MOUNTAIN PEATLAND RESTORATION:
ASSESSMENT, GOALS, AND APPROACHES

Rodney A. Chimner and David J. Cooper

OVERVIEW OF MANUAL

The purpose of this manual is to provide a free and up-to-date guide for the restoration of mountain peatlands. The guide will be updated regularly, so check back for updates. We are also interested in hearing from you. Please let us know if you find an error, have new ideas, techniques, restoration projects we can highlight, or information you would like to see included in the next update.

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Cover Photograph: Restoration of a fen on Ophir Pass, Colorado, USA.

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1. INTRODUCTION TO MOUNTAIN PEATLANDS

Mountains support different types of wetlands due to changes in local and landscape-scale landforms that affect the topographic, hydrologic, and geochemical conditions that drive wetland formation (Cooper et al 2012). Steep elevation, aspect, and landscape position-controlled climate gradients can also cause significant differences in wetland composition in mountains. There are three major wetland types common in mountains: (1) herbaceous non- peat-accumulating wetlands, including marshes, wet meadows, and salt flats; (2) peatlands (fens and bogs); and (3) riparian areas along streams and floodplain meadows and marshes (Cooper et al 2012).

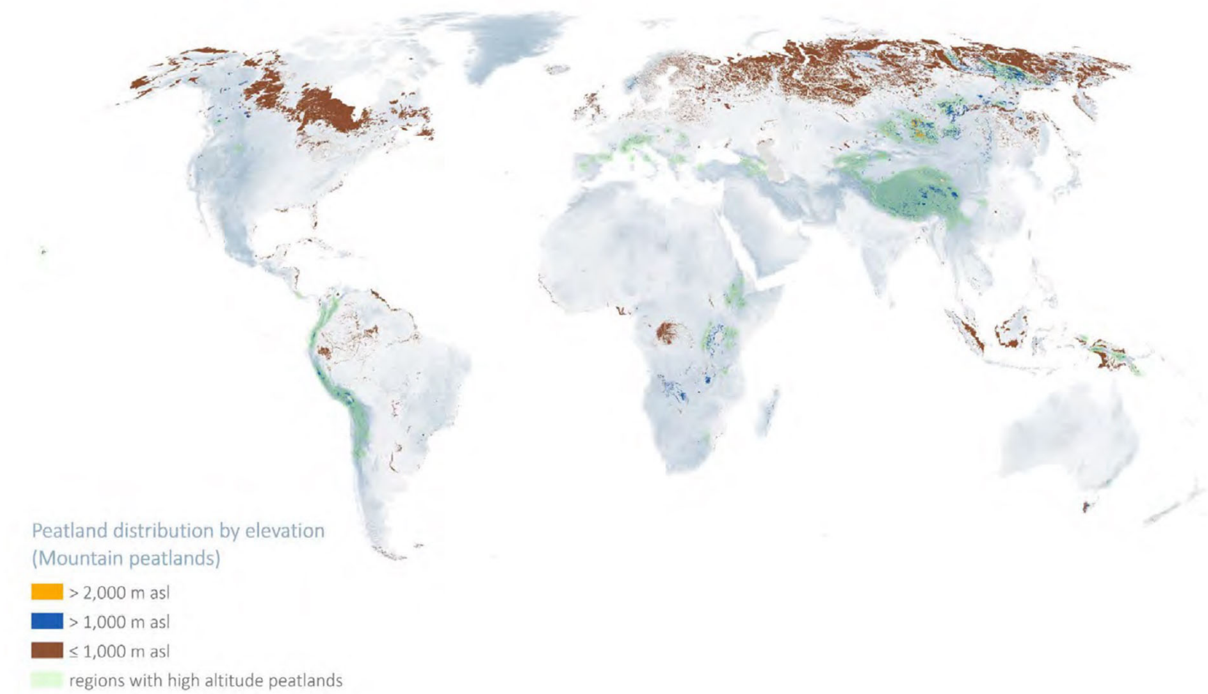

Figure 1. *Global peatland distribution and locations for mountain peatlands (green shaded areas). Source UNEP (2023).*

Peatlands are wetlands that accumulate thick layers of organic soil formed *in-situ* known as "peat" (Trettin et al 2020). Peatlands typically form where anaerobic soil conditions occur for long duration during the growing season and limit the decomposition of organic matter, resulting in annual plant production surpassing decomposition and other carbon losses. This slight imbalance between plant production and decomposition leads to a net accumulation of organic matter over thousands of years burying landscapes under organic layers. Peat accumulation leads to the formation of distinctive landforms, soils, vegetation types and habitat for a multitude of species.

Peatlands cover 4 million km^2, approximately 4% of the Earth's land surface, and occur from the tropics to the Arctic and Antarctic (UNEP 2022). They are most abundant in low-lying areas mainly in boreal and tropical regions (Figure 1). However, peatlands are also common in mountain ranges such as the Rocky Mountains, Appalachians, and Sierra Nevada of North America; the Andes of South America; the Himalayas, the Alps and Carpathian Mountains of Eurasia, and the Snowy Mountains of Australia and Southern Alps of New Zealand (Figure 1) (Cooper et al 2012). High volcanic peaks in Africa, Papua New Guinea, and Hawaii, also support peatlands (Chimner 2004; Hope 2014; Dullo et al 2015). Mountain peatlands may cover large areas in these landscapes. For example, more than 2,000 peatlands occur in a single mountain range in Colorado (Chimner et al 2010), and in Peru and Ecuador, 8% and 16% of high mountain landscapes were covered by peatlands (Hribljan et al 2017; Chimner et al 2019a). Mountain peatlands on the Zoige plateau (~3400 m elevation) in China support large areas of high-altitude peatlands, covering ~9,000 km^2 (Liu et al 2012; Bao et al 2014). Considering the widespread abundance of mountain peatlands and the limited identification and mapping, there are likely hundreds of thousands or millions of mountain peatlands worldwide.

Peatlands are typically classified into two broad types, bogs and fens, based on their hydrogeochemistry as determined by their water source(s) (Vitt and Chee 1990; Bedford and Godwin 2002; Middleton et al 2006). Bogs are ombrotrophic, and receive their water and nutrients solely from precipitation. In addition to precipitation, fens receive additional water and nutrients from groundwater or surface water and are considered to be minerotrophic. Most mountain peatlands are fens, especially in continental regions such as the central Andes, Himalayas, Alps, Sierra Nevada, and the Rocky Mountains (Cooper and Andrus 1994; Chimner et al 2010; Lemly and Cooper 2011; Zhao et al 2014; Wolf and Cooper 2015; Tomaselli et al 2018; Benavides et al 2023). Bogs occur mainly in hyper-maritime mountain regions, including coastal regions of Alaska, British Columbia, Chile and Argentina, Scandinavia, and Japan, and perhaps some locations in the Andean paramo (Warner and Asada 2006; Gallego-Sala and Colin Prentice 2013). There are also ombrotrophic bogs reported for the Italian Alps (Segnana et al 2020), and Olympic Peninsula, Washington in the USA (Rocchio et al 2021).

The thickness of peat varies greatly between peatlands within and between regions, and even within a single mountain range. For instance, peat thickness averaged 70 cm in 100 fens in the California Sierra Nevada (Wolf and Cooper 2015), 125 cm in Colorado (Chimner et al 2010), and

400-500 cm in the northern Andes of Colombia, Ecuador and Peru (Comas et al 2017; Chimner et al 2023). Mountain peat typically has a lower carbon content than low-relief tropical or boreal peatlands because they form in valleys where mineral sediment is transported downslope by rain runoff, snowmelt runoff, eolian processes, and mass movements, and in areas with active volcanos ash may be depositied in the peat (Chimner and Karberg 2008). While mountain peat generally has lower C content than low elevation boreal and tropical peat, it is typically denser and long-

Figure 2. *Common vegetation types of mountain peatlands. Sedges (top left), forested (top right), cushion plants (center), sphagnum mosses (bottom left), and shrubs (bottom right).*

term C accumulation rates may be similar or even greater in mountain than lowland tropical and boreal peatlands (Hribljan et al 2024). For instance, Hribljan et al. (2024) found that Andean peatlands had a mean C storage of 1,745 Mg ha^{-1}, which exceeds the average of 1,037 Mg ha^{-1} across the Pastaza Marañón Foreland Basin (the largest known peatland complex in the Amazon basin), and boreal peatlands, which averaged 1,275 Mg ha^{-1}.

Mountain peatlands occur in distinctive elevation zones with the upper boundary controlled by the watershed size. Watersheds must be large enough to store and produce sufficient groundwater flow to maintain soil saturation. At higher elevation cold temperatures, glaciers, and rocky terrain also limit peat formation. The lower limit is controlled by high temperatures and excessive evapotranspiration the limit where perennial saturation can occur. However in coastal regions mountain peatlands may occur at sea level and adjacent to the ocean (Bisbing et al 2016). In non-coastal mountains, such as southwestern Colorado, fens are concentrated in the subalpine zone between 2,300-3,800 m elevation (Chimner et al 2010). In northwestern Wyoming, fens occur largely at 1,880 to 2,710 m, with a mean of 2,264 m (Lemly and Cooper 2011). Fens are most abundant between the elevations of 3600–4900 m in mapped areas of Ecuador and Peru (Hribljan et al 2017; Chimner et al 2019a). In the California Sierra Nevada fens occur from 1207 to 3233 m, with a median of 2094 m elevation (Wolf and Cooper 2015), but occur at much higher elevations in the more arid southern Sierra Nevada. Peatlands in the Himalayas are typically found between 2500 to 5000 m (Sun et al 2023).

The size of many mountain peatlands is constrained due to valley confinement, steep slopes, and small catchment sizes. Mountain fens in the Rocky Mountains and Sierra Nevada average ~2 ha in area, with the largest fens generally being <100 ha (Chimner et al 2010; Lemly and Cooper 2011; Wolf and Cooper 2015). Peatlands can be much larger in maritime mountains, exceeding 6,000 ha in Alaska and other coast ranges and 10,000 ha on the Zoige basin in China (Riggs 1925; Lichthardt 2004; Gaffney et al 2023).

Hydrologic regime is a key factor driving the formation and persistence of peatlands (Price et al 2023). Hillslope groundwater discharge is the dominant source of water sustaining mountain fens. It may discharge from springs, along fault lines, at the base of slopes, or at geological discontinuities (Winter and Woo 1990; Cooper et al 2019). Mountain fens are not typically fed by streams but discharge into streams maintaining base flow conditions. In mountains with abundant snow, groundwater recharge is dominanted by snowmelt that can keep fens saturated throughout the year. Although groundwater is often the dominant source of water supporting fens, precipitation is also important and can modify water table levels in the growing season. Glaciers can be common in some high mountain areas, but glacial meltwater may not provide water to fens but instead is channeled into streams (Cooper et al 2019).

The flora of mountain peatlands is distinct (Figure 2) from lowland peatlands. Variation is influenced by water chemistry and controlled by watershed geology (Vitt and Chee 1990; Cooper and Andrus 1994; Bedford and Godwin 2002; Chimner et al 2010; Benavides et al 2023) and the hydroperiod (water table variation through time). Many boreal peatlands are dominated by *Sphagnum* spp. mosses (Warner and Asada 2006), with species of Ericaceae and some small conifer trees. Mountain peatlands in hypermaritime climate regions can be dominated by *Sphagnum* (Riggs 1925; Risvold and Fonda 2001; Asada et al 2003). Many mountain peatlands, especially fens, are dominated by herbaceous plants, particularly species of *Carex*, and brown mosses in the family Amblysegiaceae (Chadde 1998; Cooper et al 2010; Chimner et al 2010; Lemly and Cooper 2011; Wolf and Cooper 2015; Benavides et al 2023). Sedge and brown moss dominated fens are termed rich and moderately rich fens (Cooper and Andrus 1994). Up to 50 species of Cyperaceae occur in Rocky Mountain fens south of the Canadian border, with the circumpolar *Carex aquatilis* being widespread in fens throughout western North America and also in hypermaritime regions. Treed peatlands are uncommon but can occur in mountain peatlands (Johnson 1997). Bryophyte cover and diversity is dominated by brown mosses, with 49 species in Idaho and Montana, 46 species in Wyoming, and 57 species in Colorado, and particularly abundant are *Aulacomnium palustre*, *Tomenthypnum nitens*, *Warnstorfia fluitans*, *Drepanocladus aduncus*, *Ptychostomum pseudotriquetrum*, and *Climacium dendroides* (Chadde 1998; Chimner et al 2010; Lemly and Cooper 2011). Cushion plants (Figure 2) are common in many Andean peatlands and are distinctive due to their dense, compact, and rounded form (Cooper et al 2010; Polk et al 2019; Benavides et al 2023; Martínez-Amigo and Jaramillo 2024). Many common cushion plant species are in the family Juncaceae, and include ecosystem dominants such as *Distichia muscoides* and *Oxychloe andina*, and other species are in the families Plantaginaceae and Asteraceae (Cooper et al 2010; Benavides and Vitt 2014; Salvador et al 2014; Polk et al 2019).

Mountain peatlands in many regions have been highly impacted by past and present human activities (Figure 3). Approximately 25% of fens in a large-scale assessment region in SW

***Figure 3**. Common disturbances that occur in mountain fens. Reservoir constructed over a fen (top left), mineral mining (middle left), domestic livestock grazing (top right), gully (bottom left), poor culvert design (bottom middle), and ditches (bottom right).*

Colorado had some level of disturbance (Chimner et al 2010). Similar disturbance levels were found in Ecuador (Suárez et al 2022) while 77% of the fens on the Ruoergai Plateau in China were in various stages of degradation due to ditching and livestock grazing (Zhang et al 2012).

Dewatering of peatlands is a common disturbance that has been accomplished using drainage ditches, water diversions, gullies, road ditches, and groundwater extraction (Cooper et al 1998;

Patterson and Cooper 2007; Chimner et al 2010; Zhang et al 2012; Zhang et al 2014; Cooper et al 2015; Li et al 2015). Ditching can lower water table levels >30 cm below the soil surface and up to a 1 m or more if they are intensively ditched (Zhang et al 2012; Zhang et al 2014; Schimelpfenig et al 2014; Planas-Clarke et al 2020). Peatland dewatering has severe impacts because the lower water table leads to oxidation of accumulated peat, subsidence of the ground surface, modification of the vegetation, and increases the susceptibility to fire (Chimner and Cooper 2003a; Patterson and Cooper 2007; Turetsky et al 2011; Benavides 2014; Cooper et al 2015; Wilkinson et al 2023). Too much water is also detrimental to peatlands. Mountain peatlands can be flooded by reservoirs or have impeded drainage (Austin and Cooper 2016) and many peatland plants, especially mosses die from prolonged inundation (Borkenhagen and Cooper 2018).

Roads commonly impact mountain peatlands by intercepting water flow, bisecting habitats, and introducing mineral sediments. Some roads have a limited effect on peatlands, but others can have severe impacts, especially where poor culvert placement causes downgradient erosion, upstream inundation, or incision that intercept groundwater. Some roads also can cut through peatlands with no cross drainage that dewaters the downslope side and inundates the upslope side (Bocking et al 2017). Roads allow vehicle access onto peatlands that can cause tire ruts and gully formation. Near the Rochford Cemetery in the Black Hills, South Dakota roads are created from limestone base material placed over naturally acidic fens, completely altering the downgradient chemistry and leading to widespread plant mortality.

Grazing by cattle, sheep, horses, alpaca, llama, and other domesticated animals is widespread in mountain regions. In arid regions with little forage in the uplands, mountain peatlands with high forage production provide the majority of forage for grazers. This occurs in fens in the puna region of the Andes (Peru, Bolivia, Chile, Argentina) (Chimner et al 2020; Oyague et al 2022; Suárez et al 2022; Young et al 2023) the southern Sierra Nevada of California (Wolf and Cooper 2015), and the Himilayas (Zhang et al 2012). Impacts increase as the intensity of grazing increases. High intensity grazing can degrade peatlands by trampling vegetation and exposing bare peat (Wolf and Cooper 2015) or by creating trails that can erode into gullies. High densities of native animals can also damage peatlands, for example, high populations of elk, deer and moose have modified mountain fens in the Rocky Mountains through trampling and herbivory (Chimner et al 2010; Lemly and Cooper 2011).

Peat mining and mineral exploration and exploitation can also be prevalent. Although peat mining is less common in mountain regions it impacts many peatlands that are rarely restored (Cooper and MacDonald 2000). In mineral rich regions, the peat can be mined for minerals, such as bog iron, that is incorporated in the peat. Mining leaves bare peat surfaces that remain bare for many decades with little plant colonization (Chimner 2011). Disturbances can also occur where mining occurs adjacent to peatlands. Tailing piles can be deposited near or on peatlands with chemical discharges. Several peat mining areas have remained barren for decades and require active restoration (Cooper and MacDonald 2000). Infrastructure and land development such as golf courses, parking structures, housing, and ski runs can affect mountain peatlands, often by the placement of fill or building structures that modify groundwater flow.

Degraded peatlands reduce water storage and degrade habitat for many species, and are a significant source of greenhouse gas emissions (10% of all greenhouse gas emissions from land use changes is derived from degraded peatlands (UNEP 2022), peatland restoration is needed globally. Nevertheless, the majority of peatland restoration projects have been conducted in low-lying boreal or tropical areas, while the restoration of peatlands in mountainous landscapes typically requires specialized techniques due to their placement in high-energy environments and remote settings (Chimner et al 2017). **The objective of this manual is to present an overview of approaches and methods for the restoration of mountain peatlands.**

Peatland restoration training in Ecuador

2. PRE-RESTORATION MONITORING

Pre-restoration monitoring allows the researchers and designers to understand the scope, type and scale of disturbance(s) in any site and develop pre-treatment data to use in assessing restoration success or limitation. Complex sites may require 2-3 years of monitoring through wet and dry periods, and to develop a detailed understand of all impacts to the site. This will allow the development of detailed restoration goals, concepts and also approaches. Funding for this step may be difficult to obtain, because restoration funding may be targeted at executing the restoration and not for impact assessment and restoration design. Nevertheless, pre-restoration monitoring is essential to ensure that site characteristics and impacts are clearly understood, and restoration

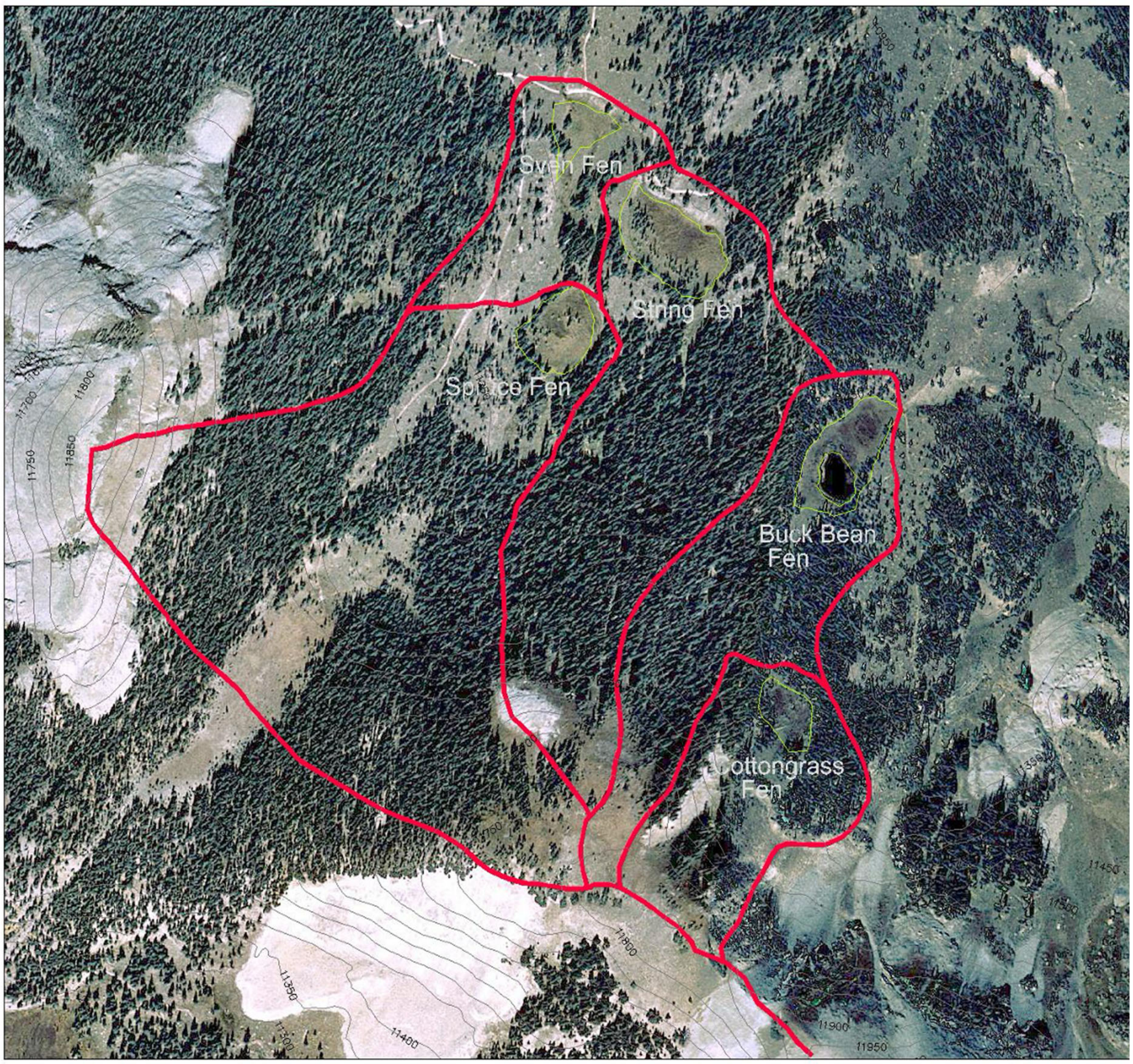

Figure 4. *Example watersheds identified for mountain peatlands in Southwest Colorado.*

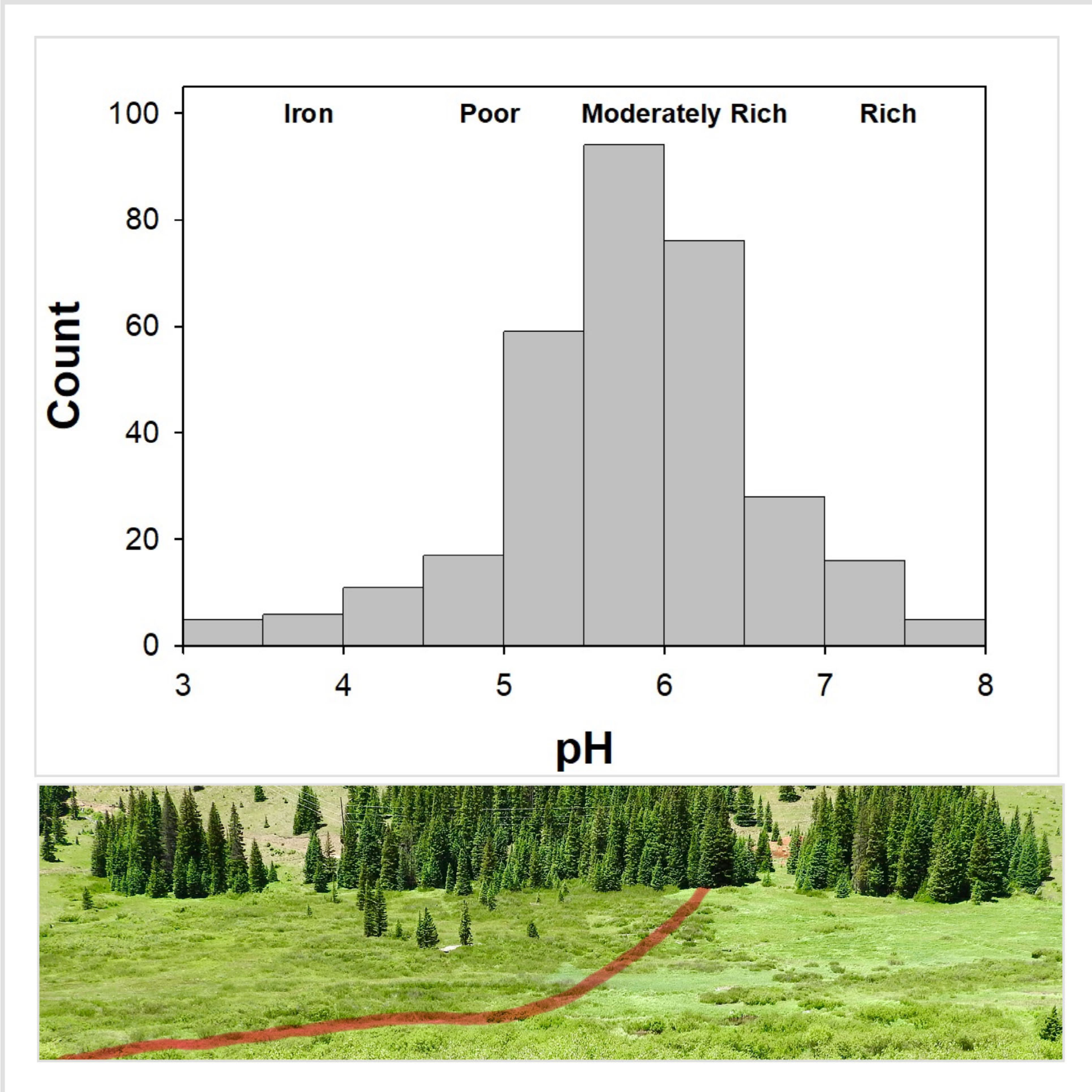

Figure 5. *Fen types based on pH levels in Southwest Colorado fens (top). Fen types can vary in the same site due to changes in water chemistry (bottom photo). The pH on the left side of the red line is 6.5 (rich fen) and the right side is 3.5 pH (iron fen).*

actions address the impacts. Lack of pre-restoration monitoring data is one of the leading causes of restoration failure. Pre-restoration data is also essential for quantifying post-treatment effects of the restoration. Data on water table depth through time, vegetation composition and cover across the site, and other variables that are critical to monitor, including greenhouse gas fluxes, water budgets, nutrient fluxes and budgets, animal populations, etc. may also be important variables to analyze.

2.1. CHARACTERIZE THE SITE

2.1.1. WATERSHED CHARACTERISTICS

Understanding the watershed area (Figure 4) supporting a fen is critical for restoration planning. Mountain fens are intricately linked to their watershed. Delineating boundaries of the fen's watershed will help quantify water available to the fen, its chemical composition, and the area that should be assessed for stressors that can impact the peatland (Vitt and Chee 1990; Cooper and Andrus 1994; Bedford and Godwin 2002; Cooper et al 2010; Chimner et al 2010).

The chemical content of groundwater is especially important in fen classification and characterization (Vitt and Chee 1990; Cooper et al 2002; Chimner et al 2010; Lemly and Cooper 2011) and can vary between and within sites (Figure 5). Catchments dominated by granite and other intrusive igneous rocks release few ions and tend to have pH levels near 5 and are termed either poor (pH 4.5-5.5) or moderatly rich (pH 5.5-6.5) fens (Figure 5). Conversely, calcareous watershed dominated by limestone and dolomite rocks have pH above 6.5 and support rich and extremely rich fens (Cooper 1996; Cooper and Sanderson 1997). Acidic iron fens occur when rocks with iron pyrite oxidize to form sulphuric acid that is dissolved in ground water and produces water with pH <4.5 (Cooper et al 2002; Cooper et al 2010; Chimner et al 2010).

2.1.2. LANDSCAPE CHARACTERISTICS

Mountain fens form in distinct landscape positions (Figure 6). This is important to understand for designing and implementing restoration because it can provide information about water sources, water depths, flow paths, and energy. Basin fens occur in depressions, and typically form through infilling of shallow lakes or ponds by mineral sediment and peat (Figure 7). Basin fens may have areas of open water with tall sedges, rushes or bulrushes and floating mats on the edges. If the pond or lake is small, the basin fens can be entirely covered in vegetation with no surface water present. Large inter-mountain basin fens also develop in valleys between mountains (Figure 8). Fens in basins are generally flat with little or no slope and require small inflows to keep them saturated.

In many regions, sloping fens are the most common type (Chimner et al 2010; Wolf and Cooper

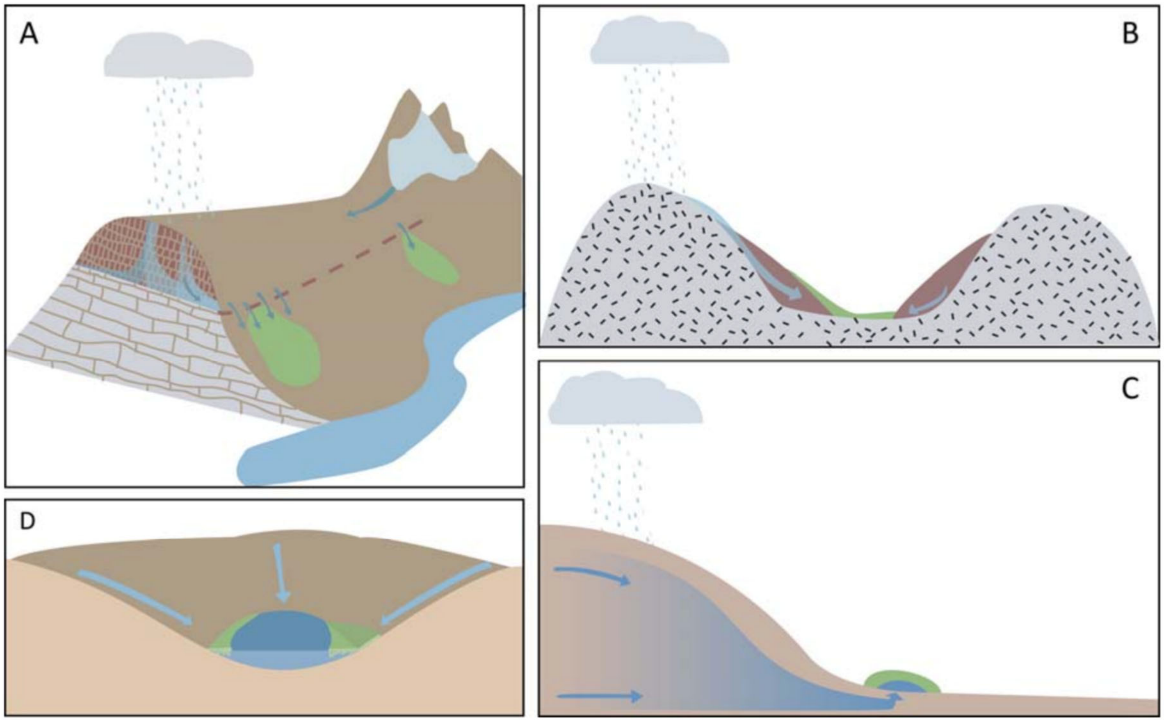

Figure 6. Figure of mountain fen landform types. Fens can form from groundwater discharging from geological discontinuities (A) or changes in topography often near the bottom of a slope (B), upwelling from a spring (C), or in a basin (D). Figure is reproduced from Mires and Peat Vol. 15, Article 8.

2015) and form where groundwater discharges into the fen and flows in one direction towards the valley bottom (Figure 6 and Figure 7). These fens may occur on gentle or steep (up to 20 –30%) slopes where perennial groundwater discharge must occur to support them (Patterson and Cooper 2007; Chimner et al 2010; Lemly and Cooper 2011; Wolf and Cooper 2015). Peatlands also form at the bottom of slopes "toe-slope" where groundwater discharges from glacial till, alluvial fans, or colluvium at the base of a slope (Figure 6 and Figure 7). Slope fens are easily disturbed due to the erosive energy of flowing water and may be more difficult to restore if an erosional gully has formed. Sloping fens may also occur in the bottom of high mountain valleys and receive groundwater inputs from several valley sides. Large U-shaped glacial valleys can have large toe-slope and valley fens with the Kawuneeche valley in Colorado and Quilcayhuanca valley in Peru being examples (Figure 9).

Bogs form in regions that typically have consistent rainfall and high humidity, with low ET rates. Some bogs form in basins and can attain a dome shape. In other areas, they form on the top or slopes of mountains, covering the landscape like a blanket of peat, hence the name blanket bogs

(Figure 8). Blanket bogs are common in the UK and Ireland, southeastern Alaska and coastal British Columbia and maybe in parts of Ecuador and Colombia (Gallego-Sala and Colin Prentice 2013). Although this manual focuses on restroration techniques of mountain fens, many of the techniques are applicable to mountain bogs as well.

Figure 7. *Landscape types of mountain fens. Small depression fen (top left), sloping fen (top right), valley fen (bottom left), and toe slope fen (bottom right).*

Figure 8. *Large intermountain basin peatland in China (top) and a Scottish blanket bog (bottom) where all landscapes were covered in peat including the sides, tops, and bottoms of the slopes.*

2.1.3. SOIL CHARACTERISTICS

Analysis of a study site's soil is an important step for restoration planning to determine the type(s) of wetlands present. An initial step should be identifying if the site has organic soil and can be classified as a peatland. Many mountain wetlands are complexes supporting multiple wetland types, including fen, marsh, wet meadow and riparian areas. Each of these wetland types can be identified by analysis of the soil, vegetation, landform and hydrologic regime. It is important to distinguish and map the different wetland types as each may require different restoration techniques. A topographic survey of the site may be essential for restoration design if the site requires earth work for filling ditches or gullies, removing fill, and other activities.

Figure 9. *Large glacial valley in Peru with peatlands located at groundwater discharge locations.*

Peatland definitions vary between countries, but they are wetlands with organic soil formed *in-situ* under saturated conditions (Trettin et al 2020). The U.S. soil taxonomy system identifies

***Figure 10.** Pictures of sedge peat (top left), cushion plant peat (middle left), sphagnum moss peat (bottom left), cushion plant peat overlying mineral soil that is the same color (top right), woody peat (bottom right), and mineral wetland soil (bottom middle).*

organic soils (peat) as having organic layers >40 cm thick within the upper 80 cm of soil. They also have an organic carbon content greater than 12% - 18% depending on the clay content, and is formed in saturated conditons (USDA 1975). Many countries have similar definitions, but the required organic layer thickness varies between 30 and 40 cm thick (Trettin et al 2020). In addition, many country definitions do not specify the % organic carbon necessary to be considered an organic soil. According to U.S. soil taxonomy, the least decomposed organic soils (fibrists) are called peat, while the more decomposed organic soils (hemists and saprists) are called muck. However, it is common to identify all organic soils as peat, and we follow this convention in this manual.

The presence of peat soil must be determined by digging a pit or augering or coring to at least 40 cm deep (Figure 10). Peat feels more like plant than mineral matter (sand, silt or clay) and you

Figure 11. *Trampling (top left), frost heave (top right), erosion (bottom left), and burial by sediment from adjacent slopes (bottom right), are common soil disturbances found in mountain fens.*

might be able to see partially decomposed roots, moss fragments or leaves. If the soil is wet, squeeze it and if water comes out and the soil become lighter and more compact than it is likely peat. When the organic soil is rubbed between your fingers it may almost dissolve into a watery paste, which mineral soil would not do. If you cannot squeeze water out and the soil, feels gritty, sandy, or like clay, and dense, it is likely not an organic soil. Organic soils are usually brown to black in color when highly decomposed, but when the plant material is well preserved it may be reddish or brownish reflecting the composition of the species that formed the soil. Mineral soils may be gray in color from iron being reduced or removed in the process of gleization. There also may be clearly seen oxidized iron deposits around living roots indicating that soluble forms of iron, ferrous iron or $FeII^{+}$, are mobile and oxidized around roots that are releasing oxygen into the soil forming ferric iron or $FeIII^{+}$.

It may be necessary to analyze the soil in a laboratory to determine the percent organic carbon and mineral fraction. Once the soil is analyzed and confirmed to be peat, you can analyze the rest of the study area using a probe to assess peat presence and thickness. The probe can be a specialized soil probe, grounding rod, or an avalanche probe. It is important to push the soil probe into the soil adjacent to the open hole to calibrate your understanding of how the probe moves through organic vs. mineral soil. In most cases, you can push the probe through the peat until you hit mineral layers, which create much greater resistence and a scratching sound as the sediment rubs against the metal probe. With this approach you can walk the site and identify the approximate peatland boundries. However, probing can produce confusing and erroneous results if not based on local reference sections. So, we suggest doing several borings or soil pits, through the peat section, paired with probing to determine the feasiability of probing in your study site.

Areas of bare peat, or areas without vegetation cover, should be identified on site (Figure 11). Bare peat may be caused by severe overgrazing, burial by eroded sediment from upgradient, chemical pollution, erosion, extreme periods of drought or other disturbances. If possible, it's important to determine the cause of the disturbance and why the site did not revegetate naturally.

Frost heave occurs when nighttime temperature drops below freezing, causing needle ice formation that can push the soil up 1-5 cm, loosening the surface peat, uprooting plants and increasing erosion (Groeneveld and Rochefort 2002). Research in Colorado found that frost heave was greatest in fens when the water table was 10–20 cm below the surface but less common when soils were wetter or drier (Chimner 2011). Frost heaving can be identified by the telltale bumpy peat surface that can easily be eroded by wind or rainfall (Figure 11).

2.1.4. HYDROLOGIC CHARACTERISTICS

The persistence of soil saturation and the source(s) of water are key factors driving the formation of peatlands. Fens are created and supported by perennial groundwater inflow that

Figure 12. *Groundwater monitoring wells inserted into the fen (left) and two types of slotted PVP pipe (right).*

maintains anaerobic soil conditions that limit the rate of organic matter decomposition. The water table can differ among mountain fens types, but general patterns exist. Intact mountain fens have a water table near the soil surface during the growing season (Chimner and Cooper 2003b; Chimner et al 2019b; Cooper et al 2019; Planas-Clarke et al 2020), however, it can drop 20-30 cm seasonally, and occasionally to 50 cm or more during extreme drought periods (Chimner and Cooper 2003b; Cooper et al 2017; Sánchez et al 2017; Chimner et al 2019b; Planas-Clarke et al 2020). Dewatered fens often have water tables more than 30 cm below the soil surface and sometimes more than a meter below the surface (Cooper et al 1998; Schimelpfenig et al 2014; Cooper et al 2015; Planas-Clarke et al 2020).

Quantifying the water table position relative to the ground surface is a critical step in the design of peatland restoration projects. The water table depth indicates whether the site, or portions of the site are too dry, or too wet due to deep inundation, and hydrologic restoration is an essential first step in site restoration. An understanding of ground water depth and dynamics in the peatland, provides baseline hydrologic data to compare with post-restoration site conditions, and should be used to guide plant selection. The most common method of monitoring peatland water table levels is through the use of groundwater monitoring wells.

Groundwater monitoring wells can be either purchased or constructed. A groundwater monitoring well can be made (following methods modified from Cooper and Merritt 2012) by either purchasing PVC tubing with machine-made slots or by cutting handmade slots into the PVC pipe (Figure 12). We find that 1-2” inside diameter (2.5 – 5 cm) PVC pipe works well. The slots should extend from the bottom of the casing to just above the soil surface. The holes or saw cuts should be as thin as possible to prevent sediment from the borehole from entering and filling the well casing. A filter sock can be wrapped around the PVC to limit sediment flux into the pipe. To install the well, you hand-drill a bore hole, logging the thickness of layers encountered, and being careful not to penetrate confining layers of dense peat or clay because below such layer’s water may be under pressure, creating upward artesian flow in the pipe that does not represent the water table in equilibrium with atmospheric pressure that you want to monitor. The hole should be deep

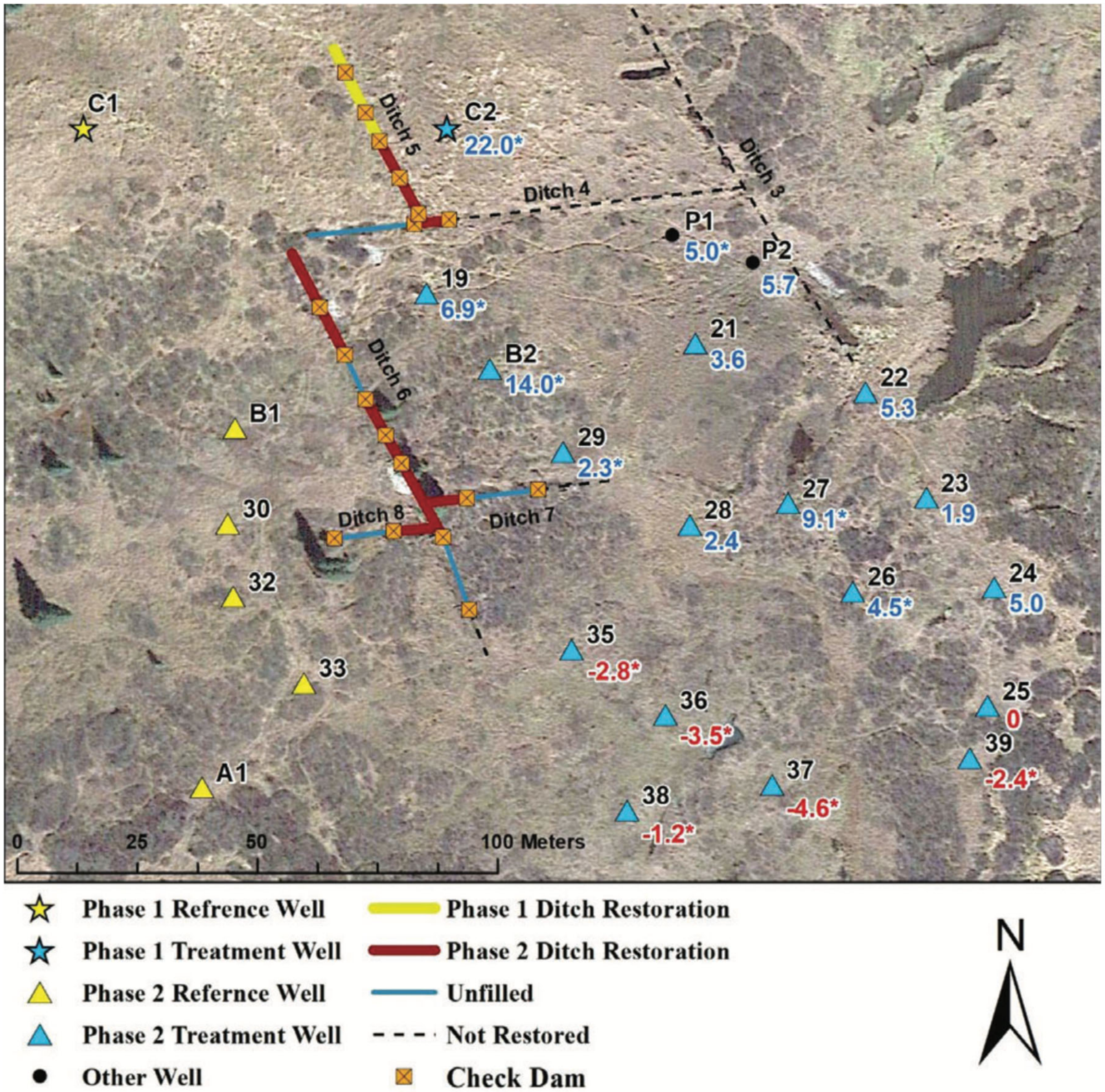

Figure 13. *Location of groundwater monitoring wells for reference sites (yellow stars and triangles) and treatment wells (blue stars and triangles) for a fen that underwent restoration of ditches. Blue (wetter) and red (drier) numbers next to wells show the average change in water table levels (cm) at each well post-restoration compared to reference wells. From Chimner et al. (2018).*

enough to have water in the well during the dry season if possible. The water table should be encountered when the bore hole is augured, and if possible, the wells should be installed during the dry season when the seasonal water table is at its deepest. After the well is installed, the hole around the casing should be filled to near the ground surface with the material removed from the hole. A bottom cap should be installed prior to installation with a hole drilled through it to allow water to drain freely from the PVC if the water table drops below the bottom of the slots. A top cap is required to keep rain and debris out of the well casing. A wide range of caps are available, some of which allow locks to be added to the cap, and some that allow logging pressure transducers to be suspended from the bottom of the cap.

The number of monitoring wells needed will vary by site conditions and the goals of the restoration program. We recommend the installation of a grid of monitoring wells to allow the characterization of site hydrologic conditions. Greater variation in hydrologic conditions requires more wells. In our restoration projects we have used a few to as many as dozens of wells (Figure 13). Wells oriented along transects allow the creation of water table elevation and gradient maps.

Once the monitoring wells are installed, they must be measured frequently to provide data needed for restoration planning (Figure 14), preferably every week or two. If possible, install pressure transducers in wells to collect water table information several times per day. When using pressure transducers, it's important to measure the water table depth manually several times per year to confirm the pressure transducer calculated water table depth. This allows for spatial patterns to be seen with manual measurements and temporal patterns identified with pressure transducer data. Monitoring water chemistry parameters such as pH and specific conductivity can also be conducted in the groundwater monitor wells, after they are bailed multiple times and allowed to refill. Other common water quality parameters that are commonly measured are Ca^{+2}, Mg^{+2}, K, Na^{+}, Fe^{+3} but should be tailored to meet individual needs.

Wells are used to measure the distance of the water table below the soil surface. The first step is to measure the distance from the top of the well casing to water table. If the water table is near the ground surface, a tape measure or ruler can be lowered into the well and the water table can be identified when ripples occur as the tape hits the water. If the water table is deep, then you use a commercially available sensor that beeps or moves a needle when the tape reaches the water table, or a "blow stick", a hollow plastic tube you lower into the well while blowing into the tube. You will hear bubbles when the air contacts the water surface. The length of tube below the surface can then be measured. Next measure the distance the well casing sticks above the soil surface with a ruler, commonly called the "stick up". The water table depth is then calculated as the water table distance from the top of casing minus the stick up. For increased accuracy when taking repeat measurements of stick-up and groundwater levels, it is recommended to mark the exact location on top of the well casing with a sharpie or small notch. This is particularly useful

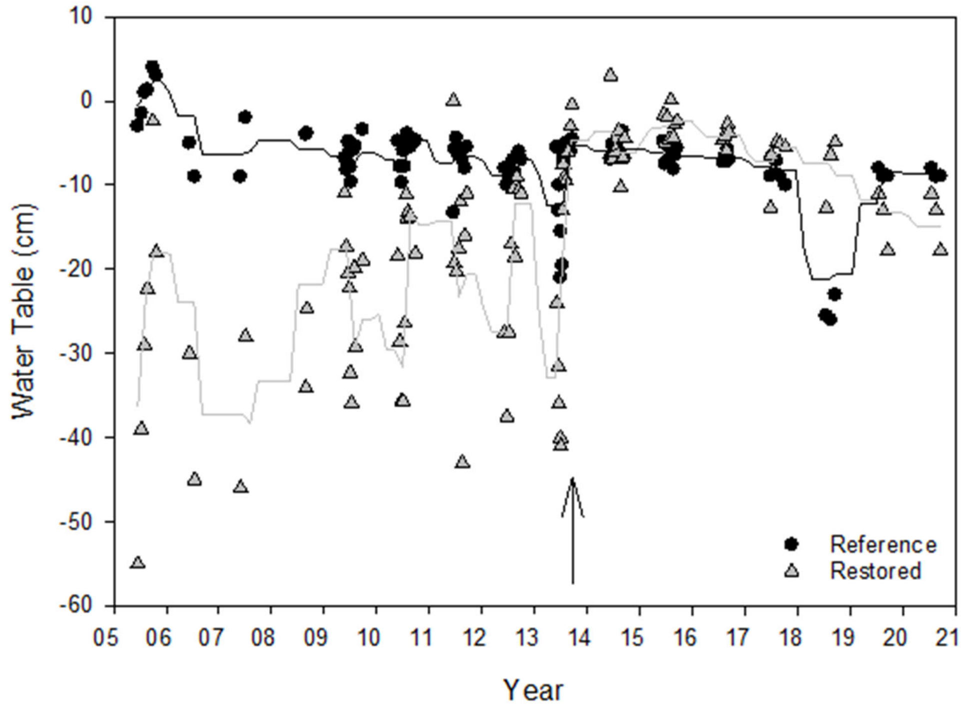

Figure 14. *Water table measurements in reference fen wells (black circles) and restored fen wells (grey triangles) over a 16-year period. Arrow indicates when restoration of ditches occurred. Water table data clearly shows that the ditch restoration increased water table levels around 25 cm to match reference water table levels.*

when the ground is sloping or uneven, or if the well casing was cut at an angle.

In remote areas where pressure transducers are not available, there are alternative methods to monitor water levels. Metal rods or PVC tape can be inserted into the peat and the discolored zone can be used to inexpensively determine the zone of water table fluctuation (Belyea 1999; Chimner et al 2011). WALRAGs are wells with an internal float design that measures minimum and maximum water table levels over long periods (Bragg et al 1994).

2.1.5. VEGETATION CHARACTERISTICS

Peatland vegetation is vital to assess and monitor because it stabilizes the soil, fixes carbon that is used by herbivores and creates input to form peat soils. The scope of vegetation sampling will vary depending on the type of restoration being planned. At a minimum, the site should be assessed for the presence of dominant, invasive or rare plant species. Additional useful information is determining if the vegetation is composed of native peatland plants, or non-peatland plants that

Table 1. *A common vegetation cover class system (Ellenberg and Mueller-Dombois 1974).*

1	0-1%	plant is rare, insignificant cover
2	1-5%	plant is well established in plot, minimal coverage
3	5-25%	plant common in plot, >5% cover
4	25-50%	small group, near 50% cover
5	50-75%	large group, definitely >50% cover
6	75-100%	nearly completely covered

invaded after a disturbance. For instance, if the peatland has been ditched and drained, or very heavily grazed, it's vegetation may be dominated by non-wetland plants (Figure 15: Planas-Clarke et al 2020). Long-term intensive grazing can alter the composition of peatland vegetation (Cooper et al 2015). Vegetation analyses can help researchers develop a list of plant species for use in post restoration planting. Pre-restoration vegetation surveys are also important for long-term monitoring to follow vegetation changes after restoration.

A map of vegetation types can be created using vegetation sampling techniques. Sample frames from 1-4 m^2 can be used to analyze vegetation in homogenous plots. Within each plot the identification and abundance or each plant species is recorded. Abundance can be recorded as percent canopy cover or cover class (Table 1). The plot locations can be chosen along transects (Mcbride et al 2011), randomly, or using a stratified approach. We often recommend a stratified approach for restoration because of the number of disturbances and gradients encountered in most restoration sites. The strata would be mapped in community areas, or disturbance types within communities. A good way to identify homogenous stands of vegetation for sampling is through the use of drone images, or mapping onto aerial photographs. Impacts such as ditches, gullies or sparsely vegetated areas should be identified for sampling as well. At each plot its important to measure environmental variables to correlate with vegetation composition. The plot location should be identified uing GPS, or marked with a small post, so the site can be resampled in the

Figure 15. *Changes in vegetation due to changes in hydrology in a Peruvian fen. Reference condition showing fen vegetation in good shape (top left), dried area next to a ditch with fen plants stressed or dead (right), and severely dried fen with total loss of wetland vegetation and replacement by non-fen vegetation (bottom left).*

future to quantify changes due to the restoration treatments. Corners can also be marked with buried metal pieces that can be found with a metal detector incase the plot corners go missing. We often include ground water monitoring wells adjacent to vegetation plots to link water level and vegetation changes at the same location. A vegetation map can be made of the restoration site that can be overlaid on a drone or other remote image.

2.1.6. ADDITIONAL MONITORING

Photo documentation can be useful for developing a restoration plan and for monitoring success. This is usually accomplished with repeat photo points to show before, during and after restoration. Historical ground photos and aerial photos are very useful for restoration planning if you can find them.

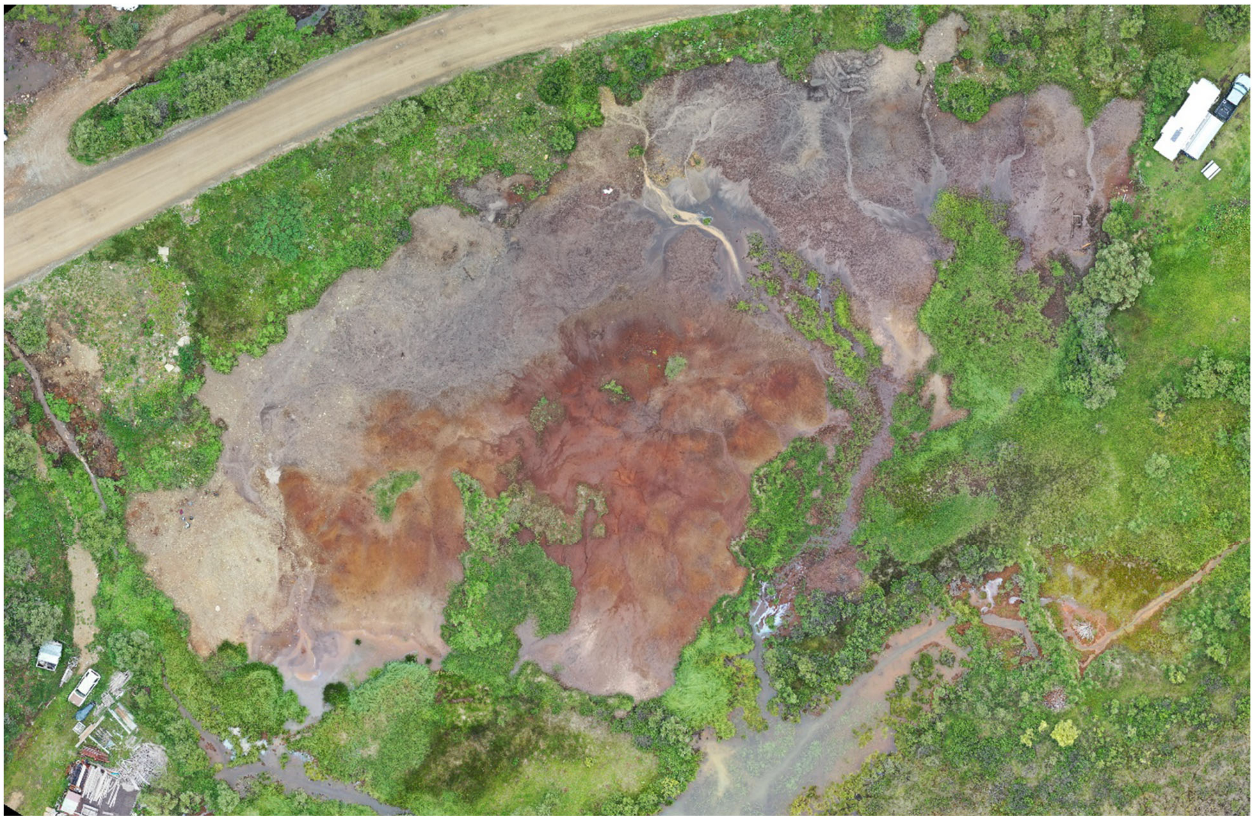

Figure 16. *Georectified drone image created from multiple images stitched together of a degraded Colorado fen undergoing restoration planning.*

Aerial photos taken from drones provide many benefits to restoration projects (Figure 16). Drone overflights can create georectified JPEG and TIFF images and digital elevation models that can be imported into ArcGis and Qgis to facilitate restoration planning (Figure 16). Drone images are useful for identifying many disturbances that are difficult to see on the ground, and allow the mapping of ditches, erosion gullies, and sparsely vegetated areas. Drone images are also useful for developing a vegetation map, and a restoration plan map. However, drone usage is not allowed in

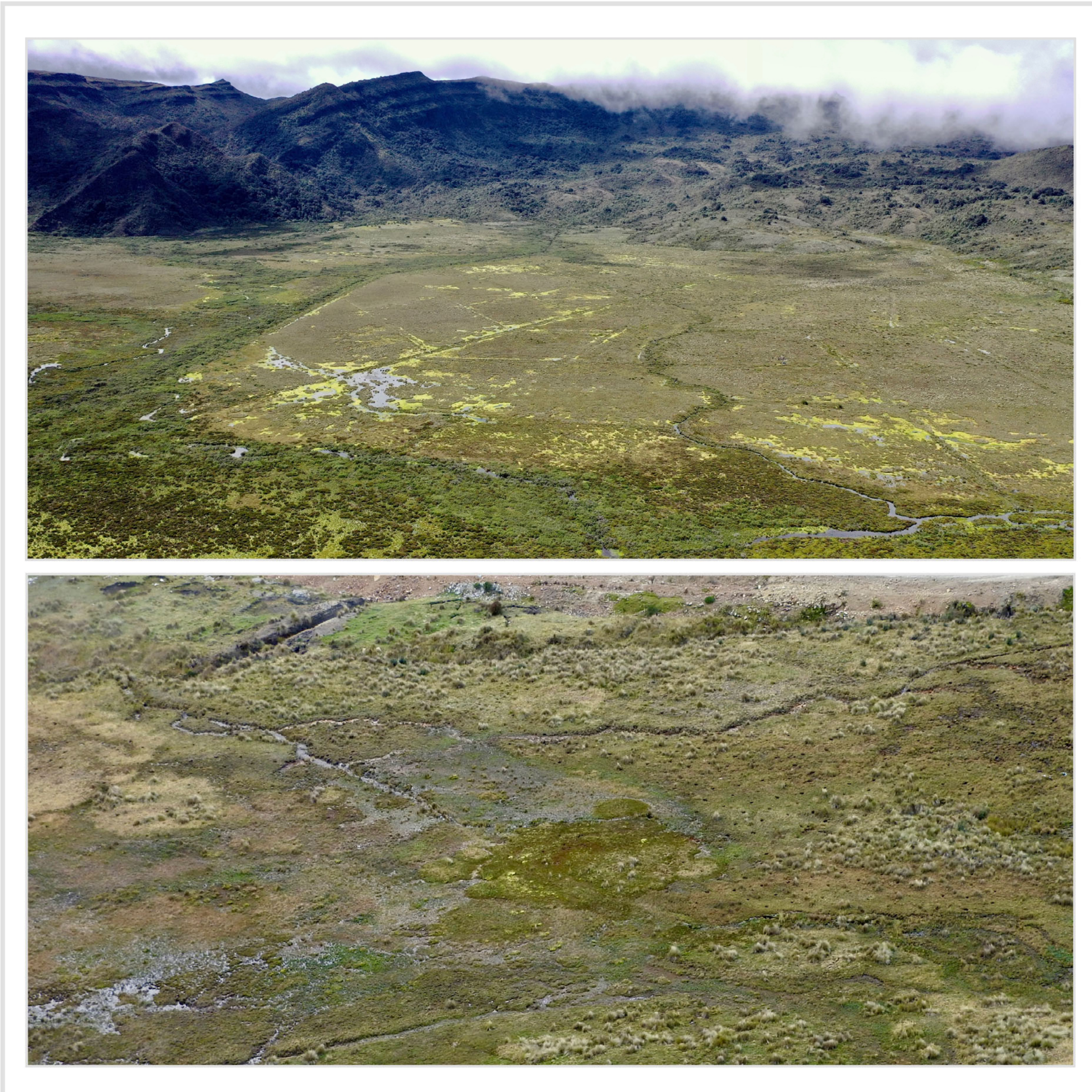

Figure 17. Drone (top) and photo from ridge top (bottom) showing a series of ditches and channels in fens in Colombia (top) and Peru (bottom). Top photo courtesy of Nicolas Skillings.

many natural areas, such as most US national parks without specific permission. Taking photos from nearby ridges or slopes, or using tethered balloons can also provide good information if drones are not available or allowed (Figure 17).

Depending on the goals of the restoration project, many additional monitoring approaches can be used. If peatlands are being restored for natural climate solutions (Leifeld and Menichetti 2018), its important to monitor carbon cycling, including carbon dioxide, methane, and dissolved organic carbon (see Bansal et al. 2023 for in-depth wetland carbon methodology). Other parameters such as water quality, soil, microbial communities, insects, birds, or amphibians can also be monitored.

2.1.7. REFERENCE SITES

The success or failure of any restoration effort must be quantified by comparing the restored area with suitable reference sites before and after project implementation. One or more reference sites should be monitored simultaneously with the restoration site to provide information for restoration planning. Quantifying the water table depth and duration in reference sites can help determine the pre-restoration condition of the study site, and provide a water table target or benchmark for post-restoration success. Similar goals should be developed for vegetation composition.

Reference sites must match the type of peatland being restored and provide a suitable goal for restoration. This requires determining the restoration site fen type, for example a sloping rich fen, its hydrogeomorphic condition, water source, water table depth and dynamics, water chemistry, vegetation, peat type, historical images, and local knowledge. Reference sites need not be pristine, as this may not be possible or desireable. If restoring an overgrazed peatland, there might not be any ungrazed peatlands in the region so lightly grazed peatlands can be used as reference sites. Reference sites can also be part of the wetland being restored if a significant portion is undisturbed. For instance, when restoring a ditched peatland portions of the site may be unaffected by the ditch and retain the natural hydrologic regime and vegetation (Figure 13). A successfully restored peatland could also be a suitable reference site.

2.2. CHARACTERIZING THE PROBLEM(S)

Identifying the stressors, or impacts that caused the peatland degradation should be identified **before** developing concepts for restoration and designing the site restoration approach. If a peatland is manipulated before fully understanding the causes of degradation, it is not possible to target the variables affecting the peatland in a restoration plan. Lots of time and money can be spent restoring a gullied peatland, but if the gully was created by a poorly installed culvert that discharged water from a road on a slope above the peatland the gully likely will reform because the cause of disturbance was not addressed. In this case, the culvert must be addressed before the gully repair is attempted. If a peatland has a ditch it might quickly be concluded that the ditch is the cause of the peatlands' deep water table. However, more detailed hydrologic analysis could indicate that the water source for the peatland has been diverted, and fixing the ditch will not address the dewatering problem (Patterson and Cooper 2007). In another example, a peatland may be hyrologically modified by groundwater pumping that is on site or off site, and not readily apparent (Cooper et al 2015).

Identifying stressors and impacts is the most important pre-planning task and should be the goal of pre-design monitoring and guide the overall restoration design. For example, if the peatland has several ditches, the monitoring wells network should quantify the effects of each ditch, which are different from a site that was not ditched but was overgrazed. Common stressors in mountain peatlands include ditches, gullies, other erosion features like rutting from vehicle tires, bare or sparsely vegetated areas, peat harvesting, mineral mining impacts, reservoir development, agriculture, sediment influx, roads directly above or through the peatland, over grazing, invasive species, built structures or land conversion, and recreational impacts such as hiking or snowmobiling trails (Figure 3). Offsite impacts can be identified from drone imagery, satellite imagery like Google Earth, and from walking the watershed. Once the stressors and problems are identified, restoration techniques can be targeted to the exact impacts occurring on your site (see Section 3.0).

3. RESTORATION TECHNIQUES

3.1. DITCHES

Ditches are common hydrological disturbances in many wetland types, including mountain peatlands (Cooper et al 1998; Patterson and Cooper 2007; Hartman et al 2016; Chimner et al 2019b). Ditches are designed to capture surface water, sheet flow and shallow ground water to rapidly channel the water out of the peatland to lower the water table. Most ditches are constructed to allow forestry, grazing and hay cutting, and other uses. The lowered water table allows peat to oxidize and may result in the peat surface subsiding (Krause et al 2021). Dewatering can increase dissolved organic carbon export from peatlands (Kane et al 2014), alter vegetation composition (Cooper et al 1998), and make peatlands more susceptible to burning when local and regional forest fires occur (Turetsky et al 2011). 2011). Sloping fens are highly effected by ditching because they are dominated by laminar groundwater inputs, which means that even one ditch running perpendicular to the slope can dewater a large area downslope (Chimner et al 2019b).

Several ditch restoration methods have been used, and several factors should be analyzed to determine the most suitable approach. The depth and width of a ditch, its slope, and the annual volume of water flow are key factors to consider. **We categorize ditches as low and high flow ditches (Figure 18)**. Low flow ditches have slopes less than ~2% and water always flows slowly through the ditch, even during intense precipitation events. This often occurs when ditches run parallel to the slope or when peatlands are relatively level (Figure 18). High flow ditches have slopes greater than ~2% and at times may have water flowing rapidly down the ditch. These types of ditches are typically oriented down the slope and occur in areas with high intensity precipitation

***Figure 18.** Examples of low flow ditches (top left and right, center) and high flow ditches (bottom left and right). Low flow ditches have slopes less than ~2% and water always flow slowly through the ditch. This often occurs when ditches run parallel (middle photo) to the slope or when peatlands are generally flat (top left and right). High flow ditches have slopes greater than ~2% or have periods of fast water flowing down the ditch. These types of ditches typically occur running downslope (bottom right) or in areas with high intensity precipitation or snowmelt that can produce high flows in the ditch (bottom left).*

or snowmelt that can produce high rates of runoff (Figure 18).

Other issues to consider in ditch restoration are site accessability, availability of ditch spoils (sediment sidecast from the ditch construction), how deeply the ditch is embedded into the peat, goals of the land owner, and available funding. Many ditched peatlands have multiple ditches, and each might be distinct enough to require different restoration approaches.

Figure 19. *Example of filling in a ditch with native peat. Ditch before restoration in 2007 (top left), during restoration in 2012 (right), and after restoration 2023 (bottom left).*

Two main approaches to ditch restoration exist; 1) filling the entire ditch, and 2) blocking water flow within the ditch with dams. Large restoration projects can completely fill ditches when possible because filling is a permanent solution with a high success rate if done properly. If funds are limited, or the site is remote, ditch blocking may be the only option. While ditch blocking is initially easier, it is more likely to fail and require long-term maintenance. The techniques described below are designed for ditches less than ~3 meters wide and ~2 meters deep. Larger ditches, often called canals, may require different techniques.

3.1.1. DITCH INFILLING TECHNIQUES

Figure 20. *Using fiber bales for ditch infilling. Ditch before restoration (top left), during restoration (top right and bottom left), and five years after restoration (bottom right).*

Figure 21. *A 200 m long ditch in Drakesbad Meadow, a fen in Lassen Volcanic National Park, California was completely filled with sediment in 2012. The ditch was first cleaned and grubbed to make sure no undercut banks or vegetated areas were present (top left). Then the ditch was filled with sandy loam sediment (top right). The sediment was tamped to remove all voids and create a suitable planting surface (bottom left). Then plugs of vegetation removed from the grubbing stage were added back in rows across the fill material.*

Filling ditches (where cost and logistics allow) eliminates the chance of ditch dams failing, due to high water flows that overtop the dam or erode around the dam. Filling with sediment allows plants to colonise the fill material and stabilize the surface. Both low and high flow ditches can be filled. Filling large ditches may require heavy machinery that increases cost and limits this approach to sites with road access for vehicles.

Determining the material suitable for filling ditches is important. Ditches can be filled with native peat if available (Bess et al 2014). This method was employed in a high elevation fen in Colorado that had a ~60 m long ditch that was 3 m wide and 1 m deep (Figure 19). Portions of the fen required reprofilling that created a surplus of old peat. Vegetation was first removed in sod clumps from the ditch, then the ditch was filled with peat using heavy equipment and packed down. The vegetation sod was then placed on top of the fill. Three check dams constructed from plywood were installed across the ditch to provide short term stability for the fill as the vegetation grew on the site (Figure 19).

Filling ditches with native peat is rarely possible, because spoil piles decompose and erode over time. Therefore, material other that peat is typically used. In an experimental ditch infilling project in a large sloping fen in Colorado, ditches were filled with shredded aspen wood bales (Chimner et al 2019b). All vegetation within the ditch was removed as sod blocks (Figure 20). The bales were then placed in the ditch by hand. After the bales were in place, peat from the ditch berms was removed and packed around the bales and at least 15 cm of the peat was placed on top of the bales as a growing medium. Along with bale placement, plywood sheets were inserted vertically and perpendicular to the ditch, to stabilize the bales and function as ditch dams in case the bale permeability was higher than the surrounding peat. Plant sod was then placed on the fill. Remaining bare areas were planted by hand with locally collected sedge plugs. Pre- and post-restoration monitoring of water table levels indicated that this ditch filling technique restored hydrological conditions 150 m downstream of the ditches and was similar to reference areas (Chimner et al. 2019). Ditches can also be infilled with bales created using heather, wood chips, or sawdust in a similar manner as the fiber bales (Mcbride et al 2011; Joosten 2021).

Mineral soil can also be used to fill ditches (Figure 21 and Figure 22). Particle size analysis should be used to match the hydraulic conductivity of the sediment to the project needs. For example, gravel or coarse sand may have rates of ground water flow that are too high to effectively slow the drainage of water in the filled ditches. The fill should contain suitable fine-grained sediment to retard water movement through the ditch but not so high that groundwater movement is prevented and limits the growth of vegetation over the filled ditch. The chemical composition of the fill should also match the chemistry of the groundwater in the peatland. For instance, if you are filling a ditch in a high pH rich fen, you should not use acid mineral soil which would lower the pH of the groundwater flowing through the fill. Conversely, if you are restoring a low pH peatland you should not use high pH fill material.

If there is insufficient material to fill the entire ditch, portions of the ditch can be filled with a combination of ditch blocking techniques or creating ponds occurring in the remaining area (Figure 23: Similä et al 2014).

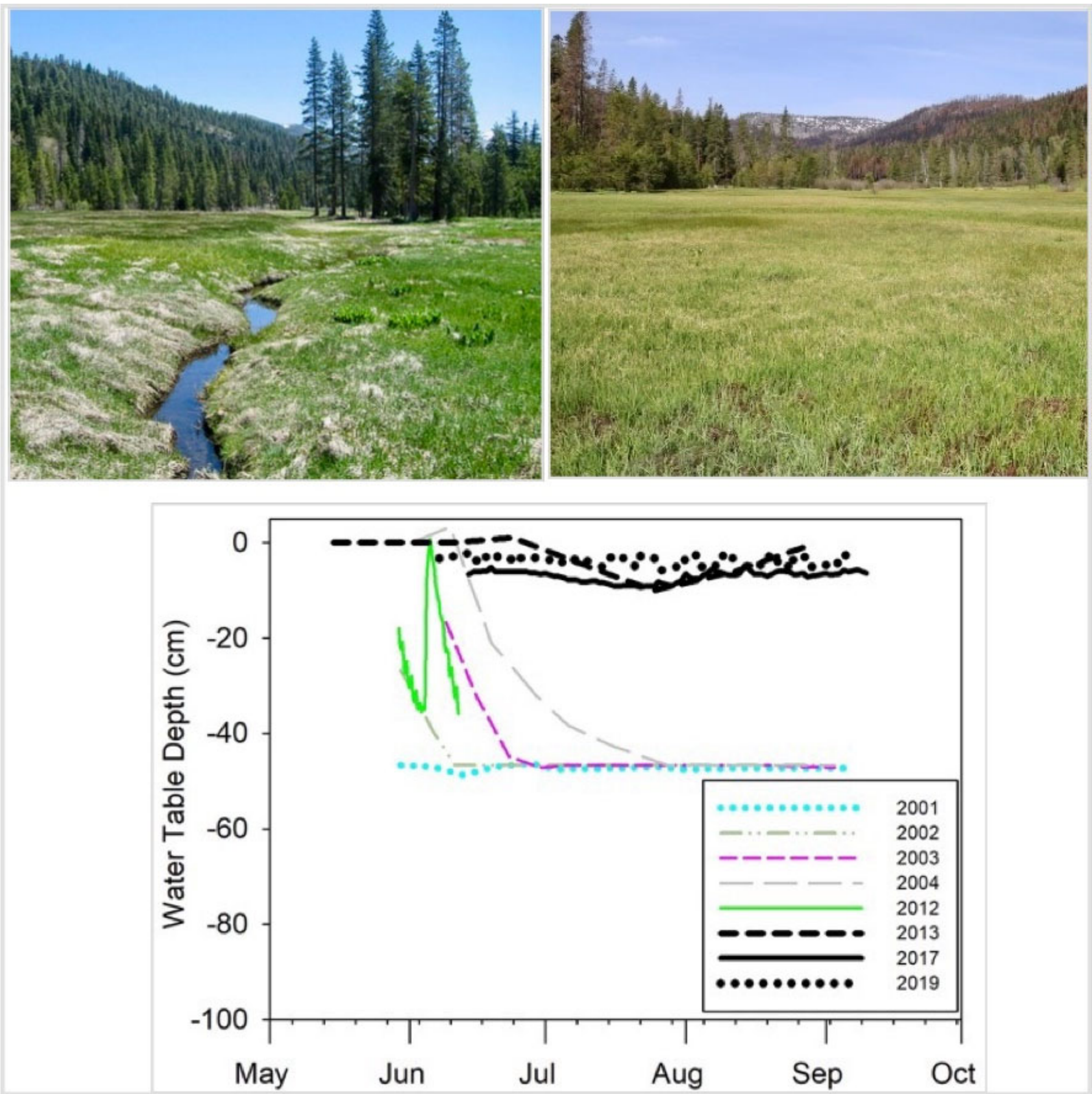

Figure 22. *Pre-restoration ditch in Drakesbad Meadow (top left) and the same area in 2019 after restoration (top right). Lower panel shows depth to ground water in Drakesbad Meadow for pre-restoration years 2001-2004 and 2012, and post restoration 2013-2019 showing the increase in water table levels after restoration.*

3.1.2. DITCH BLOCKING TECHNIQUES

Blocking ditches is a much more common technique than ditch filling because it is cheaper and easier to achieve, even in remote areas. The goal of ditch blocking is to stop or slow water flow in the ditch by creating a series of dams. Blocking ditches can be an effective restoration method for rewetting mountain peatlands (Cooper et al 1998; Cooper and MacDonald 2000; Patterson and Cooper 2007; Schimelpfenig et al 2014; Hartman et al 2016; Planas-Clarke et al 2020; Suárez et al 2022). Ditch blocking can also lead to changes in vegetation, reflecting the new wetter conditions (Cooper and MacDonald 2000) and can also restore pre-ditch carbon cycling processes allowing the resumption of carbon accumulation (Schimelpfenig et al 2014; Planas-Clarke et al 2020). However, not all ecosystem processes are quickly restored. For instance, soil physical structure (e.g., bulk density, hydraulic conductivity) may take decades or longer to recover after ditch restoration (Schimelpfenig et al 2014).

Two general styles of ditch dams are typically used: 1) impermeable dams and 2) permeable dams. **We recommend using impermeable dams for low flow ditches and permeable dams for high flow ditches (Section 3.1 and Figure 18)**.

3.1.3. IMPERMEABLE DAMS

Small ditches on low gradient slopes with limited water flow have been successfully blocked using a variety of materials to create impermeable dams (Armstrong et al 2009; Parry et al 2014; Schimelpfenig et al 2014). Native peat, bales of plant materials, wood planks, plywood sheets and steel sheets have all been used successfully to create ditch dams (Figure 24). Plastic has also been used (Armstrong et al 2009), but we do not recommend plastic in mountain landscapes due to the high UV that can degrade many plastics and they also release micro-plastics (Figure 24). Each material has benefits and drawbacks, and correct installation is critical.

Figure 23. Using peat dams to partially fill a small ditch in Scotland.

3.1.3.1 PEAT DAMS

In many parts of the world, especially in large flat peatlands, ditch blocking is often accomplished using peat blocks placed into ditches (Quinty and Rochefort 2003a; Vasander et al 2003; Lunt et al 2010; Haapalehto et al 2011; Parry et al 2014). This technique can be used in mountain peatlands that have small and shallow ditches, less then ~0.5 m deep and wide. Peat sod can be cut by hand from the sides of the ditches and wedged into the ditch. Peat sod should be a little bit larger than the ditch area so a tight seal can be created. Peat can also be anchored by wooden stakes on the downgradient side of the dam. We have also seen peat wrapped in geotextiles before wedging into the ditches. Ideally, if peat with vascular plants is used the plant roots can grow into the side of the ditch and help hold the peat dam into place (Figure 24).

Bags filled with loose peat can be effectively used to block small ditches, or can be used in tandem with other ditch blocking methods. Peat bags are especially useful at remote sites since empty bags can be carried in a backpack and filled at the restoration site. We recommend filling bags with peat collected on-site to limit variance in peat chemistry, but other material could be

Figure 24. *Examples of impermeable ditch dams to be used in low flow ditches. Peat dam (top left and bottom left), plastic (top right), steel (center), and wood (bottom right). Notice the degrading plastic (top right) from UV.*

used, including mineral soil. In order to remain effective in high flows, peat bags must be anchored securely to the ground surface using wooden stakes both up and down gradient of the bags. Without anchors, the bags may move during high flows. We have tried several peat bag types and found that jute bags work well. Less expensive plastic bags remained intact for only 1–2 years due to high UV in high mountain areas. Jute bags can also be planted to make "living" ditch dams (Figure 25). By establishing plants, especially sedges on the jute bags, the bags are protected from sunlight and plant roots will hold the dam and keep it from degenerating. Peat bags can also be vegetated by adding seed or transplanted rhizomes or nursery grown seedling into the tops of the bags, or by placing sod on the tops and sides of the bags.

Ditch blocking with peat (Figure 24: bottom left photo) using heaving machinery has been used widely in sloping blanket bogs in the UK. Similar approaches could be used in mountain fens. Techniques from the UK (Thom et al 2019) are summarized here: Peat dams can be created by digging up peat with a low-pressure machine either straddling or beside the ditch. If vegetation occurs in the ditch where the dam will be made, first remove the vegetation to a depth sufficient to ensure the root zone stays intact 0.5 - 0.6 m on either side of the ditch and to a depth of 0.2 - 0.3 m into the base of the ditch, for a length of approximately 1.5 - 2.5 m upstream of the dam site. Set the vegetation aside. Peat used for the dam construction should be from the ditch (upstream from the dam placement) or areas adjacent to the ditch (avoiding dried out or unconsolidated peat). The required dimensions for the peat dam depend on ditch size. Turn the peat over in an area stripped of vegetation to create a wedge-shaped dam 1.2 - 1.8 m thick, making sure that the dam is wedged into both sides of the ditch by 0.5 - 0.6 m and the base by 0.2 - 0.3 m. The finished peat dam should be 0.5 m higher than the surrounding ground to allow for settlement and flow of impounded water away from the dam. An overflow can also be created by making a crescent-shaped shallow overflow channel to the new dam, ensuring excess water can be dispersed onto the peatland without causing subsequent surface erosion.

Caution must be used in placing peat dams in mountain peatlands (Mcbride et al 2011). Although peat dams are commonly used in other parts of the world, they can fail in high gradient settings. Many mountain ranges, especially temperate and boreal zone mountains, receive abundant winter snow and rapid spring time snowmelt can create high flows. In addition, many mountain regions receive periodic intense precipitation also creating high flows that can be erosive.

3.1.3.2. BALE DAMS

Impermeable check dams can be created from straw, wood, or heather bales (Armstrong et al 2009; Thom et al 2019; Suárez et al 2022). To create a dam using bales, each bale must fit snugly against the ditch wall. This may require cutting the ditch side wall to the shape of the bale. If the

Figure 25. *Example of using bags to create living impermeable ditch dams for low flow ditches. Filling and placing jute bags in bottom of ditch (top), then placing peat sod on top of bags (bottom).*

ditch is narrow, bales can be placed longways in the ditch, and if wider are placed sideways, or a combination of both directions to fit the ditch. The use of peat bags to fit into smaller spaces also works well with bale dams. Wooden stakes should be inserted upwlope and downslope of the bales to hold them in place.

Modifications to bale dams is to use them to create a “living” ditch dam. Once the bales and

Figure 26. *Example of how to build living ditch dams using bales for low flow ditches. A trench is dug and bales placed (top left) followed by peat sod being placed on the bales (middle right). After 1 year the sedges covered the bales and held it in place (bottom). Several years later, the dense sedge cover completely hid the bales (top right).*

peat bags are in place, they can be covered with a layer of peat and planted or seeded to encourge plants to grow over the bales (Figure 26). The advantage of living ditch dams is that the plant roots hold the dams in place and the site will attain a natural appearance.

3.1.3.3. WOOD DAMS

Wood is a common material for damming ditches and is widely available, easy to transport, easy to create custom dam designs in the field, and under the right conditions can last for many years. We recommonded using non-treated wood when possible to minimize chemical leaching. Three types of wood dams normally used are plywood, horizontal planks, and vertical planks.

Plywood can be used to block smaller ditches by cutting the plywood to the desired size, which should be at least 50 cm wider than the ditch on both sides, and at least 50 cm deeper than the depth of the ditch (Figure 24). A slot is then created in the peat and then the plywood is pounded into the peat being careful not to break the plywood. Plywood dams can be very difficult to install

Figure 27. *Vertical wood dams being installed in an Indonesian peatland. Notice the V-shape cut on bottom of the planks to facilitate pounding them into the peat. The first plank has been installed in the middle of the ditch with following planks installed adjacent to the first plank.*

in dense peat containing wood and dense roots, or in deep ditches. In these cases, vertical wooden planks are recommended.

Shallow ditches can be blocked with horizontal wooden planks. Horizontal planks can be cut to size, at least 50 cm wider than the ditch on each side and placed on top of each other acoss the ditch. Verticals wood stakes are placed behind the planks to hold them in place. Its important to make sure the bottom planks are deep enough into the peat that water cannot flow under it.

Deep ditches, ditches with loose peat on the bottom, or dense or rooty peat can be restored with vertical wood planks (Figure 27) pounded deep into the peat. This can be facilitated if the bottom edge of each plank is cut into a v-shape. First install a horizontal board across the ditch anchored by two square planks to use as a guide. Then insert the central plank first as it will usually be the longest and most difficult to install. Make sure each plank is inserted at least 50-60 cm into the peat or deeper if the peat is poorly consolidated. Continue installing the planks working from the center outward until you are at least 50 cm past the ditch bank to keep water from flowing around the planks. After all the planks are in place, you can attach each plank to the cross boards and cut the planks to the appropriate height. Peat can then be placed upstream and downstream from the planks to stabilize and cover the installation (Joosten 2021).

3.1.3.4. STEEL DAMS

Check dams made of sheet steel have been efficiently used to block ditches in mountain peatlands (Cooper et al 1998; Patterson and Cooper 2007). When properly installed, annual maintenance is minimal, and they may be effective for many decades, unlike wood which can break down over time. Installation of steel sheet is identical to plywood. An example occurred in Big Meadows, a large fen in Rocky Mountain National Park, Colorado that was ditched by a homesteader in the 1890s and had been dewatering the fen for nearly 100 years. 16-gauge galvanized sheet metal, 3 mm thick and up to 150 cm wide and 90 cm deep, were installed across the ditch in 1988 and 1989 that immediately increased water levels across the fen (Cooper et al 1998). After 35 years, the sheet metal dams are solid, not rusted and without channels under or around them (Figure 28).

3.1.4. PERMEABLE DAMS

We recommend using permeable ditch dams for high flow ditches (Section 3.1 and Figure

Figure 28. Steel dams installed (top) in 1988 and their condition 33 years later (bottom).

18). Permeable dams should be used on high flow ditches as they are designed to allow water to pass through or over them. Permeable ditches are also useful if the ditches are entrenched (Section 3.1.5.3.).

3.1.4.1. PERMEABLE WOOD DAMS

V-notch dams can be created easily from many standard impermeable ditch dam designs with

Figure 29. Two examples of wood permeable ditch dams for use in high flow ditches. Vertical wood planks (top) and horizontal wood planks (bottom).

wood being an especially common material to make v-notch dams (Figure 29). Construction follows the instructions for the impermeable wood dam design in Section 3.1.3.3. and add a v-notch at the top of the dam to allow excess water to flow over the dam. The bottom of the notch should correspond to the highest level of water that is desired in the ditch. Notches can be cut in the plywood sheets or horizontal planks or can be created by uneven vertical planks in the dam (Figure 29). Notches can be made from one large cut, or several smaller notches (Thom et al 2019;

Joosten 2021). Notches can also be cut in stainless steel or other impermeable dam material. Permeable wood dams can also be created by leaving a small gap between the top two horizontal planks.

3.1.4.2. STONE DAMS

In areas where ditches are cut into dense peat, thin peat, or to mineral soil, rocks can be used to create small check dams. Rock structures are porous, and water can percolate through. Stone dams are good for trapping sediments, however, over time the pores may fill with sediment and slow or stop the percolation. Stone dams are probably most useful in wide shallow ditches in low gradient settings where rock is available nearby and importing other material would be difficult. Rock dams are not commonly used in mountain peatlands but have been used some in UK blanket bogs (Thom et al 2019) and in wet meadow restoration in North America where they are called "one rock dams" (Zeedyk and Clothier 2014). The chemical composition of the rocks should match the chemistry of the groundwater in the peatland.

Guidelines for the use of stone checkdams on blanket bogs in the UK (Thom et al 2019) suggests they span the full width of the ditch and be a minimum of 75 cm high and 75 cm from upstream to downstream. The rock dams should be no taller than 1 m tall for safety reasons. Dams

Figure 30. *Example of ditch dam spacing by placing dams in a location that when the water backs up from the bottom dam the ditch is filled with water to a level above the base of the next dam up slope.*

should have a steep face (approximately 60 degrees) on the upstream side and a 45 degree slope on the downstream face. Stone dams should be higher on each side than in the middle to allow water to flow over the middle of the dam to prevent scouring around the sides.

Rock dams used in wet meadow restoration in North America are similar to the stone check dam in the UK. They are best used in wide shallow ditches on firm soil. They can have one layer of rock on the ditch bottom to slow the flow of water and trap sediment. Rocks should fit together tightly, and be the same height to create a relatively uniform top height. A footer should be used as a splash apron on the downstream end that extends far enough downstream (2x the height of the one rock dam) to slow water running over the structure in high flow events. For in-depth construction and use of one rock dams consult Maestas et al (2018).

3.1.5. DITCH BLOCKING DESIGN ISSUES

Figure 31. *Example of poorly designed impervious ditch dam showing where water eroded under the dam.*

3.1.5.1. DITCH DAM SPACING

Multiple dams may be required to block most ditches. The distance between dams should vary based on the ditch slope, and could range from 3 to 12 m apart with greater spacing for lower gradient peatlands with less water flow. In UK blanket bogs the average spacing of peat dams is recommended to be 7.5 m, with 12 m apart on relatively level sites and 5 m apart on steeper slopes

Figure 32. *Example of poorly designed impervious ditch dams allowing water to flow around the dams.*

(Thom et al 2019). Another way to determine the spacing of dams is that the placement of each dam should back up water to reach the base of the next dam up slope (Figure 30). The placement of ditch dams should be fine-tuned during the design phase to improve project success. Ditch dams are most effective when placed in narrow pinch points and areas where ditch water can infiltrate into the adjacent wetland.

3.1.5.2. Erosion

Poor ditch dam design can results in erosion and the destabilization of dams. This could lead to dam failure and erosion that can exacerbate the degradation. Frequent monitoring of ditch blocking should occur after construction, especially after hard rains or snow melt, to identify problems. Undercutting of dams typically occurs from two processes, high pressure from water backed up behind the dam or water flowing over the top of the dam allowing head cutting. As the water becomes deeper behind the dam, the water pressure becomes greater and can erode the dam (Figure 31). To stop this from happening, the ditch dams must be inserted at least 50 cm below the bottom of the ditch if possible. This is especially important if the peat is soft beneath the ditch.

Erosion from water flowing over a dam, especially v-notch dams, can undercut it and lead to failure. To minimize erosion the ditch dams should be spaced close enough so water pooled behind a downstream dam is at least 20 cm deep at an upstream dam (Figure 30). This allows water flowing over the v-notch dam to contact water that dissipates its erosive energy. In addition, rocks

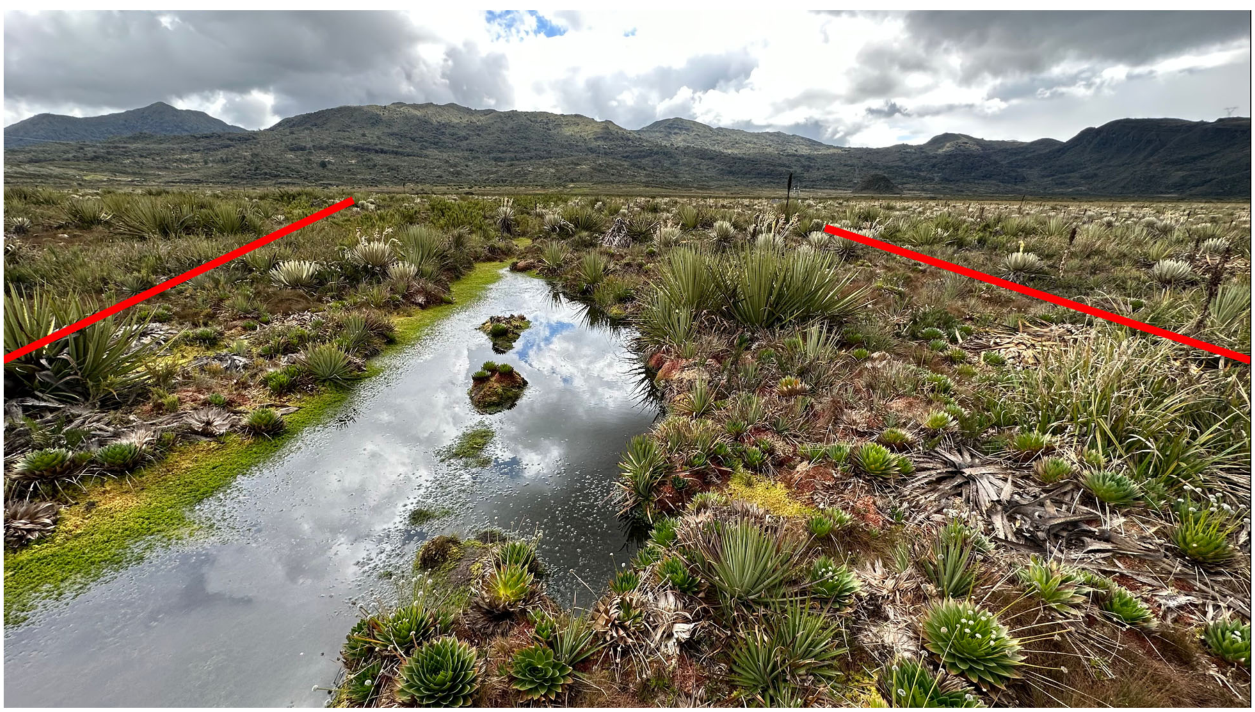

Figure 33. *Example of an entrenched ditch in Colombia. The red lines show where the peatland surface slopes towards the ditch. Ditch dams can span the width of the open water or extend to the red lines.*

can be placed on the downstream side of the dam to dissipate water energy and provide extra protection if water in the pool is low.

Ditch dams can also erode on their sides. This can occur due to the wrong type of ditch dam being used such as building an impermeable dam when water flow is too great (Figure 32) or not making the dams wide enough. Ditch dams should be at least 50 cm wider than the ditch on each side, but wider is better especially in less dense peat. Erosion can also occur if water flows out of the ditch and onto the wetland creating new channels, which can be minimized by ensuring that water flows on densly vegetated sections.

3.1.5.3. PROFILING DITCHES

Steep ditch sidewalls can limit plant growth in restored ditches (Figure 18). To encourage better growth, reprofile the ditch sidewalls between the ditch dams by removing peat from below the sod layer and pack into the channel (see Section 3.2.2 for more information on reprofiling). However, reprofiling is only recommended for low flow ditches as loose peat will be flushed away in high flowing ditches.

3.1.5.4. ENTRENCHED DITCHES

Some ditches can become entrenched over time which makes blocking them more complicated (Figure 33). Entrenching happens when the area next to the ditch is undercut or influenced by increased decomposition and compression (Krause et al 2021). Therefore, dams can either extend from the top of slope to top of slope on each side or just across the open ditch portion.

3.2. GULLIES

Gullies form when channelized surface water erodes through the soil and subsoil deeply enough to drain entire valley bottoms (Evans et al 2005; Cummins et al 2011). Gully formation results from down-cutting (vertical lowering of the gully bottom that leads to deepening and widening), and head-cutting (upslope erosion that extends the gully upslope lengthening the gully and increasing the number of gully tributaries). Gully restoration should occur as soon as possible because large gullies are difficult and costly to repair (Evans et al 2005). In general, gully restoration involves stabilizing the gully, reprofiling the sides, and diverting and modifying the flow of water through it so scouring is reduced, and sediment accumulation and re-vegetation

Figure 34. Gully (top left) in Sequoia National Park that was filled (top right), planted and covered with geotextiles (bottom left) and fully restored a few years later (bottom right). The road was replaced with a bridge in addition to filling the gully (top left vs. bottom photos).

occurs. It is essential to stabilize the gully head to prevent damaging water flow and headward erosion that allows the gully to increase in length. Restoring gullies in peatlands is similar to restoring ditches; they can be blocked or filled (Evans et al 2005).

3.2.1. GULLY INFILLING TECHNIQUES

Simular to infilling ditches, gullies can be infilled over their entire length. A large gully in Halstead Meadow, Sequoia National Park (California, USA) was filled and illustrates the general procedure (Figure 34). This wet meadow/fen complex was an enclosed livestock pasture in the early 20th century when the livestock denuded the wetland vegetation. Construction of a highway

Figure 35. *Gully reprofiling in Scotland. A gully causing peat erosion and drying (top left), gully reprofilling with an excavator (bottom right), steep side walls covered with coir matting and planted (top right), and restored gully (bottom left).*

across the wetland with a single main culvert collected water flows as sheet flow into one channel that eroded vertically upgradient and downgradient through the entire meadow. This created a gully 6 m deep, 15 m wide and more than 400 m long that threatened to remove all of the mineral sediment and peat from the meadow.

Beginning in 2009, the gully upslope of the highway was filled with more than 7,000 m^3 of mineral sediment installed in 20-30 cm layers. Curlex matting (aspen shavings held in place by thin photodegradable material and netting) was used to protect the bare sediment but was not strong enough to resist the forces of high flows in steep valleys. For steeper reaches RoLanka HioD-Mat 90 woven coir (coconut fiber) matting, overlapped and staked in place, was used; this was able to withstand the large snowmelt flows in the meadow. Pre-vegetated coir matting (PVCM) was also used at this site. PVCM is double thickness coir matting into which seedlings are planted and grown in shallow water or other wetland conditions until the seedlings root throughout the mat. The matting is then rolled and transported to the restoration site, where it is unrolled and staked in place. PVCM provided excellent erosion protection and very rapid growth of plants in critical portions of the study area, such as the steepest valley sections and other highly erosive valley areas. Seedlings of nursery grown *Scirpus microcarpus, Glyceria elata* and *Oxypolis occidentalis* were planted at a density of 4 m^2 in all restored areas.

The meadow area below the highway crossing was restored in 2012–2013. This involved filling the remainder of the gully with more than 10,000 m^3 of sediment; removing the highway, which was built on fill, and replacing it with a bridge to allow the sheet flow system to be restored through the entire meadow; and planting primarily *Scirpus microcarpus*, which forms a clonal plant cover suitable for other species including bryophytes, to invade. Recovery has been rapid, and formation of dense clonal vegetation with nearly 100 % cover occurred within three years (Figure 34).

3.2.2. GULLY PROFILING AND BLOCKING TECHNIQUES

Must gullies cannot be filled, due to a lack of available sediment, or limited budget, and must be treated by reprofilling and blocking. Gullies typically have very steep and bare side walls that make it difficant for vegetation to establish. This facilitates continued erosion (Figure 35: bottom right photo showing left side with steep side walls and overhanging vegetation). The general technique for treating gullies is to reprofile the gully to have lower gradient slopes, if bare side walls steeper than 30 degrees are present. After reprofilling, gully blocking is recommended if the gully has water flowing down it.

Reprofilling creates slopes at no more than a 3:1 (33 degree) angle. The first step is to salvage vegetation on the slopes including sufficient soil thickness to include the plant root structure. Then reshape the slopes to create a stable slope by pulling peat into the bottom of the gully creating a U-shaped cross section (Figure 35). The vegetation sod should then be placed back onto the slopes (see Section 3.8).

Gully reprofiling can be done with heavy equipment, but this is often not pratical in remote mountain regions, and must be accomplished using hand tools. When hand-reprofilling digging peat out from under the established slope vegetation is most feasible. This soil can then be pulled into the gully bottom. The formation of 3:1 slopes may not be possible, and the newly created slopes can be covered with jute matting or other geotextiles to stabilize the soil while the site is revegetated (Figure 35).

After profiling the gully, most mountain peatlands should be blocked using check dams to stop erosion and trap sediment (Evans et al 2005; Lunt et al 2010). Check dam design in the gully bottom could use techniques described in Section 3.1. We recommend using a permeable ditch dam design because a gully forms due to running water so an impermeable design may not be successful unless water flow in minimal. If enough sediment is trapped behind the dams that the gully starts filling in, the dams can be increase in height. For example, horizontal timber plank dams could be created with taller supporting posts so additional planks could be added on top as the dam infills behind it (Thom et al 2019).

Another important step is to slow water entering the gully or divert water away from the gully to reduce flow and erosion potential. Channels entering the gully could have permable ditch dams slowing the water before it reaches the gully. If possible, water chould be diverted around the gully, being careful not to create a new gully.

3.3. ROADS

Roads can have significant effects on peatlands by intercepting groundwater, eroding peat from discharge areas, and being a source of sediment, dust or salt to the peatland (see Section 3.4 for techniques of sediment removal). The approach for restoring roads impacts depends on the issue(s) the road is causing.

Figure 36. Construction of a permeable roadbed (top) with the finish road shown (bottom).

A common impact from roads is hydrologic alteration, including sheet flow (discussed above) and groundwater. Several techniques can be used to address groundwater interception and dewatering of peatlands. One approach for small unpaved roads is to increase the number of locations where groundwater and surface water can flow over or under the road. This option was used on a restoration project in Lassen Volcanic National Park, California where an access road was intercepting groundwater to a fen (Patterson and Cooper 2007). The road was breached in 21 locations that allowed water to flow across the road and down into the fen.

Adding additional culverts to a road to increase flow is another option to restore groundwater flow. The design of culverts is beyond the scope of this restoration manual, but there are many manuals on best management practices for culverts. Culverts can create significant problems for mountain peatlands and wetlands in general. Culverts typically are fed by a wide road ditch system that collects water, channels it under the road, and the water exits the culvert as a point source with relatively high energy. Culverts can create channels that erode soft peatland soil downstream of the culvert. A single culvert under the General's highway in Sequoia National Park created a gully 6 m deep, 15 m wide and more than 400 m long that was complex and expensive to restore.

Because culverts can cause erosion and groundwater impacts alternatives have been developed. One option for allowing groundwater to flow under roads is creating a permeable roadbed (Figure 36). This design was tested in two forested fens in Northern Minnesota by removing the existing roadbed and replacing it with a base of geotextile fabric, alternating 12-inch layers of 4 to 6-inch diameter rock, and geotextile fabric with a mineral soil road surface on top (Figure 36). A culvert was also incorporated to enable more rapid transport of water across the road in the event of large flooding events. This technique was successful in allowing water to flow under the road and minimizing ponding.

3.4. BURIED OR BARE PEAT

Peatlands can be buried by sediment from mines, mills, roads, or slope erosion; or purposely filled for development of housing, golf courses, or highways. The main technique for restoring buried peatlands is to first discover whether peat soil remains beneath the fill and document changes to the hydrological regime from buried drains or water diversions. This can be accomplished by excavating pits through the fill to identify the original soil surface. Monitoring wells can be used to determine if the water table is still near the original soil level. If the original peat surface can be identified, and there is no change in hydrologic regime, then the original peat soil surface is the target for a fill removal project.

It is critical to determine the water table position beneath the fill by using monitoring wells (see Section 2.2.1.4.) inserted through the fill into the buried peat. If the water table is still near the surface of the buried peat surface, then hydrological conditions are suitable for recovery of the

Figure 37. *Sequence of photos showing a golf course that was built on top of a fen (top left), excavation of fill from golf course (top right), revegetation of excavated fen (bottom left), and restored fen (bottom right).*

peatland. If it is not, then drains, diversions and other hydrological modifications of the peatland and its catchment must be identified and removed. Once the peatlands hydrological regime has been restored, the fill can be excavated to expose the former peat surface. Or if after excavating the overburden and the water table is still deeper than optimal for a peatland then surface peat can be removed to lower the ground elevation to match the water table. Fill placed by heavy machinery can result in compaction of underlying peat, and after removal of the fill, the site is wetter then suitable reference areas requiring the establishment of species suitable for such seasonal ponding. The final step is to re-establish vegetation because the buried peat is bare and susceptible to erosion, although there may be some recruitment from a soil seed bank if the original ground surface is perserved (Section 3.8).

Figure 38. *Frost heaving bare fen soil (top left) was mulched with excelsior and planted with sedge transplants (top right), which was fully revegetated after four years (bottom).*

Figure 39. *Example of erosion control on a steep mountain fen in Colorado. The slope is initially covered with mulch (left), followed by jute matting, and straw wattles are placed to reduce water flow (right).*

This approach was used to restore several fens that were filled and buried by golf course construction in the town of Mountain Village, Colorado during the 1990s (Cooper et al 2017) (Figure 37). Approximately 5 ha of fens were analyzed to determine the depth and character of the buried peat. The natural hydrological regime was restored by excavating the mineral sediment using heavy machinery and removing all subsurface drains. The sites were planted with native fen species. The fens were monitored annually for five years post-restoration, and again at 15 years. Water table regimes in the restored fens are indistinguishable from those of natural fens in the region, and a dense cover of native fen plants including bryophytes has established. Most sites have 100 % canopy cover of native clonal plants such as *Carex aquatilis* or *Carex utriculata*, and typical fen mosses such as *Drepanocladus aduncus* and *Cratoneuron filicinum*.

Frost heave is a major problem limiting the revegetation of bare peat and can affect the survival of planted and naturally recruited plants (Chimner 2011). Frost heaving occurs when soil is uplifted by needle ice formation from nightly freezing and daytime thawing. This loosens the surface peat, breaks up plant fragments, uproots seedlings and increases erosion (Groeneveld and Rochefort 2002). Frost heave in a disturbed Colorado fen was greatest when the water table was 10–20 cm beneath the soil surface (Chimner 2011). Frost heave can be controlled by establishing a plant cover (Section 3.7) and using mulch (Figure 38).

Straw mulch is the recommended choice for minimizing frost heave from harvested peatlands in North America (Quinty and Rochefort 2003b; Groeneveld and Rochefort 2005). However, straw mulch did not work well in fens in the San Juan Mountains of Colorado because of the deep snowpacks that compressed the straw mulch into the peat with little to no loft (trapped air) (Chimner 2011). Excelsior mulch held up better in the deep snowpack and retained much of its original loft after several winters and controlled frost heave (Figure 38).

Because many mountain fens are sloping, sometimes steeply, erosion control can be an important consideration in restoration. A large number of commercial erosion control products are available, and selection should take into account the potential for erosion based on the volume of water expected, slope steepness, and existing vegetation. Working on a mountain fen with ~20% slope, we have successfully layered a ~5 cm layer of Excelsior mulch on the peat surface, then placed jute matting on top of that (Figure 39). The matting was staked to the peat soil to limit sliding downslope. On top of the matting, rows of straw wattles were placed perpendicular to the slope. The combination of mulch and matting reduced raindrop splash, which dislodges soil particles and increases erosion. The straw wattles reduced the amount and velocity of water flowing over the surface of the soil.

3.5. GRAZING

Most peatlands, especially those dominated by *Sphagnum* spp., have little or no forage to

Figure 40. Bare soil and erosion are indicators of disturbance from livestock trampling.

support domestic livestock grazing and have low rates of herbivory by native animals. However, many mountain fens are dominated by sedges and other graminoids and provide the best forage for domestic livestock, especially in summer dry climate regions such as the Sierra Nevada, of California (Vernon et al 2022), the Alps (Graf et al 2022), the central and southern Andes of Peru, Boliva, Chile and Argentina (Cooper et al 2010; Young et al 2023), the Himalayas (Wu et al 2015), and in Africa (Trettin et al 2008).

Overgrazing may directly effect plant species composition, nutrient runoff, plant production and vegetation cover, resulting in immediate changes to carbon cycling, and greenhouse gas emissions (Allen-Diaz 1991; Ward et al 2007; Urbina and Benavides 2015; Sánchez et al 2017; Vernon et al 2022). Trampling can cause soil compaction and create bare patches by hoofs punching holes in the peat, causing erosion and gully formation, removing vegetation, and reducing plant production and carbon sequestration rates (Figure 40). Some mountain fens are more resilient to grazing than others. For example, sedge dominated fens have dense networks of shallow rhizomes that can stabilize the surface soil. However, moss dominated fens with low cover of clonal vascular plants may have relatively unconsolidated peat that can be easily damaged by large animals. As a general rule, livestock should be removed or restoration occur when ~10-20% bare soil is visible (Mcbride et al 2011).

Peatlands that have been disturbed by livestock use can be restored using a combination of passive and active techniques. Passive restoration removes grazers assuming that once the disturbance is removed the peatland will recover without additional treatment. This can be accomplished by erecting fences or removing livestock from the peatland (Carevic et al 2019), however, erecting an excloser alone may not be sufficient for restoration (Merriam et al 2018). If total livestock removal is not desirable or possible, the use of alternative grazing practices can be used such as rotational grazing, seasonal grazing, using a lower density of livestock, or grazing limited to short periods when deeper water tables occur creating drier and more stable ground surface conditions, such as the end of the summer (Mcbride et al 2011) in the northern hemisphere or during the dry season in other regions (Fraser et al 2022). Virtual fencing for cattle, which uses collars and GPS tracking, can also be used to keep cattle out of sensitive areas (Fraser et al 2022).

Hydrological changes can be caused by grazing or grazing management, either through ditches deliberately dug to dry out the peatland, or through the erosion of cattle tracks to form channels that can cause gullies or small drains. It is possible that many heavily grazed peatlands are currently in an alternative stable ecological state created by legacy livestock grazing that completely altered the hydrological regime, vegetation, and/or soils. Active hydrologic restoration might also be required if channels, ditches, gullies or other erosional features that impact peatland hydrology are present (see Sections 3.1 and 3.2).

Re-establishing peat-forming plants (see Section 3.8) is a critical next step. However, if the grazing was so severe that the ecosystem potential has changed it might be difficult to determine which plant species should be introduced. In this case, palaeoecological or seed bank studies, or reference site analyses, are required to help define the potential native species pool.

Figure 41. *Peat harvested by hand in Peru for fuel (top) that can recover if cut shallow (middle right). Peat that was just started to be harvested in Scotland for fuel (left) and peat drained for harvesting in Colorado (bottom right). Top and middle right photos from Christina Rengifo Faiffer.*

3.6. PEAT HARVESTING

Peat harvesting is less common in mountain peatlands that other peatland types in Britain, Ireland, Scandinavia, and Canada. Most peat harvesting in mountain peatlands is done by cutting peat by hand, but it has also been harvested by machine (Figure 41). Some peat cutting, especially shallow peat cutting done by hand, can regenerate on its own (Figure 41), while other more intensively ditched and harvested peat does not regenerate well and requires active restoration (Cooper and MacDonald 2000).

Peatland restoration following mechanical peat harvesting in bogs has occurred for several decades and extensive research has produced good methods for reclamation and restoration. For the restoration of mountain peatlands, especially machine harvested peat, we refer you to several excellant manuals (Quinty and Rochefort 2003a; Similä et al 2014). There are less developed techniques for restoring peatlands from peat harvested by hand. The general procedure would be to contour any side walls to a 3:1 slope to minimize erosion and facilitate vegetation regrowth (see Section 3.2.2.). Next steps would be to revegetate the site with appropriate plant species (see Section 3.8) and block or fill any ditches that are used to dewater the site (see Section 3.1).

3.7. RECREATION IMPACTS

Mountains are hotspots for recreation including hiking, horse-back riding, mountain biking, off-road vehicles, skiing, and snowmobiles, and can impact peatlands (Figure 42). Recreation impacts vary widely depending on the activity and can range from small localized impacts from off trail walking or biking to widespread impacts from mountain-scale ski areas.

Trails created by hiking, horseback riding, or mountain biking, can cause erosion and loss of peat (Figure 42). Restoration should include repairing the degraded or incised trail as well as altering the trail so further damage does not occur. If trails are incised into the peat, they can function as small ditches or gullies and can be restored using techniques covered in Sections 3.1 and 3.2. The goal of restoration is to stop water from flowing down the trail to eliminate additional erosion and gullying. This is accomplished by either filling the trail or creating small check dams. Revegetation should also occur if natural revegetation is not sufficient (Section 3.8). If the trail will continue to be used it should be routed around the peatland or constructed to eliminate further erosion. Trail construction options including building board walks, flagstone walkways, or a raised trail constructed of rocks or gravel that allow water to pass through the rocks (Figure 42). If trails are built in peatlands, care needs to be taken to not impeded groundwater flow or introduce rocks that vary greatly in chemical content from the peatland groundwater (Section 3.3).

Figure 42. *Peat erosion from hiking across a mountain peatland in Wales (top left), new gravel trail built across the peat in Wales (bottom left), flagstone walking path in Scotland (top right) and vehicle tracks in a Colorado fen that are at least 15 years old and initiated a small gully (bottom right).*

Tire tracks from off-road vehicles can be very damaging to peatland vegetation and soil especially if the tracks go up and down steep slopes (Figure 42). Off-road vehicles impacts are similar to hiking trails and cause erosion and gullying but are often worse because the rutting is deeper and more widespread due to the vehicle weight. Techniques are similar to fixing hiking trails and include stopping water flowing down the tire tracks so further erosion and gullying will

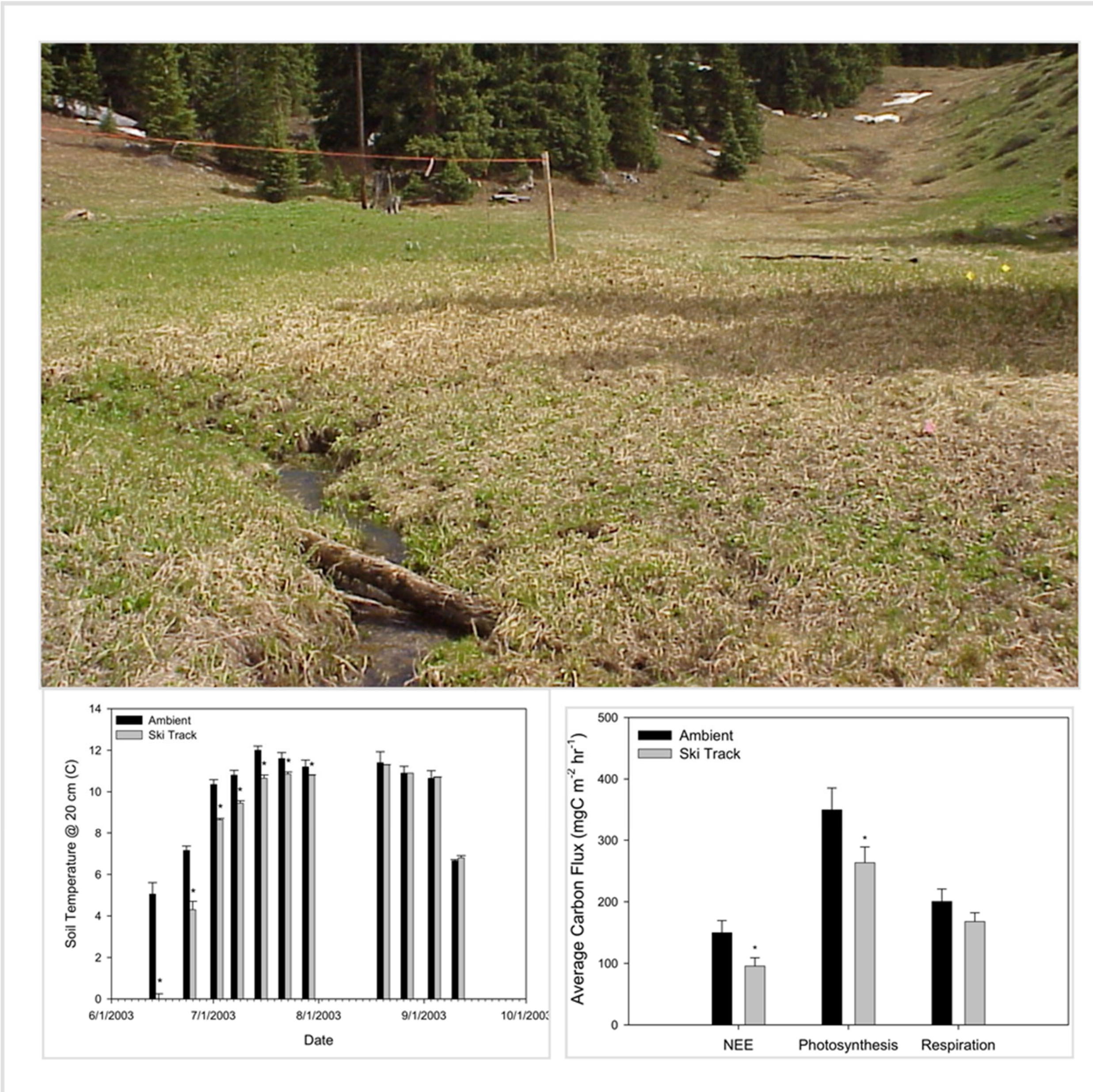

Figure 43. *The brown sedges indicate the location of the groomed ski run vs the green sedges just outside the ski run (top). The soil in groomed trail was colder than the soil in the ungroomed trail (bottom left), which resulted in lower gross photosynthesis and net ecosystem carbon storage (NEE) (bottom right).*

not occur. This can be done using check dams or filling in the rutting and revegetation may be needed (Section 3.8).

Downhill ski runs commonly cross peatlands. Attempts to open trails as early as possible may necessitate using tracked vechicles to pack snow, particularly in areas with ground water discharge, such as fens. When the snow is thin, this can be particularly damaging to vegetation and soil. Compaction of the snow throught the season changes the character of snow, from low density with lots of air trapped in the snow, to more dense and solid snow. The initial character of the snow provides excellent insulation to the ground, and in most areas peatland soils do not freeze, even in sites at 3000-4000 m elevation. However, once the snow is compacted, it loses much of its insulation capacity, and conducts the cold of the atmosphere into the ground and the soil freezes. In the Telluride Ski Area in SW Colorado, ski runs cross two fens, and soil in the reference portion of each fen outside the ski runs never froze over many years of continuous monitoring (Figure 43). However soils under the ski runs froze in December or January, and remained frozen in many years until well into June or even early July, which affected plant growth and carbon storage (Figure 43).

Snowmobiles on deep snow usually do not impact peatlands. However, snowmobiles can cause damage to vegetation and peat when they are running on shallow snow. If snowmobile trails are being groomed, then deep ice can form under the groomed trails simular to ski runs.

3.8. ESTABLISHING VEGETATION

The first step in restoring plant cover is to determine which plant species are appropriate and can survive in the newly restored site conditions. Native plant species should always be used and plants or seeds should be collected as close to the restoration site as possible. Species should be native community dominants determined by the analysis of reference peatlands. Its critical to select species that are suited to the chemical and hydrological conditions of the restoration sites.

Soil moisture and water table position are critical for establishing wetland plants because most wetland plants cannot survive in dry conditions and each plant has a distinct hydrologic niche. In addition, many peatland species cannot tolerature deep or prolonged inundation, which can occur in some restored peatlands where compaction, decomposition or mining has created depressions. Transplant survival of *Carex aquatilis* in locations where the average water table level was within 25 cm of the soil surface was found to be more than double that at sites where the water table was deeper than 25 cm (Cooper and MacDonald 2000; Chimner 2011). Cooper and MacDonald (2000) found that survival of many fen vascular species was dependent upon water table level; and the survival of mosses after re-vegetation is also strongly controlled by soil moisture and water table position (Rochefort et al 2003; Chimner 2011; Borkenhagen and Cooper 2018). The plant species to be reintroduced also needs to be matched to the groundwater chemisty (Section 2.1.1) as each plant has a biogeochemical niche (Chimner et al 2010; Lemmer et al 2023). Therefore, the ecological tolerances of plant species being introduced must match the hydrological and chemical conditions of the restored site.

3.8.1. MOSSES

Bryophytes including species of *Sphagnum*, *Polytrichum*, and brown mosses can be successfully incorporated into mountain peatland restoration projects. Brown mosses can be common, although inconspicuous under a canopy of sedges, in fens with pH > 5. *Sphagnum* mosses are common in more acid fens with pH < 5, although some *Sphagnum* (*S. teres, S. warnstorfii, S. miyabeanum*) occupy habitats with slighly acid to circumneutral water. Species of *Polytrichum* are pioneering mosses found in many fen and bog types (Chimner et al 2010). *Sphagnum* moss re-introduction has been conducted on few mountain fens (e.g., Chimner 2011), and we have found no cases of *Polytrichum* or brown mosses being re-introduced, other than in reclaimed fens (Borkenhagen and Cooper 2018). Mosses should be a high priority for inclusion in all peatland restoration projects. Methods for reintroducing *Sphagnum*, *Polytrichum*, and brown mosses for peatland restoration

Figure 44. *Sphagnum moss growing from translocation under Excelsior mulch.*

have been developed by restoration practitioners for cutover peatlands in Canada (e.g., Groeneveld and Rochefort 2002; Quinty and Rochefort 2003a; Groeneveld and Rochefort 2005; Graf and Rochefort 2008). The approach involves collecting the top 5–10 cm of moss from donor sites (scissors are used for small sites and farm machinery for large areas), chopping this into small fragments (greater than 1 cm in length), and spreading uniformly across the peat surface at a rate of 1 m^2 of donor to 10–20 m^2 of restored area.

Mulch is important for moss reintroduction for minimizing frost heave (Figure 38) and improving moisture levels for the moss (Chimner 2011). However, mulch may not be needed in areas that are constantly wet, such as shallow pools or seeps as the mulch may slow moss growth (Bess et al 2014). Mulch is needed for translocated mosses where bright sunshine, long periods without precipitation, and warm or hot days can desiccate the mosses (Chimner 2011). Straw mulch has been recommended for restoring harvested peatlands in North America (Quinty and Rochefort 2003a). However, Chimner (2011) found that (Excelsior 'shredded aspen') mulch worked better for fens in the San Juan Mountains of Colorado (Figure 44), and wood strand mulch was found to not be effective in the establishment of mosses in a constructed fen in Alberta. The straw mulch was compressed into the peat after one winter, while the Excelsior mulch retained much of its original loft after three winters in the San Juan Mountains of Colorado (Figure 44). Other materials such as shadecloth (Prior et al 2023) and wood chips can also be used. Care must be taken not to apply thick mulch that can block sunlight. The application of rock phosphate fertilizer is recommended for moss regeneration in cutover bogs in Canada, especially for the initial establishment of *Polytrichum* (Quinty and Rochefort 2003a); however, it is not clear whether fertilizer is necessary for mountain peatlands.

3.8.2. SEDGES, CUSHIONS, AND GRASSES

Many mountain peatlands are dominated by vascular plants, particularly species in the family Cyperaceae (Chadde 1998; Chimner et al 2010; Lemly and Cooper 2011; Wolf and Cooper 2015). For instance, in fens of the San Juan Mountains of Colorado, 30 species of *Carex* were found and ~80% of sampled stands were *Carex*-dominated (>50 % cover) (Chimner et al 2010). Besides being abundant, sedges produce extensive root systems that stabilize peat and root growth is the dominant carbon input driving peat accumulation in many peatlands (Chimner and Cooper 2003b). Establishing species of Cyperaceae is a critical component of many mountain peatland restoration projects.

Figure 45. *Techniques for reintroducing sedges include direct seeding (top left), rhizome transplanting (top right), greenhouse grown seedlings (bottom left), and pre-vegetated coir matting and seedlings– the widely spaced plants were individual seedlings, while the sods are PVCM) (bottom right).*

Four principal methods are commonly used to introduce Cyperaceae, and these methods should apply to many grasses as well, into restoration sites: 1) transplant live plugs from nearby donor peatlands; 2) plant seed collected from nearby peatlands; 3) plant nursery grown seedlings from locally collected seed; or 4) grow sedges in pre-vegetated coir sod matting (Figure 45).

Transplanting sections of sedge rhizomes and shoots can be straight forward and has been successful in several Colorado fen restoration projects (Cooper and MacDonald 2000; Chimner 2011; Chimner et al 2019b). The procedure is to dig up small clumps of sedges in donor sites and separate rhizomes and put the soil back in the hole if possible. Sedges are then planted in the restoration site by inserting one rhizome section with at least two shoots attached into a small hole. This technique might be successful if the site water table is within 30 cm of the ground surface, and we have had high mortality in sites with deeper water tables. Transplants are cheaper than greenhouse-grown sedges, although transplants grow more slowly initially and may require more plants per unit area to obtain desirable coverage. Transplants also disturb the donor site and a large number of transplants cannot usually be collected in this way.

Seed has been used as the principal mode of introducing plants to restored or created fens (Borkenhagen and Cooper 2018). Collected seed must first be analyzed to determine the viability by analyzing embryos with tetrazolium. Seeding can be done in the fall so seeds can get the cold and wet treatment they need to germinate. If this is not possible, then seeds should be cold and wet stratified before introduction in the field. Depending on the seed mixture and the germinability of the seed, one or more species may come to dominate the vegetation. A seedbank study can be conducted to determine if a viable seedbank is present that can be incorperated into the restoration project (Middleton et al 2006).

Sedges and grasses grown in greenhouses, from locally collected seed, have been successfully planted in many mountain peatland restoration projects. This approach can be expensive but can be used to target the exact species desired and, in the numbers, required. Some restoration projects can require many thousands of seedlings. Pre-vegetated coir matting (PVCM) has also been used for sedge reintroduction. PVCM is double thickness coir matting into which seedlings are planted and grown in shallow water or other wetland conditions until the seedlings root in the matting (Figure 45).

There is limited information on revegetating cushion plants in peatlands. However, the available information suggests that cushion plants can be revegetated similarly to sedges. Cushion plants have been observed to revegetate naturally from seed dispersal in restoration areas and cattle exclosures in Ecuador and Peru (Suárez and Rengifo Faiffer, personal communications). Cushion plants have also been transplanted successfully in Colombian peatlands using small ramets. The ramets were 5-10 cm long and are bundled in 5-10 stems, which were then inserted into the peat (Benavides personal communication). Similar to sedges, cushion transplant success is best in saturated conditions, with poor survival in dry peat.

3.8.3. HERBACOUS

Herbacous plants are most commonly introduced into restoration projects by collecting seeds from plants near the restoration site and either growing them into seedlings for planting on site or direct seeding.

3.8.4. SHRUBS

Shrubs seeds can be collected and grown in greenhouses for outplanting. Many wetland shrubs can also be introduced into a restoration site as cuttings or live stakes (Figure 46). We have had good success transplanting willows (*Salix*) into our restoration projects, but dogwoods (*Cornus*), alder (*Alnus*) species and others can also be successful. Shrub stems should be cut near their base at a 45-degree angle with sharp clippers. Stems should be young and flexible. Stems are typically cut in the spring before leaf out, but shrub stems can be cut in the summer with leaves on the stem, but leaves should be removed to reduce transpiration that could dry out the stem before it develops roots. After cutting, immediately place the stems in a bucket of water, or a backpack style dry bag in more remote areas, and store in the shade for a week or two (Figure 46). You can add a rooting hormone to the bucket, but it's not necessary for willow species. After a few days to a few weeks of soaking in water the shrub stems will develop fine adventitious roots (Figure 46). Shrub cuttings can then be planted into small holes that are created by using a metal bar pushed into the soil creating a stem sized hole, after which the shrub stem can be inserted into the hole and the hole sealed with native soil. Stem cutting lengths can vary, but short stems with above ground length of ~20-30 cm, and below ground being equal or longer are suitable. We have successfully transplanted shrub stems into 2 m tall dense invasive grass where short stems would likely be completely shaded and struggle to survive. In this case, we used much longer shrub cuttings (Figure 46), however this could have limited applicability in dry climates due to the higher water

Figure 46. *Techniques for establishing willows and shrubs from live stakes. Cut the shrub stems and soak in water (top left) until roots start to develop (top right). Use a pole to create a hole and insert the stem (bottom left). If site is wet enough the stem will form new roots and leaves (bottom right). Sometimes the stem will die back to ground level and new leaves will sprout from the base.*

needs of longer stems.

Water availability is the most important factor in the success of shrub cuttings (Gage and Cooper 2004) because initially the stems lack roots. The shrub transplants will not survive if planted in dry soil with success much greater in sites with a shallow water table. You can improve your success rate by inserting the stems deeper into the soil if the water table is deeper, waiting for the stems to develop adventitious roots before planting, and not planting during the hottest and driest part of the year. A second method uses stems collected in the winter and placed into pots to grow roots for 1-3 months (Cooper et al 2017). These rooted cuttings are then planted in the field.

3.8.5. TREES

Trees are uncommon in many mountain peatlands, especially high elevation peatlands, but are components of some peatlands. The most common method for planting trees is either bare root or containerized seedlings grown in a greenhouse. Tree seedlings can be purchased from local nurseries if available, or local seeds can be collected and grown in a greenhouse.

Planting trees in wetlands is complicated by the small-scale variation in topography. Peatlands and other wetlands may look flat from a distance, but the surface of many peatlands is complex with small mounds (hummocks) and small water-filled depressions (pools) (Chimner and Hart 1996). This microtopography is important for planting trees in peatlands (Figure 47). Seedlings should be planted on top of the hummocks and not in lower topographic areas. Microtopography can also be created during restoration projects to improve tree survival and better mimic natural

Figure 47. *Wetland trees planted on the top of created hummocks.*

peatland conditions. For instance, a project in northern Michigan constructed artificial microtopography by building hummocks during the restoration of a forested wetland from old farm fields (Kangas et al 2016). After 5 years, tree seedlings planted on hummocks had a 75% survival rate compared to only 15% survival when planted between hummocks. In addition, the tree seedlings grew much faster on the hummocks (30 cm/yr) than non-hummock areas (8 cm/yr).

Fen pools in the San Juan Mountains, Colorado, USA.

4.0. PUTTING IT ALL TOGETHER IN A RESTORATION PLAN

Every restoration project should start with goals and a restoration planning effort. The plan should include characterization of current site conditions, development of restoration objectives and design elements, pre-project activities such as permitting and land use permission, implementation plan, post-construction monitoring program, and detailed maps of access, transportation corridors, storage areas including fuel storage, material stockpile areas and human needs facilities.

The initial phase of the restoration planning involves site characterization and identifying all disturbances that are the goal of restoration and that could influence restoration success (see Section 2). The site condition analysis will lead to the establishment of restoration goals and objectives, which will guide every aspect of the project. Goals are crucial as they determine the overall direction of the project, how the land uses will change, the acceptable level of restoration, and ultimately the needed efforts, costs, and criteria for success. Restoration goals can be developed through an expert approach led by one or a team of peatland restoration professionals, or through a participatory approach in which one or more interested parties, including experts, contribute to the development of restoration goals. It is also imperative to obtain input from local and indigenous community members in the goal setting, restoration planning, and restoration processes. Permits from local, regional and national regulatory agencies are also vital to address and obtain. These could address present and future land uses, water rights, water quality and other needed permits.

The Society for Ecological Restoration defines ecological restoration as a process to aid in the recovery of degraded, damaged, or destroyed ecosystems (Gann et al 2019). The overarching goal of mountain peatland restoration projects should include returning the degraded site to its historical range of variation and condition. In areas where there have been permanent changes to the landscape that have altered its hydrologic regime in ways that cannot be restored, the goals should consider and account for these changes. Also where climate changes have already had a significant effect on a watershed, these changes must also be considered. The history of disturbance is important to interpret current conditions. The peatland may not necessarily return to its former state due to present-day ecological conditions, such as described above, and cannot be reversed, or cost constraints that limit restoration options. While having an overarching goal is good, precise

__Figure 48.__ The use of mats can be important for driving on soft organic soil, especially where the peat is soft or equipment is not specialized for wetland work.

SMART goals may be more useful.

SMART goals (Specific, Measurable, Achievable, Relevant and Time-bound) are often recommended for restoration work (Galatowitsch 2012). Specific goals mean that they are more precise than "make the site better" or "return to pre-disturbance condition". Goals must be measurable and quantifiable. It is critical that project goals be reasonable and achievable without over-promising to funders, land managers, and stakeholders. Lastly, goals should include a specified time frame, recognizing that various objectives may require different time as each aspect of the ecosystem may change at varying rates. For example, some aspects of site hydrology can be restored within weeks, vegetation recovery will take years to decades, and soil recovery may take decades to centuries (Schimelpfenig et al 2014). Examples of relevant mountain peatland restoration goals are "rewet areas impacted by ditching to match reference water table conditions within one year". Or "increase native plant canopy cover to 75% within 5 years".

The restoration plan must have a section on each proposed activity (Section 3). Actions must be feasible and within the financial, legal and logistical constraints of the budget and restoration proponents and plan. This section should be deailed including maps, data, photos, or other visual aids, to help with actual implementation. If the project includes restoration of a ditch, the restoration plan should not just state that ditches will be restored but should indicate how each ditch or even each section of a ditch should be restored in detail including what type of ditch blocking technique will be used, their spacing, and locations.

If revegetation is required, a comprehensive planting plan must be prepared. The plan should include a list of species that will be introduced. If restoration occurs in more than one peatland type, more than one species list may be required. Additionally, the plan should specify the exact revegetation method (direct seeding, transplants, greenhouse-grown, diaspore transplant, etc.) and the method of obtaining the propagules. Additional information to be considered includes whether mulching is proposed, options for protecting against herbivory, and protocols for managing invasive species.

If heavy machinery is needed for earthwork, a section detailing the earthwork plan must be included. This should identify areas where the land surface will be modified by reprofiling, infilling, and reshaping. Typically a detailed map showing the current topography, and an additional map showing the proposed changes is included. This section should include measures to minimize physical disturbances to the peatland, such as only working during certain times of the year, the use of swamp mats (Figure 48), use of wide tracks or low-pressure tires, and designated driving areas to prevent rutting or compaction. A map should be created to depict the optimal route for the machinery, minimizing the number of trips across the peat to avoid disruption.

5.0. POST-RESTORATION MONITORING AND MANAGEMENT

Monitoring should begin prior to restoration activities, and continue through the restoration work and into the post restoration years. Monitoring methods should address the project goals and objectives. However, at a minimum the project should monitor water table depth over time in a network of shallow wells, and plant survival, growth and vegetation composition (refer to Section 2 for monitoring methodology). The objective of post-restoration monitoring is to gather data for adaptive management and to evaluate the effectiveness of your restoration efforts relative to the project goals.

A widely used method for assessing the effectiveness of ecological restoration is the before-after-control-impact/treatment (BACI) design (Christie et al 2019). This non-randomized design entails monitoring at least two sites over a period of time, restoring one while the other is left as a control. It is crucial that the control site is as similar as possible to the restored site and the more control sites monitored, the more robust the findings will be. The BACI design enables the consideration of natural variability or time responses following restoration, allowing for estimation of the restoration's impact.

Post-restoration monitoring is crucial for developing adaptive management practices, if necessary. Adaptive management refers to managing natural resources by learning from previous actions and changing methods and actions accordingly. To ensure the efficacy of adaptive management, the restoration site should be monitored frequently immediately after the restoration to identify any issues. Monitoring can be less frequent as time progresses.

Immediately following restoration activities, it is crucial to assess the effectiveness of check dams, erosion control, revegetation, and any other restoration measures. It is highly recommended to inspect the site during or shortly after significant rainfall events to quickly identify if there are any issues with the check dams or erosion control, and whether immediate adaptive management is necessary. It is also important to monitor the site during dry periods as this can be a significantly stressful period for the reintroduced vegetation. Additionally, the site should be assessed for invasive species, and if detected they must be promptly controlled. An example of adapted management is in Halstead meadow documented earlier (Figure 34). All the large meadows in this region of the Sierra Nevada of California have large trees that have fallen across the meadow and appear to stablize the land surface. Therefore, large dead trees were added during restoration in the

Figure 49. *Example of repeat photography of a fen undergoing restoration from a ditch in Michigan.*

hopes they would disperse the water and stablize the land after planting. However, monitoring showed that instead they acted to channelize water and caused erosion. The added trees were therefore removed. The issue was that while trees were abundant in mature meadows, in newly restored meadows with mostly bare soil and recently planted seedlings, the soil was easily eroded.

Repeat photo documentation (Figure 49) is valuable for monitoring the success of restoration and visualizing changes that occur over time. To ensure accuracy, establish photo points prior to restoration and take photos at regular intervals. Drone imagery can also be repeated and can provide an aerial monitoring view of the entire site. Drone imagery can reveal sites with erosion, limited plant growth, invasive plant species, or areas with a high prevalence of herbivory or trampling. Monitoring post-restoration can also be conducted using remote sensing, particularly to monitor vegetation cover and ponding (Minasny et al 2023).

Fen in the Cairngorms National Park, Scotland

6.0. SUMMARY

This technical manual reviews restoration techniques for mountain peatlands. Peatlands are a common and important wetland type in mountain ranges worldwide, but many have experienced disturbances such as ditching, overgrazing, erosion, air pollution, mining, and road crossings that can be restored. Restoring mountain peatlands can present challenges due to steep slopes, saturated soils, cold temperatures, and remote work sites. Ditches are a frequently encountered issue that can be addressed through filling or blocking. There are various restoration methods, and the appropriate approach relies on peatland and ditch characteristics, as well as the available funding and access. Restoration techniques for gullies (filling or damming) are similar to those for ditches, although gullies present greater difficulties and risks due to their higher erosion rates, and much greater volume.

Peatlands can be buried by sediments from eroding roads, mines or mills, or purposely filled for development. However, restoration can be successful by adressing the original cause of burial if required, then excavating the fill, restoring the land surface that is in contact with the regional water table, and introducing plants that can lead to peat formation. Grazing by cattle, sheep, alpaca, llama, and other species, including native ungulates can alter site vegetation and hydrological processes necessitating active or passive restoration. The high elevation and cold climate where many mountain peatlands occur can result in frost heaving that can confound re-vegetation efforts unless mulch is carefully applied to reduce ground freeze and thaw processes. Steep peatland slopes or slopes adjacent to mountain peatlands often require erosion control measures during restoration. Many restoration sites require the re-establishment of vegetation, and choosing a suitable re-vegetation method and the correct species is critical. All restoration programs should include post-restoration monitoring of groundwater levels, plant species establishment, survival and growth, erosion, and herbivory. A carefully designed monitoring program can help identify problems and provide information that can be used to address problems before they threaten the success of the project. Many mountain peatlands require restoration from a range of disturbances. However, with proper planning and implementation, many of these peatlands can be successfully restored.

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