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Climate Change Considerations for Forest Operations in Northern Forests

Ryan Toot, Stephen Handler, P. Danielle Shannon, Amy Amman, Charlie Blinn, Patricia Butler-Leopold, Jennifer Shakun, and Maria K. Janowiak

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Abstract

Forest operations, including timber harvest, are an important component of managing forests. Operations are often planned or designed around anticipated weather based on past climate conditions. Climate change is altering current weather patterns and may complicate forest operations. With consideration of current climate in planning and practices, foresters, loggers, landowners, and land managers can continue efficient and sustainable forest operations. Adapting to climate change can begin with gathering relevant information, evaluating risks, and creating plans that reduce risk. It can include intentional contract provisions, site layout, and infrastructure design; flexibility through supplies and equipment; monitoring and responding to real-time conditions; sale closure practices; and practices to prevent erosion, compaction, rutting, wildfire, and the spread of invasive species. This guide presents climate change impacts on operations in northern forests, considerations for planning, and practices that may be useful for protection of natural resources and continued forest operations in the changing climate.

KEYWORDS: climate change, forest operations, logging, best management practices

Cover Photo

A forwarder moving logs during a winter timber harvest. Courtesy photo by Rexx Janowiak, Green Timber Consulting Foresters, Inc.

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About the Authors

RYAN TOOT is a watershed forester with the Saint Paul Field Office, Eastern Region State, Private, and Tribal Forestry, 1992 Folwell Avenue, St. Paul, MN 55108, ryan.toot@usda.gov.

STEPHEN HANDLER is the acting deputy director of the USDA Northern Forests Climate Hub and the Northern Institute of Applied Climate Science with the USDA Forest Service, Northern Research Station, 410 MacInnes Drive, Houghton, MI 49931, stephen.handler@usda.gov.

P. DANIELLE SHANNON is a climate change adaptation specialist with the USDA Northern Forests Climate Hub, Northern Institute of Applied Climate Science, Michigan Technological University, College of Forest Resources and Environmental Science, 1400 Townsend Drive, Houghton, MI 49931, dshannon@mtu.edu.

AMY AMMAN is a forest soil scientist with the Ottawa National Forest, USDA Forest Service, E6248 US Highway 2, Ironwood, MI 49938, amy.amman@usda.gov.

CHARLIE BLINN is a professor and extension specialist with the Department of Forest Resources, University of Minnesota, 2005 Upper Buford Circle, St. Paul, MN 55108, cblinn@umn.edu.

PATRICIA BUTLER-LEOPOLD is a climate adaptation specialist with the Northern Institute of Applied Climate Science and the USDA Forest Service, Eastern Region State, Private, and Tribal Forestry, 410 MacInnes Drive, Houghton, MI 49931, patricia.leopold@usda.gov.

JENNIFER SHAKUN is the Bioeconomy Initiative Director for the New England Forestry Foundation, PO Box 1346, 32 Foster Street, Littleton, MA 01460, jshakun@newenglandforestry.org.

MARIA K. JANOWIAK is the acting director of the USDA Northern Forests Climate Hub and the acting director of the Northern Institute of Applied Climate Science with the USDA Forest Service, Northern Research Station, 410 MacInnes Drive, Houghton, MI 49931, maria.janowiak@usda.gov.

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Learn more about the USDA Northern Forests Climate Hub at: https://www.climatehubs.usda.gov/hubs/northern-forests

Contents

Introduction

Weather is an important consideration in forest operations planning and implementation because it affects the timing and efficiency of operations and influences the type of impacts operations can have on natural resources, including soil, water, and vegetation (Bick et al. 2019, Geisler et al. 2016, Nash et al. 2022, Rittenhouse and Rissman 2015). Although weather conditions vary seasonally and annually, climate change is shifting long-term weather dynamics, resulting in changes to average conditions and patterns of extreme events (U.S. Global Change Research Program [USGCRP] 2023). These changes complicate forest operations (e.g., timber harvest and hauling, site preparation) associated with forest management activities across northern forests in the Midwest and Northeast regions of the United States (Bick et al. 2019, Conrad et al. 2017, Demchik et al. 2017, Geisler et al. 2016, Rittenhouse and Rissman 2015).

Climate change affects many dimensions of forest management, including management goals and outcomes, silvicultural strategies, and harvest operations (Rittenhouse and Rissman 2015, Swanston et al. 2016). Land management planners, foresters, and silviculturists increasingly incorporate climate change considerations into the development of on-the-ground projects (McGann et al. 2022, Swanston et al. 2016). Many forest management projects that are designed to help forests adapt to changing conditions use a variety of active forest management techniques, including harvest, designed to increase the diversity and resilience of forests to the changing climate. Forest operations serve an important role in climate adaptation by helping land owners and managers achieve their desired forest conditions.

Forest operations are routinely designed to reduce their potential impacts to natural resources (Cristan et al. 2016, Edwards et al. 2016). Further, each State has identified best management practices (BMPs) for forestry, which are updated periodically. Forestry BMPs provide an important and often flexible foundation for the protection of natural resources—particularly water and soils—and support efficient operations (Cristan et al. 2016, Edwards et al. 2016). Well-planned forest operations can support long-term sustainable land management and maintain the ecological services that forestry BMPs provide. Actions that reduce the risks of forest operations to natural resources may require time and investment but may also be able to broaden the operating window and increase efficiency.

Importantly, changes in climate and weather patterns impact natural resources and can interact with or compound existing risks to natural resources from forest operations (Table 1). Climate change can also result in economic losses by limiting site access for forest operations, increasing downtime for workers (e.g., loggers), increasing repair and maintenance costs for infrastructure and equipment used for operations, and altering the forest conditions and associated benefits. Using forestry BMPs may be increasingly beneficial for protecting natural resources during forest operations due to climate change. Furthermore, different approaches, designs, or techniques that specifically consider climate change can be used to help ensure the protection of infrastructure, human health and safety, and natural resources, and to support continued forest operations. Evolving to meet the challenge of climate change may help loggers and the timber industry remain viable within the context of a dynamic market, advances in equipment, and management trends (Bick et al. 2019).

This guide presents climate change impacts, considerations that can inform planning, and a suite of example practices that may be useful for continuing forest operations and protecting natural resources in the context of climate change. It focuses on timber harvest, but the principles in this guide may also be useful for site preparation, timber stand improvement, wildland firefighting, hazardous fuels reductions, prescribed burns, and other forest operations that remove vegetative cover and require heavy equipment, roads, trails, or other forest infrastructure. The guide is designed to be used in conjunction with specific information about site conditions and constraints and also with the knowledge and expertise of landowners, loggers, foresters, and others (e.g., hydrologist, engineer, or soil scientist) involved in a particular project. It is intended to be a useful companion to BMPs and other guidelines and available resources. This guide does not replace BMPs or guidelines for forest operations in your jurisdiction (regulated or otherwise) nor does it prescribe solutions for specific situations. State BMPs and associated information are available through the National Association of State Foresters website.

Table 1.—Risks to natural resources from forest operations that may interact with climate change

Potential impacts to natural resources from forest operations	Primary forest operations source	Interacting climate change impacts[1]
Rutting and soil compaction (soil disturbance)	Equipment operation: ground contact	Fewer frozen ground days; less snow cover; more extreme precipitation and runoff events; hotter, drier summers
Erosion (soil disturbance)	Equipment operation and forest roads: vegetation removal, soil compaction, increased overland flow velocities	More extreme precipitation and runoff events
Sediment introduction to water bodies	Erosion, rutting, and soil compaction, particularly from roads and at crossings	More extreme precipitation and runoff events
Increased surface water temperatures	Vegetation removal: decreased shade associated with riparian tree canopy	Hotter, drier summers
Altered hydrology (water levels and flow volumes, patterns)	Soil disturbance and vegetation removal; road and trail crossings of streams, ditches, and wetlands	More extreme precipitation and runoff events; hotter, drier summers; less snow cover
Introduction and spread of invasive species	Equipment operation: seed transport mechanism, soil disturbance, and vegetation removal	Fewer frozen ground days; less snow cover; hotter, drier summers; longer growing season; more extreme precipitation and runoff events
Wildfire ignition	Equipment operation: heat or sparks	Hotter, drier summers; less snow cover
Negative impacts to forest productivity and composition	Soil disturbance, invasive species, wildfire, and vegetation removal	Fewer frozen ground days; less snow cover; hotter, drier summers; more extreme precipitation and runoff events

[1]See the "Climate Change Impacts" section for details.

Climate Change Impacts

The forests of the northern Midwest and Northeast United States (hereafter referred to as northern forests) are experiencing unprecedented changes in climate, including increased temperatures, less snow cover, more frequent and severe drought, and extreme precipitation. These impacts are expected to continue and intensify throughout the 21st century (USGCRP 2023). These changes can impede forest operations and amplify risks to natural resources (Bick et al. 2019, Rittenhouse and Rissman 2015).

Warmer Winters

Some of the most pronounced changes in the climate have been observed during the winter season. Winters have warmed significantly in recent decades (Ford et al. 2021) (Fig. 1), and minimum (nighttime) temperatures are increasing at a quicker rate than average or maximum temperatures. Cold spells are also becoming less severe and less frequent (Gutiérrez et al. 2021).

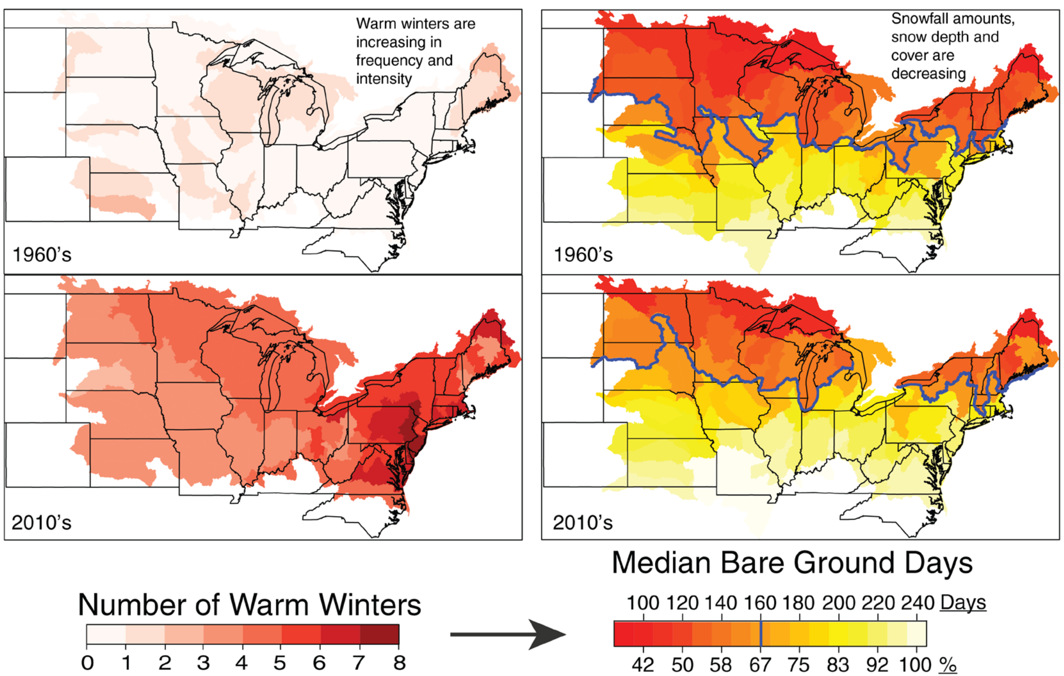

Figure 1.—Depiction of observed historical warm winters and median bare ground (no snow cover) days, summarized for four-digit hydrologic unit code—4 watersheds in the north and central eastern United States. Warm winters were calculated using multiple parameters. Daily average and minimum temperature averaged for the entire snow season (October–May) and daily minimum and average temperature averaged for winter months (December–February) and spring months (March–May) were normalized against a 60-year median. A buffer was applied to the central value, above which winters were classified as warm. The figure is a portion of the graphical abstract from Ford et al. (2021), reproduced with permission.

Less Snow Cover

Increasing winter temperatures are causing an increased proportion of precipitation to fall as rain rather than snow, resulting in less snow cover across northern forests, particularly in early to mid-winter (Ford et al. 2021, Notaro et al. 2014). As winters continue to warm, snowpack will likely continue to decline across most of the northern United States. Compacted and frozen snow itself can help protect soils and vegetation from the impacts of heavy equipment (Crawford et al. 2021, Nash et al. 2020). In addition, both the depth of snow and the timing of snowfall relative to cold temperatures influence onset and duration of frozen ground conditions. Unpacked snow can insulate the ground from both freezing and thawing temperatures (Hardy et al. 2001).

Fewer Frozen Ground Days

Although decreased snow depths may mediate the effect of warmer temperatures on soil frost depths (Friesen et al. 2021, Stockstad et al. 2022), some research shows warmer winters are causing a decrease in the number of days when the ground is frozen. Frozen ground is often relied on to protect soil, vegetation, and roots during heavy equipment operation on wet or sensitive sites that are susceptible to compaction, rutting, and erosion (Contosta et al. 2019). Rittenhouse and Rissman (2015) found frozen soil conditions decreased by 2 to 3 weeks in Wisconsin from 1948 to 2012. The duration of frozen ground conditions may decrease in the coming decades (Campbell et al. 2010).

Hotter, Drier Summers

Summers are becoming warmer across the northern United States, and growing seasons are getting longer. The trends are projected to continue. Drought risk is projected to increase as higher temperatures drive more evaporation of moisture from soils and more transpiration of water from plants and trees into the atmosphere (USGCRP 2023). Drier soils may ease or enable heavy equipment access to sites with sensitive soils that may have otherwise required frozen ground or additional mitigations due to high soil water holding capacity (Stone 2002). Drier vegetation can also increase the risk of wildfire.

More Extreme Precipitation and Runoff Events

Heavy precipitation events increased in frequency and intensity throughout the 20th century in northern forests (Fig. 2), and this trend toward extreme precipitation is projected to continue. More-intense and longer duration rain events produce more runoff and increased erosion, higher peak streamflows, and more severe flooding (USGCRP 2023). These events can damage forest infrastructure, including roads and stream crossings. Soil disturbed or exposed because of forest operations and associated infrastructure may be at increased risk of erosion. Extreme events may undermine BMPs when the events exceed the precipitation, runoff, or peak streamflow that the BMPs were designed to accommodate.

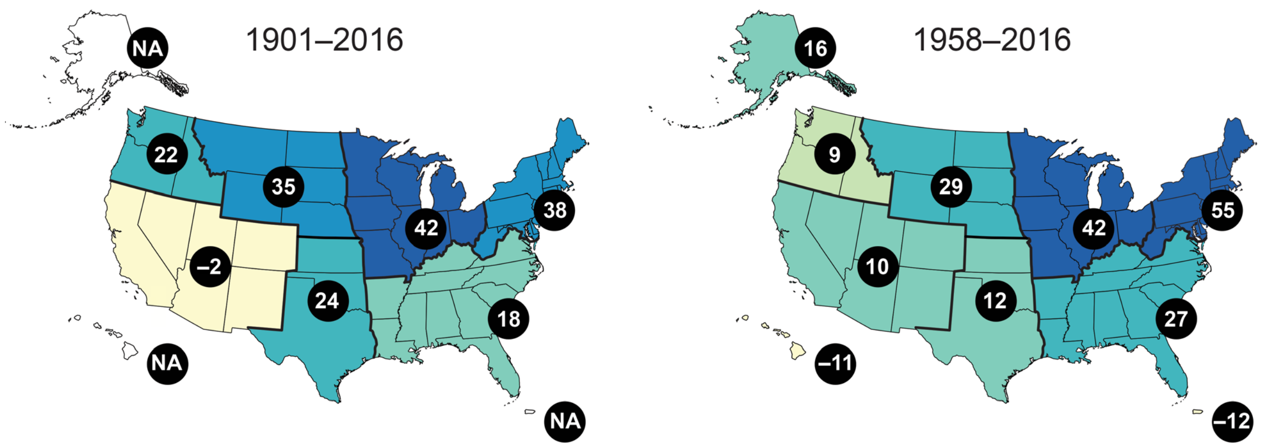

Figure 2.—Observed change (percent) in total precipitation falling in the heaviest 1 percent of events. Adapted from U.S. Global Change Research Program (2018).

Incorporating Climate Change into Planning

Planning aids efficient and effective protection of natural resources throughout (and after) forest operations. The following steps can help foresters, loggers, and other professionals incorporate climate change adaptation into specific forest operations projects (steps adapted from Minnesota Forest Resources Council [MFRC] (2012)).

- Gather information
- Evaluate risk
- Create a harvest plan

These steps can often be done as part of typical operations planning. They are not intended as a complete planning process and do not address possible regulatory or permitting requirements.

Gathering Information

Detailed site information is important to developing and designing a climate-adapted operations plan. Information can come from a variety of sources, including digital geospatial information, hardcopy maps, and onsite surveys and inventories. Publicly available geospatial datasets are increasingly able to help identify or analyze features beyond what can be easily assessed through onsite surveys. For example, Light Detection and Ranging (LIDAR) bare-earth digital elevation models can be used to identify old skid trails, and the USDA Natural Resources Conservation Service's web soil survey data describes soils to a high level of detail for many areas. However, such information does not always exist at the project scale or capture all relevant details. Onsite surveys are critical and provide site feature information at the project scale. The following list highlights information that may be relevant to planning forest operations in response to climate change impacts.

Site Feature Information

- ☐ **Streams and wetlands.** The extent, location, and water levels of streams and wetlands may become more dynamic due to climate change and increased weather variability, and this may become a more prominent factor in operations and planning.
  - More frequent and intense precipitation events may cause more frequent and severe flooding in proximity to these features.
  - Droughts may make isolated or small wetlands such as seasonal ponds more difficult to identify in the field.
  - Warmer and shorter winters may affect site access if frozen conditions are necessary for travel across wetlands.

☐ **Soils.** As frozen soil conditions become less common, other measures such as those listed in the “Reducing Compaction and Rutting on Harvest Areas, Skid Trails, Landings, and Roads” section can be taken to avoid soil disturbance during forest operations. Soil susceptibility to disturbance is influenced by texture and moisture content as well as other variables (Crawford et al. 2021, Nash et al. 2022).

- Fine-textured soils, especially silts, are generally more susceptible to compaction than coarse-textured soils (Crawford et al. 2021).
- Loamy soils are more susceptible to compaction, whereas clays are more susceptible to rutting (Miller et al. 2004).
- Higher moisture content generally increases susceptibility to rutting and compaction, except in coarse-textured soils (Miller et al. 2004, Nash et al. 2022).
- Soils with high proportions of silt and fine sand, low proportions of organic matter, and moderately low permeability are generally most erodible (Stewart 1975).

Soil composition and depth affect water movement and accumulation, which is increasingly important as precipitation events become more extreme.

- Fine-textured soils or shallow bedrock can inhibit infiltration of water and encourage runoff, especially on sloping terrain.
- Organic material and fine-textured soils hold moisture longer than coarse-textured soils.

☐ **Topography.** Topography influences both weather conditions and the effects of weather on a site. Topography can be used with other information to help evaluate how the land may respond to altered temperatures, precipitation, snowmelt, and runoff events.

- Slope aspect impacts microclimate. In northern forests, north- and east-facing slopes are generally cooler and wetter than surrounding areas, whereas south- and west-facing slopes are warmer and drier.
- Water accumulation and drainage are controlled by topography in conjunction with soils.
- Erosion and compaction risk is greater on steeper slopes, with soils, vegetation, and other variables also having an influence (Crawford et al. 2021).

- ☐ **Typical site conditions.** Knowledge of current and historical site conditions can increase understanding of risks and inform a plan.
    - Communicating with someone familiar with the property may help determine past site conditions. For instance, wetlands may become smaller or drier during periods of drought but may expand after a heavy rain event, or some streams may have a course that has recently changed from what is shown on maps.
    - Onsite surveys can provide valuable information about how the site may respond to weather events (e.g., preferential paths of runoff, flooding locations). Cues from the site that can provide insight include past high-water marks and erosion scars on slopes, soils, and vegetation. For instance, plant species or community classifications can be used to predict frequently flooded or wet soils.
- ☐ **Old and existing logging roads, skid trails, and crossings.** Using existing infrastructure from previous operations can reduce costs and may reduce impacts on a site. However, existing infrastructure's current condition, adequacy, and viability may be affected by recent or expected weather and climate conditions. For example, roads in some locations may wash out or flood more frequently than in the past, and stream crossings may not accommodate the flood flows expected to occur now and in the future.
- ☐ **Seasonal harvest restrictions or other limitations.** Seasonal harvest restrictions may exist for many reasons, including forest health concerns (e.g., oak wilt) and limiting impacts to infrastructure, threatened species, and natural resources. Climate change may alter the timing or location of weather-related restrictions, such as those designed to protect roads. Tracking these restrictions spatially and temporally can allow harvests to be scheduled accordingly.

Site Condition, Weather, and Climate Information

Although site-level observation may be the best way to understand current site conditions, weather and climate data products can give a broad-scale understanding of current conditions or future trends.

Onsite Measurements and Tests

Actionable information about site conditions can be obtained by simple measurements and tests in addition to monitoring real-time impacts from equipment. Conducted at multiple locations across a site, they can help in understanding and accounting for variation due to forest cover, elevation, soils, and other differences. They can also aid in planning and selecting practices to accommodate site-level conditions.

- ☐ **Soil frost depth.** The soil frost depth needed to support equipment and avoid damage to soils is affected by soil type, the ground pressure induced by the equipment, and other variables. Standards used for operation on wet or sensitive soils vary. For instance, the Hiawatha National Forest requires 6 inches (15 cm) of frozen soil or 12 inches (30 cm) of frozen/compacted snow, based on Stone (2002). Nash et al. (2020) list some standards used across the country. Calendar dates are sometimes used to constrain harvest activity to frozen ground. If not updated, these dates may become mismatched to the current climate. The methods listed next can be a useful low-investment approach of measuring soil frost depth. It may take practice to "calibrate" or feel the threshold of frozen soil. More accurate and precise measurements are possible but likely more suited to research than on-the-job use.

- An easy and inexpensive way to determine frost depth is to simply hammer a piece of rebar (with one end ground to a 30-degree point, if possible) into the frozen soil until it breaks through to unfrozen ground and resistance eases. Then, measure on the rebar the depth where breakthrough occurred relative to the ground surface (Nash et al. 2020).
- Another simple approach is to use a hammer drill and 2-foot (61-cm) masonry bit with clear graduations for reference in a similar manner to feel when the implement breaks through the frozen ground and then measure that depth on the drill bit (R. Rossman, Minnesota Department of Natural Resources, retired, personal communication, December 3, 2021).

☐ **Soil moisture.** Dig a hole 3 to 6 inches (8 to 15 cm) deep and form a fist-sized ball with the soil. If the ball holds together after a few tosses in the air, it is probably too wet to support equipment (Al-Kaisi 2019). Note that this threshold is an approximation and may not accurately represent different soils, nor does it consider equipment type. Both these and other variables impact whether soils can adequately support equipment.

Weather and Climate Data Products

Publicly available weather- and climate-related data products generally incorporate measurements at specific locations. Broader spatial coverage and forecasts are generally provided through interpolation or modeling. The scale of presented values is typically too coarse for site-level interpretation. Following is a list of selected national regional data sources. More products may be available at subregional and State levels. These resources are not a substitute for on-the-ground and real-time assessments of site conditions.

☐ **Snow and freeze maps.** Interactive snow information maps available from the National Weather Service offer interactive maps of cumulative, to-date freezing degree days, which are a seasonal summation of daily average temperatures below freezing. The Northeast Regional Climate Center hosts a cumulative freezing index forecast map which displays the same variable, forecasted for the Northeast. These maps indicate, at a coarse scale, accumulated freezing conditions which affect to what depth ground is frozen and whether sensitive soils can support equipment. For instance, the Minnesota Department of Transportation recommends that the winter weight premiums on pavement are allowed when the 3-day weather forecast indicates that the cumulative freezing index (CFI) is projected to exceed

280 Fahrenheit degree-days and extended forecasts predict continued freezing temperatures. Site-level variables have a significant impact on both soil and air temperature and rate of ground-freezing.

- ☐ **Snow depth maps.** Interactive snow information maps available from the National Weather Service offer snow depth maps which can inform understanding of frost depths or indicate whether snow depth might be sufficient for protection of soils. Snow depth varies significantly across a local area due to weather patterns and site-level variables.
- ☐ **Soil frost depth and moisture for various depths.** Real-time at-depth temperatures and soil moisture measurements are available through the USDA Soil Climate Analysis Network for specific locations (with a focus on agricultural areas). The National Weather Service provides temperature-at-depth maps for additional locations in the Midwest. Soil frost depth can vary significantly depending on sometimes interrelated factors like snow cover accumulation and timing, canopy cover, forest type, stem density, soil type, soil moisture, and topography (Comerford et al. 2013, Friesen et al. 2021, Kienholz 1940, Löfvenius et al. 2003), so this information cannot be directly applied to site-level forest operations but could inform a general sense of conditions.
- ☐ **Real-time and forecasted hydrologic conditions.** The U.S. Geological Survey National Water Dashboard displays real-time stream discharge and gauge information for stream monitoring station locations. Links to hydrologic forecast information from the National Weather Service Advanced Hydrologic Prediction Service are provided for the locations within the online map. Additionally, the Water Alert tool can be used to send automatic alerts to an email address or phone number based on user-set hydrologic conditions for those locations.
- ☐ **Streamflow projections.** The USDA Forest Service has published modeled and projected streamflow metrics for historical, mid-century, and end-of-century time periods for streams across the lower 48 States. While this information is not intended for use as engineering or design criteria, trends could inform some safety factors or design measures for logging roads, stream crossings, and riparian management zones.
- ☐ **Oak wilt risk management tool.** The Oak Wilt Vector Emergence Thermal Model predicts when the insect vector of oak wilt may be present based on degree days. Degree days are a more reliable predictor of oak wilt vector presence than calendar dates. This information can complement any State or local restrictions on tree cutting designed to reduce oak wilt spread.
- ☐ **Drought and fire danger information.** The U.S. Drought Monitor offers current (updated weekly) drought information, multiday, monthly, and seasonal outlooks, and a soil moisture anomaly forecast. The current drought map is based on a drought indicator blend and identifies locations experiencing short- and long-term impacts. Short-term impacts are likely most relevant to site-level operations and planning, while long-term impacts may have more bearing on planning forest management. Fire danger maps are also available on the website.

- ☐ **Weather forecasts.** Weather forecasts available through the National Weather Service offer temperature, precipitation, and other weather variables to expect in the near term (7 days). Weather forecasts are fairly accurate and important for short-term planning.
- ☐ **Long-range weather outlooks.** Available through the National Weather Service, these outlooks for temperature and precipitation are probabilities of departure from normal offered for time periods including 30 and 90 days, which may help inform scheduling on those timescales.

Evaluating Risk

Harvest, site feature, and condition information as just described can be assessed in conjunction with climate- and weather-related information to identify risks to and from a forestry operation and any associated infrastructure. These influencing factors can inform an evaluation of risks based on likelihood and severity. It might also be helpful to note situations in which climate change may decrease risk and create opportunity. Identifying and evaluating risks and opportunities provides a framework for planning (Tables 2–5). Low-risk areas on a site may be adequately addressed with monitoring and standard BMPs, whereas high-risk areas may require additional measures, even including avoiding harvest altogether. Human health and safety, while generally outside the scope of this guide, are important to consider (Box 1).

Table 2.—Characterization of common forest operations- and climate-related risks for riparian areas and wetlands

Factors that decrease risk to riparian areas and wetlands[1]	Factors that increase risk to riparian areas and wetlands[1]	Potential impacts
Stable soils (e.g., coarse sandy soils) in riparian area	Highly erodible soils (e.g., soils with high silt content) in riparian area	Erosion; sediment introduction to water bodies
Riparian area composed of undisturbed soil and native vegetation	Riparian area containing disturbed soils and impervious or compacted surfaces	Erosion; sediment introduction to water bodies
Roads and skid trails are not present in and do not influence riparian areas and wetlands	Roads or skid trails are present in or directly influence riparian areas or wetlands	Erosion; sediment introduction to water bodies; increased surface water temperatures; negative impacts to vegetation productivity and composition; economic loss
Harvest takes place exclusively in uplands	Harvest activity occurs within riparian area or wetland	Erosion; sediment introduction to water bodies; increased surface water temperatures; negative impacts to vegetation productivity and composition; economic loss

[1]In this context, "riparian" refers to the land around and influenced (e.g., in vegetation or soils) by water features, including wetlands, streams, and lakes, but not within a specified distance.

Table 3.—Characterization of common forest operations- and climate-related risks for the harvest area (including landings and skid trails)

Factors that decrease risk to harvest areas	Factors that increase risk to harvest areas	Potential impacts
Gradual or limited topography (e.g., gentle slopes)	Steep topography (e.g., >20% slopes) (Crawford et al. 2021, Solgi et al. 2018), ephemeral drainages	Rutting and soil compaction; erosion; sediment introduction to water bodies; negative impacts to vegetation productivity and composition; economic loss
Soils not susceptible to compaction, rutting, and erosion (well drained, sandy soils)	Soils susceptible to compaction, rutting, and erosion (e.g., silts and clays)	Rutting and soil compaction; negative impacts to vegetation productivity and composition; economic loss
Deciduous trees and forbs prevalent, generally low fuel loads, wet or mesic site	Conifers or tall grass prevalent; high fuel loads and ladder fuels present; xeric site	Wildfire ignition; economic loss
Invasive species not present on site	Invasive species present on site or nearby	Introduction and spread of invasive species; negative impacts to vegetation productivity and composition; economic loss
Upland-only harvests	Harvest area includes lowlands; water table close to the surface of the forest floor	Rutting and soil compaction; altered hydrology (water levels and flow volumes, patterns) economic loss
Scarification of soil is limited; bare mineral soil generally not exposed	Scarification of soil used as a silvicultural tool; bare mineral soil exposed on a significant portion of the site	Erosion, introduction, and spread of invasive species; negative impacts to vegetation productivity and composition; economic loss

Table 4.—Characterization of common forest operations- and climate-related risks for stream and wetland crossings

Factors that decrease risk to stream and wetland crossings	Factors that increase risk to stream and wetland crossings	Potential impacts
Upstream watershed is not flashy: coarse-textured soils, low relief, and a large percentage of forested/natural cover (e.g., >60-70%; Verry 1986) encourage precipitation to infiltrate soils and recharge groundwater	Upstream watershed is flashy: fine-textured soils or bedrock surfaces, high relief, and developed land use, impervious surfaces, or tiled drainages encourage precipitation to run off into surface water bodies quickly	Erosion; sediment introduction to water bodies; increased surface water temperatures; altered hydrology (water levels and flow volumes, patterns); economic loss
Gradual approaches on roads/skid trails	Steep approaches on roads/skid trails (e.g., >10% slope)	Erosion; sediment introduction to water bodies
Crossing well-designed (e.g., perpendicular to stream, appropriately sized to accommodate higher flows, appropriate cross drainage for wetlands, proper construction materials, etc.)	Crossing poorly designed (e.g., high-angled crossing, undersized for current flow regime, inadequate cross drainage for wetlands, inferior construction materials, etc.)	Erosion; sediment introduction to water bodies; altered hydrology (water levels and flow volumes, patterns); economic loss
Crossing location permits spanning channel and maintains floodplain connectivity	Crossing location requires travel through floodplain and may require floodplain fill	Erosion; sediment introduction to water bodies; altered hydrology (water levels and flow volumes, patterns); economic loss
Crossing appropriately designed and constructed for all-season use	Crossing designed for use only during frozen conditions	Rutting and soil compaction; economic loss
Crossing structure in place for shorter time, removed during high flow period (e.g., timber mat, skidder bridge)	Crossing structure in place for longer time, multiple years, or permanent	Erosion; sediment introduction to water bodies; altered hydrology (water levels and flow volumes, patterns); economic loss
Effective erosion control and water diversions implemented and maintained appropriately	Inadequate or ineffective erosion control and water diversion on approaches	Erosion; sediment introduction to water bodies; altered hydrology (water levels and flow volumes, patterns); economic loss

Table 5.—Characterization of common forest operations- and climate-related risks for forest roads

Factors that decrease risk to forest roads	Factors that increase risk to forest roads	Potential impacts
Road appropriately designed, constructed, and shaped for all-season use	Road designed for use only during frozen conditions	Rutting and soil compaction; economic loss
Road with minimal grade	Steep grades (e.g., >10% slope)	Erosion; sediment introduction to water bodies; economic loss
Unintended traffic limited (e.g., gated private access, closed to motorized use)	Use by unintended traffic not limited	Rutting and soil compaction; erosion; sediment introduction to water bodies; economic loss; introduction and spread of invasive species
Appropriate decommissioning (e.g., soil compaction remediated, access restricted, slope restored and grade reestablished, exposed soil revegetated, erosion control implemented)	Poor decommissioning (e.g., ceased maintenance, access not restricted, erosion control or other remediation not implemented)	Rutting and soil compaction; erosion; sediment introduction to water bodies; altered hydrology (water levels and flow volumes, patterns); introduction and spread of invasive species; negative impacts to vegetation productivity and composition; economic loss

Box 1: Human Health and Safety in Forest Operations

Safety is the most important consideration on a jobsite. In addition to affecting forests and how forest operations are conducted, climate change increases risks to health and safety for people who work in the woods.

- **Heat-related illness.** Warmer temperatures in the summer may be strenuous for people working outside. While northern forests may not reach the temperatures and humidity of other places in the U.S., conditions for heat-related illness do exist and are increasing as average temperatures rise. Risks can be reduced by increasing awareness of the signs and symptoms of heat-related illness and using prevention methods like hydrating adequately, taking breaks or discontinuing work, working in the shade when possible, and wearing loose fitting clothing and shade-casting headwear. More information about heat-related illness is available on the Centers for Disease Control and Prevention National Institute for Occupational Safety and Health website.
- **Tick- and mosquito-borne diseases.** Climate change is increasing the risk of and exposure to tick-borne diseases, including Lyme disease, anaplasmosis, babesiosis, Rocky Mountain spotted fever, and the mosquito-borne West Nile virus (Beard 2016, U.S. Environmental Protection Agency 2024). Warmer and more humid conditions enable range expansion of some ticks and also allow ticks to become active earlier and remain active later in the year. Mosquito development rates and bite rates increase with warmer temperatures. Preventing contact with ticks and mosquitoes, using insect repellents and treated clothing, and checking for ticks help prevent disease contraction. Knowing the early signs of tick-borne diseases can help ensure prompt treatment. More information is available on the Centers for Disease Control and Prevention websites for tick- and mosquito-borne diseases.
- **Storm hazards.** Strong storm events, which can be associated with high winds and flooding, are amplified by climate change and can cause hazards to people working in the woods. High winds can cause blowdowns when trees become uprooted or cause tree trunks to break, creating hazardous obstacles to driving or walking. Flash floods can create drowning hazards and limit or interrupt access to and from locations by damaging infrastructure. Being aware and staying out of the woods when hazardous weather is forecasted can help keep workers safe.

Creating a Plan

Thoughtful and informed operation plans facilitate efficient work and can avoid or reduce climate-related risks to operations and natural resources. Documenting and communicating operation plans can help ensure their implementation is as close to expected as possible.

- **Documentation.** Comprehensive operation plans with good documentation can help ensure that appropriate actions are taken to avoid or reduce risks related to climate and other factors. They can aid communication among landowners, foresters, and loggers. There may also be specific planning requirements associated with tax-incentive, certification, or incentive programs that will apply to lands enrolled in those programs. The following topics are often included in operation plans. Each topic relates to climate change impacts. Plans can be modified or enhanced to address climate change, efficiency, and natural resources protection (MFRC 2012, Shaffer 2009).
    - Site features and infrastructure layout (including access point(s), landings, skid trails, water features, and crossings)
    - Roads and their types or specifications
    - Identification, design, and location of BMPs
    - Scheduling and operable seasons
    - Soil moisture operability thresholds
    - Monitoring expectations for an active operation (e.g., important elements to monitor during timber sale administration)
    - Sale closure requirements
    - Other details such as equipment type to be used and pre- or post-operation cleaning of equipment
- **Communication.** Clear communication before and during activity is important in any operation (MFRC 2012). Communication helps to set expectations and build trust among landowners, land managers, foresters, and operators and increases the potential for flexibility, adaptation, and best-case outcomes from unexpected events like those caused by changing conditions. Examples of ways to encourage clear communication include:
    - A presale meeting on-site to observe and discuss site-specific concerns.
    - A well-documented plan, shared map of the site, and an understandable and unambiguous contract that protects all parties.
    - Quantitative design and condition requirements (e.g., slope percent and associated water bar spacing requirements).
    - Shared contact list that could include landowner, logger, forester, and other specialists or individuals as applicable (e.g., hydrologist, engineer, soil scientist).
    - Regular communication through phone calls or site visits.
    - Written documentation of observations, plan modifications, or issues encountered following each site visit.

Practices to Reduce Climate-Related Operations Risk

The intentional consideration of how climate change and weather variability could affect forest operations can inform harvest plans and forest operations, thereby helping to reduce any negative impacts to ecosystems. A variety of practices are presented next as options to consider for individual projects. Like tools in a toolbox, they can be selected to reduce or avoid climate-related risks associated with local site features or conditions and to maximize the efficiency of an operation. Practices denoted with an asterisk (*) are often included in State-level BMPs for forestry and water quality.

Site Layout

Site layout is an essential part of the planning process and plays an important role in promoting operations efficiency and protecting natural resources. Informed layout can help prevent traffic in vulnerable areas and reduce climate-related risks to infrastructure and natural resources.

Potential Practices

- **Minimize roads, skid trails, and landing sites.*** Well-maintained infrastructure designed according to BMPs can still impact natural resources, including water and habitat (Edwards et al. 2016). Further, infrastructure ages over time and can also be damaged during extreme precipitation events. Minimizing the total area of roads, skid trails, and landings on a site may decrease compaction and erosion risk and infrastructure maintenance requirements while also reducing the cost to build that infrastructure.
- **Locate roads and skid trails on well-drained soils away from water.*** Utilizing stable, well-drained soils away from water bodies for access can maximize site accessibility for all weather, minimize maintenance needs and costs during wet periods, and reduce ecological impacts associated with soil disturbances. This practice can also increase economic benefits by increasing the duration of conditions favorable for transport.
- **Consider microclimate when laying out roads and trails.** Taking advantage of site-level microclimates may increase operable time for roads and trails.
    - Daylighting (removing tree canopy over) roads or main skid trails can promote quicker drying and maximize operability for summer work in some circumstances (e.g., moderately well-drained soils). Conversely, maintaining shade on roads and skid trails from the tree canopy may extend frozen conditions and associated operability.
    - Locations with south and west aspects may allow for increased operability for summer work, whereas north and east aspects may be suitable longer for operations requiring frozen conditions.

- **Carefully locate landing areas.*** Avoid locating landing areas where they are more likely to become inundated during and after heavy precipitation events or during a thaw, such as low spots that concentrate water. Due to the high amount of traffic around landings, they are best located in upland areas with stable, well-drained soils and away from water bodies.
- **Eliminate or minimize stream and wetland crossings.*** More frequent and intense heavy precipitation events, higher stream flows, and fewer frozen-ground days increase the risks that crossings present to water resources. Avoiding a crossing entirely may be preferable despite tradeoffs such as longer haul distances because fewer crossings may lessen overall impacts to water resources and reduce the costs associated with constructing and maintaining the crossing.

Creating and Maintaining Flexibility

Good planning helps in anticipating possible problems, but unexpected conditions can still arise. Unpredictable or extreme weather events can pose significant challenges, and other events can also impact how or when a forest operation is conducted. The following are examples.

- A heavy rain-on-snow event during winter months can make sites inoperable.
- Equipment problems can result in a harvest occurring later in the winter than planned.
- Wildfire or wind events can disrupt site access, harvest timing, or forest conditions.

Creating and maintaining flexibility as part of planning and operations practices can help protect natural resources, prevent work stoppage, and facilitate efficient work during unexpected conditions. This can occur in part through increasing the ability of loggers to reassess and change plans, working in coordination with the sale administrator, forester, or landowner.

Potential Practices

- **Establish longer contract timeframes.** Longer contracts (e.g., extending a harvest window from 2 years to 3 years) may help ensure operators have good access to the site during the contract period (Bick et al. 2019) and decrease pressure to harvest in suboptimal conditions. This practice can create flexibility for loggers and enable them to complete work when conditions allow but may not be suitable in all instances (e.g., for salvage timber sales).
- **Use contract provisions and language that reflects site-specific information while following applicable regulations and guidelines.** Language that bases restrictions on site conditions (where allowed) as opposed to more loosely linked indicators can ensure maximum flexibility while meeting the goals of an operation. For example, calendar dates may no longer be reliable predictors of site conditions (e.g., frozen ground, oak wilt vector activity).

- **Maintain a diverse portfolio of harvest jobs.** If loggers can maintain a diverse portfolio of procured timber (e.g., soil types, accessibility, and tree species) or planned work (e.g., through an agreement with a mill or landowner), they are likely to have more flexibility with shifting weather conditions and market pressures.
- **During frozen or dry conditions, prioritize activities on challenging sites.** As climate change limits harvest on wet sites with sensitive soils, prioritizing operations to work on those sites when conditions allow can help ensure that the job is completed on time and when the site can support the equipment.
- **Invest in equipment that increases operational flexibility.** Equipment investments may increase efficiency and flexibility and help protect natural resources in unexpected conditions. Changing environmental conditions can be considered when new equipment is being purchased.
    - Cut-to-length harvest systems readily generate slash that can be used to protect natural resources as described in the "Reducing Compaction and Rutting on Harvest Areas, Skid Trails, Landings, and Roads" section.
    - Low ground-pressure equipment can operate in a wider range of conditions.
    - An excavator or dozer can be used for BMP installation and road work following extreme precipitation and blowdown events.
    - Owning redundant equipment to keep on different jobsites can greatly reduce mobilization costs when shifting conditions require pivoting to working on a different site that is less sensitive or has better access.
- **Stockpile brush, slash, and short logs.** This material can be used as corduroy or slash mats to help protect soils in unexpectedly wet areas. Brush and slash can be useful in slowing water flow or reducing erosion in some situations. If they are not generated throughout the harvest area by the harvest system, stockpiling these materials in strategic locations could save time and ensure their availability at all times (Bennett and Frohn 2018).
- **Maintain a cache of biodegradable erosion control supplies.** This may include straw wattles, erosion control blankets, seed for revegetation, and materials generated on site, such as slash, brush, or wood chips. Maintaining a cache of these materials on-site may increase the likelihood of their use, especially in unexpected circumstances, such as an extreme precipitation event or an early spring thaw, that result in high overland water flows.
- **Keep mats on hand.** Timber mats (Fig. 3) or mat systems made from other materials can be used on low-volume roads, on skid trails, or in dispersed areas to support equipment and reduce impacts to wet soils. They may also be used, where permitted, to temporarily enable wetland crossings and span or ford stream crossings. They can be operator-made, purchased, or borrowed. Some organizations lend mats at no cost. Blinn (1998) and Nash (2020) both describe various timber mat and related systems. While mats cannot prevent resource damage in all instances, keeping them on-site gives operators an easy-access tool to help protect natural resources during unexpectedly wet conditions.

Figure 3.—Timber mats in place protecting soil on a stream crossing and the approach. Courtesy photo by Wisconsin Department of Natural Resources.

Reducing Compaction and Rutting on Harvest Areas, Skid Trails, Landings, and Roads

Layout cannot avoid or reduce all risks from forest operations. The following practices can help protect soils in wet conditions, such as those due to early thaws or variable winter temperatures and heavy precipitation events, while maximizing the amount of time operators can work.

Potential Practices

- **Use back-to-front harvesting.** Harvesting the farthest area from a landing or access point first and proceeding toward the landing or access may help reduce site access limitations (Bates et al. 1991, Stone 2002). Cut areas may be wetter than uncut areas due to decreased transpiration (Kolka et al. 2011, 2018).
- **Use slash strategically.*** Slash and corduroy deployment on skid trails and in other areas where equipment operates can reduce rutting and maximize operability during wet periods (Crawford et al. 2021) (Fig. 4). Cut-to-length systems can usually integrate slash or corduroy placement easily into their workflow to protect soil, and slash may work better to support forwarders than to protect soil from skidders and skidded trees. The effectiveness of slash for protecting soil decreases with the number of equipment passes (Solgi et al. 2018), so repeated placements or other techniques may be used for high-traffic areas.

- **Use mats.*** Timber mats or other mat systems can also be used to distribute equipment weight and minimize soil compaction and rutting from equipment. Mats could be a preferred mitigation tool in high-traffic areas, because they do not lose effectiveness as much as slash and corduroy with multiple passes. Note that mats can freeze onto the ground if used when soils temperatures fluctuate above and below freezing.
- **Use equipment with high flotation and low ground pressure.*** Equipment weight can also be distributed through high-flotation tires (Fig. 5), with tracked machines, or with the application of tracks to wheeled equipment. Be aware that the churning action of tracked equipment turning can cause detrimental soil disturbance.
- **Stockpile wood in strategic locations.** Stockpiling in locations that are accessible in wetter weather can allow transportation to occur during times that other work cannot and when mills may be less busy.
- **Delay skidding or forwarding after felling.** Equipment used to fell trees typically causes less disturbance to soils than skidding or forwarding, so felling might be done with minimal site impacts in conditions that are not conducive for skidding or forwarding. Skidding or forwarding may then be accomplished at a later time when the conditions adequately protect soils from the equipment and load (Stone 2002).
- **Pack or plow snow on skid trails, around landings, and on roads.*** Compacting, removing, or plowing snow reduces the insulating layer and can enhance freezing and reduce the number of freeze-thaw cycles (Comerford et al. 2013, Friesen et al. 2021, Hardy et al. 2001, Nash et al. 2020, Stockstad et al. 2022).
    - Maintaining the plowed surface at a great enough width to allow water to collect away from the driving surface can improve drainage. This may also help ensure adequate frost penetration under the driving surface and allow space for additional plowed snow.
    - Creating gaps in snowbanks can aid drainage and prevent water from collecting during thaws (Fig. 6). Consider installing erosion control measures at these locations.

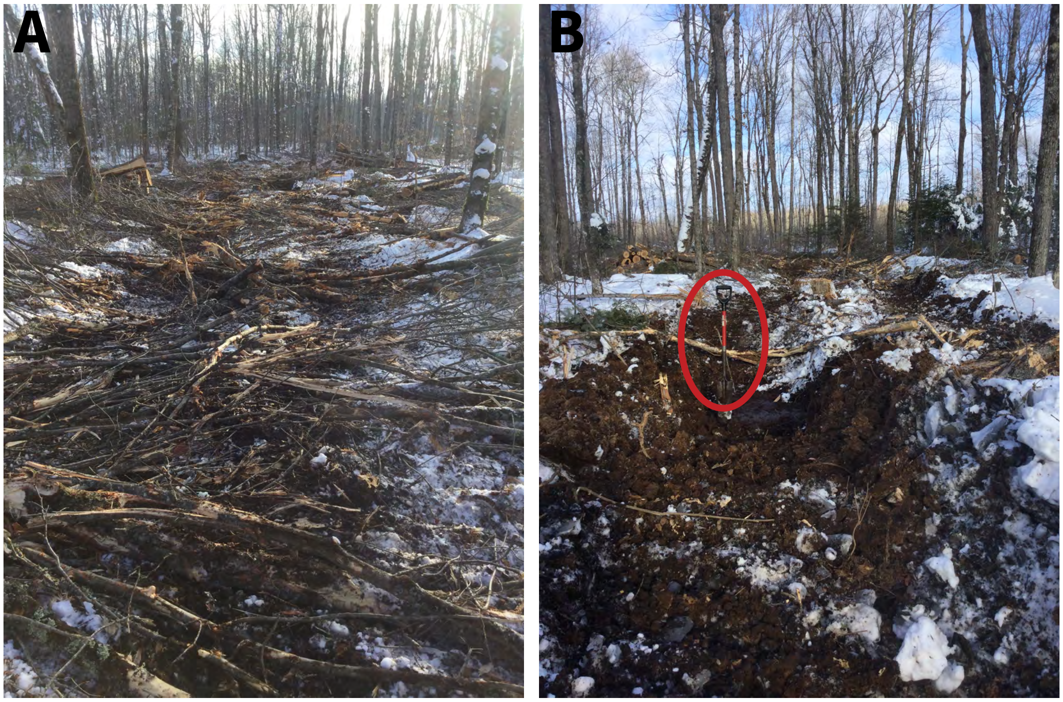

Figure 4.—Slash can be used to armor skid trails prior to equipment passage when conditions are suboptimal. Skid trail (A) armored with slash and showing no rutting and (B) a short distance away, without slash armoring, showing severe rutting. A shovel is circled for scale. USDA Forest Service photos.

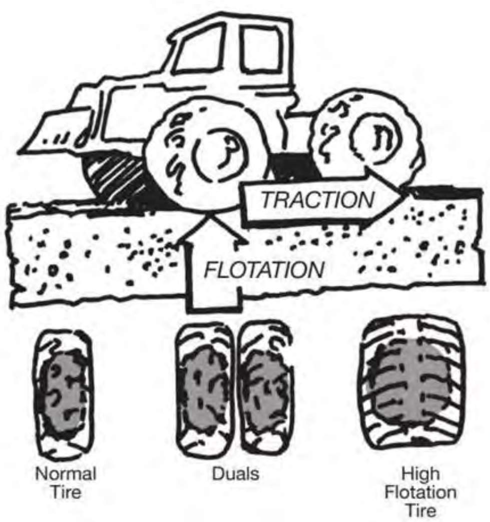

Figure 5.—Illustration of high-flotation tires (Minnesota Forest Resources Council 2014), used with permission.

Figure 6.—Water collecting in a forwarder trail during a thaw. This might have been avoided by installing adequate drainage on the downslope side. USDA Forest Service photo.

Erosion Control

The compacted or impervious surfaces of roadways, skid trails, and landings can move water downslope quickly and cause soil erosion. Concentrated flows can also cause washouts. Roads traversing sloped ground can interrupt and capture natural hillslope drainage and subsurface flows, increasing the velocity of runoff (Curran 1999). While site characteristics like vegetative cover, slope, and soil texture play a role, extreme precipitation events can generate high-velocity overland flow that increases the risk of erosion (Shannon et al. 2019). Practices can be designed to help address the increased risk of erosion brought about by increased precipitation.

Potential Practices

- **Increase the number or size of water diverters, cross drains, and other erosion control devices on roads and skid trails.** When designed and installed properly, devices like water bars and broad-based dips limit water movement over compacted surfaces. This slows water down and helps limit erosion. Fiber mats, straw bales, slash, mulch, and established vegetation can also slow the flow of water and reduce erosion (Wade et al. 2012). Close spacing of erosion control devices may help accommodate larger volumes of water resulting from extreme precipitation events.
- **Install water diverters before the ground freezes.** Because excavation is more difficult when the ground freezes, standard water diversion devices may be difficult to install during the winter. Installing water diverters before the ground freezes will allow them to function during a thaw and spring breakup (Bennett and Frohn 2018).
- **Piled snow can divert water during winter.** Compacted snow mounds across roads and skid trails (at a 30-degree angle to the road surface) can function as water bars during a thaw before they melt (Bennett and Frohn 2018). Compacted snow mounds may be most effective when frozen (i.e., constructed prior to a thaw). Snow mounds can supplement other water diversion devices which may be less effective in heavy snow cover.
- **Stabilize soil in ditches, on slopes, and near waterways, especially in areas at risk of erosion.*** Reestablishing (noninvasive) vegetation on disturbed sites, such as those created during road construction, is critical to preventing erosion (Edwards et al. 2016, Mceachran et al. 2018).
    - Establishing a diverse combination of native woody and herbaceous vegetation is likely best for overall ecosystem function. Woody vegetation can help prevent slope failure in larger runoff events (Löbmann et al. 2020).

- **Slow water in ditches and periodically disperse onto undisturbed forest floor, especially prior to stream crossings.*** Devices like check dams and straw bales installed in ditches can slow concentrated water flows and reduce erosion potential. Periodically dispersing water out of ditches onto stable, undisturbed, vegetated forest floor where it can infiltrate into the soil reduces the amount of flow in the ditch and erosion potential. Dispersing water from ditches prior to crossings (avoiding terminating ditches into water bodies) can prevent sediment suspended in ditch water from entering the stream.
- **Minimize impacts on slopes.*** Maintaining vegetation and minimizing equipment use on slopes helps reduce soil disturbance. Trees on slopes can sometimes be harvested from level ground in conjunction with cable (or aerial) skidding to minimize impact from equipment on slopes. For slopes that are disturbed from equipment or skidding, erosion control devices may be used until vegetation can be established on the areas.

Wetlands

Wetlands play a critical role in regulating the water cycle, minimizing flood peaks, and helping to sustain baseflow through retention and slow release of water downstream. This functional role may become more important as precipitation becomes more variable and extreme. Where permitted, harvesting in and around wetlands is typically accomplished on frozen ground conditions during winter months to minimize impacts to these important and sensitive features. Shorter and more variable winters generally reduce the frozen conditions that are protective, reducing operable conditions and potentially increasing risks to wetlands.

Subsurface drainage, an important component of wetland hydrology, can be altered by rutting and compaction from forest operations in or crossings through wetlands. Soil disturbance can result in blocked drainage, leading to higher water tables and longer residence time of water. A higher wetland water table can, in some sites, result in conversion from a forest to a nonforested wetland (Diamond et al. 2018, Kolka et al. 2011, Welsch et al. 1995) (Fig. 7). Higher water tables and longer residence times within wetlands may be compounded by flooding associated with more frequent and intense heavy precipitation events expected due to climate change. Alternatively, the soil disturbance may result in excessive drainage and decreased water storage (Welsch et al. 1995) and intensify downstream flooding during extreme precipitation events.

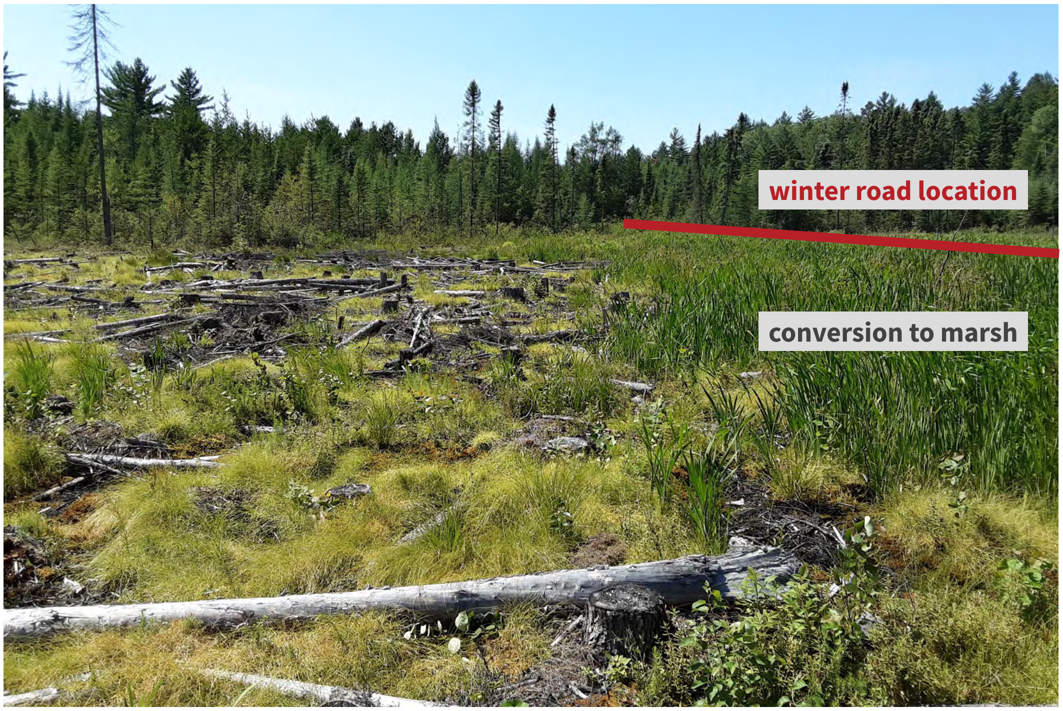

Figure 7.—Conversion from a forested black spruce wetland to a marsh (annotated on the right side of the photo) due to winter road location. A temporary winter road (annotated in red on the photo) compacted soils and resulted in restricted subsurface water flow. Together with the absence of trees driving evapotranspiration and the size and slope of this watershed, the wetland soil disturbance resulted in water ponding and conversion to a marsh. USDA Forest Service photo.

Potential Practices

- **Clearly mark wetlands, including seasonal ponds.*** Tree paint or other durable markings can help ensure that harvest exclusion expectations are followed.
- **Prevent rutting and compaction.*** Potential practices listed in the "Reducing Compaction and Rutting on Harvest Areas, Skid Trails, Landings, and Roads" section of this guide and in other resources such as State agency BMPs may become even more important if operations take place in or adjacent to a wetland.
- **Do not place upland slash and other material into wetlands.*** Timber mats are a good option to minimize compaction and rutting in wetlands, as they are easier to remove than slash or corduroy without causing detrimental soil disturbance.
- **Maintain cross-drainage with wetland crossings.*** Wetland crossings can be designed to promote wetland and infrastructure function by allowing cross-drainage during potentially higher and lower water levels. Actions may include setting the elevation and size of culverts or a porous layer (or both) with consideration of anticipated hydrology (Welsch et al. 1995).

Stream Crossings

Stream crossings can negatively impact downstream hydrologic function (and obstruct aquatic organism passage) when flow is impeded due to improperly placed structures or undersized structures or when sediment or debris accumulation blocks flows. Crossings that do not adequately convey flow can cause erosion of stream channels or road and trail approaches and delivery of sediment downstream (Edwards et al. 2016, MFRC 2012). Risks to crossings are expected to be heightened by more frequent and intense heavy precipitation. Design criteria for infrastructure are often based on historic hydrologic data that may not reflect conditions experienced now and expected in the future. Therefore, structures using historic data may be undersized in cases where climate changes have altered watershed hydrology (Milly et al. 2008). Streams and rivers may experience greater peak flow events and morphological changes that can alter the course and dimension of streams (Montgomery and Buffington 1998, Shannon et al. 2019, Wilhere et al. 2017). Crossings designed without consideration of current and expected future conditions may be at a greater risk of failure. A local hydrologist or licensed engineer can be contacted for design assistance if needed.

Potential Practices

- **Utilize temporary crossings.*** Temporary stream or wetland crossings (Fig. 8) may be appropriate if long-term access to a site is not needed. Because temporary structures are in place only during the operation, risk of infrastructure loss is reduced, and no long-term maintenance of a permanent structure on the site is required. Temporary bridges can often be rented or borrowed, and some states and other organizations lend temporary bridges at no cost. Blinn et al. (1998) offers a review of temporary crossing options. Following are some specific considerations for temporary crossings.
    - Cabling portable bridges or timber mats to a tree on one side of a stream crossing may prevent losing the structure during a flood.
    - Ice bridges made of piled and compressed snow can be useful winter crossings for some streams but may become less viable and riskier as winters become warmer and shorter.

- **Design crossings to accommodate altered hydrology.** Crossing design and placement that account for anticipated changes to hydrology can reduce risks to natural resources and to the structures themselves. Structures designed to allow for efficient water, litter, and organism passage (such as those that span the channel and maintain floodplain connectivity) can provide many benefits to ecological communities and reduce maintenance costs over time (Fig. 9). Climate change-related considerations for crossing design include the following.
    - Stream channels can be altered or become less stable due to higher flow events. The current channel state and possible changes can be assessed and incorporated into the design.
    - Avoid crossing approaches that may divert water away from a stream during large flow events.
    - Methods such as Stream Simulation Design that consider the functions of stream and riparian features may increase resilience to climate change.
    - Sizing structures large enough to accommodate expected flows and debris during floods can help reduce excessive erosion and expensive infrastructure damage, failure, and delays.
    - Aquatic organisms may rely on passage at lower low-water levels and flow rates than in the past due to increased frequency and severity of drought, further reinforcing the importance of resilient crossing designs that allow aquatic organism passage in a wide range of conditions.

Figure 8.—One example of a temporary bridge crossing for a haul road. USDA Forest Service photo.

Figure 9.—Newly installed permanent crossing sized to pass floods, debris, and aquatic organisms and designed to last 100 years. USDA Forest Service photo.

Riparian Management Zones and Filter Strips

Native trees and understory plants in riparian areas regulate hydrology and reduce surface water temperatures by shading and cooling waters. Adjacent to water bodies and wetlands, these riparian areas are typically called Riparian Management Zones (RMZs) in BMPs and are managed to maintain their important function. RMZ functions may become increasingly important to maintain cool temperatures and associated conditions for sensitive plants, wildlife, and peat soils as air and water temperatures increase due to climate change (Reiter et al. 2015, Shannon et al. 2019). Filter strips are strips of vegetation that slow overland flows and minimize potential sediment delivery to adjacent waterways. The following practices can help ensure RMZs and filter strips protect water resources under the current and expected impacts of climate change.

Potential Practices

- **Clearly mark riparian management zones and filter strips.*** Tree paint or other durable markings can help ensure that harvest expectations are followed.
- **Widen RMZs and manage for higher basal areas and resilient forest conditions.** Wider, more fully stocked RMZs may help compensate for possible windthrow (Steil et al. 2009), which could become more of a concern when soils become saturated (Frelich and Ostuno 2012) because of extreme precipitation events. Maintaining a

resilient forest in RMZs is critical to their continued function in the face of threats, including climate change. Riparian forests wider than 100 feet (30 m) may be better able to maintain cool surface water temperatures and trap fine sediment than narrower buffers (Sweeney and Newbold 2014).

- **Widen filter strips and minimize or eliminate traffic, skid trails, roads, and soil disturbance in them.** Ensuring filter strips function as intended during increasingly frequent and heavy precipitation events may require wider-than-minimum filter strips and further minimizing or remediating (e.g., with erosion blankets) soil disturbance in them.

Other: Wildfire and Invasive Species

Threats to forests from fires and invasive species are likely to increase in frequency and severity due to climate change (Handler et al. 2014a, 2014b; Janowiak et al. 2014, 2018). Forest operations can play an important role in mitigating the risk of these impacts (e.g., thinning dense ladder fuels) but can increase the frequency and spread of fire and invasive species if appropriate precautions are not taken.

Potential Practices

- **Use caution with and properly maintain equipment, especially during drought events, to prevent wildfires.** Drier conditions in the spring, summer, and fall may increase the frequency and spread of fires in conifer and oak-dominated forests and woodlands. Equipment is a significant cause of wildfires (Northeast States Emergency Consortium 2024, Wisconsin Department of Natural Resources [WIDNR] n.d.). Proper maintenance of equipment can prevent sparks from metal-on-metal or metal-on-rock contact. Avoiding driving on tall, dry grass or brush can prevent combustion of fine fuels on hot vehicle components (WIDNR n.d.).
- **Clean equipment to prevent spread of invasive species.** Invasive species can benefit from climate change through warmer temperatures and increased disturbances. Invasion by nonnative species such as common buckthorn (*Rhamnus cathartica*) or European earthworms and subsequent disruption of native species communities can affect natural resources through increasing the potential for erosion and altering nutrient cycling (Boettcher et al. 2021, Frelich et al. 2019). Forest operations can create suitable habitat for invasive plant species to thrive and outcompete native species, and equipment can transfer organisms, seeds, or viable vegetative material from one site to another or around one jobsite. Cleaning equipment on-site after working in infested areas and before leaving a jobsite can help limit the spread of invasive plants (Catanzaro et al. 2013, LeDoux and Martin 2013, Minnesota Department of Natural Resources 2018).

Monitoring Impacts and Adapting to Changing Conditions

While some of the considerations and practices identified earlier, notably in the "Site Layout" and "Create and Maintain Flexibility" sections, make it easier to react to unexpected site conditions, it is important to assess and react to current on-the-ground conditions during an operation.

Potential Practices

- **Monitor site conditions and weather forecasts.** Utilizing the relevant information sources and techniques listed in the "Site Condition, Weather, and Climate Information" section may be helpful. In addition, on-the-ground observation is critical to understanding current and changing conditions on a site. Monitoring site conditions and the weather forecast can help provide valuable leadtime for alternate or mitigating actions.
- **Install emergency erosion control measures.** Emergency measures may be useful to respond to unexpected erosion caused by extreme precipitation, rain-on-snow events, or early thaw events. While these measures are not a substitute for properly designed and installed erosion controls, they can be effective interim measures if heavy precipitation, rain-on-snow, or rapid thaw is forecasted. A report by Bennett and Frohn (2018) details possible options, such as diverting water and preventing erosion on frozen roads where proper water bars cannot be installed, and provides other erosion control methods, such as the following.
    - Logs can be impressed onto a skid trail or road (at a 30-degree angle) to divert water.
    - Straw bales, compost socks, or temporary silt fencing can be secured with stakes, which can be pounded into frozen ground, to divert and filter water.
    - Slash can divert and slow water flow, reducing erosion (Forest Guild Biomass Working Group 2010, MFRC 2012, Wade et al. 2012).
    - Tree-tops and brush placed in ditches (provided it is not a wetland) can slow water and settle sediment out before it reaches a water body.
    - Non-biodegradable temporary erosion controls can be removed and replaced with longer-term solutions such as living vegetation and excavated water bars.
- **Stop work on the site.** The best choice may be to stop work if the available practices cannot prevent excessive soil compaction, rutting, or erosion during operations. Stopping work may also prevent inefficient operations that may result in an economic net loss.
    - In some cases, work could pivot to another area on the same site or to another site altogether to keep the business operating.
    - If unfavorable weather such as a thaw or an extreme precipitation event is predicted, installing erosion control measures and removing temporary crossings before work is stopped on a site may reduce erosion.

Sale Closure

Proper sale closure can address resource damage incurred during harvest and prevent ongoing or future impacts to natural resources. A harvest operation occurs during a relatively short window of time compared with a typical stand rotation or the time between stand entries. Sale closure provides an opportunity to prevent impacts after site activities. Closure activities can take place in preparation for temporary work stoppages due to weather or other reasons as well as at the conclusion of a harvest (Fig. 10).

Figure 10.—Temporary timber mat stream crossing (A) installed and in use and (B) removed in preparation for the end of the season. Courtesy photos by University of New Hampshire Extension.

Potential Practices

- **Install erosion control measures.*** Erosion control, as described in State agency BMPs and in the "Erosion Control" section, can be installed after the operation to help prevent erosion during future weather events. For example, installation before spring breakup may prevent erosion during that wet period and until operations are reinitiated.
- **Monitor and maintain infrastructure.*** Infrastructure and practices for erosion control remaining on the site after a harvest operation pose some risk of failure, especially if not maintained. Regular monitoring can identify maintenance needs to address before they contribute to infrastructure failure. As precipitation events continue to become more extreme due to climate change, increasing stress on the infrastructure may require additional maintenance to ensure continued function and protection of natural resources. If infrastructure fails, BMPs may cease to protect soil and water resources and present safety hazards to future users.

- **Remove or decommission roads and crossings; remediate skid trails and landings.*** A variety of restoration techniques can be used to reestablish hydrologic functions and help the site cope with heavy precipitation events and drought (Apodaca et al. 2018). This may be especially relevant for old infrastructure that is not suited to the current or future climate. The following presents some possible techniques.
    - Rehabilitation practices such as soil ripping can help to restore the natural drainage and hydrologic function at these locations (Fig. 11). Ripping helps to reduce the impacts of compaction, may facilitate quicker vegetation regrowth, and increases the likelihood of soil infiltration (Switalski et al. 2004).
    - Revegetation success can be limited on compacted soils, but if vegetation is established, it can aid infiltration and reduce instances of erosion over time. Rehabilitated landings, roads, skid trails, and other areas where natural regeneration is absent can be revegetated with future-adapted tree or understory species. Tree species lists and vulnerability assessments describe how different species may be affected by climate change and provide other information and resources that may help guide planting (e.g., [USDA Climate Hubs Climate Change Projects for Individual Tree Species lists]).
    - Closing access to roads reduces unauthorized access and use, mitigating possible safety hazards and damage to infrastructure.
    - Removing culverts and associated fill from crossings (Fig. 12) can prevent washouts and reduce negative impacts resulting from extreme precipitation events.

Figure 11.—Skid trail (A) before and (B) during and after remediation for rutting and compaction. USDA Forest Service photos.

Figure 12.—Crossing removal and stream restoration. USDA Forest Service photo.

Summary

Forest operations are important to managing forested lands. Timber harvests are critical tools for manipulating vegetation towards a desired condition, addressing forest health issues, and meeting land management goals. Best management practices are commonly used to reduce risk to natural resources to protect soil and water during and after operations. Weather impacts forest operations-related risks to natural resources. Climate change is altering current weather patterns and may complicate forest operations. To continue forest operations while protecting natural resources, it may be increasingly important to plan operations and implement practices to protect soil and water with consideration of the changing climate conditions.

Climate change is causing warmer winters and less snow cover, which affects the duration and consistency of frozen ground and may result in shorter or more variable operating windows for sensitive soils. Hotter, drier summers may increase the risk of wildfire and might also provide additional access or harvest opportunities in dry conditions. More frequent and intense precipitation events may increase erosion associated with forest roads, vegetation removal, and other soil disturbance. These events may also cause flooding, which can disrupt site access or damage infrastructure.

Relevant information about site features and conditions can be used to assess forest operations risks related to climate change that may impact economic viability of a job or create challenges to protecting natural resources. Operations plans can reduce risk through contract language, through site layout, and with practices and equipment that increase operational flexibility. Delaying or refraining from some forest operations may be an important option to prevent natural resource damage and economic inefficiency in some locations or cases. Methods to reduce compaction and rutting can increase operability during less favorable (e.g., unfrozen, wet) conditions. Practices that reduce erosion and protect water bodies may require more robust designs to maintain the same effectiveness. Monitoring impacts and adapting to real-time site conditions, sale closure practices, and practices to prevent equipment-caused wildfire or spread of invasive species may be increasingly important. Following State forestry BMPs remains important and may involve planning or actions beyond business-as-usual. Considering climate change in forest operations can support continued protection of natural resources and the economic viability of forest operations.

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