure if on softground
- If theground cannot be reached, make a note including the point number (e.g., presence ofa basal ice layer at point4).
- Measure snowdepth with the scale or tape measure, or read otffrom the scale on the probe.
- Record value (cm).
- Repeat every metre.
- Estimate how accurate the measurements are (cm).
- Take a photoof the transect.

Fig. AS. Snowdepth measurement



Section 2: Permafrost - thaw depth [cm]

Where to measure: Thaw depth is known to vary substantially overvecy short distances, and the site characteristics should be accounted for when deciding on the location and spacing of the points.The 10-30 m transect should be established before taking any measurements at the site. See Section 0, above, for details of how to select and mark the transect. Note that if your site is vecy rocky, you may find that thaw depth measurements are not possible.

When to measure: Ideally, thaw depth should be measured at regular intervals around once per month from the time of snowmelt until the annual freeze-up. However, if it can only be collected once, measuring during the end of summer/early fall when the thaw depth has reached its yearly maximum should be prioritiz.ed.

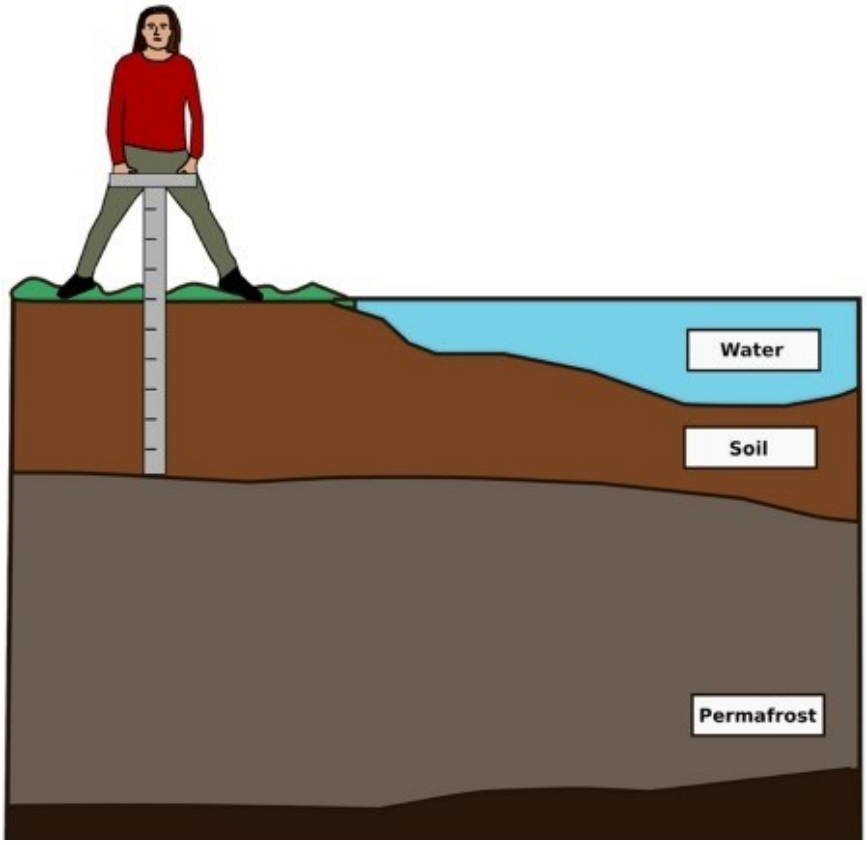
Instrument Metal rod, measuring tape.

Time: 1 minute per measurement, depending on soil properties.

Scale: 10-30 m transect, one measurement evecy metre.

Method: At each measurement point, insert a frost probevertically to the surface until the point of resistance (Fig. A6). Feel free to push against the resisting surface a couple of times to ensure that it is the frost table which you are hitting and not a rock suspended in the unfrozen soil. Measure the depth that the frost probe has goneinto the soil. Make a note if the depth exceeds the length of the rod. If the observation is suspect (e.g., due to the probe hittinga stone) or inserting the rod is impossible altogether (gravel, bedrock, etc.), try to repeat the observation within a distanceofless than1 m, or leave the box blank.

Fig. A6. Thaw**depth** measurement: the frost probe is inserted into the ground: measure the lengthof the section of the probe *that* hasgone into the ground



Actions:

- Insert the frost probe into the soilvertically until resistance against frost table is met; gently press the back of urhand against the surface vegetation layer to determine the surface position.
- Record the depth that the frost probe has gone into the soil, noting if the measurement bad to be made at another location due to an obstruction, or any other anomaly.
- Repeat every metre.
- Take a photoof the transect from either end

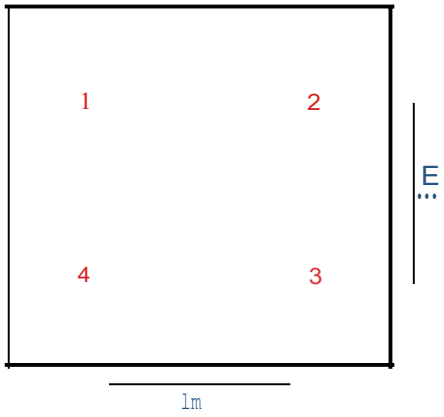
Section 3: Vegetation - height [cm]

Where to measure

For all sites: take vegetation height measurements in 1 m x 1 m quadrats (squares) at each point alongyour 10-30 m transect. This transect should be established before talcing any measurements at the site.SeeSection O, above, for details of how to select and mark the transect.

If your site is a forest measure a minimum oflO individual trees in a 15 mx 15 m plot as well as the transect.

Fig. *A'J.* Qua.drat i,r measuring vegetation height.The fourmeasureme.nt locations are shown in red



When to measure

Forest: at least once ayear, preferably duringgrowing season (June-August

Tundra and other non-forested sites: at least once during peak growing season. Preferably a seasonal overview, i.e., once every month from spring (shoulder season) to autumn (shoulder season). Mark out quadrats and revisit the same locations for repeated measurements.

Instrument: camera and ruler (forest: preferably a tape measure, tundra: preferably a carpenter's rule).

Ti.me: Quadrats: 2 min per quadrat.

Trees: 1 min per tree.

Scale: At all sites:10-30 1 mx1 mquadrats at 1 m intervals along the transect (see Section 0 above).

Forest only: 15 mx 15 m area.

Method: Measurement of vegetation cover height.

Forest measurement (for trees smaller than 2 m in height) or estimation of the tree height of 10 trees.

Actions:

LL All rile,;

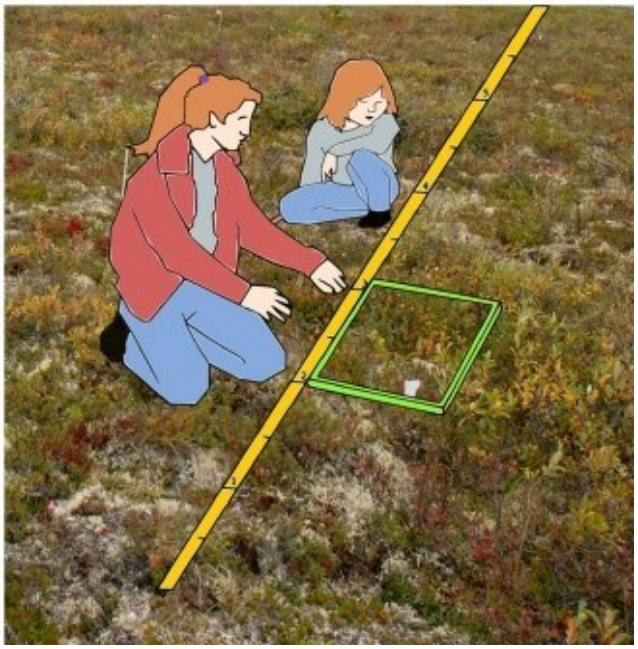
- Mark out1 mx1 m quadrats at each point along your transect.
- Mark two diagonals within the quadrant and measure vegetation (exduding moss/lichen) height at four locations along the diagonals as shown in Figures A7andAS.
- Measure vegetation height from the soil surface to the highest point of the vegetation, at each sample location without extending/pulling the plants. If there is novegetation (other thanmoss/lichen) at the location, record0.If thereis moss or lichen at the point}ml measure then tick the "moss/lichen present" box.
- Take a photoof each quadrat.

L2. **Fore>tsites *only:***

Actions:

- Mark out/estimate a15 mx15 m plot that is representative of the bigger area
- Take a picture from the middle of the plot in every direction, preferably with a tape measure or a person standing next to a tree for height reference.

Fig. AS. Measwingvei,,tation heightalong the transect.



- Estimate (trees taller than 2m) and measure (treessmaller than 2 m) the height oftOindividual trees that are typicalof the site. Select trees that cover the range of heights within the plot. If there are fewer than10trees in your plot, just measure every tree.

How to measurefestimate the tree height fur trees taller than 2 m (simple estimation):

1. Especially in denseforest, it can be hard togoas far back as needed to use ageometric measurement method. A simple solution, which needs some practice but works well, is a height estimation using the help of objects dose-by and your own height.
2. Step back and make sure you are able to see the tree topand thebase.
3. Estimate the tree height based on 2 m increments using branches for guidance.

Section 4: Water - water level

Where to measure:10-30 m transect:This should be established before taking anymeasurements at the site. SeeSection 0, above, for details of how to select and mark the transect.

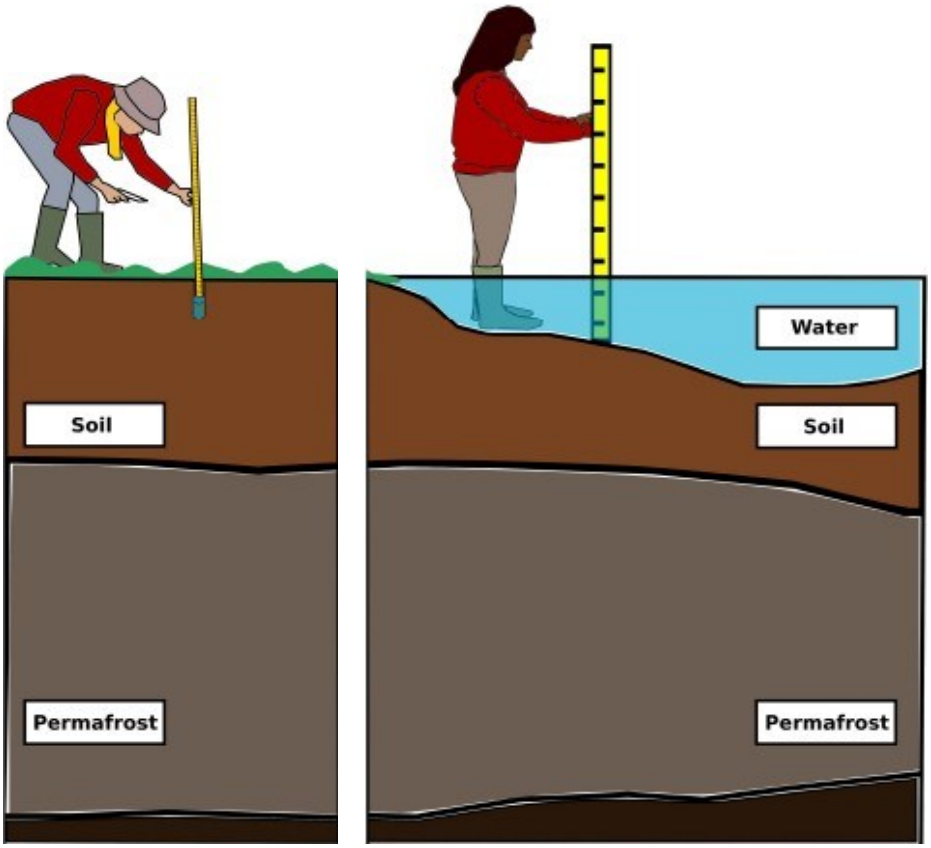
When to measure: Try to capture thechanges through the seasons, including thespring snowmelt season, (possible) drying over the summer, and any changes towards the rail/ autumn No observations are necessary when theground and sumcewaters are completely frozen. *Ideally* you *could take these measurements at the same time as the permafrost thaw depth (see* Section 2*, above) because the same equipment* is *used.* You *can even use thesame hole as for thaw depth,* to *reduce damage to the* soil

Instrument Cunera (picture) and ruler, pointed metal rod (frost probe) or somethingto make holes (could also be your hands).

Time: 2 min per measurement.

Scale: 10-30 m transect, one measurement per metre.

Fig. A9. Measuring !be water level below !be surface and ab°"' thesurface.



Method: At each point, note if the water level is found within the top 10 cm of the ground, below the top 10 cm of the ground, or above the ground surface.

Actions: If there is water above the surface, measure the depth of the water (m) with either the ruler or the frost probe.

- If there is no water above the surface, insert the frost probe10 cm into the ground and note if the hole fills with water (i.e., the water level is within10 cm of the ground surface) (Fig. A9). Tick the relevant box ("Water is Jess than 10 cm below ground - hole fills with water"; •water level is deeper than10 cm belowground - hole does not fill with water"). Repeat the procedure for all observation points.
- Take a photoof the transect from either end

Section 5: Soil - soil pit

Where to measure: Thesoil pit should be located close to the other measurements but set to theside so thatyoudo notdigup theground dose towhere the other measurements are taken.The pit should be approximately 1 m wide.

When to measure: once only, at a time when the soil has thawed to its greatest depth (late summer, early autumn).

Instrument Spade and (or)shovel, a ruler or tape measure, camera.

Time:1 h, but may take one afternoon.

Fig. A10. Examining the soil pit during swnmer: This demonstrates whata soil pit might looklike.

Scale: l-2 m wide soil pit; ideally aim for 1 m depth, but you can stop onceyou hit the froz.en layer.

Method: Determine the location and orientation of the soil pit. Decide which side of the pit you want to use to record the soil profile (Fig. AlO).*Toreducemelting in the pit, thesideyou chooseshould notbe directly exposed to the* SUll Avoid walking on or otherwise disturbing the ground on this side of the pit. Dig the pit and carefully put the excavated materials aside so you can easily backfiJJ the pit later.Describe the profile andtakea pictureof thesoilface, including the ruler{tape measure fur scale. Please refill the profile with soil and vegetation cover as well as you can afterwards.

Actions:

- Dig a soil pit.
- Take a picture of the soil face including the rulerftape measure for scalewith the O level at the surface.
- Describe the soil.

☐Estimate **the** thickness of the upper organiclayer- this is thedepth to the boundary between organic (dark brownfpeaty) and mineral soil.

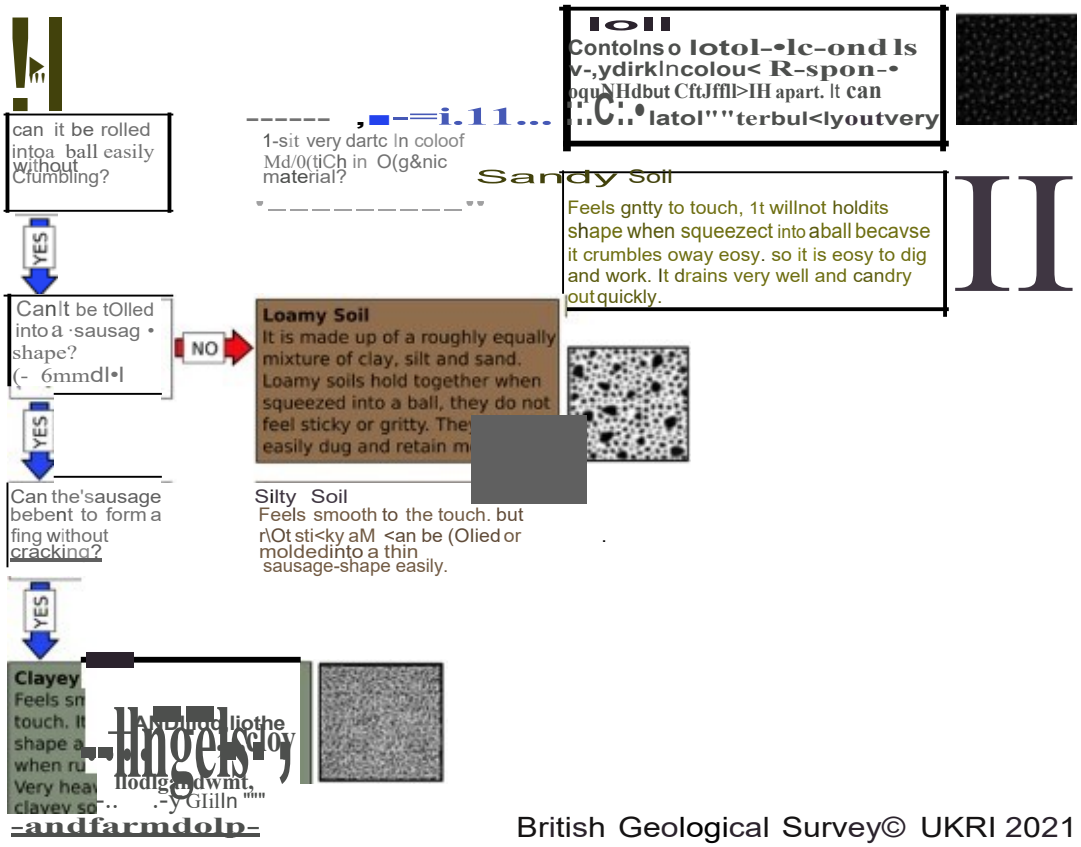
☐ Is there anyice (at the bottom of the profile)?
If yes, take a photo with aro1er included for scale.

☐Are there rocks in the soil?
If yes, take a photo with aro1er included for scale.

Select the soil texture description which most closely describes your soil

II Oaysoil
II Sandy soil
II Loamy soil
II Silty soil
II Peaty soil

Fig.A1L To determine the soil texture. weea handfulof soiland follow the instructions in the flowchart(Fig: A11) adapted and reused with permission.



- Put the soil back into the pit.
- Cover with vegetation again.

For help with selecting soil texture, please follow the instructions in the flowchart (Fig.All