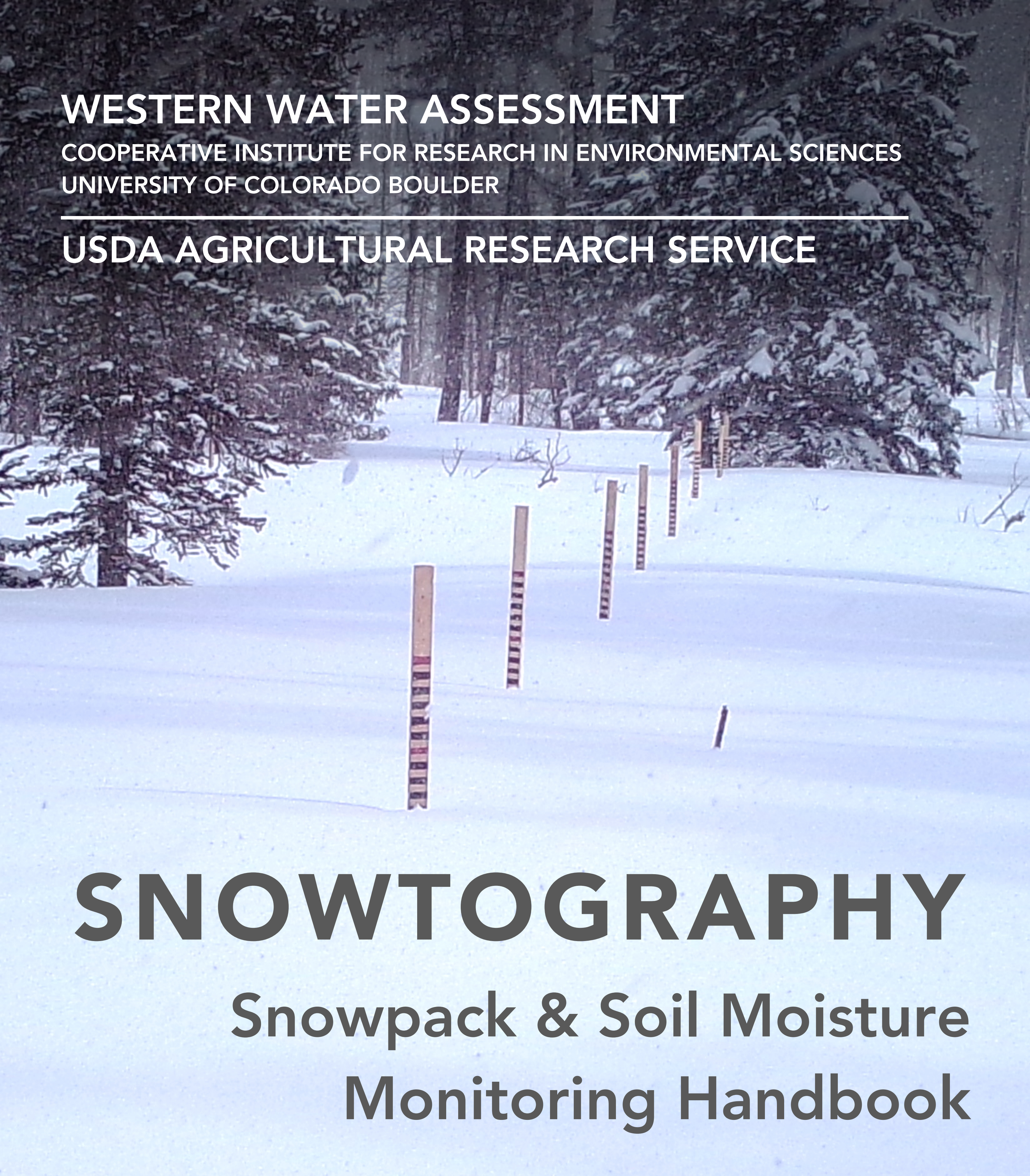

WESTERN WATER ASSESSMENT

COOPERATIVE INSTITUTE FOR RESEARCH IN ENVIRONMENTAL SCIENCES

UNIVERSITY OF COLORADO BOULDER

USDA AGRICULTURAL RESEARCH SERVICE

SNOWTOGRAPHY

Snowpack & Soil Moisture Monitoring Handbook

THE NATURE CONSERVANCY

COLORADO RIVER PROGRAM

Snowtography: Snowpack & Soil Moisture Monitoring Handbook

November 15, 2021

This handbook and additional information are available online:
University of Colorado: https://wwa.colorado.edu/resources/colorado-river-resources/snowtography-handbook
The Nature Conservancy: https://azconservation.org/publication/forest_snow_soil_monitoring_handbook/

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Cover photo: Snowtography transect in Apache-Sitgreaves National Forest, January 2017, Arizona Remote Sensing Center.

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Section

1

Introduction

Welcome to Snowtography!

Observed data are fundamental to the science and management of natural resources. Field observations of snowpack, soil moisture, and other hydroclimate variables are essential for understanding the role snowpack plays in forest resilience, stream health, and water supply. The Natural Resource Conservation Service's Snow Telemetry (SNOTEL) network of monitoring stations is the primary source of snowpack information used by water managers, flood forecasters, researchers, and myriad other parties affected by the timing and amounts of snowpack accumulation and melt.

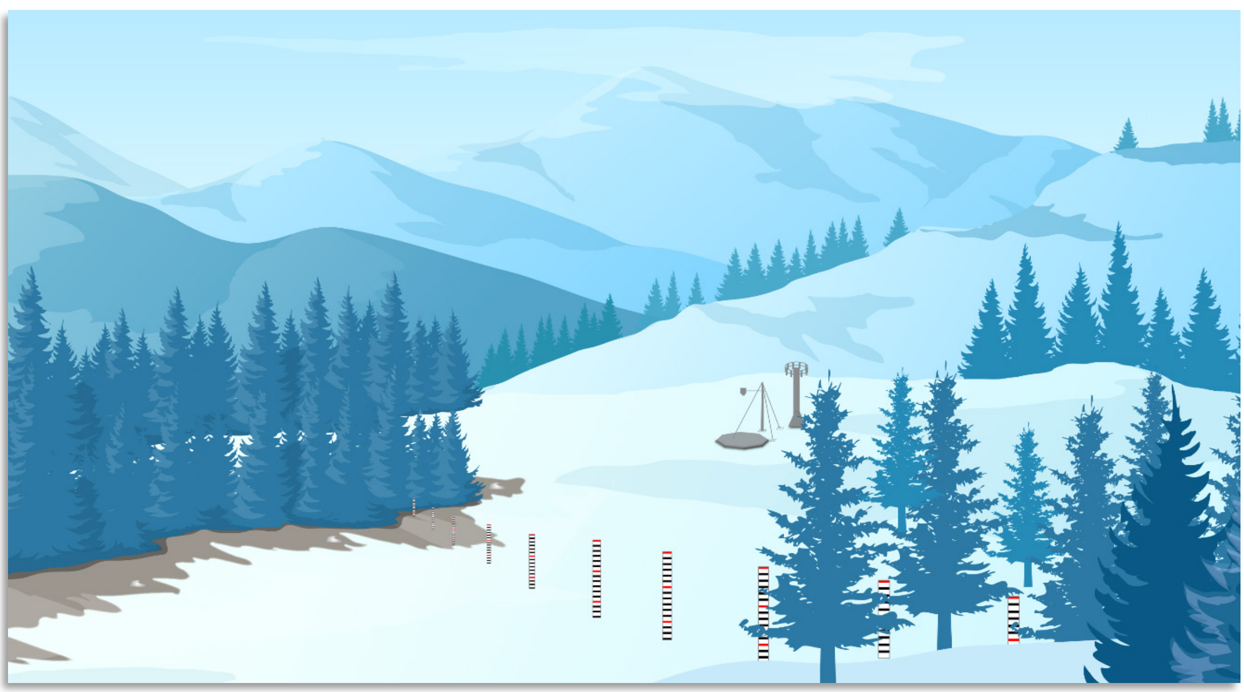

Figure 1. An idealized snowtography setting showing snow stakes in a transect across the transition between forest and clearing. A SNOTEL site is shown in a clearing in the background. Graphic: Lineke Woelders, Western Water Assessment.

Snowpack monitoring in forested settings is uneven across the West however, with monitoring traditionally done in more accessible locations and in level clearings where snowpacks won't be influenced by trees or local topography. In reality, accumulation, ablation (loss of snow from the surface due to sublimation, evaporation, wind or melt), and the spatial distribution of snow and soil moisture are strongly controlled by elevation, vegetation, slope, aspect, and other variables.

Even within very short distances, differences in key processes regulating snow accumulation and ablation may result in dramatically different amounts and timing of snowmelt water. Figure 2 illustrates the effect north- and south-facing slopes and forest fire can have on snowpack. Snowtography has many advantages in settings like these, as we detail below.

Figure 2. Photo illustrating a dramatic difference in snow distribution on north and south facing slopes. Photo: Patrick Broxton, Arizona Remote Sensing Center.

What is snowtography?

Snowtography is not a new technology but rather a novel application of fairly simple components. At its most basic, snowtography is a snowpack monitoring system composed of automated trail cameras and graduated snow stakes arranged in straight lines, or "transects," across a variable landscape (Figure 3 and Figure 4). Researchers have been using cameras to monitor snow depth for at least two decades, particularly scientists at the Arizona Remote Sensing Center and the Salt River Project; Paul Brooks at the University of Utah; and Shirley Papuga at Wayne State University.

The trail cameras record, through time-lapse photographs of the snow stakes, daily snow depths along the transects. At the end of the snow season, the station operator visits the snowtography monitoring station, collects stored photos from the cameras, and heads back home or to the office. There, the operator looks at each photo and records the snow depth for each day.

This basic system may be automated by using cameras with modems attached or integrated ("cellular cameras"). Cellular cameras automatically upload photos, making them available for review throughout the winter without visiting the site.

Figure 3. Photo of snowtography stakes taken by a snowtography camera. Source: Arizona Remote Sensing Center.

With a bit of additional effort and time, snowtography can also become a system for measuring snow water equivalent, or SWE. This added functionality cannot be inexpensively automated, so it requires site visits weekly to monthly throughout the winter to make manual measurements of snow density.

The functionality at a snowtography station can be further increased by adding a soil moisture monitoring system. These systems measure soil moisture content, a key variable for understanding forest health, wildfire risk, and streamflow generation. Adding soil moisture monitoring increases equipment costs, but typical monitoring systems are automated, so frequent site visits are not required.

All of these snowtography configurations are relatively easy and inexpensive to set up, operate, and maintain, making them attractive to managers and researchers wanting to collect observations of how forest management and disturbance affect their snowpack but who have limited resources. As a snowpack monitoring system, snowtography is a low cost approach, typically costing a few thousand dollars compared to the cost of a snow pillow, for example, that can cost tens of thousands of dollars (Domonkos, Landers, and Wetlaufer 2015).

Figure 4. Snowtography camera mounted on a tree. Photo: Patrick Broxton.

This handbook

ICON KEY
Site assessment
Time estimate
Supply list
1. Activity sequence
Important tip

The goal of this handbook is to guide users through the process of establishing their own snowtography and soil moisture monitoring stations. It is written for resource managers, researchers, and practitioners working in forested settings, where the arrangement and density of trees or the size and severity of disturbances affects snowpack persistence and soil moisture availability (Figure 5). The handbook offers guidance on site selection, snowtography options, equipment requirements, and installation. Its contents are based on snow-forest research and hands-on experience honing the snowtography method and learning what works. The instructions in this handbook have been tested by volunteer "beta testers" in Colorado and Arizona. Their feedback has helped us improve the instructions, refine lists of supplies, and identify potential pitfalls.

A note about the units used in the handbook: We used English units when specifying equipment and supplies such as lumber, conduit, tape, etc., if that is how they are typically sold. We generally used metric units for dimensions such as snow stake distances, soil moisture sensor depths, etc., if that is how they are typically described by scientists applying the methods.

Go to the "How To" sections of this handbook for the nuts and bolts of selecting and building your monitoring site.

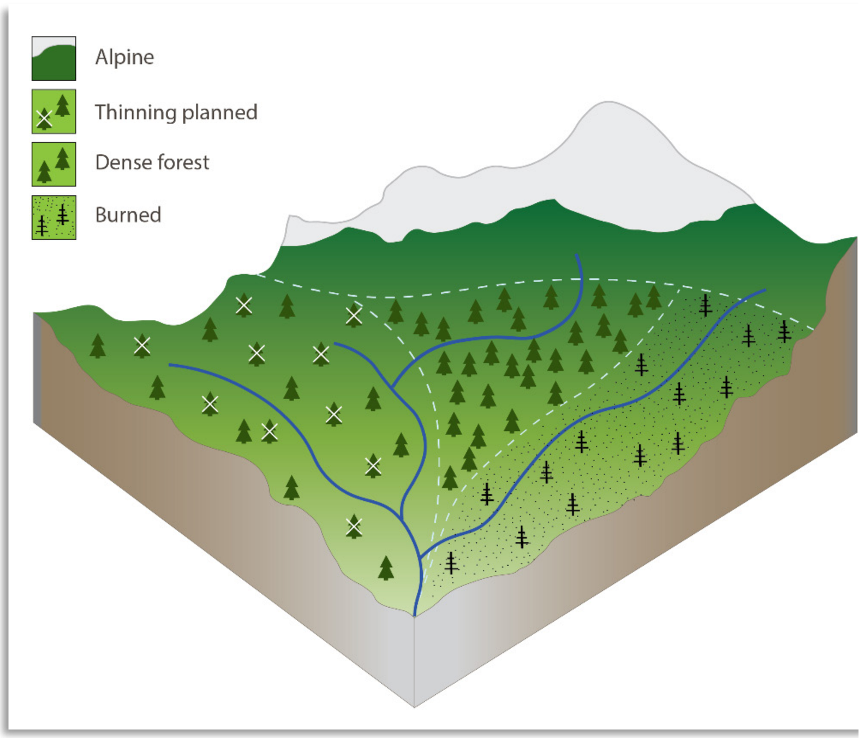

Figure 5. Potential forest conditions for monitoring. Graphic: Lineke Woelders.

The handbook is organized to support budgeting (Section 2), site planning (Section 3), and assembling, testing, and installing the three primary methods of snowtography: basic snowtography (Section 4), snowtography with snow density sampling (Section 5), and snowtography combined with soil moisture monitoring (Section 6). Troubleshooting your equipment is in Section 7 and applications, limitations, and uncertainties of snowtography are provided in Section 8.

You may need to revisit some sections of the handbook as you refine your snowtography station plan. Budgeting and planning are particularly interdependent.

We describe equipment and supplies that are essential components of snowtography, snow density, and soil moisture monitoring; however, ▶ specific brands and vendors of supplies and equipment aren't provided in this handbook, unless they appear in a photograph documenting an installation step. However, The Nature Conservancy hosts a webpage with additional information and examples of supplies and equipment at its website: (https://azconservation.org/publication/forest_snow_soil_monitoring_handbook/).

Section 2

Which method works for you?

It depends on your time and budget.

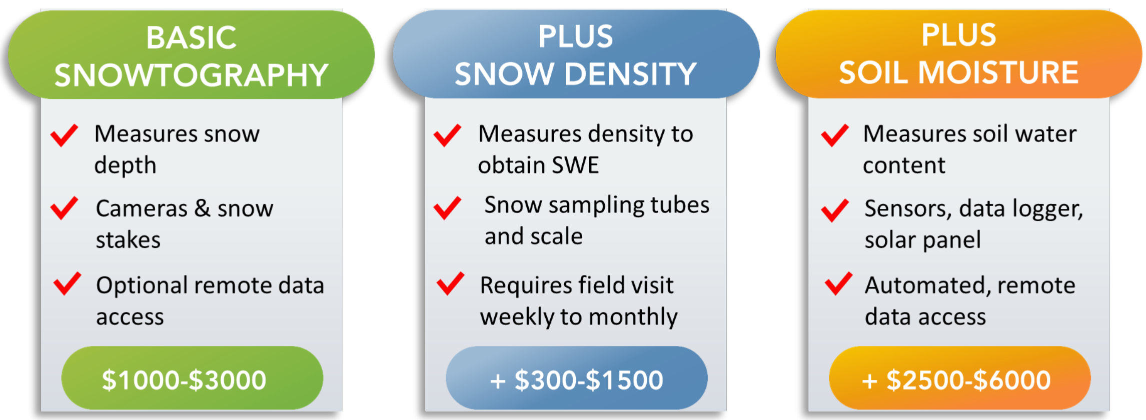

Figure 6. Key elements of the three methods. Dollar amounts are equipment cost estimates and do not include labor or travel costs.

This section of the handbook compares the costs of the three snowtography methods to help you determine approximately what your plan will cost, and what components you could amplify or shrink in order to fit your budget. Basic snowtography is fundamental to snowpack monitoring and so its costs are included in all of the methods.

▶ Throughout this section, we provide examples of the equipment costs of typical installations and estimates of the amount of time required for preparing, installing, and monitoring a typical station, but we don't attempt to translate the time estimates into a labor cost. The cost estimates provided in Tables 1-3 are for equipment only, at the time of writing this handbook, and for a particular configuration that we've chosen as an example.

Basic snowtography

Variable measured

Basic snowtography stations measure **snow depth**. Tree-mounted trail cameras take photos of snow stakes that have been painted with one-inch incremental stripes. This simple station can provide a lot of information about where and how much snow accumulates and how long it lasts.

Equipment list

The equipment listed here includes only the bigger ticket items to give you a sense of the cost of snowtography compared to other snow monitoring methods. Other items that you will need for the basic station but may already have on hand or may borrow, like a ladder, or post-pounder, are not cost out here, but are listed in later sections. Likewise, smaller items, like tape and paint, are not itemized here but will add to the total cost. They are listed in the applicable sections of this handbook.

- ✓ **Snow stakes.** Your snowtography plan, developed in Section 3, will include the number of snow stakes needed. About 20-60 snow stakes per snowtography station is typical. Each stake includes a piece of lumber, a metal post, and the hardware to attach them (described in detail in Section 4).
- ✓ **Cameras.** Expect to buy one trail camera for every 3-4 stakes in your snowtography plan; 5-20 cameras is typical for a plan with 20-60 snow stakes.
- ✓ **Cameras with integrated cell modems** are not required equipment, but having one or two will allow you to download some of your snowtography photos and keep an eye on your snowtography station remotely without making a site visit. A camera with a modem will upload the photos taken by that camera only. If winter site access is impossible and you wish to have real-time data for the entire site, you may consider buying only cameras with cell modems.
- ✓ **Camera data plan.** If you plan to use cameras with modems, you will need to purchase a data plan with each one. As discussed in the next section, be sure that you have adequate cell service matching the data plan provider.

Time & Budget

The time and budget costs of a basic snowtography station depend on the number and length of transects in your plan. The estimates below are for a typical snowtography station with about 28 snow stakes arranged in 2 transects. The more or longer the transects, the more cameras and stakes you will need, the larger your budget will be, and the more time it will take to prepare and install. When reviewing the time estimates below, remember to consider your own travel time to and from your snowtography station.

Time

Estimates of the time it will take to establish the basic snowtography station described above are listed below. Your experience will vary depending on your site characteristics and the weather conditions.

- Initial site selection, station surveying, planning, and ordering equipment: about 10 hours for 3 people, or **30** person-hours.
- Unpacking the cameras and programming and testing them before going to the field: about a half day, or **4** person-hours.
- Preparing the snow stakes: about **12** hours for 1 person, spread across several days to allow for paint to dry between steps.
- In the field, with 3 people participating, installing the cameras and testing them: about 30 minutes per camera, or about **4** person-hours in our example.
- Installing the snow stakes on-site: about 8 hours for 3 people, or **24** person-hours.
- At the end of the snow season, a visit to the station to remove the cameras can be very brief: 1 person, 15 minutes per camera, or about **2** hours.
- At home or in the lab, reviewing the images on the cameras' memory cards and entering snow depth data into a spreadsheet: about 3 person-hours per camera, or about **21** person-hours.
- Using these estimates, total time planning, preparing, installing, entering data, and removing cameras for the basic snowtography example used here, for the **first year**, would be on the order of **about 100 person-hours**.

Budget

The biggest ticket item required for basic snowtography will be the programmable, time-lapse trail cameras. Example equipment costs for a station with 28 snow stakes is shown in Table 1. For larger stations, factor up each item proportionately. A station with 60 snow stakes would be close to $3,000.

Table 1. Example equipment costs for a basic snowtography station.

Item	Price, $	Quantity	Total, $
Trail camera without modem	80	5	400
Trail camera with modem	130	2	260
Camera data plan (one year)	120	2	240
Snow stake (each spans 5 m)	20	28	560
Total equipment cost			$1,460

Add snow density monitoring

Add snow density monitoring to your snowtography station to build a more complete picture of snowpack conditions, including water content. Snow density monitoring doesn't require additional assembly or construction beyond the basic snowtography station, but it does require site visits to collect and weigh snowpack core samples on a weekly to monthly basis.

Variable measured

Snow density is obtained by weighing a column of snow sampled at a point in the snowpack, in this case near a snow stake. Adding snow density monitoring allows you to determine snow water equivalent, or SWE, in the snowpack. SWE represents the depth of water contained in the snow at the sampling point.

Equipment list

Snow density is measured with a snow sampler. Typical snow samplers are aluminum "Federal" or "Mt. Rose" samplers, or a variety of plastic or steel do-it-yourself samplers. Snow samplers have two main components: a tube used to collect a core sample of snow and a scale to weigh the tube. Federal samplers, the US Forest Service standard, are expensive, so investigate the possibility of borrowing one, or you may be able to make your own sampler for hundreds of dollars less (see Section 5 for more details about snow sampling equipment, including a detailed list of parts).

✔ Snow sampler with scale.

Time & Budget

Snow density will vary across your snowtography station, making it important to take multiple density measurements to get an estimate of SWE that is representative of the snowpack at your station.

Time

Snow density monitoring does not require installation, so the time spent on this method results from frequent site visits to collect data. Plan to take snow core samples at half of the snow stake locations each visit. Allow a half day at the station weekly to monthly for 2 people to do the snow density sampling.

Snow core collection: If 2 people visit the site every other week during a 6 month season, the time required to add snow density monitoring to the basic snowtography station described here would be **about 100 person-hours**. The actual time spent will likely be less given that this frequency of visits may not be required or achievable, depending on conditions.

Budget

An example budget for snow density sampling equipment, based on the example in Table 1 for a basic snowtography station, is provided in Table 2 below. The total cost of a Federal sampler will depend on how many lengths of aluminum tubing are required to sample the depth of snow expected at your site. Again, if you are making your own snow sampler rather than using a Federal sampler, replace the cost of the Federal sampler with the cost of your materials, about $300.

Table 2. Example equipment costs for a basic snowtography plus-snow-density monitoring station.

Item	Price, $	Quantity	Total, $
Trail camera without modem	80	5	400
Trail camera with modem	130	2	260
Camera data plan (one year)	120	2	240
Snow stake (each spans 5 m)	20	28	560
Federal snow sampler	1,500	1	1,500
Total equipment cost			$2,960

Add soil moisture monitoring

Adding soil moisture monitoring requires additional time and money to set up, but the monitoring itself is automated, so additional site visits are not required. Data can be downloaded, eliminating a manual data entry step.

Variable measured

The soil moisture sensors described in this handbook measure **soil water content**, or SWC, a variable that provides the volume of water in the soil at the point of the sensor. Some applications, particularly those focused on soil water supply for vegetation, may use soil water potential, or SWP, which is the suction required to extract water from the soil. SWP sensors are available commercially, but are not covered in this handbook. Another potential upgrade not covered here is a dual SWC-soil temperature sensor system that can provide information about frozen soils and root zone temperature throughout the year.

Equipment list

Vendors now offer integrated data logger and solar panel systems that simplify assembly and installation. The example offered here is for an integrated system, but systems with independent components can support larger sensing networks. The equipment for an integrated system and protective conduit are listed here. The lower cost items or items that you may already have on hand, such as shovels and picks, are listed in the "how-to" sections of the handbook.

- **Data logger** for receiving and uploading soil moisture data from the sensors via sensor cables.

- **Cellular data plan** for retrieving data from the data logger. The plan is typically purchased as a subscription from the data logger vendor and includes the cellular data plan as well as hosting and data access. Be sure that your site has adequate cell service from the equipment's service provider. Antennas to increase the signal range are available for some models at additional cost. Some data loggers also support data download by nearby Bluetooth®-enabled devices, like a cell phone or tablet.

- **Soil moisture (SWC) sensors with cables** for converting soil moisture to a signal and conveying that signal to the data logger. Depending on the manufacturer and model selected, data loggers may support up to 24 sensors, but in this handbook we are assuming that you will use simpler equipment that supports 6 sensors. Depending on the manufacturer, soil moisture cables are often available in variable lengths from about 5 to 25 m, priced accordingly.

- **Conduit** to prevent damage to the sensor cables from rodents, browsing animals, and weather.

Time & Budget

Time

Adding soil moisture monitoring to your snowtography station will not require additional trips to the field, assuming that you can install all of the equipment on the same day. Estimates of the additional time it will take to prepare and install soil moisture monitoring equipment are listed below.

- Testing before going to the field: Allow **8** person-hours, spread across a few days, to test the sensors under a variety of moisture conditions.

- Preparing conduit and cables before going to the field: Allow about **4** person-hours for this step if using flexible conduit. Rigid conduit requires this step to take place in the field.

- Installation in the field: Expect to spend **6** person-hours per data logger and set of 6 sensors digging sensor trenches and securing the sensors. This estimate anticipates that you would dig shallow trenches to install the sensors; the time estimate could double if the sensors are going to be placed much deeper and/or the soil type is especially challenging.

- The time required to add soil moisture monitoring to the example snowtography station used in this section would be about **18** person-hours.

Budget

An example equipment budget, based on Table 1 for a basic snowtography station plus soil moisture monitoring with one data logger/solar panel combination and 6 cables is provided in Table 3 below. Note that this estimate does not include snow density sampling. To include snow density sampling equipment costs to Table 3, add the cost of a snow sampler (see Table 2).

Table 3. Example equipment cost for a basic snowtography-plus-soil moisture monitoring station.

Item	Price, $	Quantity	Total, $
Trail camera without modem	80	5	400
Trail camera with modem	130	2	260
Camera data plan (one year)	120	2	240
Snow stake (each spans 5 m)	20	28	560
Data Logger	650	1	650
Cell plan for data logger (one year)	180	2	360
SWC sensor (5 meter cable)	125	2	250
SWC sensor (10 meter cable)	155	2	310
SWC sensor (15 meter cable)	160	2	320
Protective conduit	15	8	120
Total equipment cost			$3,470

Section

3

How to make a snowtography plan

Got maps?

Figure 7. Google Earth topographical and terrain maps of a potential site in Colorado. Notice that in this example, the maps offer sites with the opportunity to compare snowpack between treated and untreated sites and a variety of slope and aspect conditions.

Before diving into where to locate your snowtography equipment, let's define some terms. Throughout this handbook, "site" refers to the larger, approximate geographic location targeted for monitoring. "Station" refers to the smaller area encompassing the entire monitoring system, including all the snow stakes, cameras, and soil moisture sensors (if included in your monitoring plan). And "transect" refers to a single row or column of regularly spaced snow stakes and soil moisture sensors (if included).

This section of the handbook guides you through exploration and selection of potential snowtography sites, stations, and transects.

Selecting your site

A thorough and considered snowtography plan is key to successful, timely installation and operation of a snowtography station. Planning can take quite a bit of time, so during the spring or summer before installing a snowtography site, spend some time poring over high resolution maps of your watershed to find the right site for your snowtography station. Particularly important maps will be recent vegetation maps, topographic maps, and digital elevation maps (DEMs). Drone photos and recent Google Earth imagery are also helpful (Figure 7). Maps of soil type may be useful if you plan to monitor soil moisture, such as the gNATSGO map provided by the US Department of Agriculture and the Natural Resource Conservation Service.

When first choosing a site, consider these questions:

- ? Identify the questions you are seeking to study with snowtography. What is it about snow and/or soil moisture that you want to learn?
- ? What variables affect snow and/or soil moisture in your watershed or forest? Variables can be elevation, slope, aspect, wind, sun and shade, forest density, and the size and shape of tree clusters and clearings.
- ? Where is there a transition in the variable you want to study (e.g., wildfire scar, thinning treatment, transition from east to west, sunny to shady slopes, etc.)?
- ? Are there any recent or planned management activities or areas at high risk of disturbance, such as fire, where you would like to conduct pre-change monitoring?
- ? Would the site allow you to make measurements across a range of the important variable(s) while controlling for other variables? ▶ Narrow the number of variables to the one or two that are most important, and choose a location that minimizes the influence of other variables to avoid muddling your observations. For example, if you are interested in studying forest

Figure 8. Photo illustrating the complex interactions of topography and forest thinning that regulate the timing of snowpack disappearance at Mt. Bigelow, AZ. Photo: Joel Biederman

thinning as the key variable, choose a site with relatively level, uniform terrain to avoid topographic influences complicating your observations. If you want to study multiple variables (such as shown in Figure 8) and their interactions, you will need multiple sites and/or more snowtography transects per site.

- Is there a SNOTEL station in or near your watershed that could complement your snow observations? Availability of local weather data from a nearby SNOTEL site will provide context and help you interpret observations. SNOTEL stations at similar elevations that receive the same weather events on the same day, similar temperature, same side of a divide, similar precipitation, etc. would be the most relevant.

- How is the cell service at the site? Camera modems and soil moisture data loggers offer data upload and storage options. If you choose those options, consult cell service coverage maps. Check with the manufacturers of the equipment to find out which carriers they use for their data plans. The service particular to the equipment and the signal strength at your snowtography location will help you determine which equipment you choose.

- How accessible is the site in winter? This consideration is a factor if you are planning to conduct frequent (weekly to monthly) snow density measurements or visit the site to collect snow depth or soil moisture observations in the field.

- What are the permitting requirements for the site? Consider that it may be difficult to obtain timely permits at some sites. ▶ When applying for a permit, it can be helpful to clarify that snowtography is a monitoring method that involves minimal disturbance to soils or trees, requires only hand-held equipment, and can be readily removed. In some situations involving forest thinning or recent disturbances such as wildfire, it may be possible to add snowtography as a modification to an existing research or monitoring permit, which is usually simpler than initiating a new permit.

Locating and laying out your snowtography station

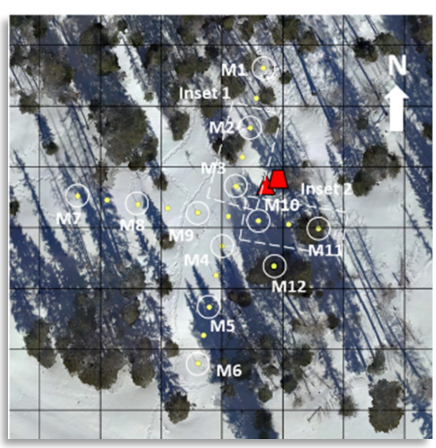

Figure 9. Typical snowtography station with transects oriented N-S and E-W to capture snow variability under sun, shade, and wind conditions in the forest. The grid cells are 10 meters square. Yellow dots indicate snow stakes 5 meters apart and red shapes indicate a data logger and solar panel. (Some systems have integrated data loggers and solar panels.) Source: Willem van Leeuwen, Arizona Remote Sensing Center.

Once you've settled on a general site area, and before you order cameras, sensors, data loggers, and solar panels (if separate), load up the following gear and visit the site in the field:

- ✓ **Cell phones** for testing cell service, potentially from multiple carriers, depending on camera and soil moisture equipment.
- ✓ **Camera** for documenting your station.
- ✓ **Maps** as described above.
- ✓ **Tablet** if available, with GPS mapping app installed, to load map layers and mark component locations.
- ✓ **Marking flags** for marking snow stake locations.
- ✓ **Ground stakes** with durable fluorescent material attached for the same purpose as marking flags, but potentially more resilient.
- ✓ **Ladder** for identifying trail camera locations.
- ✓ **Forestry flagging tape** for identifying the trees that will host trail cameras (Figure 10).

Figure 10. Forestry flagging tape. Photo: https://commons.wikimedia.org/wiki/File:Forestry_flagging_tape.jpg ~riley, CC BY-SA 4.0 via Wikimedia Commons.

- ✓ **Surveyor's tape measure(s)** 50-100 m long, and a **ground pin or tent stake** for holding the tape end.
- ✓ **Sample T-posts and U-posts** to determine which is more suitable to the soil at your location.
- ✓ **Post pounder** for driving in T-posts or U-posts (see Section 4 and Figure 18).

Spend a day walking the site and considering the issues described above. Take lots of photos, draw sketches, and use a mapping app or other system to record the setting and the final positions of each component. Here is a checklist for your visit:

- ? **Cell service.** Test the cell service. Cell service will be critical for remote access to your snowtography photos and/or soil moisture observations, if you are purchasing remote access options. ▶ Check the manufacturer's requirements and confirm that you can meet them at your snowtography station before ordering. If possible, download and use the manufacturer's app to test cellular upload ability at potential equipment locations. If service is poor, try another location or consider purchasing an antenna if offered by the manufacturer.

- **Stake locations.** Using flags and ground stakes, experiment with potential equipment locations, measuring distances to sensor positions and snowtography stake locations. Consider placing transects across spaces that stretch from one extreme to another, such as from a dense stand of trees into an open clearing. Keep in mind that trees block snow from reaching the ground directly beneath them and that they cast shadows far to the north when winter sun angles are low. For ease of photography and data interpretation, use a taught tape measure to locate snow stakes along a straight, linear transect. With flags, mark stake locations that are 5 meters apart (Figure 12). Refine the final positions of the stakes as you find the best camera locations.

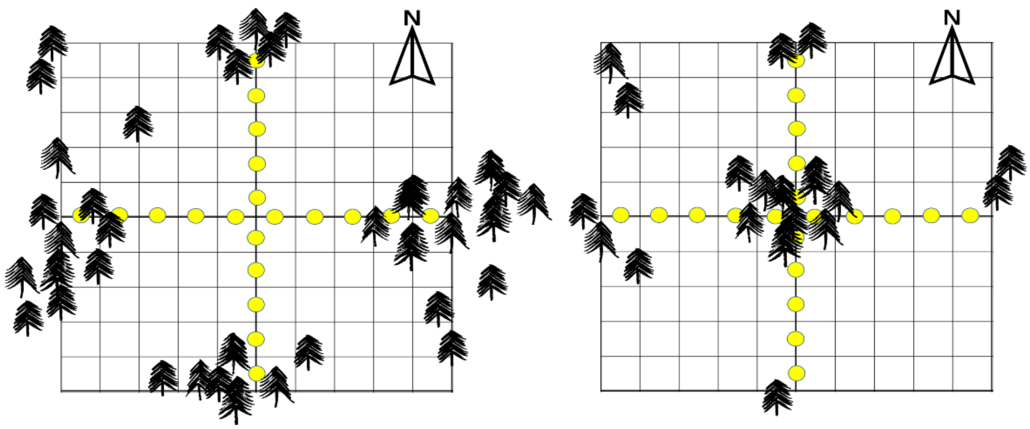

Figure 11. Transect plans, (left) with a forest clearing in the center, and (right) with a cluster of trees in the center. Yellow dots are snow stakes, placed 5 meters apart. The grid cells are 10 meters square.

- **Camera locations.** Each camera will have its own field of view, so you must confirm that it can photograph the stakes that you expect it to. Take a ladder to a suitable tree and position yourself on the ladder at a height—typically about 3.5 meters to deter theft and enhance views—that is about the same height as the camera will be. (If your station has few trees, plan to bring posts to support the cameras.) Are the snow stake marking flags visible? Expect a typical digital trail camera to capture images 50 to 70 feet away. You will need one camera for about every 3-4 stakes (Figure 12).

  Ideally, the camera line of sight is offset from the transect slightly (5-20 degrees) to avoid snow stakes near the front blocking the camera's view of the stakes behind. This important step will guide the layout of your transects and help you determine how many cameras you need. As part of your total camera count, plan to buy one or two camera modems, or cameras with integrated modems, if you would like to monitor your site without making site visits. If budget allows and site access is limited, all cameras may be modem-enabled. ▶ Mark the trees that will host cameras with forestry tape so that you can find them when you return.

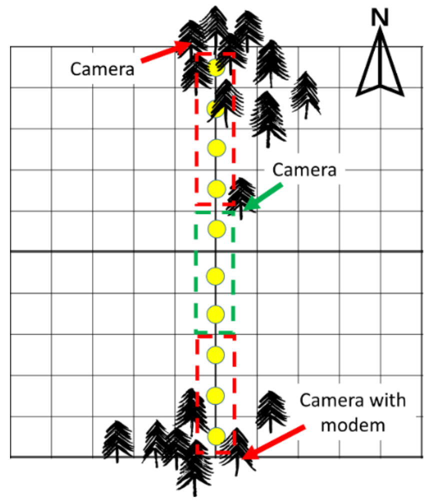

Figure 12. Example camera locations on a north-south transect. Cameras are mounted on trees to capture groups of 3-4 snow stakes, shown here with dashed lines.

- **Soil depth.** Test that there is enough soil to sink a U-post or T-post into by trying to place some using the post pounder, and determine which post type works best at the stake locations you've selected. U-posts, though convenient for snow stake attachment because they are pre-drilled, may be too lightweight and may bend when set into hard or rocky soils, in which case T-posts will be the appropriate choice. If soil moisture sensors will be part of your snowtography station, make sure that the soil is deep enough to take measurements at the environment depths of interest to you.

- **Data logger and solar panel.** Decide where to locate the soil moisture data logger and solar panel if you are monitoring soil moisture. (Some manufacturers offer data loggers with integrated solar panels and batteries.) Data loggers and solar panels can be positioned at forest transition points, such as the boundary between thinned and untreated areas, with soil moisture cables reaching into both spaces. ▶ When choosing a data logger location, keep in mind that accessing the data logger in winter should not disturb the snow near the snow stakes. ▶ The data logger and solar panel must be located together and oriented toward the south to capture at least five hours of sunlight in the winter (Figure 13).

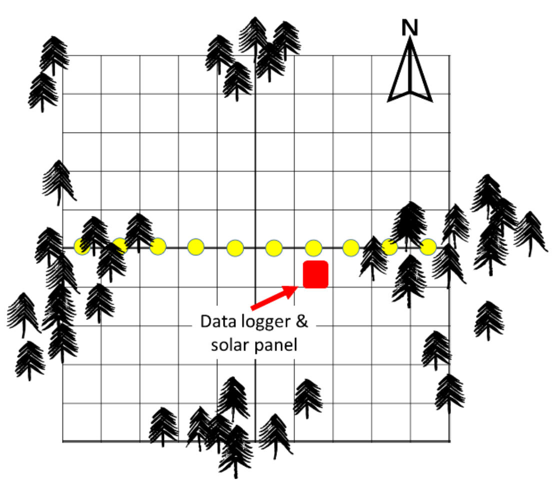

Figure 13. Example data logger and solar panel located at a transition point between forest and clearing. Soil moisture sensors will reach into both forested and clear areas.

Soil moisture sensors. Soil moisture sensors are located adjacent to snow stakes, typically at every other stake in a transect, though your configuration will depend on your information needs and how many sensor cables of each length and data loggers you purchase. Data loggers typically support 6 to 24 soil moisture sensor cables. You may plan for either a single sensor at each targeted snow stake or a pair of sensors. Paired sensors are useful for monitoring at different soil depths. A common pairing would be at depths of 10 cm and 30 cm, or at 15 cm and 50 cm, and would allow analysis of depth-dependent conditions:

- Near-surface moisture, which would influence infiltration rates, surface evaporation, and root zone moisture for most plants.
- Deeper moisture, which would represent root-zone moisture only accessible by trees and other plants with deeper root systems.

Each sensor will have its own pre-cut cable, so the method you choose will determine the lengths of cable you need. Cables typically come in lengths that are multiples of 5 meters, up to 20 meters, and are priced by length. Plan your soil moisture sensor locations based on these cable lengths, with shorter ones being closer to the data logger and longer ones being farther (Figure 14)

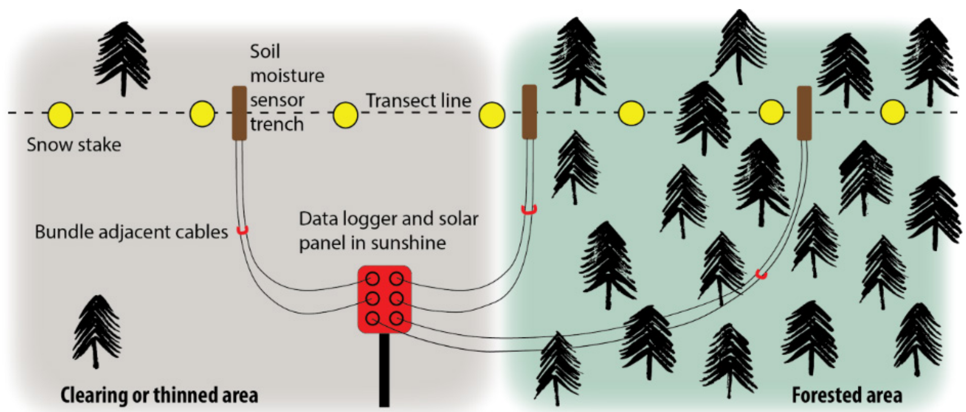

Figure 14. Snow stake transect with soil moisture sensors. In this example, forest density is the target variable, so the data logger is located near the transition between clearing and forested areas. Soil moisture sensors are paired in this example and located at alternate stakes. The sensors are placed at 2 different depths in each trench. Graphic: Lineke Woelders.

Assume that you will need to accommodate the additional cable length needed to run the cable along the bottom of the trench and back out again (Figure 45).

Estimate how much conduit you need to protect the full length of each soil moisture sensor cable. Conduit may be ½-¾-inch flexible electrical conduit, automotive wire casing, or rigid PVC pipe with appropriate connectors. Use the larger diameter conduit if you are planning to run 2 cables through the conduit. ▶ If you are using flexible conduit, calculate the lengths needed based on using a single, intact segment for each cable; do not piece together segments. If you are using rigid conduit, assume that you can assemble variable lengths with joints, fittings, and adhesive.

- Expect that there will be some wastage when estimating how much conduit to buy. Try to buy lengths of conduit long enough to accommodate your longest sensor cable. (Remember that cables and conduit may come in metric or English units.)

- **Save your work.** Before you leave the site, check that you have left flags and markers to indicate where each snowtography stake will be placed and which trees will host cameras. Number the snow stake locations—these numbers will be transferred, with a marker, to the snow stakes after installation. If you elect to do soil monitoring, mark where sensors, data loggers and solar panels (if separate from data loggers) will be located.

▶ Document everything clearly to make installation as straightforward as possible. Mark the endpoints of each linear transect, camera location, and data logger location in GPS mapping software, if possible. This will preserve the value of the work you've done even if the flags are damaged by animals or vandalism. Having GPS coordinates may allow you to view and share your proposed snowtography station design in Google Earth or GIS software. In lieu of a mapping app, mark your topo map or aerial image with symbols to indicate where the equipment will go (Figure 15 and Figure 16). Add any information that will help you and your colleagues locate the snowtography component locations when you return with your equipment.

In addition to transect layouts and locations for all the monitoring components, the snowtography station plan should specify the numbers of each component to make or order. How many snow stakes, cameras with modems, cameras without modems, soil moisture sensors, data loggers, sensor cable lengths, and conduit lengths do you need? Which ones need to be ordered and which ones do you already have or can you make yourself? Your plan should consider the staff time required for the different options and your assessment of the draft on your budget, as described previously in Section 2.

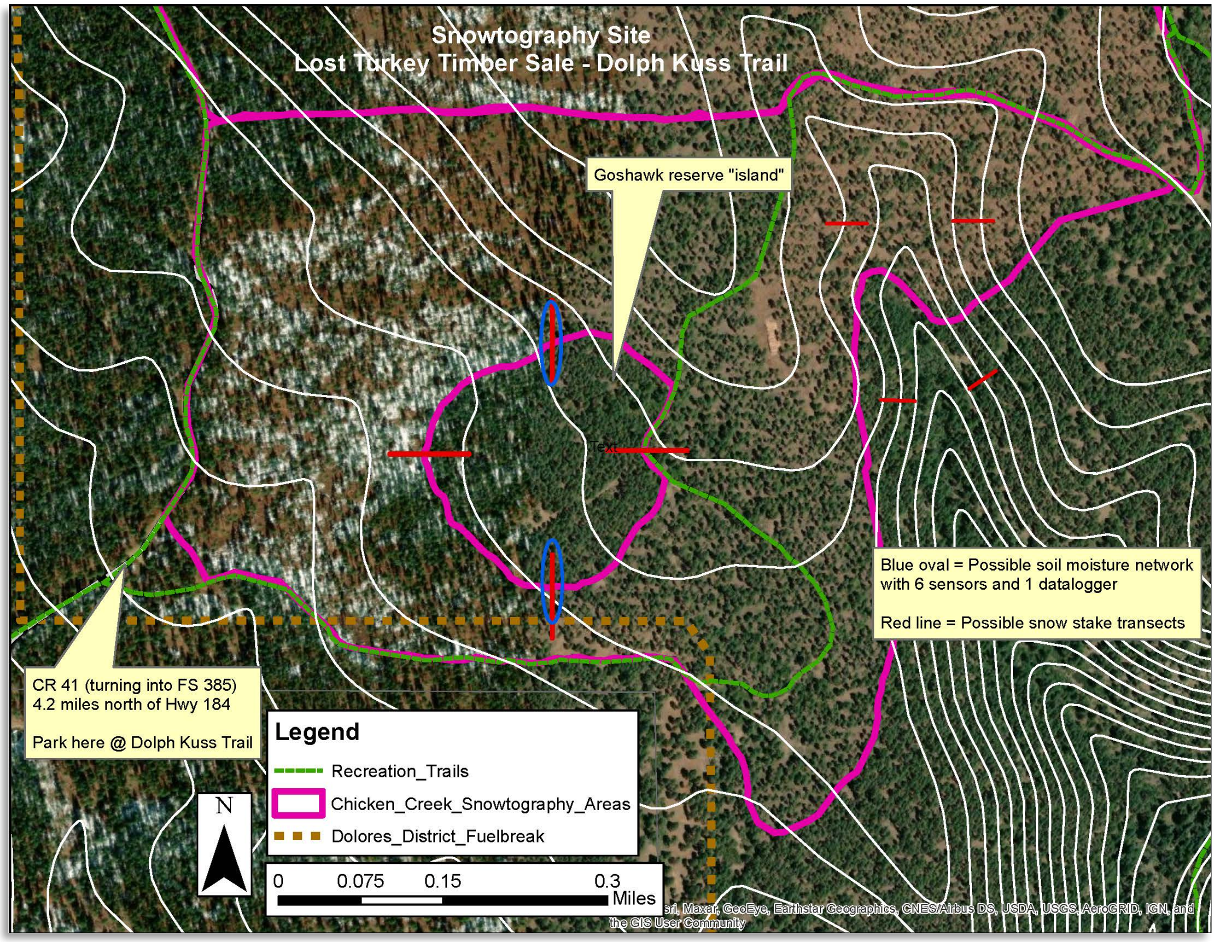

Figure 15. Snowtography station plan at Chicken Creek in the San Juan National Forest in southwest Colorado. Created by snowtography handbook beta testers from the Dolores Watershed Resilient Forest Collaborative (DWRF). The DWRF selected the snowtography location shown in the center of the aerial image above for the reasons listed below:

1. *The location has had substantial forest thinning work done and is anticipated to continue in the future, allowing DWRF to test the thinned to unthinned transition.*
2. *DWRF could control for treatment types, understory cover (oak), and elevation at the site.*
3. *The site is at the lower forest boundary for ponderosa pine and is expected to be an area that may not be able to support forests in the future.*
4. *There is relatively easy access to the site.*
5. *The site has cell phone access.*

Graphic: Danny Margoles, DWRF Coordinator.

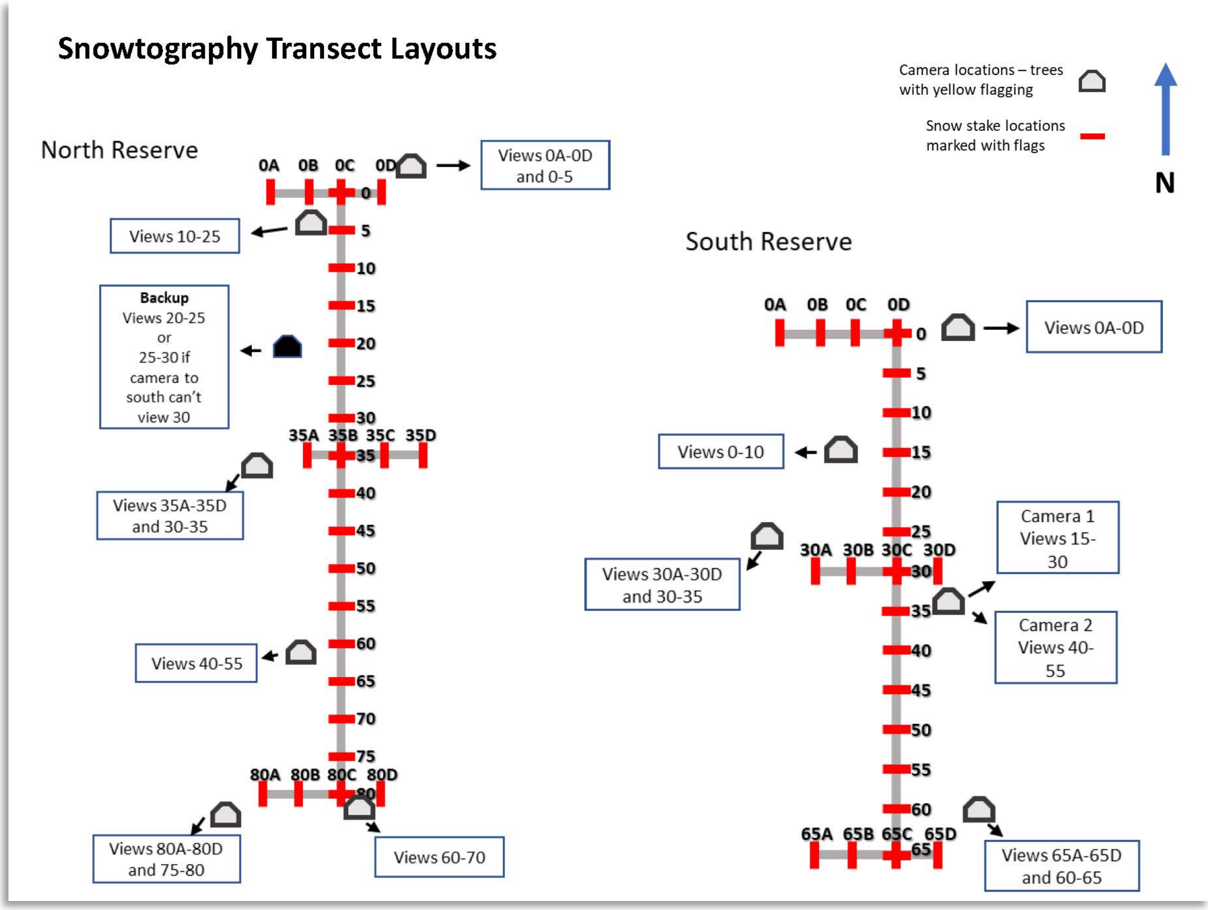

Figure 16. Snowtography transect plan for a station at Chicken Creek in the San Juan National Forest in southwest Colorado. Created by snowtography handbook beta testers from DWRF. DWRF designed their transects to test for the extremes of the variables they were interested in studying. Therefore, they sited their transects at transitions between areas of high density trees in the untreated forest and substantially reduced canopy cover in adjacent thinned areas. Graphic: Danny Margoles.

Section
4

How to build and install a basic snowtography station

Test your equipment ahead of time.

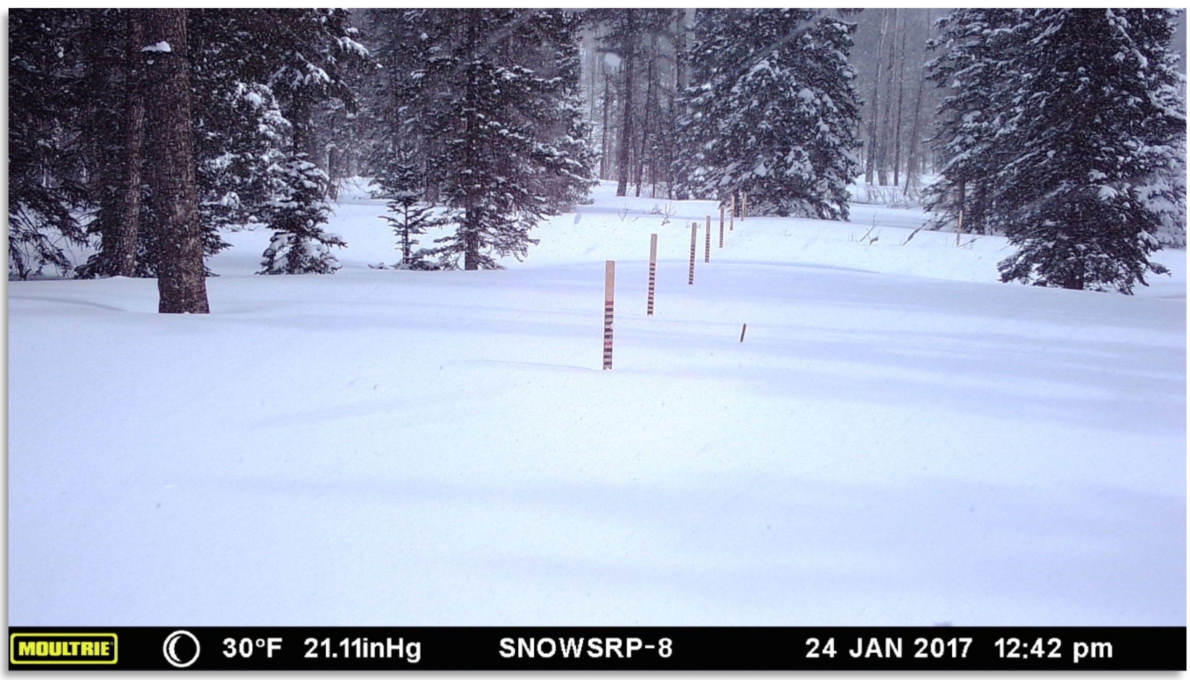

Figure 17. Snowtography trail camera transect photo in Apache-Sitgreaves National Forest. Source: Arizona Remote Sensing Center.

In the previous section, you walked your site and pinned down your snowtography station location. You made a snowtography plan, potentially augmented with snow density and soil moisture monitoring.

This section of the handbook gives you detailed instructions on preparing, testing, assembling, and installing a basic snowtography station. It assumes that you have read through the manual up to this point (Congratulations!) and have a plan at hand.

Preparing for the field

Cameras

Order the number of trail cameras with and without cellular modems that you've determined are needed in your snowtography station plan. ▶ Look for cameras with programmable time-lapse functionality, an essential feature to snowtography. Newer trail cameras may come with integrated modems ("cellular trail cameras") or modems can be purchased separately. The manufacturer's website or phone app facilitates storing and viewing your photos without a field visit. Specific brands and vendors of supplies and equipment aren't provided in this handbook. Instead, The Nature Conservancy hosts a webpage with additional information and some examples of supplies and equipment at its website.

▶ It may take a few weeks to receive some of the equipment, particularly cameras, so be sure to order them well in advance of the date you intend to take them to the field.

Follow the instructions below to prepare and test the cameras in your lab/workshop/garage before taking them to the field.

1. Read the manufacturer's user manual and watch the instructional videos, if available.
2. Obtain:
   - ✔ Fresh lithium AA **batteries**.
   - ✔ **Memory cards** as specified by the camera manufacturer, with an eye toward enough capacity to store a season's worth of photos. Buy extras for swapping in the field.
   - ✔ **Tree mount** for each camera that screws into the tree and allows camera adjustment in three dimensions.
   - ✔ **Cable lock** for each camera.
3. Make sure that the memory cards are empty. Format them if necessary.
4. Set the cameras' date and time.
5. Program the cameras to take 2 photos per day, morning and evening, ensuring at least one image each day in case animals or weather conditions obscure the view. Typical times are 10:00 a.m. and 3:00 p.m.
6. Test everything.
   - Test the battery voltages with a multimeter. Open-circuit voltage for a new battery should be between 1.5 and 1.8V.

- Test the cameras' time-lapse programming by aiming them at something a reasonable distance away and letting them run for a day or two to be sure they are taking pictures at the expected times each day.
- Set up some snow stakes at varying distances and test that you can read the 1" stripes on photos taken by the camera. Determine the maximum distance that the camera can adequately capture snow stake stripes.
- Test the cameras' image resolution setting if that option is available.
- Take out the memory card and read it with a laptop to check that the photos you expect have been saved to the card. Remember to put the memory card back in the camera.

7. Test that the cable locks attach to the cameras as designed.
8. Test that the tree mounts attach to the cameras as designed.

Cellular cameras and modems

The following instructions apply to both cellular cameras (i.e., with integrated modems) and separate modems that you connect to cameras. Integrated modems are becoming less expensive and more commonly available.

1. Read the user manual.
2. Register the modems or cellular cameras at the manufacturer's website, set up an account and/or a data plan according to the manufacturer's directions.
3. Install the necessary software on your cell phone or other mobile device to access the modems or cameras remotely.
4. Connect the modems' data cables to the cameras if not already integrated. The modems or cameras will upload photos as they are taken by the camera.
5. Test everything.
    - Test the modems' battery power using a circuit tester.
    - Test that the modems upload photos as you expect.
    - Test that you can access your uploaded photos.

Snow stakes

Supplies

Each snow stake will have two components:

- **Wood board 1" thick by 3" wide**. Eight feet is a typically available length; the final snow stake should be about a foot taller than the deepest snowpack you expect, so if the site experiences shallower snow depths, you may wish to buy shorter boards or cut them down. If the site experiences deeper snow depths, you may need to buy extra boards to extend the height of the snow stakes. ▶ Look at the nearest SNOTEL station records to identify the maximum snow depth in the record. (SNOTEL stations are usually located in protected clearings, and therefore usually show the greatest accumulations.) ▶ When purchasing boards, make sure they are straight and flat. Warped or curved boards are hard to paint and don't work well as snow stakes (Figure 19 and Figure 20).

Figure 18. A post-pounder and T-posts. Photo: [Montanabw - Own work, CC BY-SA 4.0 .]

- **T-post** (Figure 18) or **U-post**, 5-6' long, to provide the necessary anchor and support for the board portion of the snow stake. U-posts may be less expensive than T-posts and come pre-drilled with holes for screws, saving both time and money. ▶ However, if the soil at your site is difficult to drive a post into, use T-posts. Instructions for pre-drilling them are described under the heading "T-posts" below.

  Purchase as many pairs of T-posts or U-posts and boards as you need to match the number of snow stakes you've planned for your snowtography transects. ▶ It may be wise to purchase several extra boards and a few extra posts for practice and replacement.

  Other materials you will need to assemble and install the snow stakes include:

- **White high gloss exterior paint** to create a white background. The glossy surface will make it easier to remove the masking tape after painting..

- **Red and black exterior paint** to create snow depth marks in black and red against the white background. Try to buy very bright red paint to maximize its visibility under cloudy or dim conditions.
- **Clear spray polyurethane paint** to protect the painted boards from weathering. Consider adding a layer of roll-on lacquer for additional protection, though lacquer may darken the board, reducing the contrast between stripes.
- **Tape measure** and **felt pen** to mark off 1" increments.
- **Tape that is exactly 1" wide** for masking off 1" stripes. ▶ Most masking and painter's tape is slightly under 1" in width, so be sure to get tape that works for this application.
- **Roller brushes** to paint the boards. Extended handles may be helpful.

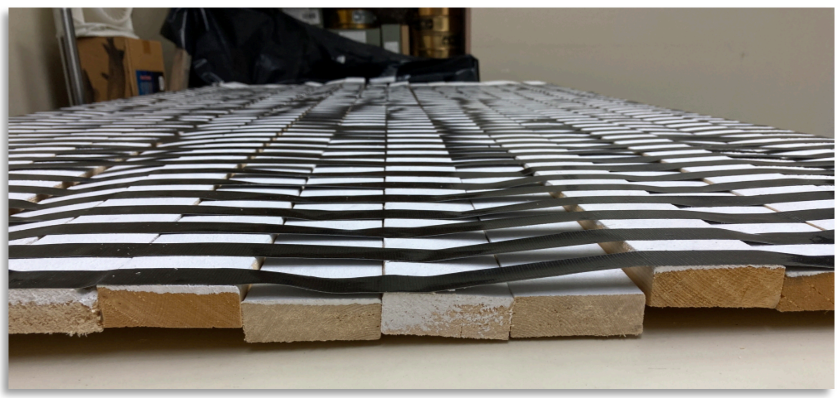

Figure 19. Snow stake boards prepped for painting with 1"Gorilla tape. The photo shows how warped boards can interfere with bulk painting efforts. Photo: Lindy Hutchinson, Northern Arizona University.

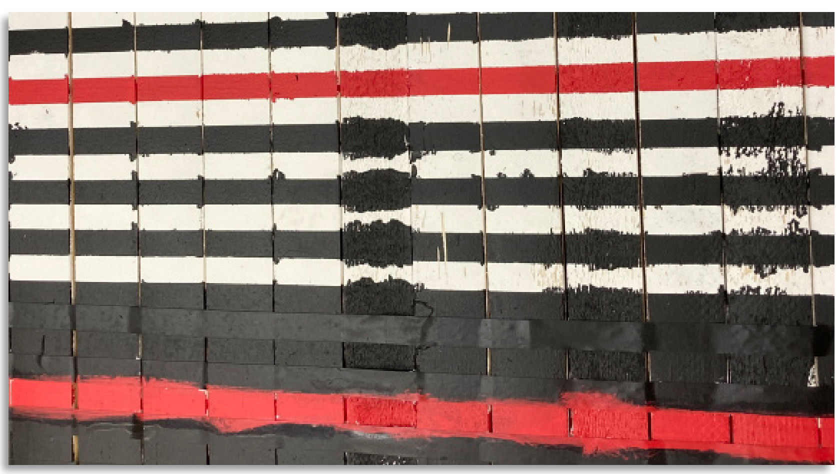

Figure 20. Photo showing how paint can bleed under the tape if a board is warped and the tape hasn't fully adhered. Photo: Lindy Hutchinson.

Preparation

Paint each snow stake board with depth marks at regular intervals that are visible to, and can be recorded by, the cameras:

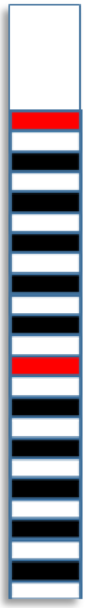

Figure 21. Pattern of 1"stripes.

1. Plan to paint the boards at least several days ahead of field installation to allow time for the paint to dry.
2. Arrange the boards side-by-side so that you can paint several boards at once (Figure 22). Some practitioners have opted to lay the boards across 2x4s to keep them off the ground.
3. Using a paint roller, paint all the boards with white, high gloss exterior paint. Let dry for 24-48 hours.
4. Starting at the bottom of the group of painted side-by-side boards, mark off 1 inch increments (measured with a tape measure) with a felt pen so that you know where to lay the masking tape in the next step. It is best to mark the increments in multiple places along the boards to guide the tape.
5. Starting at the bottom of the boards again, mask off every other inch-wide row with strips of 1" tape (see note about tape above), creating alternating rows on the boards that will be painted or will remain white. Keep the tape as straight as possible when it is laid out across multiple boards, as shown in Figure 23. Repeat until you reach the top of the boards. ▶ A larger white space at the top of the boards (~3") is useful as a place to add a stake identifier.
6. Starting at the bottom of the boards again, paint the first 5 non-masked rows black (Figure 24).
7. Paint a red stripe with a brush or very small roller on the 6th non-masked row, creating the 1-foot mark (Figure 25).
8. Repeat steps 6 & 7 until you reach the top of the boards.
9. Allow the paint to dry another 24-48 hours. After the paint is dry, remove the tape (Figure 26).
10. Finally, cover the boards in polyurethane or lacquer. More coats are better, as long as they don't make the white stripes too dark.
11. Allow to dry again before taking to the field.

Figure 22. Boards painted white in preparation for masking. Line the boards up side by side for bulk painting. All photos in this series: Lindy Hutchinson.

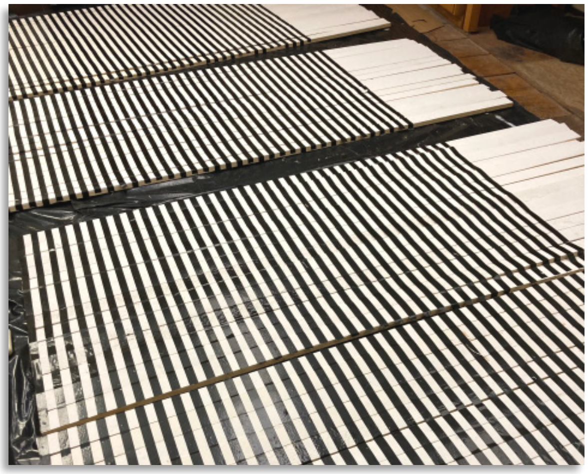

Figure 23. Mask the boards in 1" increments. Photo shows boards masked with 1" Gorilla tape.

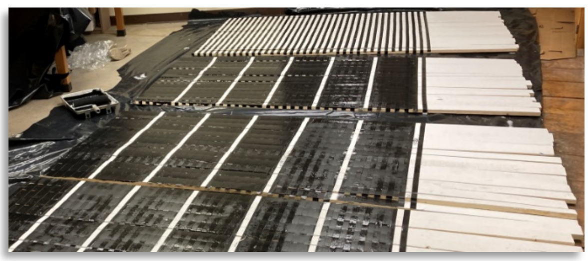

Figure 24. Paint the black stripes with a paint roller.

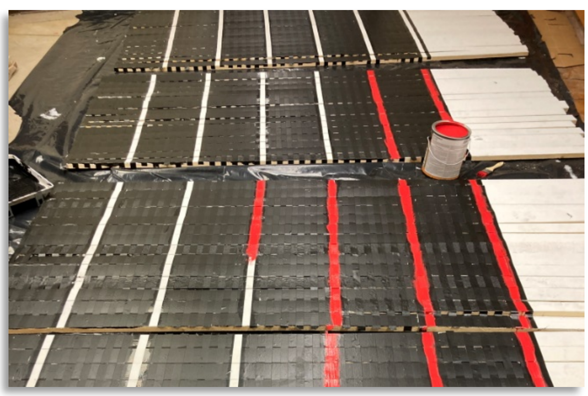

Figure 25. Paint the red stripes with a brush or narrow roller.

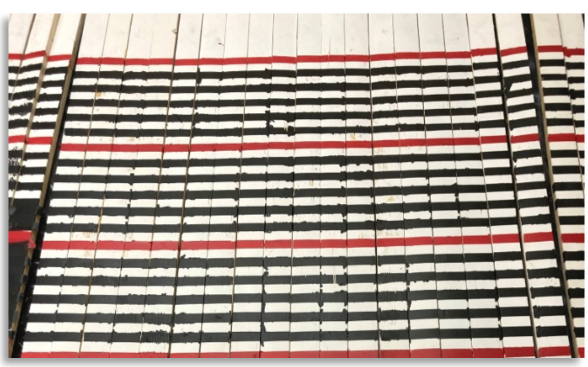

Figure 26. Remove the tape. Coat the boards in clear polyurethane or lacquer.

T-posts

If you have decided to use T-posts because of the nature of the soil at your site, and the posts are not pre-drilled, you will need to either drill holes in them before taking them to the field, or use an alternate method to affix the boards to the posts while in the field. To drill holes, use a carbide-tipped set of drill bits and a drill press. ▶ A minimum of 2 holes per board is required, 3 is better. Expect this to take from 2 hours to 2 days, depending on how many snow stakes you are making. Alternatively, attach the boards to the posts in the field with baling wire or metal hose clamps.

Setting up in the field

Supplies

Bring the following to the field with you:

- ✓ **T- or U-posts**.
- ✓ **Post-pounder** (Figure 18) to drive the posts into the ground. Both manual and gas-powered post-pounders are available. Check that the post-pounder inner diameter will accommodate the post type you've chosen. (Optional: augur drill.)
- ✓ **Gasoline and fire extinguisher** if using a gas-powered post-pounder.
- ✓ **Gloves, goggles, hearing protection**.
- ✓ **Painted boards** (i.e., snow stakes) including extras.
- ✓ **Permanent marker or paint pen**.
- ✓ **Baling wire** if posts are not pre-drilled.
- ✓ **Heavy-duty zip ties** and **adjustable metal hose clamp**s for backup and reinforcement.
- ✓ **Ladder**.
- ✓ **Cell phone, laptop**, or other device used to download photos.
- ✓ **Trail cameras**.
- ✓ **Tree mount** for each camera.
- ✓ **Cable lock** for each camera.

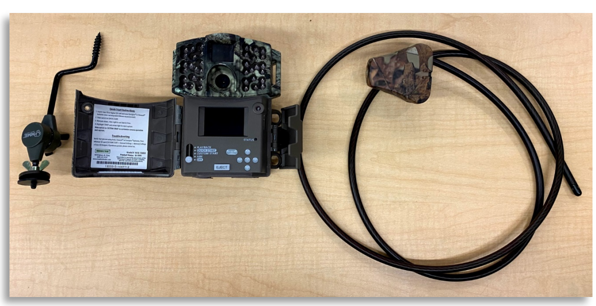

Figure 27. L-R: Tree mount, time-lapse trail camera, and cable lock used in a recent installation. Photo: Patrick Broxton.

✔ **Tools:** wire cutters (for baling wire, if using), pliers, screw drivers, cordless drill, drill bit set, saw, and pruning tools (for trimming brush away from snow stakes).

Installation

1. Find a transect point indicated by one of the survey flags you placed when planning the snowtography station (Figure 28).
2. Wear gloves, goggles, and hearing protection when using power equipment. Using the post pounder, *partially* drive the T- or U-post into the ground at the transect point.
3. Be sure the post is installed with the proper rotation such that the wooden snow stakes, when attached, will face the intended camera. Lean a snow stake against the post and check that the camera (see next steps) will take an unobstructed picture of the stake (Figure 28).

Figure 28. Snow stakes leaning on T-posts to check alignment with a snowtography camera. Photo also shows transect line (yellow tape) and stake locations (flags). San Juan National Forest. Photo: Seth Arens, Western Water Assessment.

4. Use a saw or pruning shears to trim any vegetation that is obstructing the view of the snow stake by the camera. Flatten out the vegetation around each post so that the ground surface and lowest painted mark on the snow stake is visible.

5. With a ladder, drill, and camera tree mount, install a camera on the tree you identified with forestry tape and marked in your snowtography plan. Pre-drill a hole into the tree that is smaller than the mounting screw on the camera tree mount (Figure 29).

Figure 29. Left: Danny Margoles installing a camera. Photo also shows forestry flagging tape used to mark the tree during planning. Right: Installed camera. Photo also shows the camera mount, cable lock, and zip tie used to secure the cable. San Juan National Forest. Photo: Seth Arens.

6. Secure the camera with the cable lock. ▶ The camera may shift when installing the lock, so this step should precede taking test pictures of the leaning snow stakes. If necessary, use zip ties to secure the cable to the tree mount or tree so that it doesn't shift (Figure 29).

7. Manually trigger the camera to take pictures of the stakes you've leaned against posts, remove the memory card, and review the photos to test that each stake is clearly visible in the image (Figure 30). The camera itself may have a screen for viewing images, but you will likely need to use a computer or tablet to view the images clearly. ▶ Remember to put the memory card back in the camera after this test.

Figure 30. Seth Arens (left), Raymond Rose (center), and Danny Margoles (right) reviewing test photos of snow stakes from one of the installed cameras. San Juan National Forest. Photo: Seth Arens.

8. For cellular modem integrated cameras, take a test picture (either on the physical camera or through the app on your cell phone) and verify that it is being uploaded. Verify that all snow stakes are visible in the uploaded image and make any adjustments to the stakes to ensure visibility as needed.

9. Once you are satisfied that the stakes are all visible to the camera, drive the T- or U-posts into the ground to the bottom of the welded anchor plate— that depth is sufficiently deep to prevent wind damage—deeper is not necessary. A second person wearing gloves and hearing protection may have to hold the post to keep it from rotating (Figure 33).

10. If the posts are pre-drilled, use a cordless drill and wood screws to attach the painted boards to the T-posts or U-posts (Figure 31).

11. If the posts are not pre-drilled, use baling wire, hose clamps, or your own method to secure the boards to the posts. The boards should be attached to the posts at a minimum of 2 points. The baling wire method is illustrated in Figure 32.

12. Number each stake with a permanent marker or paint pen with digits large enough to be recorded by the cameras (Figure 34).

13. At the end of the season, or more frequently, collect data by removing each camera's memory card and saving the images to your computer. Examine each photo, zooming in to see the snow stakes clearly, and record the date, time, and snow depth for each stake. A sample worksheet for recording your data is available on the TNC website.

14. Take down the cameras after the snow season to reduce the risks of theft; re-install them each year about 3-4 weeks before anticipated snow.

Figure 31. Back side of an installed snow stake that uses a pre-drilled U-post and wood screws. Photo: Joel Biederman.

Figure 32. Photos illustrating a baling wire method of attaching snow stakes to T-posts. Photo: Seth Arens.

Figure 33. Driving T-posts into rocky soils near Flagstaff, AZ. Post location and rotation are first set with a manual post pounder, then a second team drives the post to the desired depth with a gas-powered driver. Photo: Joel Biederman.

Figure 34. Snowtography transect installed and ready for snow. Photo: Joel Biederman.

How to add snow density monitoring

You can do this.

Figure 35. Joel Biederman weighing a snow tube for snow density measurement. A low-range spring scale is used for precise measurement in shallow snowpack. Coconino National Forest, AZ.

While measuring depth through basic snowtography gives us valuable information about relative snow amounts across variables of interest (like canopy density), and about snow arrival and disappearance, snow depth does not provide as much information about the amount of water available. Snow density is highly variable across the landscape due to forest structure and other factors, and is therefore a useful addition to a basic snowtography station. Combined with data from snowtography, snow density observations paint a much more complete picture of the snowpack conditions at your snowtography station.

▶ This section of the handbook describes how to integrate snow sampling with snowtography. Snow sampling equipment, procedures, and recording forms are described in detail in both the NRCS Snow Survey Sampling Guide (USDA Soil Conservation Service 1984, available at TNC's website) and the California Department of Water Resources Snow Survey Procedure Manual (Osterhuber 2014). We encourage you to consult these and other references cited in this handbook for additional information about snow sampling.

Make a sampling plan

To get the most meaningful information from snow density observations at your station, sample next to every other snow stake weekly to monthly while there is snow on the ground. Shorter intervals are better but may be difficult to achieve. One approach is to visit more frequently just before and during the melt season to capture the rapid density changes as the snow warms up. Capturing an accurate SWE estimate at the peak snowpack (the onset of melt) is critical for estimating the snowmelt volume that will recharge soil moisture and possibly produce streamflow.

While it is ideal to sample as close to the snowtography stake as possible to represent similar snow conditions, sampling on top of a previously sampled spot will distort your data, so it is important to sample at different spots each visit. In general, try to leave at least two feet between snow core locations and prior snow

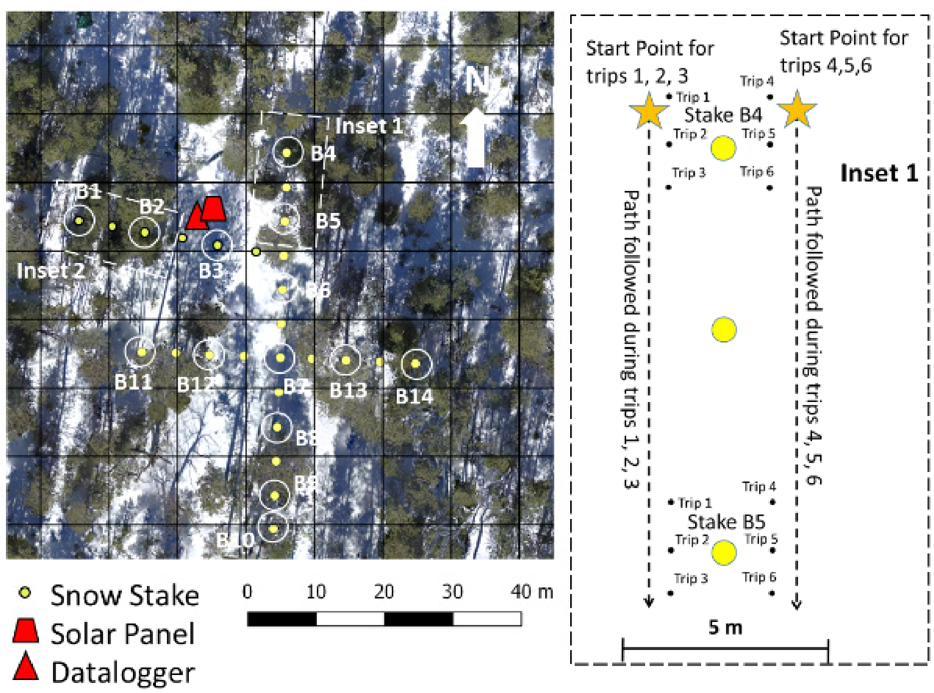

Figure 36. Map of an example snowtography transect survey showing the locations of snow density samples and the sampling protocol. Source: Patrick Broxton.

cores or the snow stake. On a map or aerial photo of your transects, mark which snow stakes should be sampled at each visit. An example plan is described below.

Figure 36 shows an aerial photo with a transect survey superimposed on it, and a plan for snow density sampling in the inset graphic. The circled yellow dots on the aerial photo correspond to the snow stakes where the adjacent snow density will be sampled. Notice that they are separated by a snow stake where density won't be sampled. In this example, the protocol for avoiding previously sampled spots is as follows: On the first trip, sample on the northwest side of each targeted snow stake; on the second trip, sample on the west side of the same set of stakes; and on the third trip, sample on the southwest sides of the same stakes. On the next three trips, sample on the northeast, east, and southeast sides.

This protocol may be adjusted to accommodate transects with different compass orientations. Just record what you do and make sure everyone visiting the site follows the pattern to avoid resampling a given location (which could be hidden by new snowfall).

If more than 6 site visits are made, you may decide to modify the plan to either make additional passes (e.g., trips 7-9 near trips 1-3 but further from the stake) or sample the previously unsampled stakes.

Assembling the equipment

Snow density can most easily be measured using a Federal sampler, the standard snow sampling equipment used by the US Forest Service. But Federal samplers are expensive; if you don't have one or can't borrow one, a home-made sampler is a reasonable substitute for shallower snowpacks. The websites of the National Weather Service and the Community Collaborative Rain, Hail & Snow Network (CoCoRaHS) both host directions for making a sampler out of plastic pipe (Hanson 2015; Fleetwood 2015).

Figure 37. Photo showing the last step in creating teeth at one end of a home-made, PVC snow tube (Hanson 2015).

Collecting data in the field

On snow density sampling days, take these items with you to the field:

- ✓ Maps of the station and a sampling plan.
- ✓ Snow sampling tubes (sections of sampler).
- ✓ Thread protector and spanner wrench if using a Federal sampler. These items are described in the NRCS Snow Survey Sampling Guide.
- ✓ Weighing scale and cradle for tubes. A Federal sampler may have a custom scale that is marked in inches or centimeters of water content. A home-made scale may or may not be labeled with conversions from snow depth to water content.
- ✓ A soft carrying case for the sampling equipment.
- ✓ Notebook and pencil or device for recording weights.

Remember that sampling and foot traffic disturb the snow—try to minimize snow disturbance near the snow stakes. Collect snow cores two feet from snow stakes and two feet from prior snow core locations (Figure 36). Also, walk, snowshoe, or ski on the outside, further from the snow stakes than the line of snow sampling cores, to stay at least an arm's length or more from the snow stakes when sampling near them. This also prevents disturbance to the soil in the vicinity of any soil moisture probes that might be located next to snow stakes.

1. Record weather, snow, and other sampling conditions.
2. Using your map, determine which snow stakes will have density measurements on each visit.
3. Assemble the snow tubes, as many as you need, to exceed the depth of the snow.
4. Holding the snow tube vertically, push and/or twist it into the snow to help the teeth cut through the snow rather than mashing the snow, being sure to reach down to the soil surface (Figure 38).
5. Measure and record the depth of the snow before lifting the tube and snow core out of the snow.

Figure 38. A federal sampler being twisted clockwise to engage the cutting teeth while being pressed through an ice layer within the snowpack. Photo: Patrick Broxton.

6. Pull the tube out and observe the depth of soil that is in the tube so that it can be subtracted from the full snow depth recorded in the previous step.
7. Scrape out the soil so that it isn't counted in the snow core weight. A small metal spatula or pocket knife may be helpful at this step.
8. If snow has fallen out the bottom, repeat the measurement. If the snowpack is soft and not very deep, it may be possible to gently tilt the sampler away from vertical before withdrawing. However, too much force may bend the tube.
9. Weigh the snow-filled tube using the scale and cradle. Record the weight (Figure 39).

Figure 39. Snow sampling by scientists Chris Johnson, USFS (retired) and Tom Vanzant, NRCS, following the Wallow Fire. Apache-Sitgreaves National Forest, AZ. Photo: Joel Biederman.

10. After weighing the snow-filled tube, gently tap the snow out of the tube and weigh the empty tube to get the net difference, which equals the weight of the snow only.
11. If you are using a Federal sampler, the weight of the snow is converted to water content in inches on the scale and no further conversion is necessary. The instructions for home-made samplers include directions for weighing the snow and converting the snow weights to inches of SWE.
12. See the NRCS and CA DWR guides for instructions for sampling under very shallow and very deep snow conditions. Snow samplers designed for very shallow conditions are available online.

Section

6

How to add soil moisture monitoring

The Cadillac version of snowtography.

Figure 40. Willem van Leeuwen, Arizona Remote Sensing Center, digs a soil moisture sensor trench at a forest thinning site near Flagstaff, AZ. Snow stake installation in progress in the background. Photo: Joel Biederman.

Snowtography combined with soil moisture sensors can be set up with minimal disturbance to the landscape, providing automated, real-time, remote access to soil moisture data year-round and requiring little additional time commitment once installed.

Preparing for the field

Preparation for soil moisture sensing primarily involves testing the equipment at your lab/workshop/garage and assembling sensor cables and conduit to the extent possible before taking them to the field.

Follow the steps below.

1. Read the user manual and watch the manufacturer's instructional videos, if available.
2. Determine how you are going to mount the data logger in the field (T-post, U-post, or other). The post must be taller than the maximum snow depth. The user manual may have useful suggestions.
3. Create a user account with the manufacturer for uploading, storing, and downloading data. Download apps if appropriate.
4. Program the data logger data upload settings. If you are using more than one data logger, program them all after testing the programming for the first one.
5. Test everything before taking it to the field
   - Connect the sensor cables to the data logger by plugging the sensor cable jacks into the data logger ports following the manufacturer's instructions.
   - Push the sensors into nearby soil or garden planters and wait an hour or two.
   - Add water to the soil and wait 72 hours.
   - Test that you can download data from the data logger.
   - Test that the data show that the sensors are registering the watering event and subsequent drying.
   - Test that the data show that the data logger is uploading data according to the programmed frequency.
   - Test that the solar panel charging system is charging the batteries and providing enough power to operate the data loggers and soil moisture sensors under a variety of light conditions (e.g., low angle, cloudy, dark).
6. If using flexible conduit, uncoil it in a lab, workshop, or warm garage, and cut it to lengths that match the sensor cable lengths you've ordered. If using rigid conduit, you will cut, assemble, and glue PVC components in the field.
7. Fish the sensor cables through the flexible conduit segments that you've cut to matching lengths. ▶ This step must take place in a lab, workshop, or warm garage because it is very difficult to do in the field.

Setting up in the field

Supplies

Bring the following additional items to the field with you when installing soil moisture monitoring at a snowtography station:

- ✓ Phone, laptop, or other device for downloading data.
- ✓ Zip ties, hose clamps, U-bolts, or manufacturer-recommended device to secure the data logger to its support post.
- ✓ Mounting post.
- ✓ Batteries. See specs for your equipment.
- ✓ Plastic pipe or tubing cutter for cutting the conduit, if necessary.
- ✓ Utility knife.
- ✓ Data loggers.
- ✓ Desiccant packets to leave in data logger housing.
- ✓ Sensor cables (in protective conduit if using flexible conduit).
- ✓ Couplers, elbows, and T-joints as well as PVC cement if using rigid plastic conduit.
- ✓ Heavy duty tape for sealing the conduit-sensor cable ends.
- ✓ Pick and shovel (optional: borehole tool for single sensor holes).
- ✓ Landscape staples for securing conduit along the ground surface.
- ✓ Matte green or brown paint to camouflage the data logger (not the solar panel!), if appropriate.

Figure 41. Snowtography station soil moisture monitoring system installation in progress at Ft. Valley, AZ. Solar panel and data logger are visible in the background, and soil moisture sensors, cables, and trenches are visible in the foreground. Photo: Joel Biederman.

Figure 42. Adam Belmonte, Northern Arizona University, installing soil moisture sensors that have been fed into flexible conduit and sealed with heavy duty duct tape at Ft. Valley, AZ. Photo: Joel Biederman.

Installation

Follow the steps below to install the soil moisture monitoring network at your snowtography station.

1. Using the post pounder, drive a T- or U-post into the ground at the data logger point indicated by the snowtography station plan, positioned where there is minimal shading from trees.
2. Use zip ties, hose clamps or U-bolts to mount the data logger to the post, orienting the data logger to receive the maximum amount of sunlight.
3. Put 1 or 2 desiccant packets in the data logger housing if they fit.
4. Consult your snowtography plan and assign sensor cables of various lengths to snow stakes according to their distances from the data logger.
5. Tag each cable entering the data logger with the location and depth of the corresponding sensor and name each port accordingly in the data logger software, if possible, to facilitate data interpretation (Figure 43 and Figure 44).

Figure 43. Gigi Richard, Fort Lewis College, configuring a soil moisture data logger at Chicken Creek, San Juan National Forest. Photo: Seth Arens.

6. If you are using paired sensors, then you will place sensor pairs at 3 stakes and dig 3 trenches. If you are using single sensors, then you will place sensors at 6 stakes and dig 6 trenches. ▶ Consider that you may need a foot or two of slack in the cables, depending on the size of the trench.
7. Dig sensor trenches about 30 cm away from the snow stakes, along the transect line, because this line is not sampled for density (Figure 36 and Figure 45).
8. Place the excavated soil on a small tarp to avoid mixing it with surface litter. If the pit is deep, try to keep track of the different soil layers in different piles on the tarp, then replace them in the same order when refilling the pit later.
9. Record your sensor trench locations to help you avoid them when sampling snow density.
10. If you are placing a **single** sensor in each trench, dig a 30 cm deep trench. Insert the sensor probe horizontally into the trench wall at a depth of 15 cm.
11. If you are placing a **pair** of sensors in each trench, dig a trench 15 cm deeper than the depth of the lowest sensor. Dig the trench sufficiently long for one pair of sensors to be offset about 30 cm diagonally. Insert a pair of sensors at

two different depths, in the same trench wall, according to your monitoring goals (Figure 44).

Figure 44. Soil moisture sensors inserted horizontally into a trench face, 15 and 30 cm below the soil surface. Note the horizontal offset between sensors to reduce mutual interference. Sensor cables have been fed through flexible electrical conduit for protection from animals. The tape is wrapped so that no portion of the sensor cable is exposed. Photo: Joel Biederman

12. For both single and paired sensors, after inserting the sensors in the trench walls, run the sensor cables along the trench bottom (15 cm deeper than the lowest sensor) and back up along the side of the trench opposite the sensors (Figure 45).

13. From the pit, run the conduit-covered cables along the ground surface to the data logger (Figure 45).

14. Tape each end of the conduit to the sensor and cable so that no portion is exposed and vulnerable to damage by rodents or other harm.

15. With large zip ties, bundle parallel sensor wire conduits together between the trenches and the data logger to reduce tripping hazards (Figure 14).

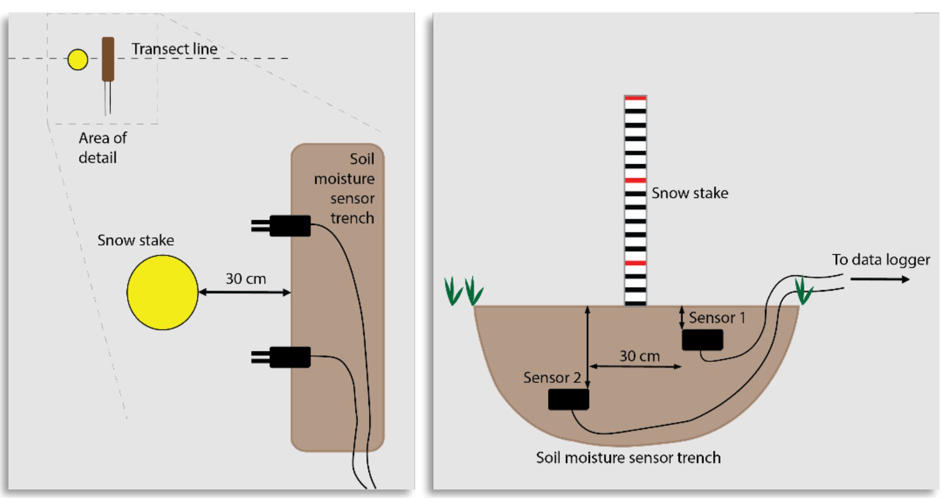

Figure 45. Plan view (left) and side view (right), respectively, of a soil moisture trench for a set of paired soil moisture sensors. Graphic: Lineke Woelders.

HOW TO ADD SOIL MOISTURE MONITORING

16. Cover the conduit on the ground surface with fallen limbs or tack them with landscape staples to prevent them from being snagged by boots, skis, or disturbed by animals.

17. Test that the data logger is registering data from the sensors and that you can download soil moisture data. Set the sampling interval to 1 or 5 minutes. Let the data logger record soil moisture data for at least 15 minutes.

18. Backfill the trench, tamping it down while backfilling to approximate the same density as the original, undisturbed soil.

19. Take a break or work on another part of the station, and then test again after some time has passed. Sample soil moisture data for a multi-day period is shown in Figure 46 .

20. If the data logger is visible from a road or popular trail, consider painting it matte green or brown to make it less visible. Cover the solar panel first to protect it from paint.

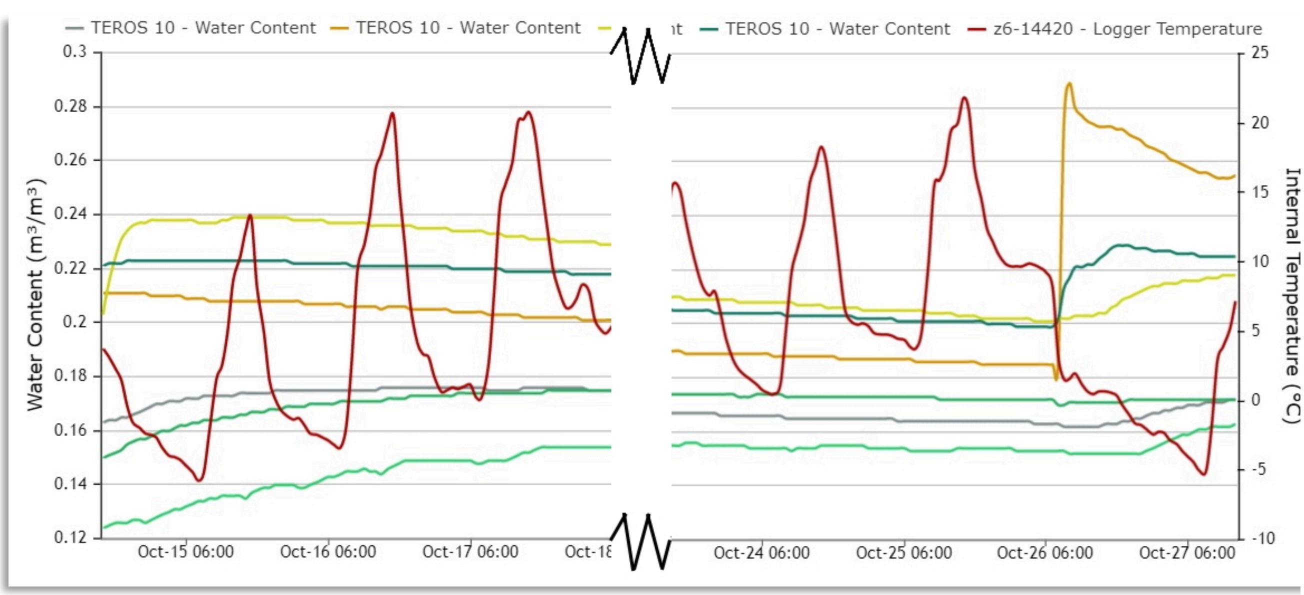

Figure 46. Sample soil moisture data. The graph shows soil moisture at 10 cm depth in 6 locations along a transect as well as internal temperature of the data logger. Data shown are collected from METER Corp. Teros 10 SWC sensors, a Meter ZL6 data logger, and the Zentra Cloud remote data collection and data management service.

Section
7

Troubleshooting

Did you try turning it off and turning it back on again?

Figure 47. Marmot.
https://commons.wikimedia.org/wiki/File:Cavell_Meadows_marmot.jpg#filelinks.

Stuff happens. We've written this handbook based on a decade of experience with snowtography and field monitoring, but unforeseen issues may still arise. Hopefully, you are able to get through a season without any hitches, but if you encounter problems, this section offers some things to check.

As you will read in the lists that follow, loss of power is one of the most frequent issues. The lithium ion batteries for your camera and camera modem should be good enough to shoot 15,000 images. Checking the battery power in the equipment is the first step for diagnosing almost any issue. Although most lithium and alkaline batteries provide enough voltage even in cold weather, some may drain faster than expected.

Cameras and photos

- Your camera hasn't recorded photos on the memory card:
    - The memory card may be full or corrupted and needs reformatting or replacement.
    - The camera was not programmed correctly. Testing the camera programming before heading to the field is essential.
    - You forgot to start the camera when you left the field.
    - The batteries in the camera have died. Good batteries should last six months. Always carry spare batteries with you when visiting the site.
- You can't remotely download any pictures from ***any*** of the camera modems:
    - You may have an inadequate cell connection, or interference with the connection by nearby equipment.
    - There may be issues with your data plan account.
    - The camera or modem batteries have failed.
    - Vandalism or theft of equipment. This is a rare problem, but it can happen. Measures to prevent vandalism or theft include locating your snowtography station in a place not visible from a popular trail or road and painting your equipment with camo paint. Using cable locks to secure the cameras to trees, and placing the cameras high enough to make reaching them difficult without a ladder (store an aluminum ladder at each station, hidden and chained to a tree) are other measures.
- You can't download any pictures from ***some*** of the cameras:
    - You may have an inadequate cell connection, or interference with the connection by nearby equipment
    - The camera or modem batteries have failed.
- Your pictures don't show snow stakes:
    - Your camera has shifted or been knocked out of position.
- There are some early pictures and then no later pictures:
    - Your batteries have died.
    - See vandalism and theft, above.

Soil moisture sensors

- There are no data from any of the soil moisture sensors:
  - The cell service may be inadequate at the site. Your logger may still be collecting data that can be retrieved manually in the field with a laptop and USB cable and/or smart phone app if your equipment supports it.
  - There may be issues with your cellular data account.
  - Something is interfering with the signal, such as large metal structures.
  - The data logger is not being powered by the solar panel because of damaged wiring or the panel is covered.
  - The support post is no longer vertical allowing water to get into the data logger.
  - See vandalism or theft, above.
- There are no data from just some soil moisture sensors.
  - There may be damage to the cables from rodents and other animals (Figure 47).

Section

8

Applications, Limitations, and Uncertainty

So many uses for snowtography!

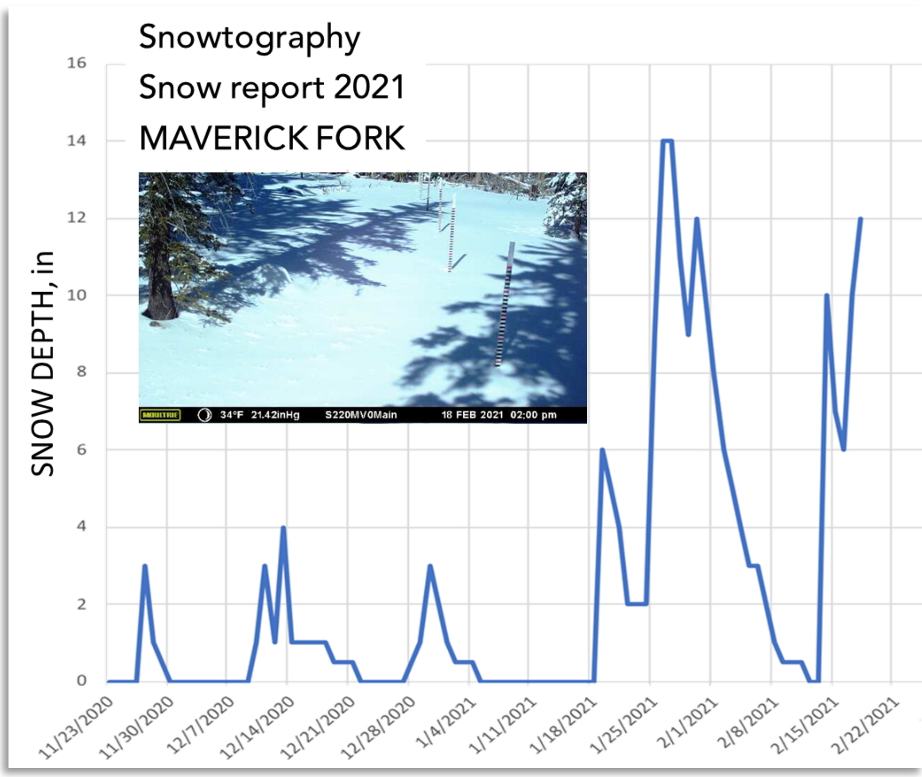

Figure 48. Daily snow depths captured by a camera from a snowtography transect, shown in the photo, entered and graphed in a spreadsheet. Source: Kangsan Lee, Arizona Remote Sensing Center.

Snowtography was developed to address a need for more snowpack data in settings that are not usually monitored. In our applications, the data are used to study how forest structure affects snowpack.

Applications

Applications of snowtography have been refined and expanded in recent years through the collaborative efforts of scientists at the Salt River Project, Arizona Remote Sensing Center, Northern Arizona University, USDA-ARS, and The Nature Conservancy. Current and anticipated applications of snowtography generally fall into the following categories:

- **Water supply.** Climate change is affecting current snowfall patterns, and projections of future trends indicate smaller snowpacks that melt out earlier. Snowtography provides monitoring data to support research into these trends and the forest conditions that tend to conserve the snowpack in time and space.
- **Forest management.** Resource managers in the mountain West are seeking to reduce catastrophic wildfire risk and increase watershed resilience through forest management. Snowtography stations established where forest treatment has or will happen, with transects positioned across transition boundaries, capture data about snow accumulation and ablation differences between treated and untreated areas, leading to better understanding of how various treatment approaches affect snowpack and soil moisture.
- **Calibration and validation of remote sensing methods.** Because data on snowpack conditions within forests, on slopes, and across elevation gradients are sparse, data from snowtography can increase the density of observations, and be used to validate remote sensing methods and support refinements to spatial datasets.
- **Forest soils.** Forests with disturbances such as wildfire, hot drought, and die-off due to insects and pathogens can have very different soil moisture conditions than adjacent undisturbed areas. Snowtography with soil moisture sensors provides real-time remote access to soil moisture data for study of these differences.

The Salt River Project in Arizona uses snowtography in the higher elevations of the Salt and Verde River watersheds to improve its water supply forecasting capability. With their snowtography equipment, SRP measures snow depth, snowpack persistence, and snowfall event duration. SRP's snowtography stations include weather instruments, giving them meteorological context for the snowtography observations. Their stations are operational year-round, so they also capture environmental and climate changes in the landscape at the stations.

Broxton, van Leeuwen, and Biederman (2019) used snowtography in a machine learning study to improve the accuracy of remotely sensed snow depths. Point observations of snowpack depth and density using SNOTEL stations are very sparse and do not represent the spatial distribution of snow well. Spatial estimates of snow depths (i.e., gridded data) can be determined through remote sensing methods, such as lidar (Light Detection and Ranging), but they must be trained to represent conditions in the field. In this study, snow depths derived from lidar measurements were compared to snow depths from SNOTEL and snowtography. The field data were used to validate and improve both the lidar data and gridded snow density estimates.

In another study, Broxton, van Leeuwen, and Biederman (2020) used snowtography to study the influence of forest structure, management, disturbance, topography, and other variables on snowpack. They collected data from snowtography sites under a variety of conditions including elevation and north- and south-facing slopes to assess whether forest cover increases or decreases snowpack. By using snowtography data and strategically placed transects, they found that SWE is greatest at intermediate levels of forest cover (~30–50%) on flat and north-facing slopes.

Limitations and uncertainty

While snowtography in various forms has been used to monitor snowpack for a decade or more, we are not aware of many efforts to rigorously address the accuracy and precision of the measurements. Direct, apples-to-apples comparisons with existing technologies, such as the ultrasonic snow depth sensors and pressure-based weighing snow pillows used at SNOTEL stations, are difficult to make due to the inherent spatial variability in snowpack depth and SWE over small distances. Over recent years, our experience with several snowtography sites deployed within 200 m of SNOTEL stations shows excellent correspondence in snow depth dynamics between snowtography and SNOTEL in similar environments (Broxton, van Leeuwen, and Biederman 2019).

Sources and estimated magnitudes of snowtography uncertainty in snow depth include manual reading of the camera images (± 2 cm); physical effects of the snow stake on snow depth including wind drifting and thermal radiation enhancing ablation (estimated to range between 0 and 3 cm); and the uncertainty of defining the ground surface vis-à-vis ground cover vegetation and litter (± 5 cm).

The main sources of uncertainty in SWE estimates relate to spatial density (e.g., sampling density at every other snow stake vs. every snow stake) and sampling frequency. SWE may be calculated with high precision for dates when density samples are manually collected, but time series of snow density for intervening periods must be estimated by interpolation or some other method.

Sources of uncertainty in soil water content measurements include the representativeness of the limited sampling locations, good contact with the soil, and calibration of sensors to site soils. Typically, default calibrations are sufficient for most users, but it is possible to program the data logger with user-supplied calibrations based on gravimetric water content laboratory testing.

It is our hope that this snowtography handbook will support a growing network of measurement stations affording continued improvement of our ability to quantify the uncertainty of the measurements. We encourage all users of this handbook to correspond with us to make us aware of your site installations, provide feedback on the handbook, and consider opportunities for sharing data and analysis tools.

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