Standardized monitoring of permafrost thaw: a user-friendly, multi-parameter protocol

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Abstract

Climate change is destabilizing permafrost landscapes, affecting infrastructure, ecosystems and human livelihoods. The rate of permafrost thaw is controlled by surface and subsurface properties and processes, all of which are potentially linked with each other. Yet, no standardized protocol exists for 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, for use by non-specialist scientists and technicians, citizen scientists and indigenous groups, to collect standardized metadata and data on permafrost thaw.
The protocol introduced here addresses the need to jointly measure permafrost thaw and the associated surface and subsurface environmental conditions. The parameters measured along transects are: snow depth, thaw depth, vegetation height, soil texture, and water level. The metadata collection includes data on timing of data collection, geographical coordinates, land surface characteristics (vegetation, ground surface, water conditions), as well as photographs. Our hope is that this openly available dataset will also be highly valuable for validation and parameterization of numerical and conceptual models, thus to the broad community represented by the T-MOSAIC project.

Keywords

snow depth, vegetation height, soil characteristics, active layer thaw depth, permafrost monitoring protocol

Background and General introduction

Northern landscapes and infrastructure are affected by the thaw of permafrost, especially in regions of ice-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; Hugelius et al., 2020; Burke et al. 2017; 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, due to local variation in snow, vegetation and soil characteristics (Romanovsky et al. 2020). These local variabilities are critical for the evaluation of permafrost thaw. Not only do 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 the Arctic, and locally shrub expansion may also be driven by permafrost degradation (Sturm,

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, while drainage and drier soil conditions favour stabilization (Nitzbon et al. 2020).
No common protocol exists that simultaneously considers both permafrost thaw and the key environmental variables which 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 multi-parameter protocol.

Here we developed simple protocols and an associated mobile app that will enable a wide range of non-expert users to make high-quality, 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-Arctic geospatial 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.

We developed 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://mosaic-expedition.org/). Originally T-MOSAiC was 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. Due to the COVID pandemic limiting 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, while the detailed protocol is available in the appendix.

Protocol overview - choice of parameters and scale issue

Protocols for everyone

The protocol’s primary target group is the ‘non-permafrost expert’ with limited prior field experience. The users comprise professionals and students from a wide range of backgrounds, including ecology, hydrology, and geology. In-depth expertise in permafrost ecosystems is not required. Citizen scientists form the protocol’s secondary target audience, ideally under guidance 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 non-specialists 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 homogenizing data transmission, and storage. Second, no specialized equipment is needed. The protocol only requires simple tools, namely a ruler, camera, tape measure, shovel and steel rod. Finally, the protocol has been streamlined so as not to take up too much of the non-specialist’s time.

The appndix gives further details of the app for data collection, as well asinstructional 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-term observatory site Bayelva on Svalbard, Norway in spring 2021 by the permafrost thaw action group and AWI.

Parameters

We group the parameters for which we provide protocols into five spheres:

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, due to their need for specialized equipment.

Figure 1 gives an overview of the spheres, 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 done once along the transect – ideally during the later part of the season when the thawed layer has reached its maximum.

The 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 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 surface 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; Nitzbon 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 different spheres conducted on the same transect.

Where to measure?

The protocol design aims to ensure that measurements capture the variability within a landscape. Since 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 models / satellite data pixels (10s to a few 100s of m to kms) and global models (10s – 100s km).

To ensure 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 long transect to allow *typical microtopographic features* to be resolved by sampling every 1 m. This means that the minimum effort (one 10 -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 plateaus/ palsas, which are typical landforms in permafrost 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 Iškoras 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 protocol section 0).

Details of the spheres

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

Background

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 (Zhang, 2005; Grünberg et al., 2020). The type of vegetation cover can significantly influence the insulating power of snow as 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) (Striegler et al., 2016). The duration and extent of the snow cover 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. Trend analyses point out an increase of snow masses in Siberian regions where others are likely to decrease (Pulliainen et al., 2020, Callaghan et al., 2011).

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 (Parr et al., 2020, Sturm et al., 2001a); whereas local depressions, or an abundance of shrubs, trap snow (Wilcox et al., 2019). Critical observation times are the onset of snow accumulation 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 the snow cover evolution 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 there is 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, deep grass or moss hummock). The vegetation (e.g. bushes) within the snowpack can also influence the measurement.

Permafrost

Background

Thaw depth is the only variable for characterizing permafrost conditions that is included in the T-MOSAiC protocol. It is defined as the distance between the ground surface and the frost table (Brown et al., 2000). Thaw depth increases over the summer period, as the thaw front penetrates deeper into the ground. 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 for characterizing changing permafrost conditions because increasing air temperatures and ground warming often cause the maximum thaw depth to increase via thawing at 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; Grünberg 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). A comprehensive quantification of permafrost thaw hence necessitates subsidence observations (Streletskiy et al., 2017). While direct observations of subsidence are not included in the protocol due to the lack of simple methods for measuring it, the measurements of vegetation and inundation (wetness) can indicate subsidence induced by thaw of ice-rich permafrost (Kokelj and Jorgenson (2013).

Measurement

Multiple methods exist for determining 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 1–1.5 m in length) into the soil until the point of resistance against the frost table at each point along the transect. The depth that the rod has been inserted into the ground can then be determined using a measuring tape or from graduated marks on the rod itself.

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

Mechanical probing works 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 may arise for substrates that are less amenable to probing. The most commonly encountered limitations are:

- In bedrock or gravel, probing may be impossible.
- It can be difficult to distinguish between subsurface 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.

- In saline marine sediments or plastically frozen clays, the unusual mechanical properties present a challenge to frost probing

Vegetation

Background

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, 2015) by altering the thermal regime, by intercepting snow, and promoting the accumulation of an organic surface layer (Bonan, 2003, 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 snow physical properties (Wilcox et al., 2019, Domine et al., 2016). 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. Commonly, vegetation height is measured from the soil surface to the highest point of the vegetation. As multiple measurements are made within each quadrat this will then provide representative average vegetation heights along the transect (similarly with height measurements of multiple trees).

Measurement

The measurement of vegetation 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 1x1 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 of 10 individual trees in a 15x15 m plot should also be measured (Kruse et al., 2019; Pérez-Harguindeguy et al., 2016). Most measurements therefore require a ruler or tape measure only, but in tall forest it might be necessary to give training in height estimation beforehand.

Water

Background

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 because of 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 permafrost 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 depth or 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 surface”. This very simple classification, carried out at points along transects, provides valuable information for characterizing soil wetness which can be used by permafrost modellers.

Soil

Background

Soil properties play a crucial role in the energy and water balance of permafrost systems, by affecting the exchange of heat and water between the atmosphere and the subsurface, and thus the rate of permafrost thaw (Chadburn et al., 2015; Walvoord and Kurylyk, 2016; Shur and Jorgenson, 2007). Permafrost-affected soil comprises a mixture of various media including organic 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 magnitude of the insulation depending on the organic layer thickness and organic matter content (Romanovsky et al. 2010). Soil texture also influences ground ice contents of permafrost, and together they control physical, thermal and mechanical properties of permafrost and its behavior at thaw (French and Shur 2010, Jorgenson et al., 2010). Gravel or coarse sand show markedly different thermal and hydraulic properties ~~than~~ compared to finer 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 (Romanovsky et al. 2010; Kokelj and Jorgenson 2013; Osterkamp 2007; Romanovsky et al. 2017).

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 close to the transect but set to the side to minimize disturbance. The pit should be approximately 1 metre wide and 1 metre deep, or until one can no longer dig due to frozen ground. The scale of 1 metre 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 the growing season when thaw depth is greatest. If digging a pit is not allowed or possible, estimating the surface layer using a hand held soil auger/drill is recommended.

The observations comprise a photograph of the clear profile and a description of visible characteristics, such as depth of organic layer, contents of ice and rocks, colour of the soil, and soil texture. For non-specialists, 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© UKRI 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 Open Geospatial Consortium (OGC) (Open Geospatial Consortium, 2021) and thus facilitates interoperability. Specifically, everything related to data processing and data management follows Observation to Archive (O2A; Koppe et al. 2015; Gerchow et al. 2017) and in turn all instrumentation parts of O2A follow sensorML specification (OGC, 2014).

The protocol requests basic information about the site location, including latitude, longitude, altitude, and the location of the nearest weather station. This information is crucial for 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 by eye, including whether the site is rocky, what type of soils are there, and how wet 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 site as a whole. 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 disturbances are recorded as these will also affect the site, impacting the hydrology and permafrost thaw. Photos are required in the four cardinal directions in a standardized 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 standardized, controlled vocabulary to have broadly applicable language for machine access and processing. We apply the O2A dataflow framework which includes the comprehensive description and management of all data 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 visualized. 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) and thus giving credit to the data provider in a data publication (Schäfer et al. 2020). A map-based search and visualization of the data with download link for the data (example: thaw depth) is planned. Data will be collected using a 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 be automatically ingested into the O2A process chain (Fig. 3).

For quality control, a first quality check is done automatically using the O2A 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 sensor.awi.de. Before archiving the data set in PANGAEA, an additional thorough manual data check will be done.

Description of mobile myThaw app for data collection

The mobile app myThaw is freely available to everybody (in appendix). The app allows the collected data to be exported to 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 offline 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 citizens today own a smartphone or tablet, we see advantages in using a mobile over a field notebook or report-based archives. The app is designed for use in cold climates and is user friendly, with help /guidelines and “pop-up window” options when necessary. Since 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 is able to identify the recurring location, thus eliminating the need to re-enter the metadata. The app will be available under CC BY 4.0 licence. Further maintenance and development, such as security updates and, if necessary debugging, are planned for the future. In summary, we provide a method of secure and collaborative data entry, resulting in a faster data analysis, visualization, access and storage.

Next steps for the data, conclusions and outlook

The database that we 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 other datasets, 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: from Arctic Soils to Hydrosystems (SPLASH) is currently working on a standardized 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 everyone: 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 accessibility.

The protocols address the urgent need for high-quality 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 wider group 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 which includes measurements, for example of ground subsidence and soil temperatures for which more advanced instruments, techniques and expertise are required. More widely, similar integrated protocols that address carbon 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 SPLASH (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

JB, SC, SZ conceived the idea and conceptualization for the protocol and paper. The original draft and outline of the paper and protocol were prepared by JB, SZ, SC, JM.

The individual sections with details of the spheres in the paper and protocol were contributed by the following: **snow**: JM, MS; **permafrost**: SZ, JB, EJW, DS, SS; **vegetation**: IA, SMS; **water**: YS, AL; **soil**: JB, SC, HL; **metadata**: SC, LC, NS, SW; **data collection, transfer and storage**: JB, NA.

All other sections were written by JB, SC, SZ.

Figures were drawn by JM with inputs from JB, SC, SZ and NS.

JB, SC, SZ, JM organized the writing and contribution from the co-authors.

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NA. set up the O2A data flow with inputs from JB.

The video tutorial from Iškoras was organized by IA and HL.

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All co-authors approved the final version of the manuscript.

Appendix A

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Tab. 1: Summary of existing protocols for parameters presented in this paper. These parameters are grouped into five spheres: snow, permafrost, vegetation, water, and soil. Citable references are given in the table; some projects (example ADAPT, CALM) provide protocols online for which we provide links in the reference section of this paper.

Fig. 1: Spheres with the associated parameters, measurement modes and observation timings along one transect over one seasonal cycle.

Fig. 2: Example of landscape variability covering palsa mire, forest and upland tundra (Iškoras; Finnmark, northern Norway). Typically, one 10-m long transect cannot cover all the characteristic features as shown in this figure. If timing and capacities allow, several transects can be established. If there is already an established transect at this site it can be used.

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Sphere	***Existing protocols, Organization***
Snow	ECV Products and Requirements for Snow, The Global Climate Observing System (GCOS) (The Global Climate Observing System, 2016a)
	Estimating the snow water equivalent from snow depth data, International Commission for Snow and Ice Hydrology (ICSH) (Jonas and Marks, 2016)
	The international classification for seasonal snow on the ground, International Association of Cryospheric Sciences (IACS) (Fierz et al., 2009)
	European Snow Booklet, WSL Institute for Snow and Avalanche Research SLF (Haberkorn, 2019)
	Chapter 5: Snow and Ice, International Tundra Experiment (ITEX) Manual, Danish Polar Center (Molau, 1996)
Permafrost	Global Terrestrial Network for Permafrost, International Permafrost Association (IPA) (Streletskiy et al., 2017)
	Methods for Measuring Active-Layer Thickness, A Handbook on Periglacial Field Methods, IPA, Circumpolar Active Layer Monitoring Network (CALM) (Nelson and Hinkel, 2004)
	Essential Climate Variables (ECVs) Products and Requirements for Permafrost, GCOS (The Global Climate Observing System, 2016b)
	Active Layer Monitoring standard protocol, Arctic Development and Adaptation to Permafrost in Transition (ADAPT) (Arctic Development and Adaptation to Permafrost in Transition)
	Chapter 6: Active Layer Protocol, (ITEX) Manual (Nelson et al., 1996)
	Assessment of the status of the development of the standards for the Terrestrial Essential Climate Variables, Permafrost (Smith and Brown, 2009)
Vegetation	Chapter 11: Community baseline measurements, ITEX Manual (Molau and Edlund, 1996)
	Vegetation standard description protocol, ADAPT (Grogan et al.)
	New handbook for standardised measurement of plant functional traits worldwide (Pérez-Harguindeguy et al., 2016)
Water	Guide to Hydrological Parameters – Volume 1, World Meteorological Organization (World Meteorological Organization, 2008)
	Soil moisture content, CALM (Circumpolar Active Layer Monitoring Network)
Soil	Sampling protocols for permafrost-affected soils (Ping et al., 2013)
	Soil Survey Fields and Laboratory Methods, U.S. Department of Agriculture, Natural Resources Conservation Service (Soil Survey Staff, 2014)
	Active Layer Sampling standard protocol for C/H/N determination, ADAPT (Arctic Development and Adaptation to Permafrost in Transition)
	Planning and making a soil survey, Food and Agriculture Organization of the United Nations (Food and Agriculture Organization of the United Nations)
	Terrestrial Instrument System (TIS) Soil Pit Sampling Protocol, The National Ecological Observatory Network (NEON) (The National Ecological Observatory Network, 2021)
	The United Nations Terminology Database, United Nations (United Nations, 2012)

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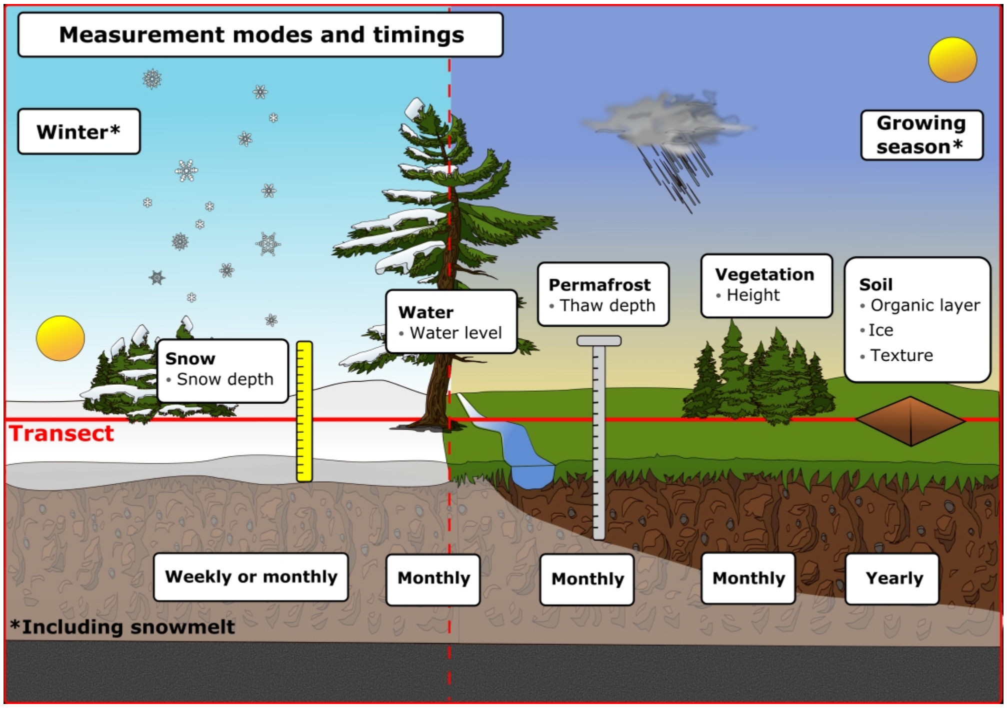

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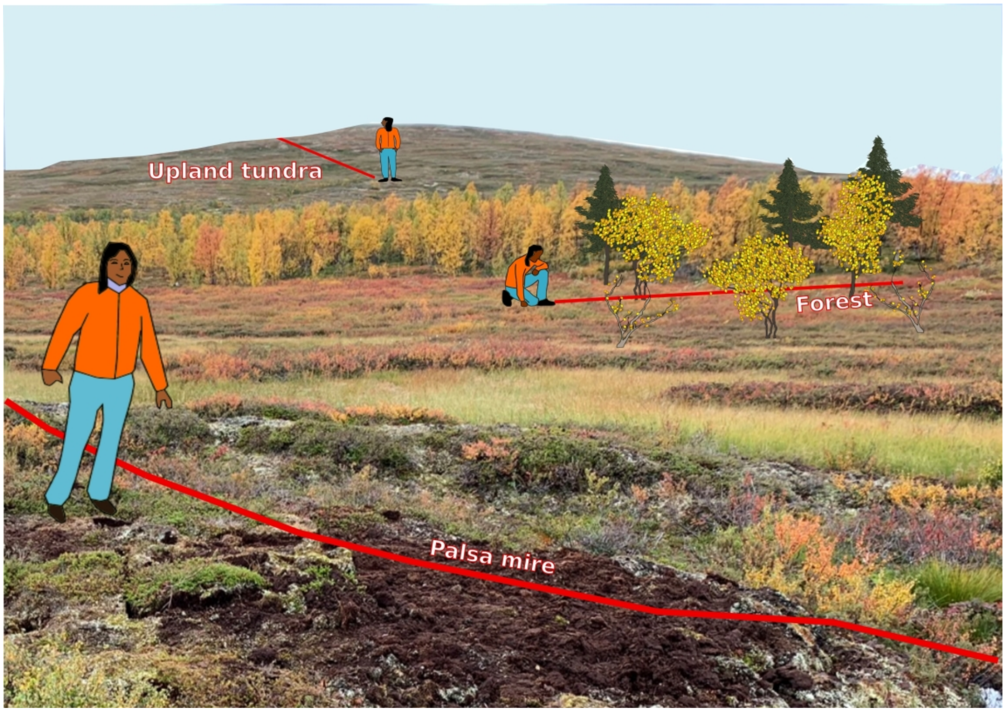

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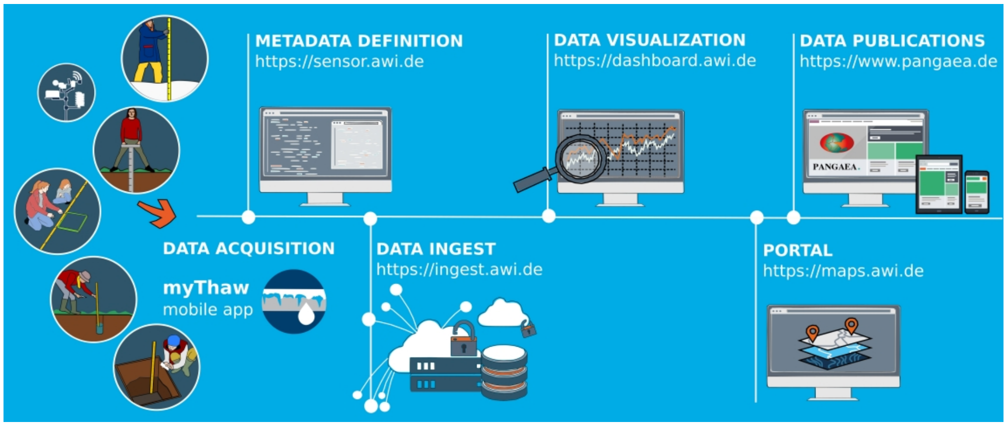

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303x127mm (300 x 300 DPI)

Protocol- T-MOSAiC Permafrost Thaw

Lead: Julia Boike, Sarah Chadburn, Julia Martin, and Simon Zwieback

Contributors: Inge Althuizen, Lei Cai, Stéphanie Coulombe, Hanna Lee, Anna K. Liljedahl, Martin Schneebeli, Ylva Sjöberg, Noah Smith, Sharon L. Smith, Dmitry Streletskiy, Simone M. Stuenzi, Sebastian Westermann, Evan J. Wilcox

We provide a user-friendly application (app) named myThaw 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 you through the measurement.

Download the myThaw app here:

https://play.google.com/store/apps/details?id=de.awi.permafrost

Video tutorials here:

Iškoras, Norway, September 2020: https://youtu.be/zTsk5NWmkdk

Bayelva, Svalbard, Norway, March 2021: https://youtu.be/G5dbh6Pix8o

Equipment needed (all measurements are in metric (SI) units):

- Your smartphone or any other device with the myThaw app installed.
- Alternatively, a weatherproof notebook and pencil (don't use a regular pen, the ink smears); you can enter the data from the field in the app later.
- Foldable ruler (1 or 2 m long) and tape measure (30 m long).

- Pointed metal rod (frost probe), around 1 cm thick, about one or two metres 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 saw or bread knife can also be very useful for this.

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

0 How to locate your measurements

The overall aim of this project is to map and monitor permafrost thaw at 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 (everything except the soil pit, Section 2), should be measured along *a* **single transect** which you can return to each time you take measurements. We recommend that the transect has a **minimum** of 10 measurement points spaced 1 m apart [a 10-m transect], 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 site/ landscape" and orient the transect to encompass the variability present at the site. Please take a photo of the transect, and if at all possible annotate this photo with numbered measurement points. *It is important to be very careful when taking measurements or walking near your transect, to 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 you must keep the numbering of the measurement points consistent when entering data in the app. If you cannot obtain a measurement at any point, just leave the appropriate box empty.

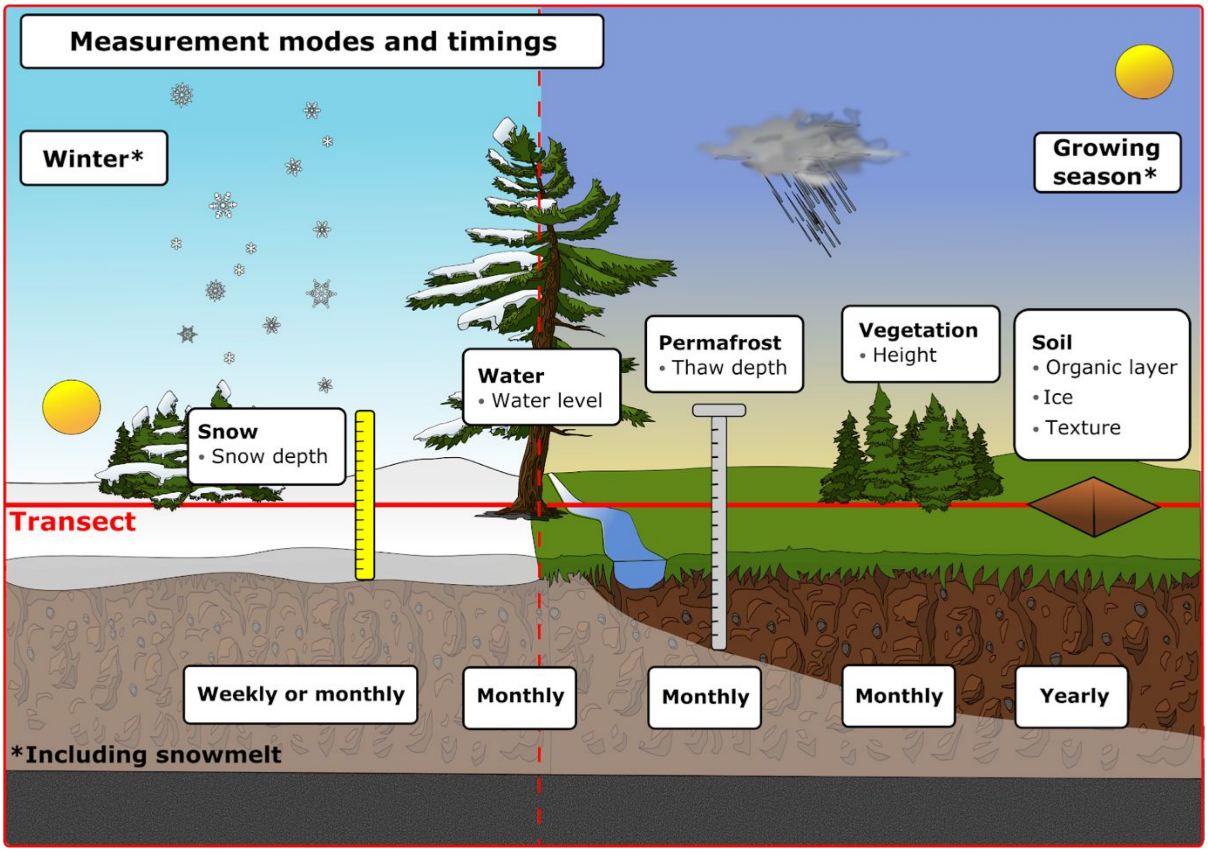

Fig. A1: An overview of the measurements to take along one transect over one seasonal cycle.

Optionally, indicate any additional information on the photo that you can – 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.

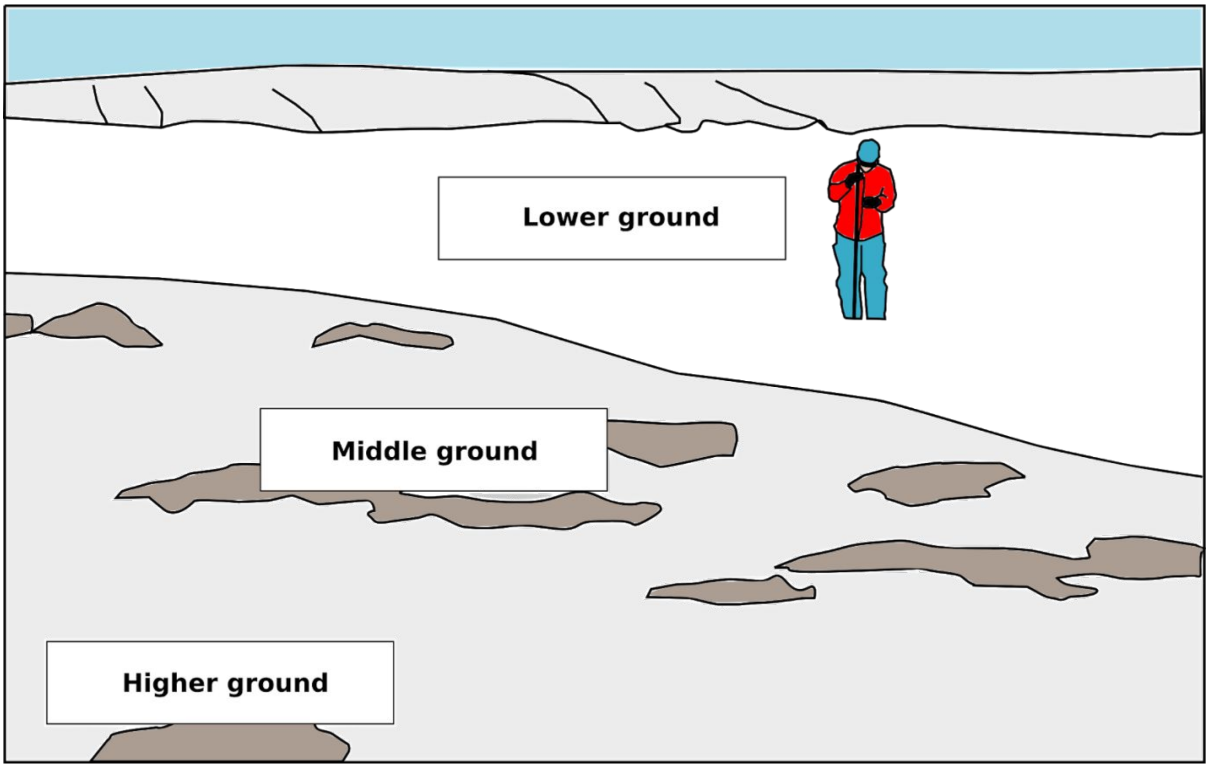

Fig. A2: An example of how you could label your transect photo.

Actions:

- Mark the beginning and end of each transect with a pole or similar (Fig. A3). In presence of rocky ground or a basal ice layer it may be necessary to use drilling equipment. To prevent microplastic pollution, please do not use plastic tape or flags.
- Record GPS coordinates of the middle of the transect using your phone. Alternatively, you could also use e.g. Google Maps on your smartphone by holding your finger in your current location to drop a pin, and then swiping up to see the coordinates of the dropped pin.
- Make sure you don't walk in your transect, especially in winter for snow depth measurements.

Fig. A3. Measuring snow depth on the transect during winter. This illustrates what a transect might look like.

Metadata

? **When to fill out:** All information needs to be provided once for each transect,and updated once per year if there is any change.

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. Is there climate data available at the site itself? [ ] Yes [ ] No

   If Yes, answer the following:

   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

   [ ] Air pressure

   [ ] Humidity

   [ ] Shortwave radiation

   [ ] Longwave radiation

   [ ] Rainfall

   [ ] Snowfall

   [ ] Snow depth

8. How do you access your site?

9. How far to the nearest road [m] ?

What do you see at the site (30 m x 30 m area)?

10. Ground surface (the layer below the vegetation)

[ ] Rock

[ ] Soil

If you ticked 'soil' in the previous question, tick all that apply:

[ ] Peat

[ ] Gravel

[ ] Sand

[ ] Silt

[ ] Clay

[ ] Unknown

11. How wet is the ground?

[ ] Wet (water above the surface)

[ ] Moist (soils are damp)

[ ] Dry

[ ] Unknown

12. Water features (tick all that apply):

[ ] Wetland

[ ] Lake

[ ] Wet depressions

[ ] River/creek

[ ] 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. Tick one checkbox.

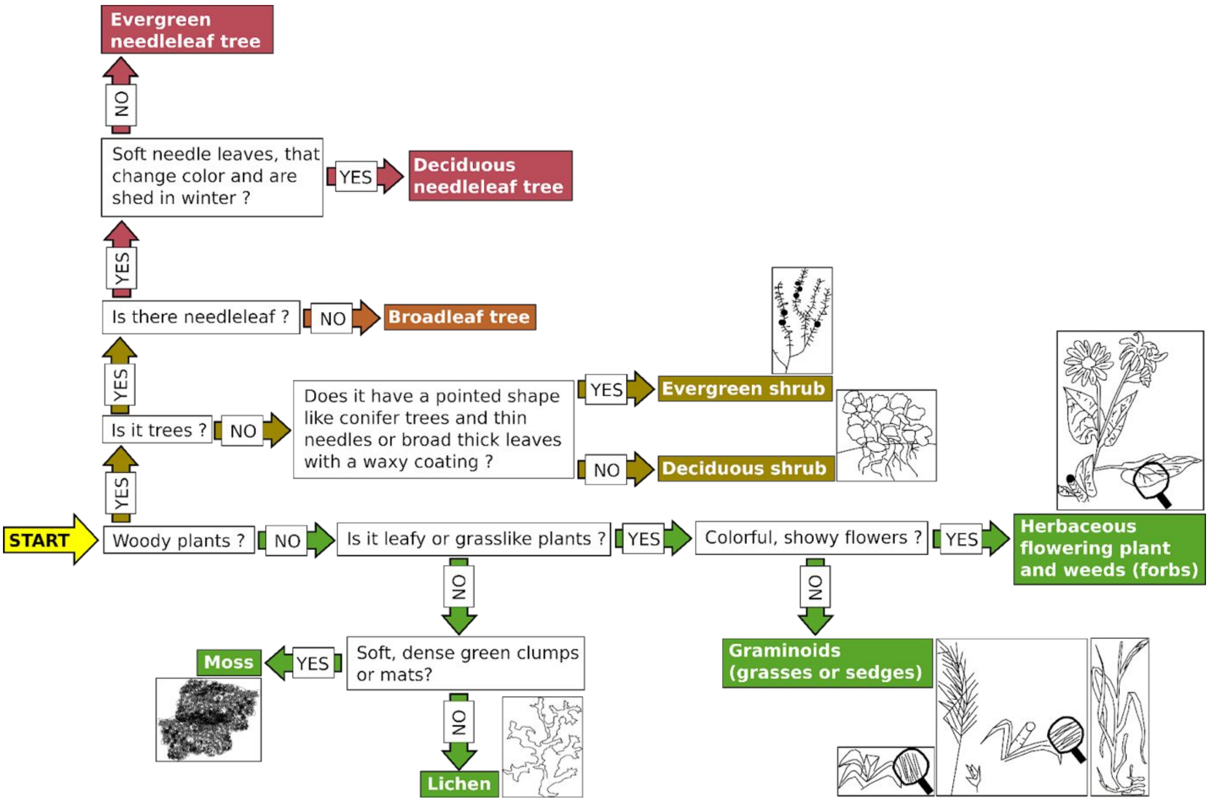

Fig. A4: Flowchart vegetation.

[ ] 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

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

[ ] 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

In the wider area as far as you can see.

15) Disturbance

[ ] No disturbance

[ ] Natural disturbance (example: burned area, slumps)

[ ] Disturbance 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. 50 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 be good 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 size to indicate the scale.

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 0 (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: 2–3 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 a graded 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).

Actions:

- Put the pole or the avalanche probe straight (90° to surface) through the snowpack.
- Make sure the pole reaches the ground (not just stuck on an ice layer or crust) – you may need to apply more pressure than you think or less pressure if on soft ground.
- If the ground can't be reached make a note including the point number (e.g. presence of a basal ice layer at point 4).
- Measure snow depth with the scale or tape measure, or read off from the scale on the probe.
- Record value [cm].
- Repeat every metre.
- Estimate how accurate the measurements are [cm].
- Take a photo of the transect.

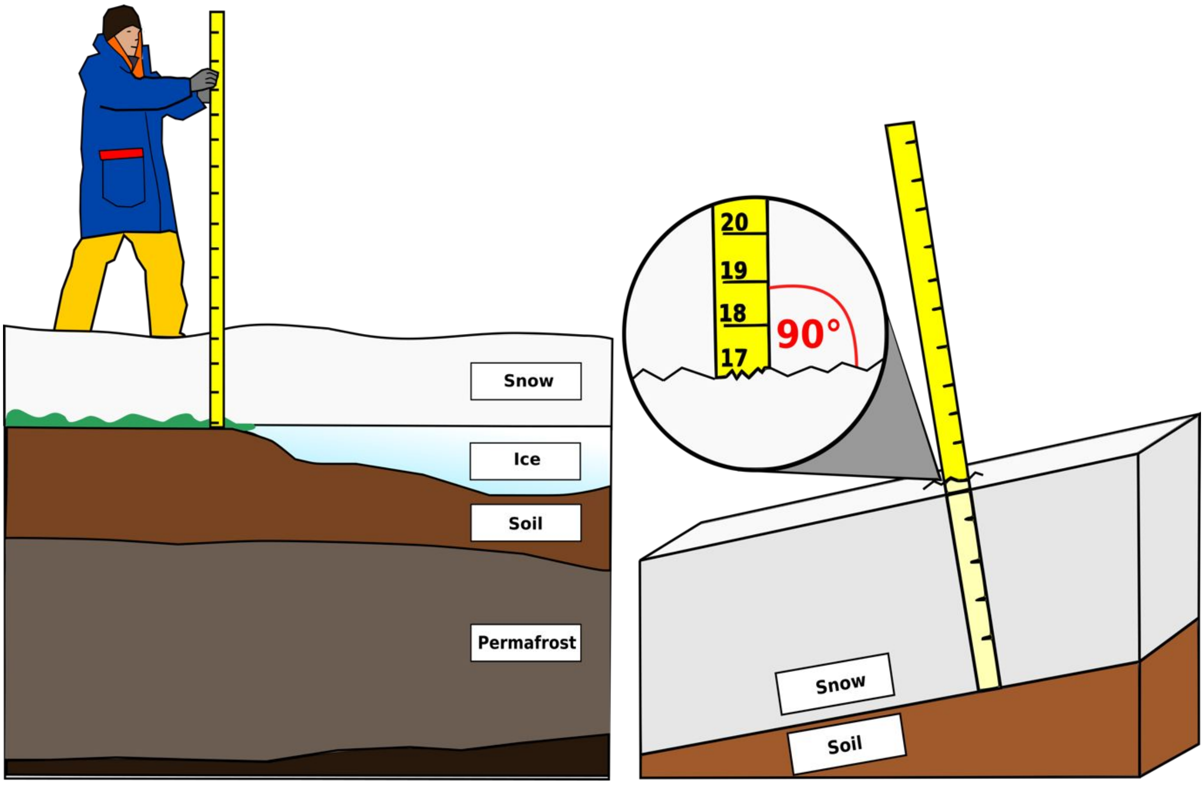

Fig. A5: Snow depth measurement.

2 Permafrost - Thaw Depth [cm]

? **Where to measure**: Thaw depth is known to vary substantially over very 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 very 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 prioritized.

Instrument: Metal rod, measuring tape

Time: 1 minute per measurement, depending on soil properties

Scale: 10–30 m transect, one measurement every metre

Method:

At each measurement point, insert a frost probe vertically to the surface until the point of resistance. 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 gone into 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 hitting a stone) or inserting the rod is impossible altogether (gravel, bedrock, etc.), try to repeat the observation within a distance of less than 1 m, or leave the box blank.

Actions:

- Insert the frost probe into the soil vertically until resistance against frost table is met; gently press the back of your hand 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 had to be made at another location due to an obstruction, or any other anomaly.
- Repeat every metre.
- Take a photo of the transect from either end.

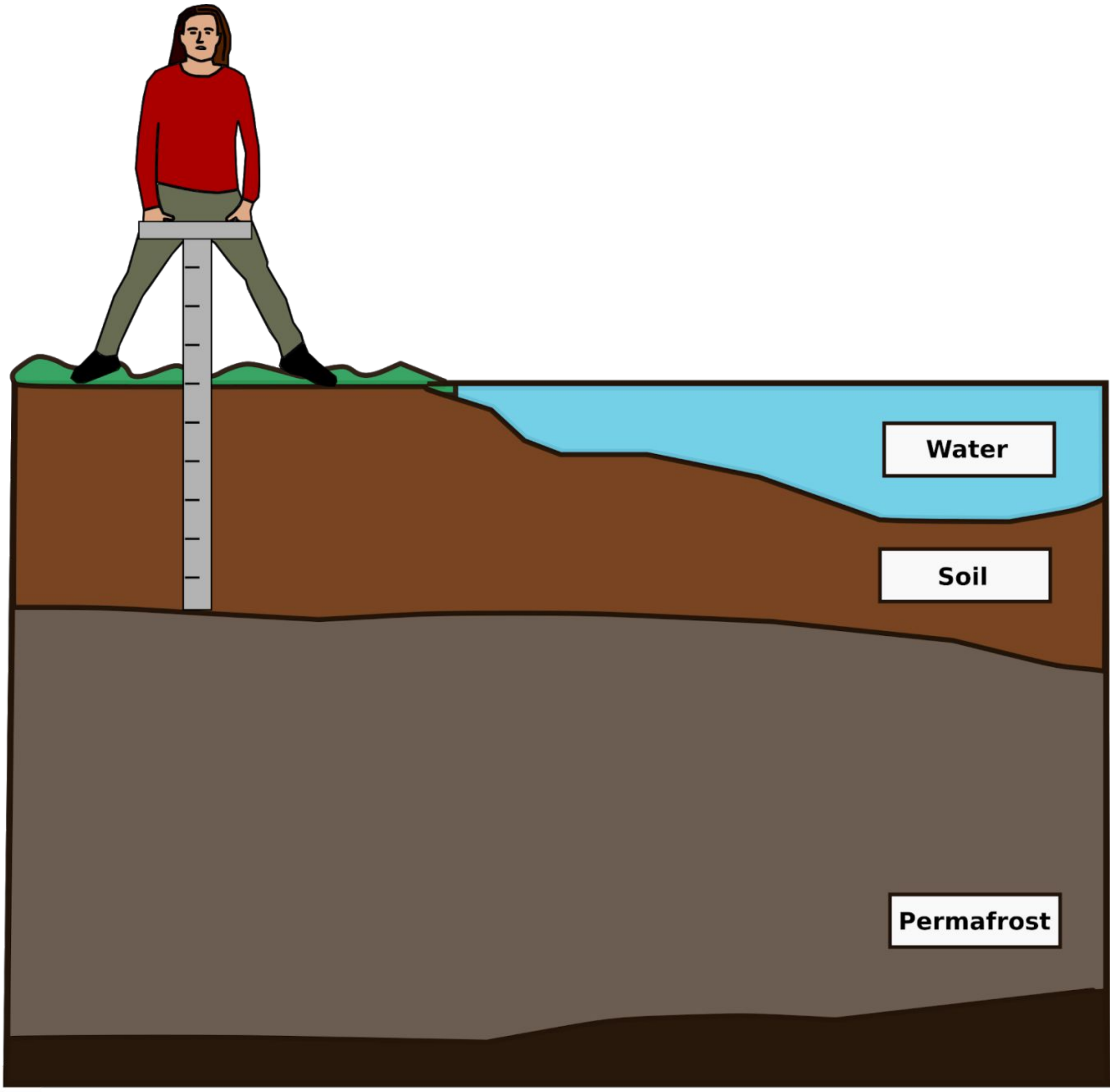

Fig. A6: Thaw depth measurement: the frost probe is inserted into the ground; measure the length of the section of the probe that has gone into the ground.

3 Vegetation - height [cm]

? Where to measure

For all sites: take vegetation height measurements in 1x1 m quadrats (squares) at each point along your 10–30 m transect. This 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.

If your site is a forest: measure a minimum of 10 individual trees in a 15x15 m plot *as well as the transect*.

? When to measure

Forest: at least once a year, preferably during growing 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).

Time:

Quadrats: 2 minutes per quadrat

Trees: 1 minute per tree

Scale:

At all sites: 10–30 1x1 m quadrats at 1-m intervals along transect (see Section 0)

Forest only: 15x15 m square area

Method:

Measurement of vegetation cover height.

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

Actions:

1.1 All sites:

- Mark out 1x1 m quadrats at each point along your transect.
- Mark two diagonals within the quadrant and measure vegetation (excluding moss/lichen) height at four locations along the diagonals as shown in Fig. A7.
- 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 no vegetation (other than moss/lichen) at the location, record 0. If there is moss or lichen at the point you measure then tick the "moss/lichen present" box.
- Take a photo of each quadrat.

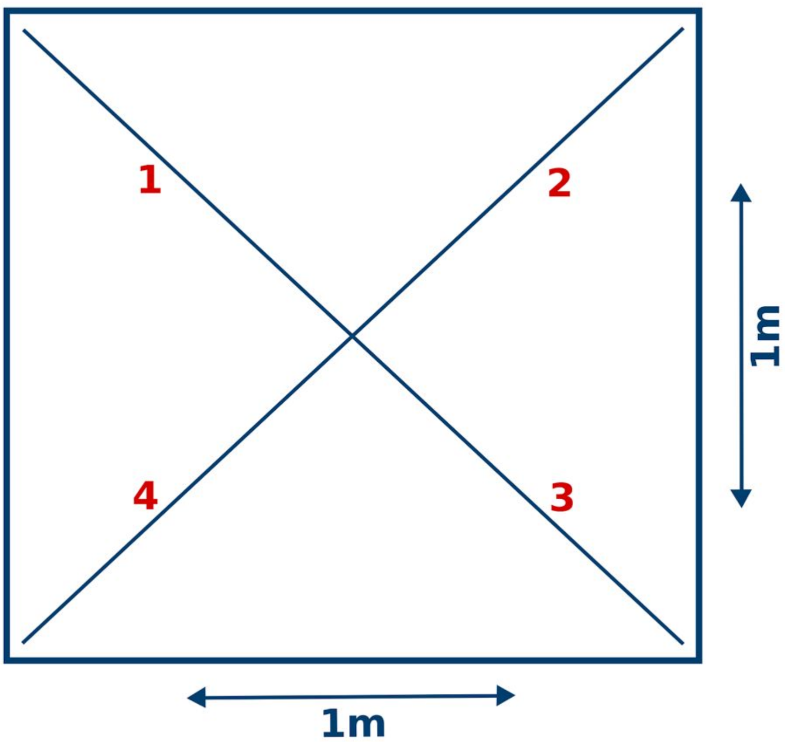

Fig. A7: Quadrat for measuring vegetation height. The four measurement locations are shown in red.

1.2 Forest sites only:

Actions:

- Mark out / estimate a 15x15 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.
- Estimate (trees taller than 2 m) and measure (trees smaller than 2 m) the height of 10 individual trees that are typical of the site. Select trees that cover the range of heights within the plot. If there are fewer than 10 trees in your plot, just measure every tree.

  How to measure / estimate the tree height for trees taller than 2 m (simple estimation):

  - Especially in dense forest it can be hard to go as far back as needed to use a geometric measurement method. A simple solution, which needs some practice but works well, is a height estimation using the help of close by objects and your own height.
  - Step back and make sure you are able to see the tree top and the base.
  - Estimate the tree height based on 2 m increments using branches as guidance.

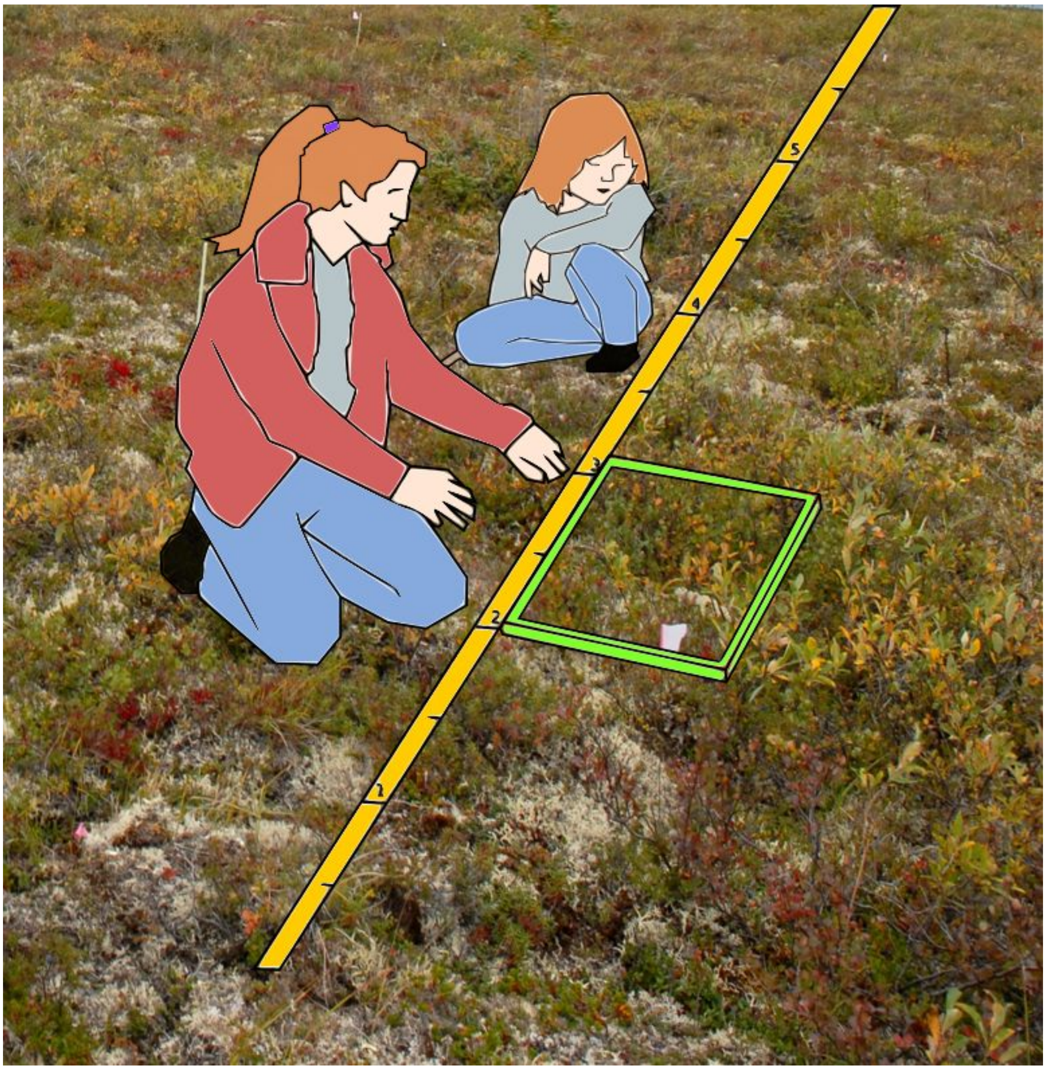

Fig. A8: Measuring vegetation height along the transect.

4 Water- Water Level

? **Where to measure**: 10–30 m transect: This should be established before taking any measurements at the site. See Section 0, above, for details of how to select and mark the transect.

? **When to measure**: Try to capture the changes through the seasons, including the spring snowmelt season, (possible) drying over the summer, and any changes towards the fall/autumn. No observations are necessary when the ground and surface waters are completely frozen. *Ideally you could take these measurements at the same time as the permafrost thaw depth (Section 2), since the same equipment is used. You can even use the same hole as for thaw depth, to reduce damage to the soil.*

Instrument: Camera (picture) and ruler, pointed metal rod (frost probe) or something to make holes (could also be your hands)

Time: 2 minutes per measurement

Scale: 10–30 m transect, one measurement per metre

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 probe 10 cm into the ground and note if the hole fills with water (i.e. the water level is within 10 cm of the ground surface). Tick the relevant box (‘Water less than 10 cm below ground – hole fills with water’, ‘Water level is deeper than 10 cm below ground – hole does not fill with water’). Repeat the procedure for all observation points.
- Take a photo of the transect from either end.

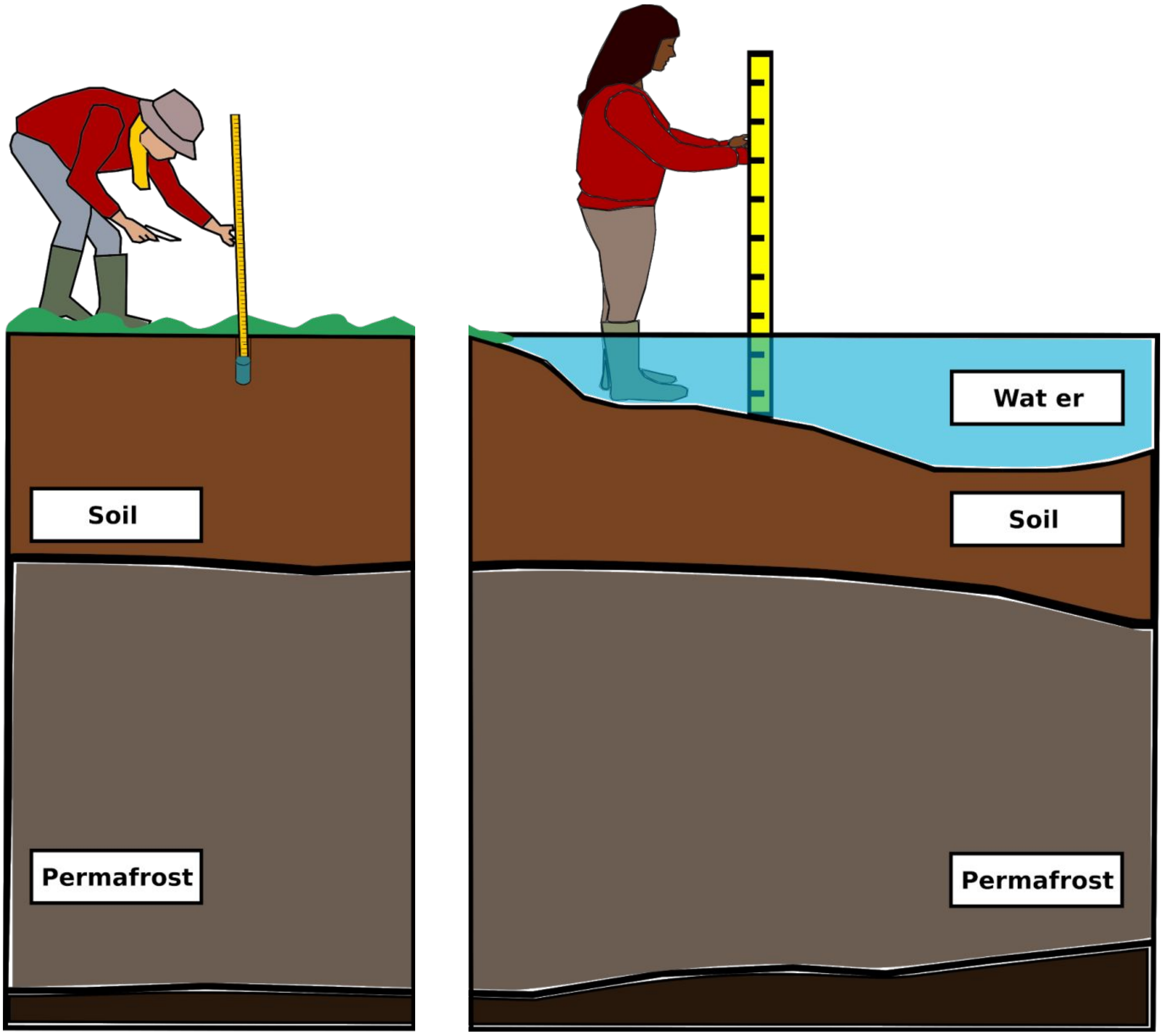

Fig. A9: Measuring the water level below the surface and above the surface.

5 Soil – Soil Pit

? **Where to measure**: The soil pit should be located close to the other measurements but set to the side so that you don't dig up the ground close to where the other measurements are taken. The pit should be approximately 1 metre 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

Scale: 1–2 m wide soil pit; ideally aim for 1 metre depth, but you can stop once you hit the frozen 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. *To reduce melting in the pit, the side you choose should not be directly exposed to the sun.* 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 backfill the pit later. Describe the profile and take a picture of the soil face, including the ruler/tape measure for scale. Please re-fill 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 ruler/tape measure for scale with the 0 level at the surface.
- Describe the soil

☐ Estimate the thickness of the upper organic layer – this is the depth to the boundary between organic (dark brown/peaty) and mineral soil.

☐ Is there any ice (at the bottom of the profile)?

If yes, take a photo with a ruler included for scale.

☐ Are there rocks in the soil?

If yes, take a photo with a ruler included for scale.

Select the soil texture description which most closely describes your soil

[ ] Clay soil

[ ] Sandy soil

[ ] Loamy soil

[ ] Silty soil

[ ] Peaty soil

- 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. A11).

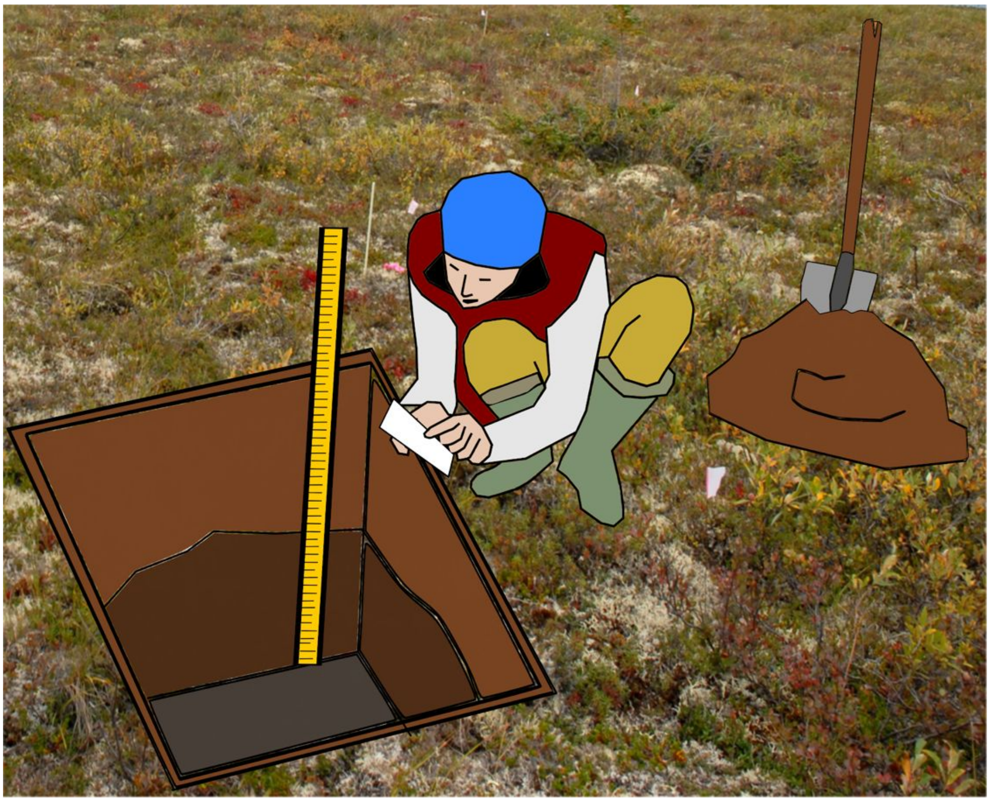

Fig. A10: Examining the soil pit during summer. This demonstrates what a soil pit might look like.

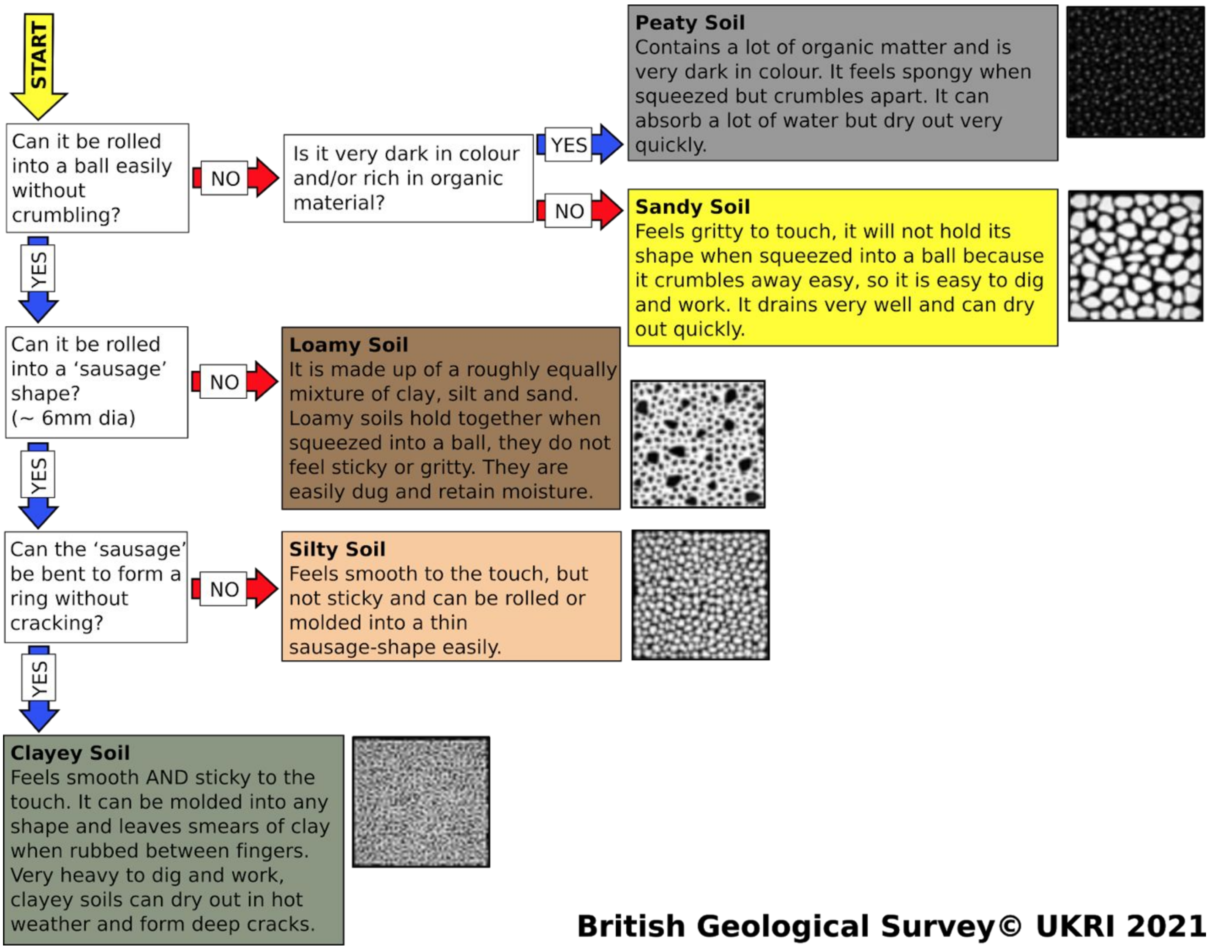

Fig. A11: To determine the soil texture, take a handful of soil and follow the instructions in the flowchart (Fig. A11 adapted and re-used with permission. British Geological Survey© UKRI 2021, mySoil Growing our knowledge (Version 5.0) [Mobile App]. Available at: https://www.bgs.ac.uk/mysoil [accessed 16 February 2021]).