PREVENTING SOIL COMPACTION AND RUTTING IN THE BOREAL FOREST OF WESTERN CANADA

A Practical Guide to Operating Timber-Harvesting Equipment

Brad J. Sutherland

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Brad Sutherland

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Forest Engineering Research Institute of Canada (FERIC)

Eastern Division and Head Office
580 boul. St-Jean
Pointe-Claire, QC, H9R 3J9

(514) 694-1140
(514) 694-4351
admin@mtl.feric.ca

Western Division
2601 East Mall
Vancouver, BC, V6T 1Z4

(604) 228-1555
(604) 228-0999
admin@vcr.feric.ca

www.feric.ca

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Introduction

When forest harvesting equipment moves across a cutblock, soil compaction and/or rutting can result. Forest practitioners are therefore concerned about the long-term effects of harvesting on forest soil health, water quality, and tree growth.

The purpose of this handbook is to provide practical advice to forestry contractors and equipment operators, and their field supervisors, about the risk of damage to forest soils during harvesting operations, and how to avoid it.

The opportunity to protect forest soil occurs at each step of the forest-management process, from harvest planning to field layout to harvesting and post-harvesting activities. Operators of forestry equipment, harvesting contractors, and field supervisors are vital links in this process.

To help identify when the health of forest soil is at risk, this handbook offers a brief introduction about forest soils, and explains why and how soil is susceptible to damage. The soil terminology used is defined in a glossary along with other equipment related terms (Appendix I).

For harvesting contractors and equipment operators, the handbook explains how visual indicators like landscape features and tree species can be used to estimate soil moisture, and offers simple field tests to help them anticipate when soils become at risk.

For contractors, equipment features that influence soil compaction and rutting are discussed, and operating techniques to reduce soil damage are suggested.

For field supervisors, harvest scheduling options that minimize soil damage are included. As well, the handbook offers ways to modify harvesting operations when soils have become susceptible to damage.

Maintaining soil health during harvesting requires knowing when soils are at increased risk of compaction and rutting, and understanding how equipment operation interacts with the soil. If contractors, operators, and field supervisors can anticipate susceptible soil types and conditions, they will be able to plan ahead and make changes to their operating schedules and techniques.

Recommendations made in this handbook regarding equipment and operating techniques are to serve as guidelines only. Local operating conditions and regulations, as well as equipment availability, must be considered when interpreting this information.

The importance of soil

Why is soil important and why protect it?

Soil is one of the most important components of a forest ecosystem. All plant life in the forest depends on the soil to supply nutrients, gases, moisture and support for roots. Soil also plays a key role in providing clean, high quality water to lakes, streams, and rivers. Maintaining soil in a healthy state is essential to the overall health of a forest ecosystem and ensures a stable environment for the plants and animals that live there.

Soil forming processes take time, and soil structure can be fragile. Once soil is damaged it can take years to repair. Damaged soil can provide an unhealthy environment for plants, leading to reduced survival and growth. Trees can take decades longer to grow to merchantable size. If soil stability is lost, soil erosion may occur, leading to sediments entering streams and rivers, and reduced water quality.

Forest harvesting is a highly mechanized activity. All phases of wood handling require careful consideration to reduce the negative impact on soils. How and when equipment is operated in a forest environment can make a big difference in protecting the soil from damage.

Forest companies derive their economic livelihood by managing forests in a long-term sustainable manner. By striving to protect soil and forest ecosystems from becoming damaged during harvesting operations, the forest industry ensures its own continued viability and the economic, environmental, and social benefits that go with it.

Soil components

Soil is a complex mixture of mineral and organic particles surrounded by pore space that can be illustrated in a simplified manner (Figure 1). Pore space can make up half the volume of soil, and is filled with water and air. Aeration porosity, or the amount of air-filled space relative to the volume of soil, can vary from over 25% on coarse textured soils to as low as 12% on very fine textured soils. The proportion of air and water shifts constantly. However, if aeration porosity drops to less than 10%, the soil will not contain enough gases (oxygen) to support tree growth. Maintaining aeration porosity is very important to maintaining the health of the soil.

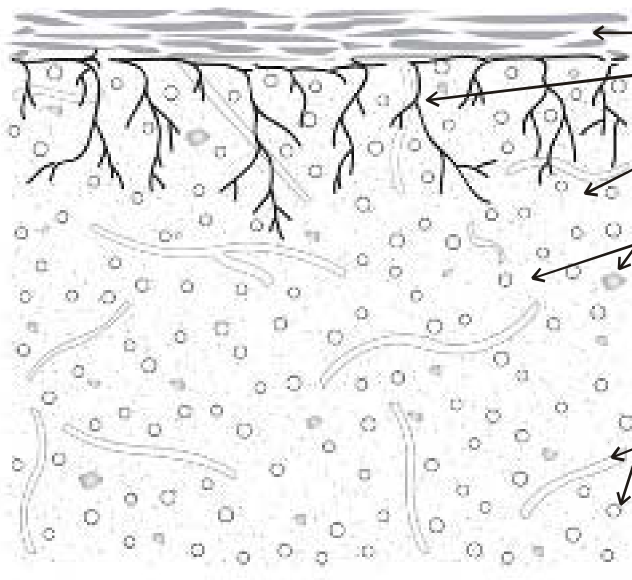


Figure 1. Soil components.

Damaged soil

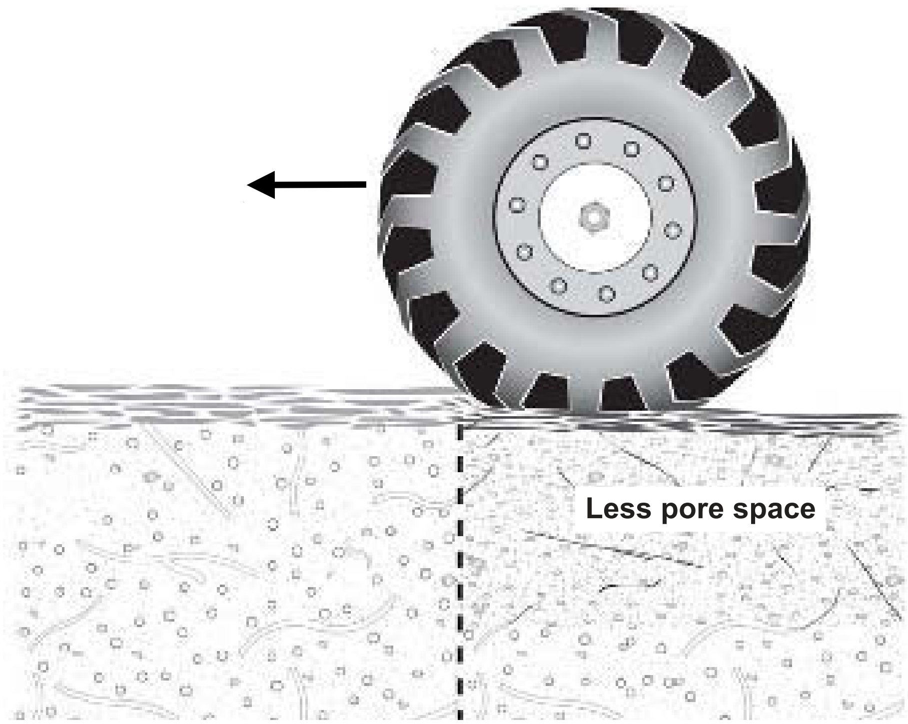
Soil becomes damaged when it is compacted and/or rutted. The extent of the damage depends on the severity of the compaction and/or rutting and the amount of the cutblock impacted.

Soil compaction

What is it? Compaction is the compression of the soil caused by a load (or by pressure) that exceeds the strength of the soil to resist it. Soil compaction, unlike rutting, is usually not visible from the surface.

How does compaction happen? Soil compaction occurs when the soil is compressed so much that its particles and aggregates are pushed together, and the large pore space is reduced, thus increasing the density of the soil. The greatest reduction in pore space occurs after one machine pass. Additional passes reduce pore space further, but to a lesser degree as progressively more force is required to push soil particles together. A common indirect measure of soil porosity and strength is soil bulk density.

Figure 2 shows the change in soil structure resulting from compaction. Compaction often extends to a depth of 20 cm. Only two or three machine cycles may be necessary to compact the soil. (Each cycle = 1 pass loaded + 1 pass empty.)



Undisturbed Forest Soil | **Compacted Forest Soil**

In non-compacted soils:

Soil is porous - This means that:

- There is adequate infiltration of rain and unimpeded drainage.
- There is sufficient aeration porosity and gas exchange with the atmosphere, and for plant roots and soil organisms.

How does soil compaction damage the soil?

Less pore space - Compaction changes the soil structure by reducing some or all of the large pore space. This means that:

- It's harder for the exchange of gases to occur, therefore less oxygen is available to the tree roots.
- Drainage of water through the soil is reduced and/or modified which can result in fewer nutrients available to the tree roots.
- The water stays on top of the soil and becomes surface run off, which can lead to erosion as it starts to puddle or flow.
- It's harder for roots to penetrate the soil.

Figure 2. Compaction reduces soil pore space and affects soil processes.

Why is it bad? The reduced pore space and slowed or modified drainage of soil water can reduce the exchange of gases and the amount of oxygen available to plant roots. Over the longer term, fewer nutrients are available. In addition, slower infiltration of water into the soil can lead to increased surface flow and soil erosion. The reduced pore space also makes it hard for the tree roots to penetrate the soil.

Soil compaction can cause enough damage to make the soil unable to support normal forest growth. Compaction is of most concern when it occurs over a broad area. Silt and clay soils common in west-central Alberta and north-eastern British Columbia, frequently have poor soil structure. As a result, their naturally-occurring aeration porosity is only slightly greater than the critical level of 10%. Any reduction in porosity, for example from compaction, can be detrimental to tree growth. Soil can remain damaged by compaction for decades (**Figure 3**).

Which soils are most easily compacted? Medium-to-fine textured soils having a moisture content at or near field capacity.

Soil rutting

What is it? Ruts are the trenches or furrows created by machine tires or tracks (**Figure 4**). Rutting displaces soil and damages soil structure.

Figure 3. Poor natural regeneration of aspen adjacent to a log deck, ten years after harvesting (photo courtesy of Paul Sanborn, University of Northern British Columbia).

Figure 4. Ruts made by a rubber-tired skidder (photo courtesy of Ken Van Rees, University of Saskatchewan).

How does rutting happen? Rutting is caused by repeated passes of equipment, for example when a skidder goes back and forth over the same skid trail. If soil strength is low however, as in the case of saturated soils, rutting can result from one pass of a skidder or feller-buncher.

Why is it bad? Figure 5 shows how rutting displaces the soil and causes changes to the soil structure. It explains how rutting can impede root development and soil drainage. Ruts in a wet depression can indicate that compaction has occurred in moist soils nearby. Ruts create an unsightly visual impact in a natural landscape.

Which soils are rutted most easily? Rutting occurs most easily on medium-to-fine textured saturated soils, and on organic soils with a well-decomposed surface organic layer.

Soil strength

Strong soils are resistant to damage by rutting and compaction. Not all soils are strong.

Organic soils have thick (>40 cm) surface layers that can cushion the underlying soil from compaction but they may be prone to rutting if the organic material is well decomposed. Maintaining the surface root mat intact can help to support equipment passage on organic soils. Soil protection may depend on frozen conditions.

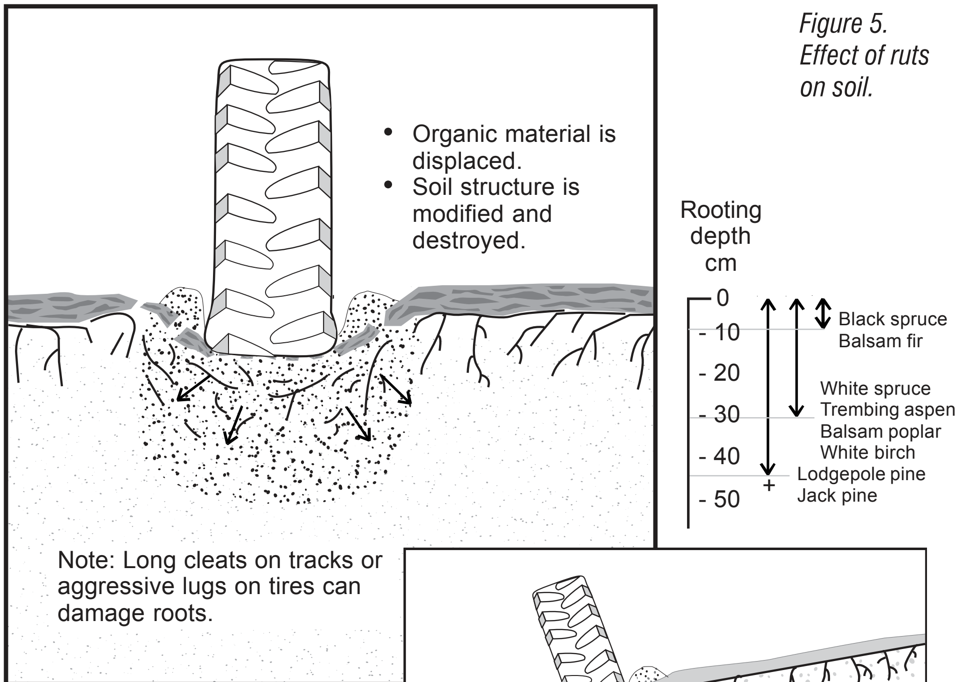
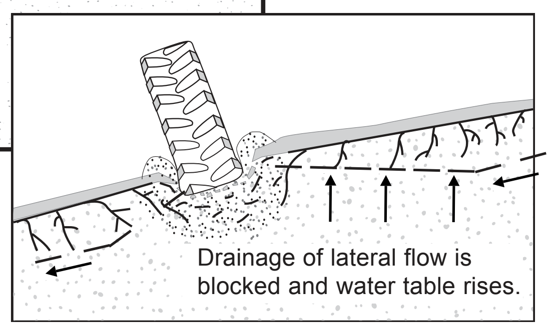


Figure 5. Effect of ruts on soil.



How rutting damages the soil

Rutting displaces and moves the soil. The resulting changes in soil structure and strength mean that roots and drainage are severely affected.

Effect on roots

- It is difficult (or impossible) for roots near the surface to develop and penetrate soil.
- Even shallow ruts can damage or break roots near the soil surface. Also, long cleats on tracks, or aggressive lugs on tires, can damage roots.
- When roots are damaged or broken, trees are more susceptible to disease and to toppling during high winds.

Effect on soil drainage

- Lateral (sideways) flow of water through the soil is blocked, causing a localized rise in the water table and pockets of saturated soil or ponding on the uphill side of the rut.
- Saturation causes the soil temperature to drop, which reduces tree growth, and it prevents the exchange of gases.
- Surface water flowing along the rut can cause soil erosion and sedimentation.

For mineral soils, soil strength depends on the amount of contact between soil particles and is influenced by soil texture and water content.

Soil texture

Soil texture depends on the amounts of sand, silt, and clay particles contained in the soil. Sand is the largest, and clay is the smallest. Soil particles less than 2 mm can be classified by texture, and by susceptibility to compaction and rutting, as shown in **Figure 6.**

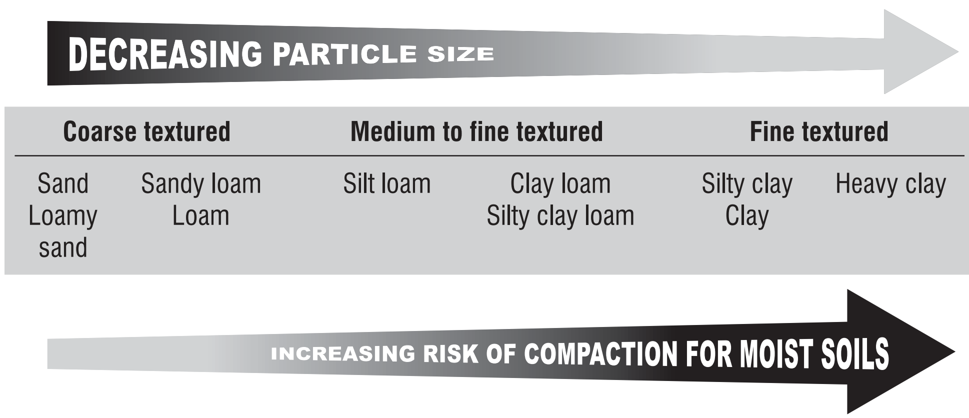


Figure 6. Soils classified by texture, and by the effects of high soil moisture on compaction.

Fine-textured soils—those with the finest particles—are strong when they are dry due to numerous points of contact between the particles. However, fine-textured soils become compacted very easily when moist or wet as water surrounds the particles and reduces the number of contact points. This allows the particles to separate when a force is applied (such as by harvesting equipment).

Coarse-textured soils—such as pure sands—have large particle size and are weak when they are dry due to few points of contact between particles. These soils are prone to rutting and displacement. Under well drained condition, the strength of coarse sands may increase temporarily following rainfall, due to increased cohesion between particles.

Mineral particles larger than 2 mm are called coarse fragments. Soil strength can be increased if the content of coarse fragments in the soil is high (70% by volume).

Water content of the soil

The water content, or wetness, of the soil is constantly changing and depends on soil porosity, rainfall, the rate of drainage, and vegetation/forest cover. Finer textured silts and clays have a very large number of small pores (gaps) between particles that allow them to hold more water and hold it more tightly (drain more slowly) than coarser textured soils (**Table 1**).

Table 1. Water-holding capacity of different types of soil

Type of soil particle	Size of soil particle	Water-holding capacity
Sand	Largest	Low
Silt	Small	Medium
Clay	Smallest	High

When all the pore space is filled with water, soil is saturated. Saturated soils have low strength and are most prone to rutting. Frequently-saturated soils tend to have a thicker forest floor or dark soil horizons at the surface. An abundance of some plant species, such as labrador tea and horse tails, are good indicators of high soil moisture. To tell if the soil is frequently saturated, take a small sample from close to the surface, and check for mottles (rust-coloured spots or blotches) or gleying (light grey to pale bluish coloured soil). These are indicators of saturation.

Water drains quickly from large soil pores over a few days. But, at that point, water is still held in the smaller pores, and the soil is said to be at field capacity. It can stay this way for long periods of time. Soils near field capacity also have low strength.

How long does it take the rain to drain from the soil? Soil strength is affected by the amount of rainfall absorbed by the soil through infiltration, and this depends on the duration and intensity of rain events as shown in **Table 2**. After prolonged rainfall, it takes approximately two days for the soil to drain if the soil is free draining. On poorly drained soils, it may take a week or more. Poorly drained clay soils with no vegetation or forest cover, and subjected to frequent summer rains, may stay wet for weeks. If soils become saturated, soil strength is low.

In stratified soils where the soil texture changes at various depths, drainage can be slowed and the soil will hold moisture for a long time. Such soils are common in the boreal plains region of western Canada.

How can slope and topography indicate soil drainage and moisture? Figure 7 illustrates how slope position affects soil moisture content. Usually, crests and upper slopes tend to be well drained; midslopes to level ground are moderately well drained to imperfectly drained where soils are saturated for long periods; and level to lower slopes are imperfectly to poorly drained.

Table 2. Effect of rainfall on soil strength for medium and fine textured soil

	General effect of rain event on soil strength	
Intensity	Duration (1–2 hours)	Duration (1–2 days)
Heavy rainfall	Possible effect - low infiltration	Major reduction - considerable infiltration - ponded surface water **Caution** - high risk of soil compaction and rutting
Light rainfall (showers)	Usually little effect - very little infiltration	Some to major reduction - some infiltration **Caution** - some to major risk of soil compaction and rutting

Note: This table demonstrates general trends that will vary with pre-existing moisture levels, soil texture and topography (drainage).

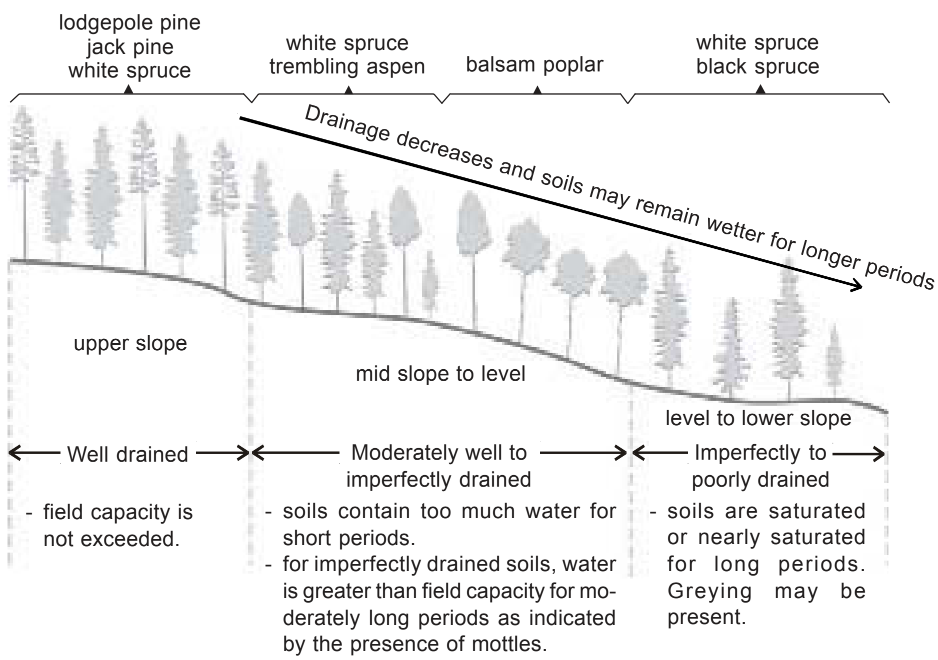


Figure 7. Slope preference of common tree species in a northern Alberta boreal mixedwood (adapted from Beckingham and Archibald 1996).[1]

[1] Beckingham, J.D.; Archibald, J.H. 1996. Field guide to ecosites of northern Alberta. Canadian Forest Service, Northwest Region, Northern Forestry Centre, Edmonton. Special Report 5.

Typically as you travel down a slope, soil strength decreases because soil drainage is poorer and soil wetness is greater. Water drains the slowest from flat landscapes and low-lying pockets or depressions. The topography or shape of the landscape along with slope can be examined to anticipate changes in soil moisture as shown in **Figure 8**.

Tree species can also be indicators of soil moisture and drainage. **Figure 9** shows the range of preferred soil moisture for common boreal tree species.

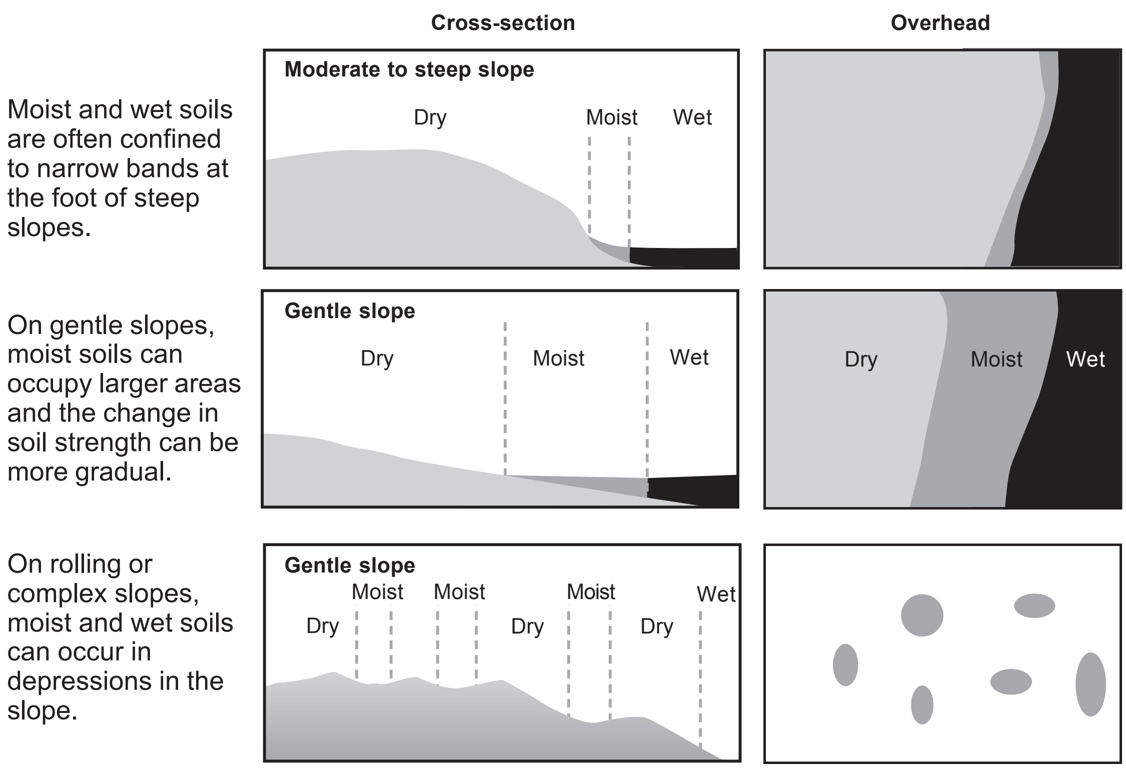


Figure 8. Topography can be used to indicate changes in soil moisture (adapted from Arnup 2000).

Note
Horizontal lines indicate the preferred soil moisture for boreal tree species. Moist soils often contain a mix of several species. A stand of primarily aspen typically would be found on well-to-moderately-well-drained soils whereas a stand with a 50/50 mix of aspen and balsam poplar would indicate more moist, imperfectly drained soils (adapted from Beckingham and Archibald 1996).

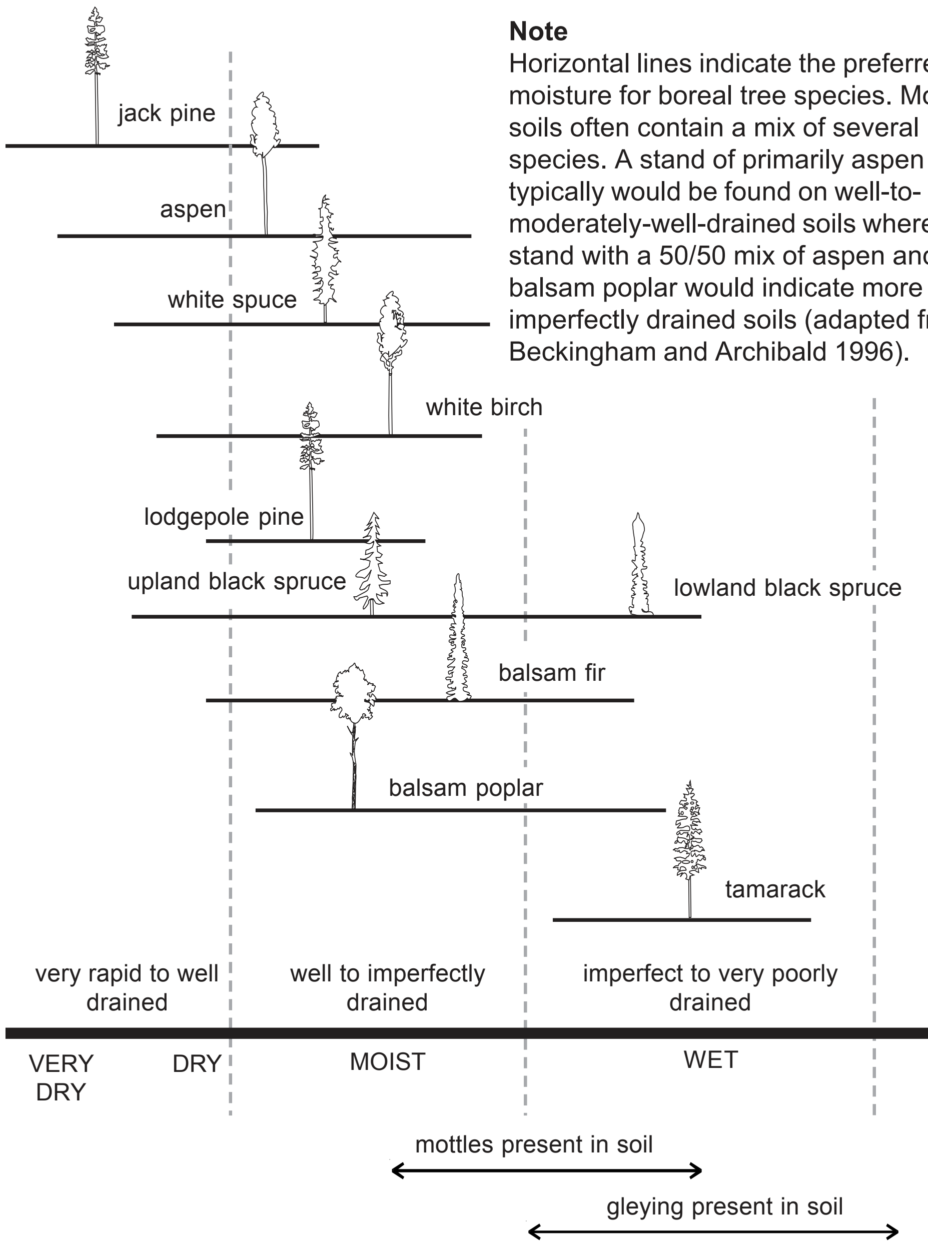


Figure 9. Tree species can be an indicator of soil moisture and drainage.

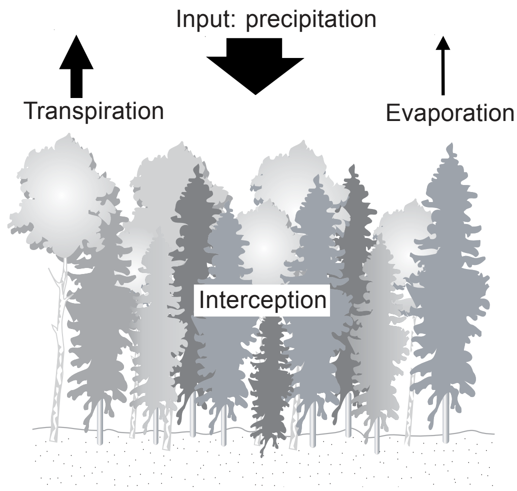


Figure 10. The role of vegetation/forest cover in the water cycle.

How does vegetation/forest cover affect water content? Water (moisture) is constantly moving through our environment, in a water cycle (**Figure 10**). Soil receives water from rain and melting snow. Some moisture is intercepted by vegetation and evaporates from the surface. Some is taken up by tree and plant roots and returns to the atmosphere through transpiration. Some becomes surface runoff while the rest is stored within the soil, and drains down and laterally.

How does removal of the forest cover by timber harvesting affect water content? Following felling, the water content of normally moist and wet soils will increase because trees are not transpiring (**Figure 11**). Precipitation that occurs between felling and skidding will rapidly increase the moisture content of the soil, and result in water ponding and greater surface runoff.

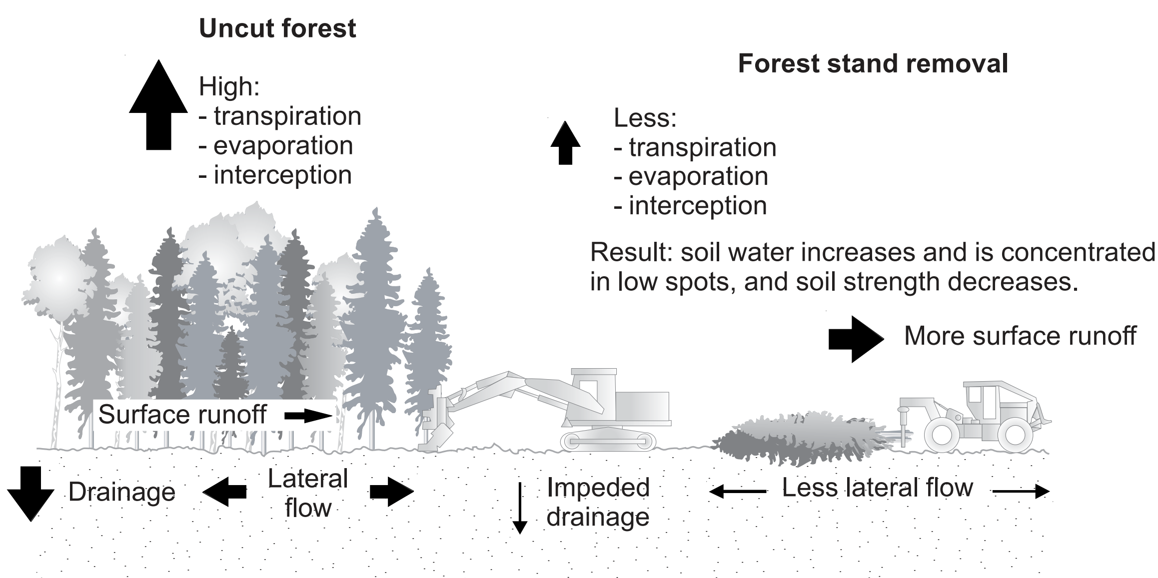


Figure 11. Removal of the forest cover increases the water content of the soil. Soil compaction and rutting from equipment traffic slows soil drainage.

How does forestry equipment affect the water content of the soil? Equipment traffic can cause compaction and rutting. These changes to the soil structure can alter the drainage pattern and in turn cause the site to remain wetter longer.

How to minimize soil damage

Seasonal changes and what they mean for soil protection

In terms of protecting the soil, the most favourable conditions for operating forestry equipment are: dry soils in summer/fall, or frozen soils in winter.

Soil conditions change as the seasons change. **Figure 12** illustrates how soil strength fluctuates with the season.

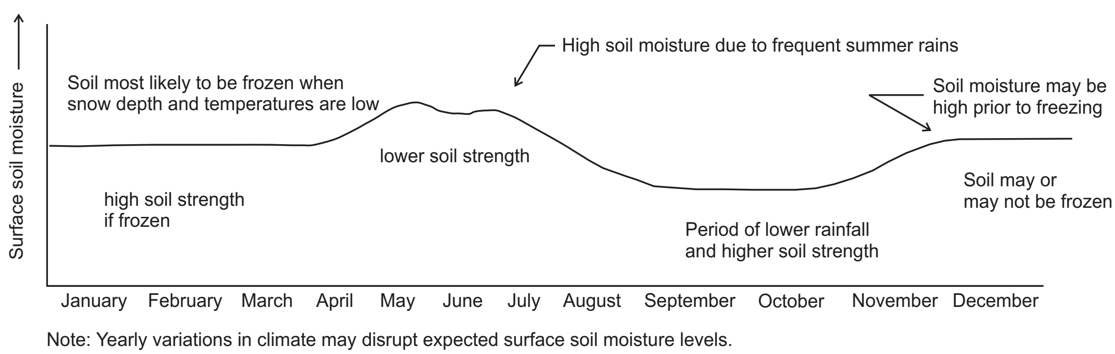


Figure 12. Season and moisture content affect soil strength.

Moist/wet soils. Soils that are moist or wet are the most fragile, and harvesting activities may need to be delayed until the soils become drier or frozen.

Dry soils in summer/fall. Soil strength in boreal forests is usually highest in late summer and early fall when soil moisture content is lowest due to less rainfall and higher levels of evaporation.

See **Appendix II** for more information about how to check the soil wetness using a simple hand consistency test.

Frozen soils in winter. Harvesting when the soil is frozen can minimize the risk of compaction and rutting but only if soils are very well frozen. Soils with a low moisture content may not freeze but are less prone to damage.

The depth of frost penetration is affected by soil type, amount of soil moisture, vegetation type, snow depth and climatic conditions. Coarse textured soils if moist, will freeze sooner and to a greater depth than fine textured soils. Organic soils will also freeze sooner than fine textured soils due to higher moisture content.

Snow depth affects frost penetration. Undisturbed snow depths of 30 cm can reduce frost depth by the same amount. If significant snowfall occurs, even after the soil freezes, heat stored in the soil will tend to thaw this frozen layer. The layer will not easily re-freeze because it is insulated from freezing temperatures by the blanket of snow.

Under certain conditions, snow can protect the soil from equipment activity. Wet/compressible snow >60 cm deep, and frozen/crusty snow >40 cm deep can help support the weight of equipment and offer good protection. Dry powdery snow provides little support or soil protection.

Depth of frost penetration. For mineral soils, the depth of the frost's penetration into the soil needs to be 7–15 cm to prevent most harvesting equipment from rutting and >15 cm to prevent compaction. For organic soils, at least 50 cm of frost depth is required to prevent rutting for wet conditions, and at least 70 cm for dry conditions. Operating heavy equipment on soils with less than adequate frost depth may compact the underlying soil. **Appendix III** explains how to use a simple frost probe to estimate the depth of frozen soil.

Techniques to promote frost penetration and protect the soil. In winter conditions where the soil may not be frozen to an adequate depth, compacting or blading off some of the snow can decrease the insulating effect of snow and allow frost penetration. Sufficient time must be allowed for the soil to freeze properly before the trail can be used.

- Operate the feller-buncher in a pattern perpendicular to the road so that the trails will freeze and can later be used safely by the skidder (**Figure 13a**).
- Harvest and skid wood that is closest to roadside first to promote frost penetration in this high-traffic area (**Figure 13b**).
- Skid bunches in a wide swath fashion to allow sufficient time for frost penetration prior to skidding the next swath (**Figure 13c**).
- Where cutblock boundaries cause the skid trails to converge, skid high-traffic areas first to allow time for the soil to freeze prior to skidding the area beyond the construction (**Figure 13d**). If the soil in the high-traffic area is wet, establish a designated skid trail.

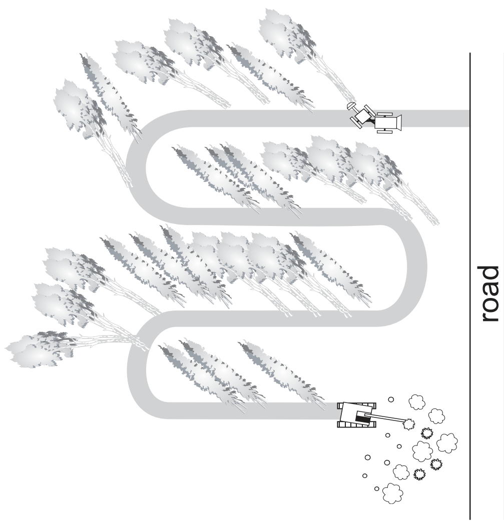


Figure 13a. Fell perpendicular to the road and skid on frozen trail.

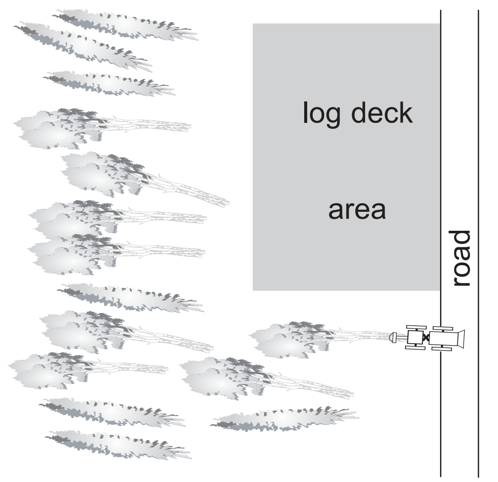


Figure 13b. Skid log deck area first to promote soil freezing.

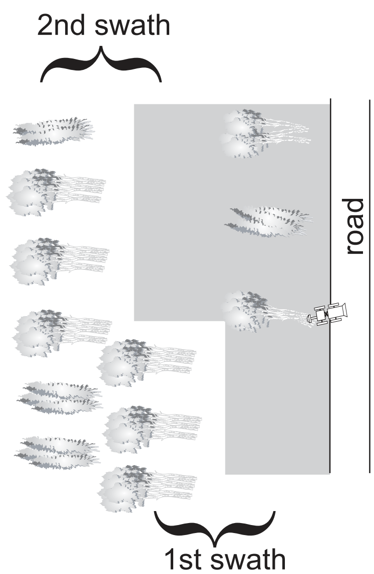


Figure 13c. Make each skid swath wide to promote soil freezing prior to next swath.

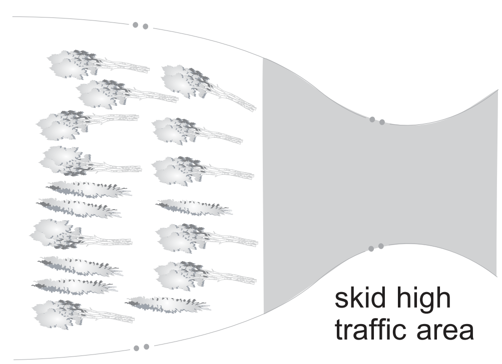


Figure 13d. Skid constricted areas first to promote freezing prior to additional traffic.

Checklist to assess changing operating conditions

Knowing when to expect temporary changes in soil strength on medium- and fine-textured soils is essential to assessing operating conditions. Changes in site conditions and weather can be indicators of higher soil moisture.

When to check soil moisture in the summer/fall operating season:

- √ At the start of a new cutblock.
- √ Change in slope position – from higher and better drained to lower and more poorly drained.
- √ Change in tree species – from an indicator of drier to a wetter site.
- √ Significant rainfall (several hours) – either just prior to or during operating day.
- √ At locations of repeated machine traffic (i.e., >3-5 passes).

Use the simple field procedure for estimating soil wetness (see **Appendix II**) to determine the risk of compaction and rutting. **Table 3** provides operating tips for different levels of compaction risk.

Table 3. Soil wetness: operating tips, by level of compaction risk

When the level of compaction risk is: [a]	Then do the following:
High	• Relocate to drier ground, or to coarser textured soils.
Some	• Consult with supervisor about options for avoiding compaction and rutting including: - Relocate to drier ground, or to coarser textured soils. - Reduce machine traffic by avoiding multiple passes. - Decrease load size and minimize turning.
Low	• Operate normally while minimizing repeated passes, but re-check conditions when an increase in soil moisture occurs as indicated by a change in slope position, tree species, or rainfall. • Avoid pockets of high soil moisture, such as natural depressions and seepage areas.

[a] Assumes use of tires with width of 85 cm or greater.

When to check for frozen soil in the winter operating season:

√ When soil moisture levels would be high if not frozen.

√ At the start of a new cutblock.

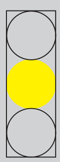
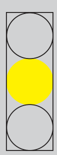
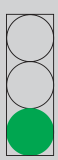
√ Warmer temperatures – can lead to thawing of previously frozen ground.

√ Significant snowfall – can insulate the ground and prevent soil freezing or if frozen, lead to soil thawing. If soils are dry, freezing may not occur.

√ Change in ground condition to a wetter site – as indicated by operating on a lower slope position or by a change in tree species.

Use a frost probe to estimate the depth of frost penetration (**see Appendix III**) to determine the risk of compaction and rutting. **Table** 4 provides operating tips for different levels of compaction risk.

Table 4. Soil frost depth: operating tips, by depth of frozen soil

When the soil is:		Then do the following:
Not frozen - check soil moisture		• Check soil wetness and refer to Table 3 for operating tips.
Frozen less than 15 cm - some risk for large equipment, minimal risk for small equipment		• Consult with supervisor for options to avoid compaction and rutting including: - Relocate to drier ground, or to coarser textured soils. - Reduce machine traffic by avoiding multiple passes. - Decrease load size and minimize turning. Another option is to blade or compact snow to promote soil freezing.
Frozen to 15 cm or greater		• Operate normally and re-check condition when a warming trend occurs or you suspect an increase in soil moisture from change in slope position or tree species.

Use the appropriate equipment

Understanding what equipment features contribute to soil damage is a key step towards appropriate equipment selection and operation. The following equipment-related features have an impact on soil damage.

Overall machine weight and load distribution

Figure 14. Overloaded skidder with front wheels off the ground (photo courtesy of Tony Sauder, FERIC).

- The lower the machine weight/load, the better.
- Don't overload skidders as this concentrates the load on the rear axle (**Figure 14**).
- Selecting a skidder with as long a wheel base as possible ensures a balanced weight distribution between axles, and reduces the shifting of weight from front to rear when loaded.
- For forwarders, the wider a machine's track width and the lower the load height, the more balanced the load distribution will be from one side to the other during travel.

Ground pressure

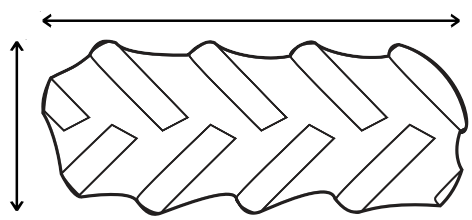


Figure 15. Tire contact area or footprint. The larger the area of contact, the lower the weight applied to a given area of soil.

- The more tire or track area touching the soil, the lower the pressure on the ground. Distributing the load over a greater area by increasing the contact or footprint reduces the risk of soil compaction and rutting (**Figure 15**).
- Increasing the tire footprint area can be accomplished by using wider tires at reduced inflation pressure. Increasing the footprint length without increasing the width can be accomplished by using larger diameter tires or decreasing tire pressure (within manufacturers' specifications).
- Tire pressure control systems allow an operator to change tire inflation pressure while travelling to suit the ground conditions.
- An approximation of ground pressure under each wheel can be calcuated using the following formula from Makkonen (1989):[2]

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[2] Makkonen, I. 1988. Review of forwarders. FERIC, Pointe Claire. Technical Note No. TN-123. 12 pp.

Footprint pressure for a tire is defined as: P=W/(R•B)
Where P = footprint pressure in kPa (psi), W = wheel load in kN (lb), R = tire overall radius (unloaded) in metres (in.), and B = tire width (unloaded) in metres (in.).

- For a track, the formula for footprint pressure is P=W/(B(1.25R+L)) where B = track width, R = track wheel overall radius, and L = the distance between track wheel centres.

Tire or track slip

- Some slip is needed to engage soil strength for traction, but excessive slip increases compaction and rutting (**Figure 16**).
- For tires, slip is affected by the type of tire tread, by weight or load on the tire, as well as by uneven distribution of power (torque).
- The grip between the ground and each tire on a machine travelling across rough terrain varies constantly due to shifting wheel loads. The use of differential locks permits the full utilization of different driving forces to each wheel. However, with differential locks engaged, turning is resisted and can cause more soil damage (ruts) than with a normal differential. When turning on soft ground, soil damage can be avoided if the differential locks can be disengaged.
- Best control of slip occurs with independent traction control to each wheel. The use of a hydrostatic transmission and independent hydraulic motors in wheels with automatic slip control can minimize slip better than a mechanical transmission and all-wheel-drive.

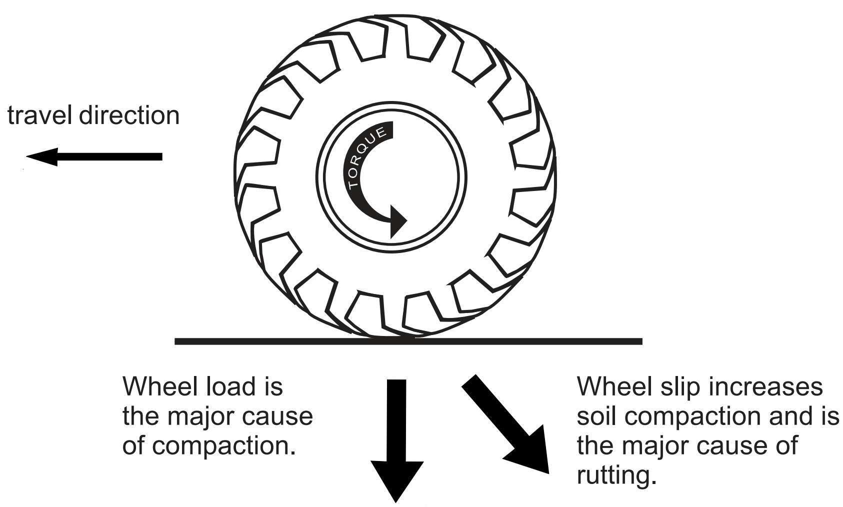

Figure 16. Wheel load and slip.

- For rigid-frame tracked machines, sharp turns usually cause severe ground disturbance. Slip is affected by the method of power distribution to tracks while turning. Planetary or hydrostatic drive systems minimize skid steering and reduce damage to the soil while turning, compared to clutch systems. Hydrostatic drive systems usually permit infinite track speed control and maintain constant turning rates on mineral soils. On organic soils, high grousers on tracks can be used to minimize spinning and tearing of the organic layer.
- Track grousers prevent slip but high grousers can damage shallow tree roots. Using track pads with double grousers (lower height) increases ground protection compared to single grousers, while maintaining traction.

Bogie versus single axle

- Bogie axle systems allow more tire surface to be in contact with the ground.
- Bogies reduce the vertical lift of the machine to one half the height of the obstacle encountered (**Figure 17**). This can reduce shock loads to the ground and the machine.

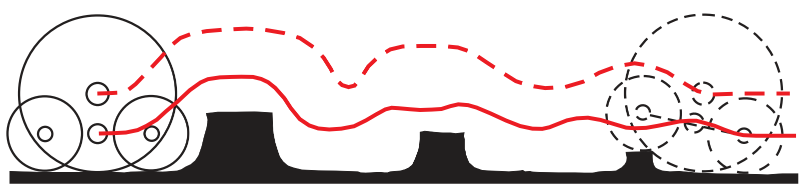

Figure 17. Comparison of axle movement on bogie and single axle (Makkonen 1989).[3]

- In thinning or partial cutting operations in soft ground conditions, bogie axles allow narrower machine widths than wide, high flotation tires.
- Bogie axles weigh more than single axles, and in sharp turns bogie wheels slide sideways and are more likely to tear the forest floor and upper soil layers.
- For machines with a single axle in front and a bogie axle on the rear, the proper selection of tire sizes between front and rear is critical. The outside diameter ratios of the front and rear tires must be maintained to prevent soil rutting.

For equipment used in the primary transport of wood, **Table 5** compares equipment features that affect soil disturbance.

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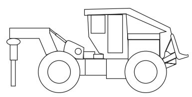
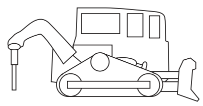
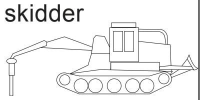
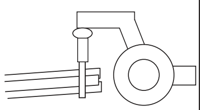
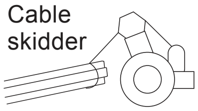
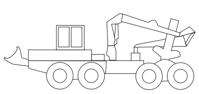
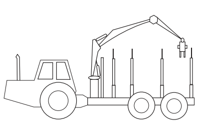
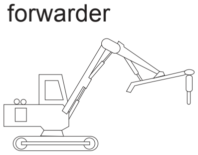
[3] Makkonen, I. 1989. Choosing a wheeled shortwood forwarder. FERIC, Pointe Claire. Technical Note No. TN-136. 12 pp.

Table 5. Equipment features and their effect on soil

Equipment	Effects on the soil: Pros	Effects on the soil: Cons
Wheeled skidder 	- Can switch to wide tires or add tracks to reduce ground pressure, or add chains to reduce slippage. - The rounded edges of tires are less likely to shear surface layers (i.e., damage roots) than the sharp edges of tracks.	- Capable of high speeds and is therefore subject to bouncing which can increase soil compaction. - Worn tires are prone to slippage. - Articulation while stationary can displace soil and result in considerable damage to soil and roots.
Tracked skidder-rigid frame 	- Tracked machines travel more slowly than wheeled machines so may cause less soil damage. - Can have better traction than tires, so less slippage and rutting occurs.	- Skid steering can cause considerable disturbance. - Track grousers can cause damage to tree roots. - Unbalanced load distribution may result in higher ground pressures than wheeled machines.
Flexible tracked skidder 	- Tracks conform to shape of the ground so weight distribution is maximized. - Low or non existent grousers prevent damage to tree roots.	- Combination of high speed and skid steering can increase soil displacement and root damage. - Unbalanced load distribution may result in higher ground pressures than wheeled machines.
Grapple skidder 	- Less manoeuvring of skidder is needed with swing grapples compared to conventional grapples.	- Must maneuver skidder to the location of each load resulting in more travel over the ground. - May need to reposition several times to collect a full load if bunch size is small.
Cable skidder 	- Can minimize area of ground disturbance when cable is pulled from main skid trail. - Can reduce soil damage if load is released and winched when traversing wet areas.	- Use has been declining in favour of grapple skidders, due to the efficiency and operator safety of the latter.
Clambunk skidder 	- High load capacity requires fewer passes than conventional skidders. - Rotating clam and articulated boom mean less turning and maneuvering are necessary when loading. - Some models have a swing cab allowing machine travel in either direction.	- Not suitable for small confined areas and short skid distances that require considerable maneuvering to build a load. - Very heavy loads can increase compaction.
Forwarder (6 or 8 wheels) 	- Carries rather than drags load so potential for wheel slippage is less than with skidders, and ground disturbance is less. - Usually travels over a mat of slash created by the harvester. - Bogie tracks can be added to reduce ground pressure. - Can maneuver around obstacles easier than a loaded skidder.	- Greater weight of loaded forwarder compared to skidder may increase compaction. - Bogie drive system can skid steer when turning and result in more rutting with heavy loads than four-wheeled machines. - Slash mat can be pushed into soft soil.
Loader-forwarder 	- Machine is stationary while load is forwarded in stages so much less ground disturbance occurs than with other equipment. - Can forward wood from sensitive areas to ground better suited for skidders. - Can corduroy wet spots.	- Equipment is specialized, so it is best used in conjunction with conventional skidders. - Equipment is heavy. - Load imbalances may result in point loading.

Tires, wheel tracks and chains

Appropriate tires, tire pressure, and add-on components can make a big difference in reducing ground pressure and controlling slip. The following list provides some tips when choosing tires, chains and tracks.

Tire size

- Using wider tires (i.e., >85 cm) reduces rutting, and combining wider tires with reduced inflation pressure increases flotation and reduces compaction (**Figure 18**).
- Using wide tires may give a false sense of security if operators choose to travel on wetter low-strength soils that would normally be avoided with regular tires (**Figure 19**). Compaction damage can occur with no visible ruts.
- Using wide tires can increase the damage to residual trees.

Figure 18. Skidders equipped with wide tires (photos courtesy of Mark Ryans and Brad Sutherland, FERIC).

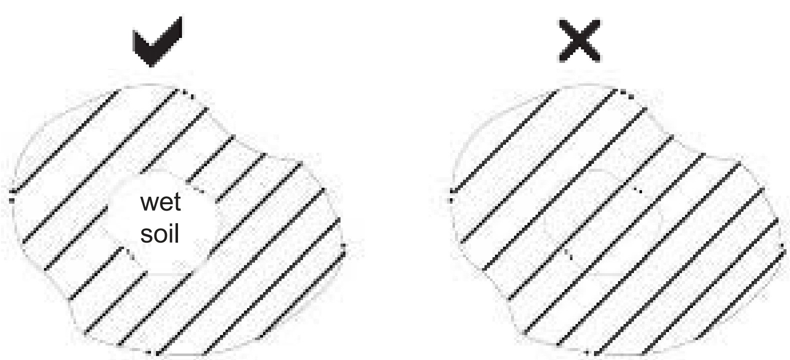
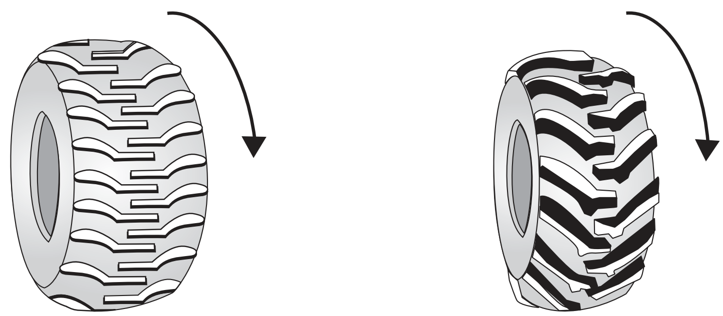


Figure 19. Do not operate on wet, low strength soils even with wide tires.

Treads and lugs

- Tread or lug depth affect slip. Deeper or aggressive lugs can offer better traction. However, deeper lugs give higher resistance to rolling such that overall traction may not be improved compared to tires with less aggressive lugs (**Figure 20**).



Non-aggressive tread		Aggressive tread	
Pros	Cons	Pros	Cons
reduced soil damage	increased risk of slip	reduced slip	increased risk of soil/root damage

Figure 20. Tread depth affects wheel slip.

- The tread active edges of a tire (i.e., surface and edges of tread) are what provide traction. As tire width is increased, traction is maintained by an increase in the length of tread active edges (**Figure 21**).
- Rounded shoulders on lug ends will reduce disturbance during turning especially for tires on bogie axle systems (**Figure 22**).

Chains

- To reduce excessive slip, chains should be added to all tires (**Figure 23**).
- Cleats on chains may injure roots near the soil surface.

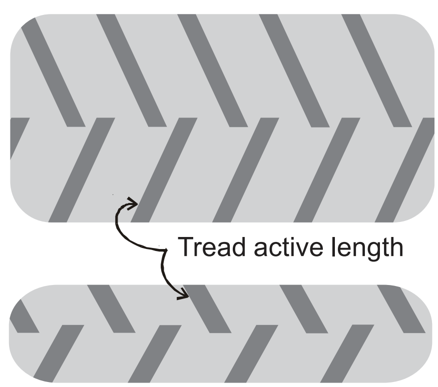


Figure 21. Tread active edges provide traction. Increasing tire width increases the length of active edges, thus maintaining traction while reducing ground pressure.

Figure 22. Rounded shoulders on lug ends reduce disturbance during turning (photo courtesy of Peter Dyson, FERIC).

Figure 23. Using chains on tires reduces slip (photos courtesy of Tony Sauder, FERIC).

Wheel tracks

- Tracks reduce slip and increase flotation as well as lower the maximum travel speed of wheeled equipment (**Figure 24**).
- Select tracks designed with the links as close as possible to the outside surface of the tire. This ensures a similar speed of travel for all track pads or grousers in contact with the ground along the track length, which avoids slip.
- Aggressive track grousers should be avoided to prevent injury to tree roots.

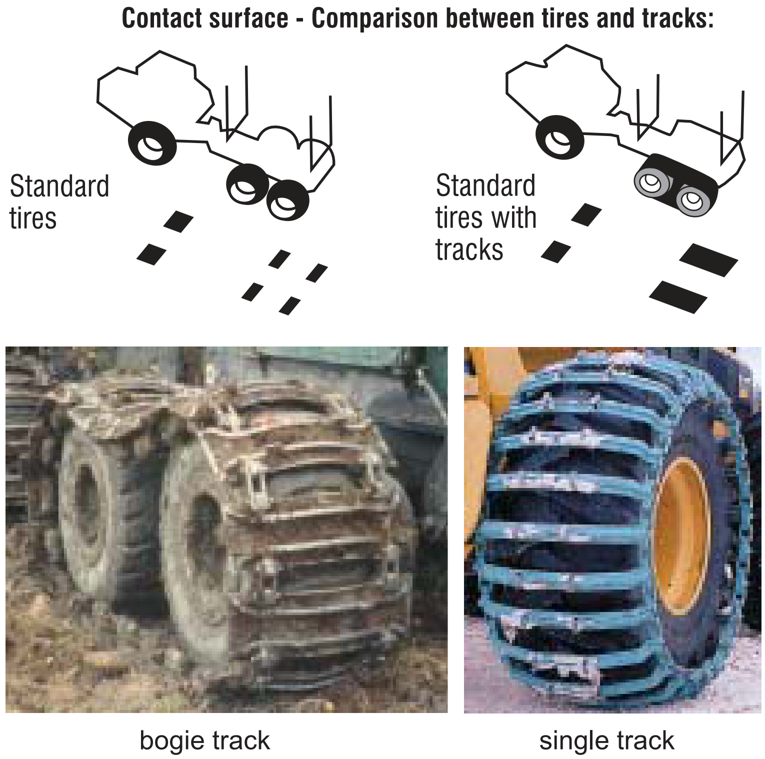


Figure 24. Using tracks reduces slip and increases flotation (photos courtesy of Tony Sauder, FERIC and Gunnar Bygdén, Olofsfors, AB).

- Special track designs are available for operation on low strength soils. These designs feature very wide tracks (up to 1.5 m) and smaller gaps between track pads (**Figure 25**).

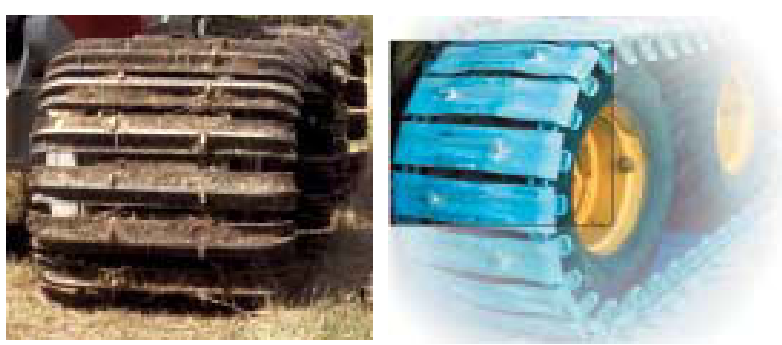


Figure 25. Track designs for low strength soils (photos courtesy of Kris Kosicki, FERIC and Gunner Bygdén, Olofsfors AB).

- Tracks having pads with rounded ends do not cut the forest floor as much as tracks with sharp corners (**Figure 26**).
- Tracks require tires to have higher inflation pressures and on hard ground, the peak loads transmitted by track grousers can increase damage to tree roots.
- To achieve maximum flotation with bogie tracks, proper track tension is required to ensure that track pads not supported by the tires also carry the load.

Figure 26. Tracks modified by the addition of rounded widening plates (arrow indicates plate) to increase flotation (photo courtesy of Jacques Lirette, FERIC).

Use appropriate felling techniques

The felling phase is an important first step in preventing soil damage. Operators of felling equipment need to consider how their decisions affect the skidding or forwarding phase. In addition, as the first to traverse the block, felling equipment operators can provide valuable feedback on soil conditions prior to skidding or forwarding.

The following list provides some tips to help operators minimize soil disturbance and damage.

Space passes widely and make neat bunches

- Space feller-buncher passes as far apart as possible to reduce the area of soil disturbance. Make neat bunches that are as parallel as possible to the skidding path. This will minimize the amount of maneuvering the skidder needs to do during hook-up (**Figure 27**).

Cut perpendicular to the road

- Cutting should progress perpendicular rather than parallel to the road, to minimize the number of skidder passes. Skidding should remain dispersed unless soil is frozen.

Optimize bunch size

- Make the bunches the optimum size for the skidder (**Figure 28**). Bunches that are too small or too large cause the skidder to make more turns than necessary.

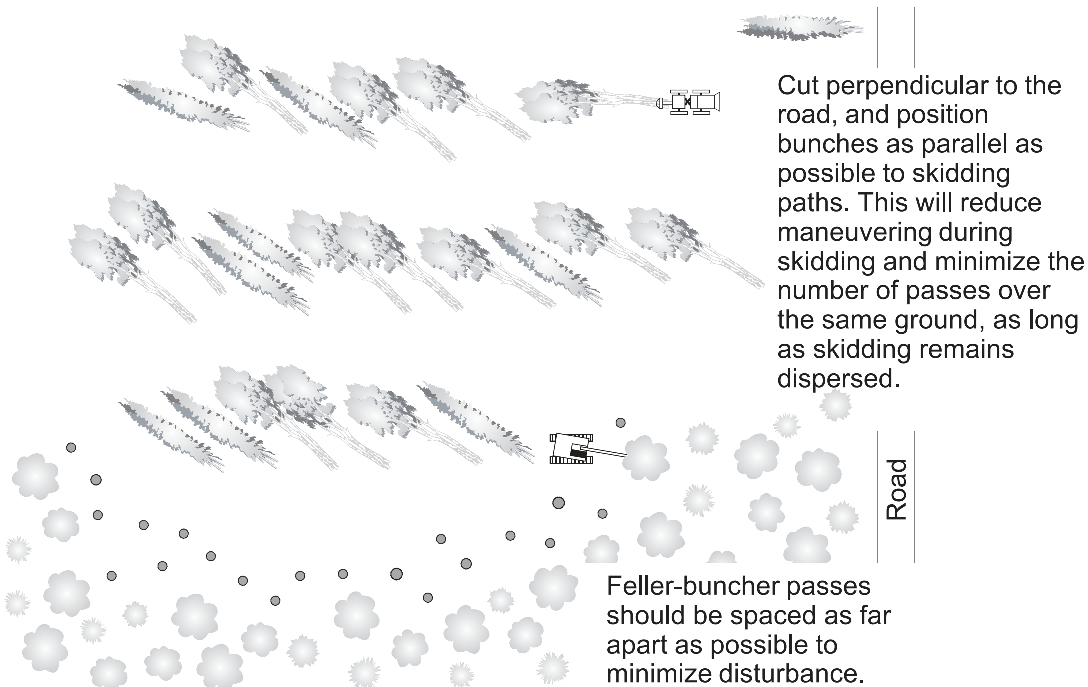


Figure 27. Tips for harvester operators to minimize soil disturbance and damage.

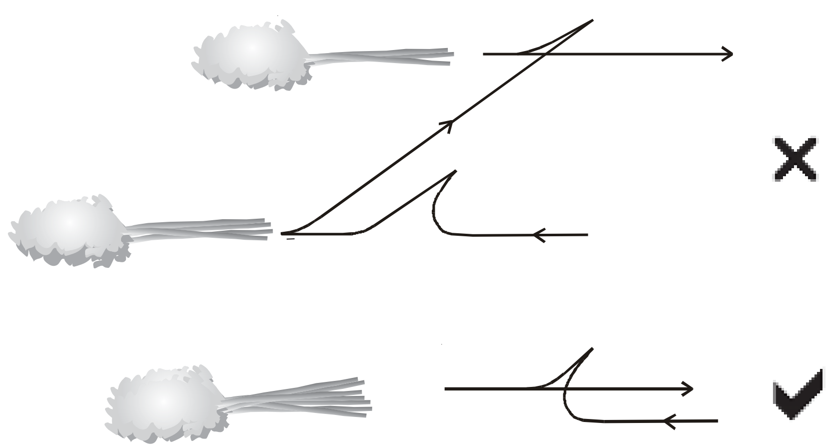


Figure 28. Feller-buncher operators should optimize bunch size to minimize travel required by skidders to build a load.

Sudden changes in conditions

- If it rains while felling is underway on poorly drained areas, move operations to a better-drained location until the soils recover. Transpiration from the remaining uncut trees will speed recovery time.
- Alert skidder operators to areas of wet, low-strength soils encountered unexpectedly during harvesting. If areas are small, feller-bunchers can position bunches outside of wet spots to avoid further traffic by skidders.

Distribute woody debris

- For harvesting systems that feature at-the-stump delimbing, keep woody debris evenly distributed over the block to serve as a protective mat for skidding.

Use appropriate skidding and forwarding techniques

The following list provides some tips to help skidder and forwarder operators minimize soil disturbance and damage.

Skidding pattern options

There are two kinds of skidding patterns:

1. *Dispersed* — Machine travels a different route for each turn.
2. *Designated trail* — Machine travel is confined to predetermined routes/trails.

Dispersed skidding may cause soil sompaction over a large area which may be difficult to rehabilitate. Skidding with designated trails affects a small area but may cause severe rutting that is relatively easy to rehabilitate. Skidding patterns are compared in more detail in **Table 6**.

Match techniques to conditions

- Soil moisture can increase rapidly after a site has been clearcut. Therefore, skidding should take place very soon after harvesting—ideally, within two to three days—to ensure that compaction and rutting are minimized.
- Skid with an optimum load size to limit the number of cycles in a block. When soil strength starts to deteriorate due to rainfall, for example, but conditions are still operable, reduce load size until conditions improve (**Figure 29**).

Table 6. Comparison of skidding patterns

Skidding pattern	Pros	Cons	Where/when to use	Where/when not to use
Dispersed	Distributes impact over a large area.	Can cause widespread compaction and rutting if soil strength is low. Advanced regeneration is damaged.	Use in dry or frozen conditions. Use on coarse textured sands that retain soil strength when moist or wet.	Do not use on fine to medium textured soils if moist or wet.
Designated trail	Can avoid widespread compaction and rutting. Trails can be rehabilitated. [a]	Repeated use of a skid trail with as few as two to three cycles can result in significant compaction. Can lead to rutting in fine-textured soils that are wet.	Use in moist conditions that are susceptible to compaction if unable to shut down operations. Use where slopes or other land features restrict travel to confined areas. Use near landings to limit the impact to small areas.	Do not use if soils are wet or have low strength, or if rehabilitation is not feasible.

[a] Rehabilitation treatments consist of soil decompaction and replacing organic material.

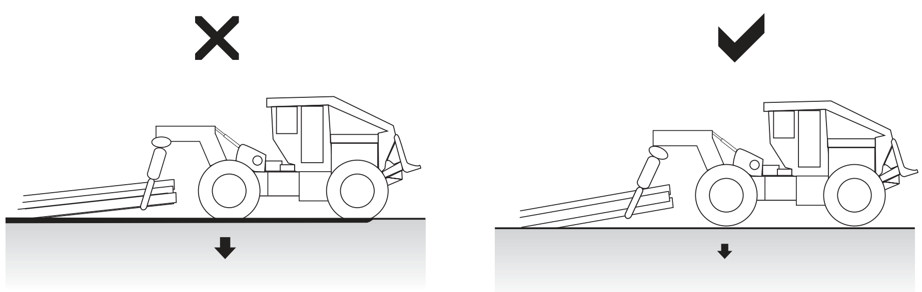


Figure 29. Reduce size of load when soil strength decreases (e.g., during or after rain).

- Where possible, try to skid downhill rather than uphill. The risk of compaction and rutting is less with downhill skidding, because wheel slippage is less likely to occur (**Figure 30**).

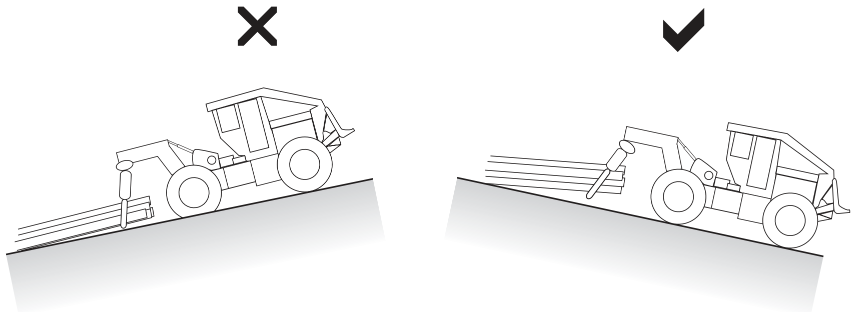


Figure 30. Try to skid downhill rather than uphill to keep axle loadings balanced and reduce slippage.

- Avoid skidding on side slopes. Slippage can occur easily on side slopes, and can damage or break roots, or displace the protective forest floor exposing mineral soil to erosion (**Figure 31**).
- Do not skid through or near wet patches/depressions.

Number of passes

- If utilizing dispersed skidding, avoid funneling traffic over the same ground (**Figure 32**). The majority of compaction occurs after two or three cycles, or less if soil moisture is near field capacity.

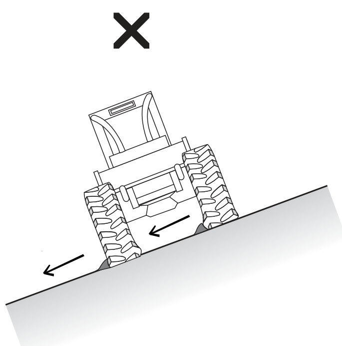


Figure 31. Avoid skidding on side slopes to reduce slippage that can damage or break roots, or tear the forest floor.

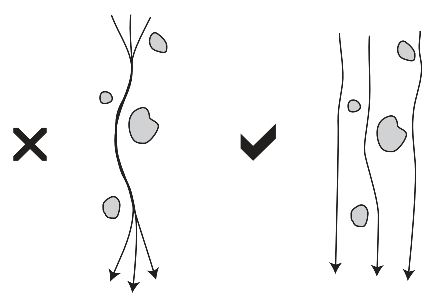


Figure 32. When avoiding obstacles in a block, avoid funneling traffic and keep skidding dispersed if possible.

- Rut depth is influenced by the number of passes over the same trail and soil strength. On saturated fine textured soils, ruts can be formed in one pass. Maintaining the forest floor intact and utilizing brush mats, for example, can protect soils from rut formation.

Travel speed

- A constant travel speed is recommended whenever possible.
- Avoid rapid speed changes and travel at lower speeds to reduce bouncing, help prevent load imbalances, and reduce tearing of the forest floor (**Figure 33**).

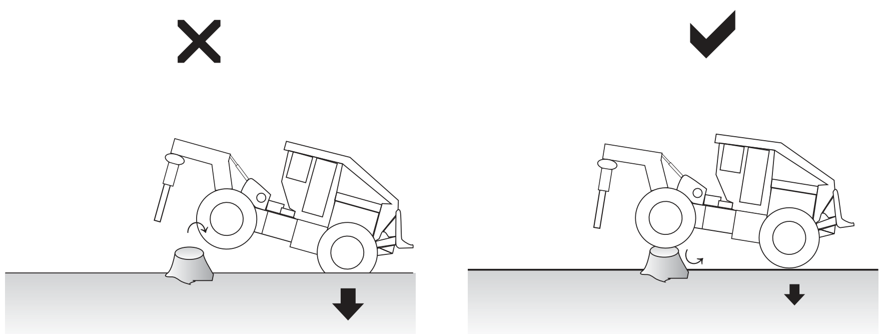


Figure 33. Avoid high travel speeds. High speed causes the skidder to bounce and contributes to load imbalances, which increases soil compaction and displacement.

Turning

- Minimize turning and pivoting as much as possible and execute turns with as large a turning radius as possible.
- Where possible, turn skidders on high strength ground or on the road rather than on the cutblock or landing.
- For skidding distances less than 100 m, return to the cutblock in reverse (back-up), rather than turn the skidder in the block, to retrieve the next bunch (**Figure 34**).
- The skidder's approach to the landing or decking area should be as straight as possible.

Match equipment to conditions

- Use grapple or cable skidders or loader-forwarders where high maneuverability is required such as in small or irregular areas of a block.
- Use grapple skidders for short skidding distances (150–200 m).

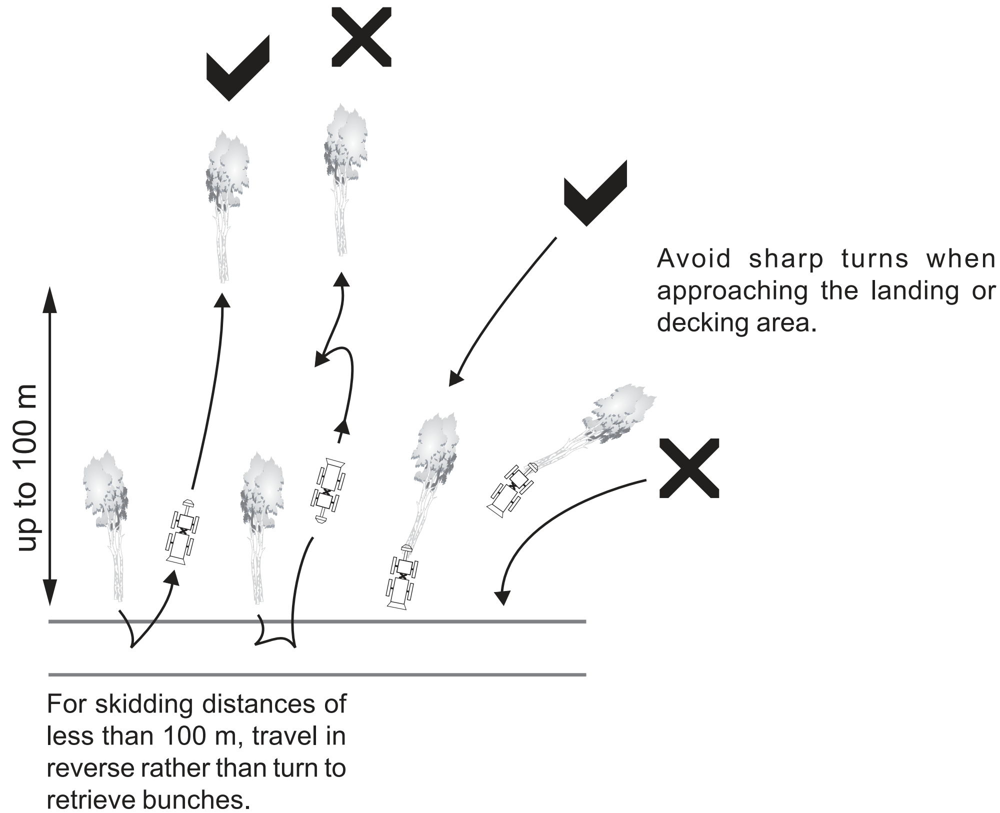


Figure 34. Minimize turning in the block to reduce soil damage.

- Use larger capacity clambunk skidders for long, relatively straight skidding distances.
- Use loader-forwarders or cable skidders in areas with lower soil strength.

Minimize equipment traffic on sensitive sites

Some harvesting operations occur in sensitive areas such as riparian zones where equipment traffic may be limited to protect low strength soil and avoid damage to remaining trees. The following harvesting and wood extraction techniques can be used to reduce disturbance to the soil and stand.

- Hand fell trees outward, toward the zone boundary. Top skid tree-lengths with a cable skidder or remove stems with a loader-forwarder (**Figure 35**).
- Enter stand with a feller-buncher, accumulate several trees, back out, and pile bunches on drier ground for skidding.

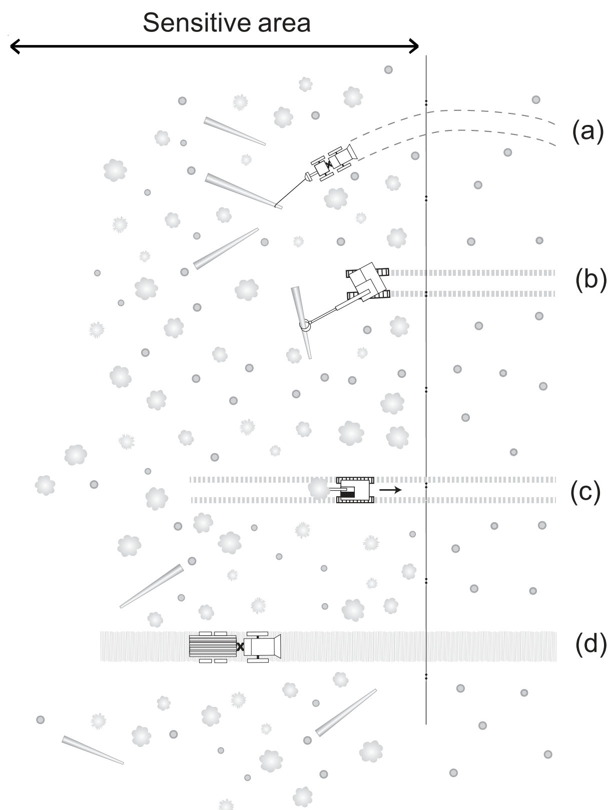


Figure 35. Techniques to reduce soil and stand disturbance by equipment: (a) top fell and cable skid, (b) remove with loader-forwarder; and (c) fell, bunch, and backtrack with stems (d) cut-to-length and forward on brush mat.

- Use flotation mats or corduroy and brush mats to reduce impact on trails, or to cross seepage areas or saturated depressions.
- Use a cut-to-length harvesting system where limbs and tops can be spread along the extraction trail as a protective debris mat for forwarding.

Use appropriate wood-handling techniques at roadside

The risk of soil damage around landings and decking areas is high because machine traffic is more concentrated here than elsewhere on the site. Landing or decking areas should not be located in low-lying, poorly drained depressions with low soil strength.

The following list provides some tips for minimizing machine traffic when handling wood at roadside.

Operate or turn equipment on the road

- Skid trees right to roadside and process, load, and pile from the road when possible (**Figure 36**).
- Turn skidders on the road.

Piling

- Minimize travel, and avoid uprooting stumps and organic material if piling with a crawler-tractor or, as a lower impact alternative, pile with an excavator.
- Use a loader-forwarder working in conjunction with a skidder to build log decks.
- Avoid using the skidder blade to push the logs into a higher pile.

Scheduling of harvesting

The co-ordination of various components of the harvesting process can reduce the potential for soil disturbance, as follows.

- Operate when weather conditions are favourable. When possible, schedule maintenance and crew time off when rainfall stops operations.
- Alternatively, identify drier sites nearby with higher soil strength. Operations can be shifted there when rainfall forces shutdown on low strength soils.
- Minimize the time between felling and skidding to reduce the risk of rain saturating the ground prior to skidding.

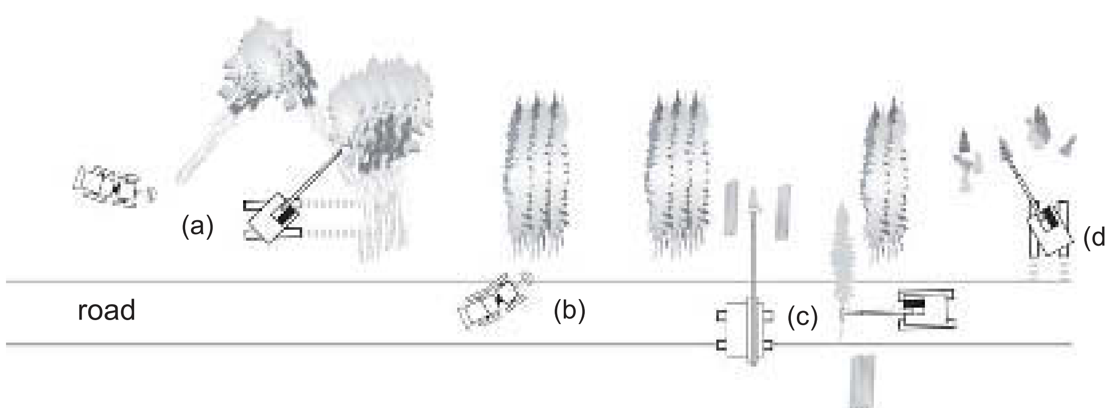


Figure 36. Techniques for reducing machine traffic at roadside: (a) deck with skidder and loader-forwarder, (b) turn skidder on the road, (c) operate equipment from the road, (d) pile debris with an excavator.

- Avoid scheduling operations during darkness in difficult conditions when limited visibility reduces the operator's ability to identify and avoid wet ground.

Scheduling of mechanical site preparation

Mechanical site preparation treatments are commonly applied to blocks following harvesting to improve the growing conditions for regenerating seedlings. These improvements include increasing soil temperature, improving soil drainage around seedlings, and providing vegetation control. Site preparation treatments do not cause soil damage when applied properly. The potential for soil damage lies primarily with rut formation caused by wheels or tracks of the prime mover. If site preparation on a block is extensive and ruts are formed, wide spread disruption of site drainage is possible (**Figure 37**). The potential for rut formation on medium and fine textured soils is increased for site preparation, as the treatments often occur several months or the season following harvesting. Soil moisture increases over time after the forest cover is removed, and soil strength decreases.

Mechanical site preparation, like harvesting, involves large-sized skidders or tractors and therefore, prevention of soil damage follows similar guidelines as described for harvesting. The following precautions can help to avoid damage from site preparation operations.

- Do not operate when soil strength is low. Schedule site preparation when ground strength is sufficient to allow equipment passage without rut formation. This may include semi-frozen conditions for some treatments.

Figure 37. Rutting caused by prime mover duing site preparation (photo courtesy of Mark Ryans, FERIC).

- Treat higher hazard areas first if conditions are operable, and save the best ground such as coarse-textured, well drained soils for later when operating conditions may deteriorate.
- Avoid repeated passes over the same ground.
- Orient continuous furrow treatments along slope contours to avoid channeling of surface runoff that can cause soil erosion.
- Use wide tires, tracks or chains to increase flotation and avoid slip.

Roles and responsibilities

How stages of forest management affect soil protection

The protection of soil during timber-harvesting activity requires a team effort involving the input and co-operation of a variety of individuals over the following stages.

Pre-harvest planning

As a first step, important decisions for soil protection are made by planners. These decisions include the operating season for harvesting activity (summer or winter), the location and extent of in-block roads and landings, and the identification of sensitive areas such as fine-textured moist soils.

Harvest block surveys and mapping

Cutblocks are ground checked by field survey and layout crews, and maps are generated showing the location of all boundaries, roads, and forest type changes. If identified during pre-harvest inspections, areas with low soil strength should also be indicated.

Harvesting and primary transportation of wood

This involves felling, and skidding or forwarding of wood to road-side, and requires the interaction of machine operators, contractors, and field supervisors (**Figure 38**). Soil protection involves the proper choice of equipment and operating techniques for the soil conditions existing at the time of operation.

Post-harvest rehabilitation and site preparation

Areas of a cutblock exposed to heavy equipment traffic, e.g., high use skid trails or ground adjacent to landings, may require rehabilitation treatments to repair soil damage. Schedule equipment used in post-harvest

Figure 38. Team approach to prevent soil damage (photo courtesy of Tony Sauder, FERIC).

treatments, including mechanical site preparation, when soils are resistant to further damage.

Team work

As members of a team, machine operators, contractors, and supervisors have different levels of responsibility for decisions about soil protection. However, each should possess a general understanding of how machine operation affects soil, how terrain and other site conditions provide clues about soil moisture and drainage, and how all these variables affect soil strength. More specific roles and responsibilities of each are as follows.

Roles and responsibilities of the machine operator

- Review block maps with a supervisor prior to commencing operations, and have a clear understanding of the location of boundaries and sensitive areas that may require a change in equipment configuration or operating technique.
- Be aware of the operating conditions around the machine at all times, with the goal of anticipating general changes in soil moisture and modifying practices before damage to the soil occurs.
- Understand locally established rules for shutdown, relocation, or changes in operating technique when soil strength deteriorates, and take steps accordingly.
- At all times, operate machines with the goal of reducing unnecessary travel and manoeuvring on a cutblock.

Roles and responsibilities of the contractor

- Be aware of changing conditions and apply local rules for shutdown or modify operations accordingly to prevent soil damage.
- Co-ordinate equipment activity and traffic patterns to reduce repeated travel over the same ground.
- Select equipment features/options and implement operating techniques that can reduce soil damage.

Roles and responsibilities of the supervisor

- Ensure that the harvesting contractor is aware of the location of sensitive soils on a cutblock prior to the start of operations.
- When changing conditions reduce soil strength, ensure that previously established rules for shutdown or modifying operations are understood and applied.
- Promote operating techniques that reduce soil damage and maintain natural drainage patterns.
- Co-ordinate harvesting equipment in a manner that reduces soil damage.

Where to get more information

If you would like to know more about soil disturbance, a number of related documents offer practical advice using an easy-to-read format.

Archibald, D.J.; Wiltshire, W.B.; Morris, D.M.; Batchelor, B.D. 1997. Forest management guidelines for the protection of the physical environment – version 1.0. Ont. Min. Natural Resources Information Centre, Room M1 – 73, Macdonald Block, 900 Bay Street, Toronto, Ontario, M7A 2C1. 39 pp.

Arnup, R. 2000. Minimizing soil disturbance in forestry operations – a practical field guide for resource managers and equipment operators in northeastern Ontario. The Lake Abitibi Model Forest, 142-3rd. St., Cochrane, Ontario, P0L 1C0. 26 pp.

Logan, R.S. 1999. A handbook of forest stewardship for 21st century workers. Montana State University Extension Forestry, and Weldwood of Canada Limited. The University of Montana, 32 Campus Drive, Missoula, Montana, 59812-8121. 85 pp.

MacDonald, A.J. 1999. Harvesting systems and equipment in British Columbia. FERIC, Vancouver, Handbook No. HB-12. 197 pp.

Peacock, H. 1996. Manual for environmentally responsible forestry operations in Manitoba – a practical guide towards sustainable forestry operations. Technology Transfer Committee, Manitoba Model Forest Inc. 47 pp.

Appendix I

Glossary

Aeration porosity - The amount of air-filled pores relative to the total soil volume. For a given soil bulk density, aeration porosity can fluctuate based upon how much water the soil contains.

Bogie axle system - Where two wheels are attached to a bogie frame or box driven by a single axle. Ground pressure is reduced compared to a single wheel, and the addition of tracks to bogies can reduce ground pressure an additional 35 to 50 percent.

Bulk density - A common, indirect measure of soil porosity and soil strength, i.e., the proportions of soil occupied by solids and fluids (water and air). An increase in bulk density of a soil indicates that aeration porosity is reduced.

Differential locks - A device or system to lock a differential to distribute power to both wheels rather than the power being lost to spinning on the wheel with least resistance. There are two types of differential locks: automatic and manually-activated. A "no-spin" automatic differential lock transfers all power to the inside wheel during a turn which can disturb soil more easily than a normal differential. Manually activated differential locks can be engaged only when necessary and can be disengaged during turning to prevent soil damage such as rutting. However, if the operator fails to react in time to engage differential locks when slipping occurs, a machine may become stuck.

Drainage - Refers to the rate of the removal of free-moving water, in excess of field capacity, from the soil relative to the supply. The drainage class is an indicator of how long to expect free-moving water to be present in the soil. The drainage classes are as follows:

- *Very rapidly drained* – Common in coarse-textured sands and gravels. Soils are dry.
- *Rapidly drained* – Common in medium sands, fine sands, or loamy sands. Soil water content seldom exceeds field capacity.
- *Well-drained* – Highly variable soil textures. Soil water content does not normally exceed field capacity for a significant part of the year. No mottles in first 100 cm of depth.
- *Moderately well-drained* – Contains free soil water (saturated) for short periods and drainage can be restricted. A few mottles may be present.
- *Imperfectly drained* – Soil saturated for moderately long periods of the year, therefore mottling and gleying are present.

- *Poorly drained* – Soil saturated or nearly saturated for prolonged periods of time, therefore mottling and gleying are present.
- *Very poorly drained* – Soil saturated at or within 30 cm of the ground surface for most of the year, and prominent mottles and gleying are present within 30 cm of the ground surface.

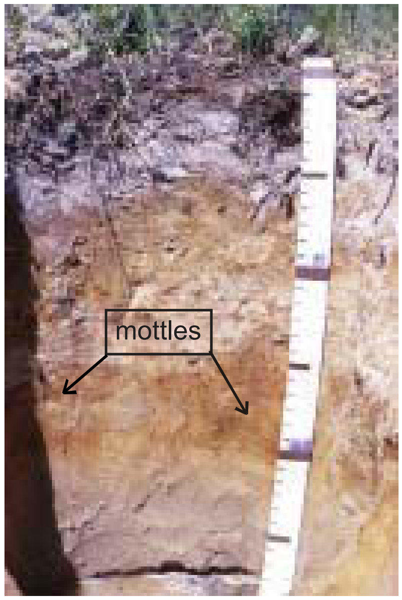
Field capacity - The maximum amount of water that the soil can store or retain three days after a large rainfall when the drainage of free water becomes negligible.

Forest floor - All dead vegetation on the mineral soil surface including leaf litter and unincorporated humus.

Gleying - A distinct grey to blue colour of soil that indicates lack of oxygen due to long periods of saturation by free water. Soils may emit a rotten egg odour. Gleyed soils have wetter conditions than those associated with mottles.

Photo courtesy of Andrei Startsev, Alberta Research Council.

Hydrostatic drive system - Power transmission to wheels or tracks is via hydraulic motors. Both the fully variable gear range over a wide range of speeds and the built-in braking action when going downhill offer advantages for reducing ground disturbance compared to mechanical or torque converter systems.



Mottles - Rust-coloured spots or blotches in soil that contrast with the dominant soil colour. Mottles result from a lack of oxygen due to the presence of free water in the soil for a significant part of the year.

Photo courtesy of Darwin Anderson, University of Saskatchewan.

Organic soils (peat, muskeg or swamp) - Material of organic origin (plants and animals) in various stages of decay having a thickness equal to or greater than 40 cm if the material is mesic or humic, or equal to or greater than 60 cm if the material is fibric. Humic material consists of strongly to completely decomposed peat having low strength, and is prone to rutting unless frozen. Fibric material is fibrous in composition with recognizable plant structure and can withstand equipment passage with high flotation capabilities. The underlying mineral soil can be compacted if the organic mat is broken and ruts are formed.

Photo courtesy of Mike Adams, Natural Resources Canada.

Porosity - The ratio of volume of pores to the total soil volume (soil matter plus pores). Total porosity is when no pores contain water (oven dried soils).

Riparian areas - The area of land and water forming a transition from aquatic to terrestrial ecosystems along streams, lakes and open water wetlands.

Saturation - When all pore space is filled with water.

Seepage areas - Small areas of wetland that occur when groundwater comes to the surface. Soils at these sites remain saturated for a portion or all of the growing season and often stay wet throughout the winter.

Slip - How much further a point on the periphery of a wheel or track moves than the vehicle itself, expressed as a percentage of the vehicle movement. Slip occurs because soil is typically compressed and sheared to develop necessary traction. Excessive amounts of slip can cause shearing between the soil engaged by the tire or track lugs and the underlying soil, which in turn can contribute to rut formation.

Transpiration - The movement of water from the ground through plant leaves into the atmosphere.

Appendix II

A simple field procedure for estimating soil wetness and risk of compaction and rutting

In medium-to-fine-textured soils, a simple field procedure can be used to estimate soil wetness. The procedure will help assess the risk of compaction occurring if a machine with standard tires (<85 cm or 35 inches) or wide tires (≥85 cm) would operate on the soil.

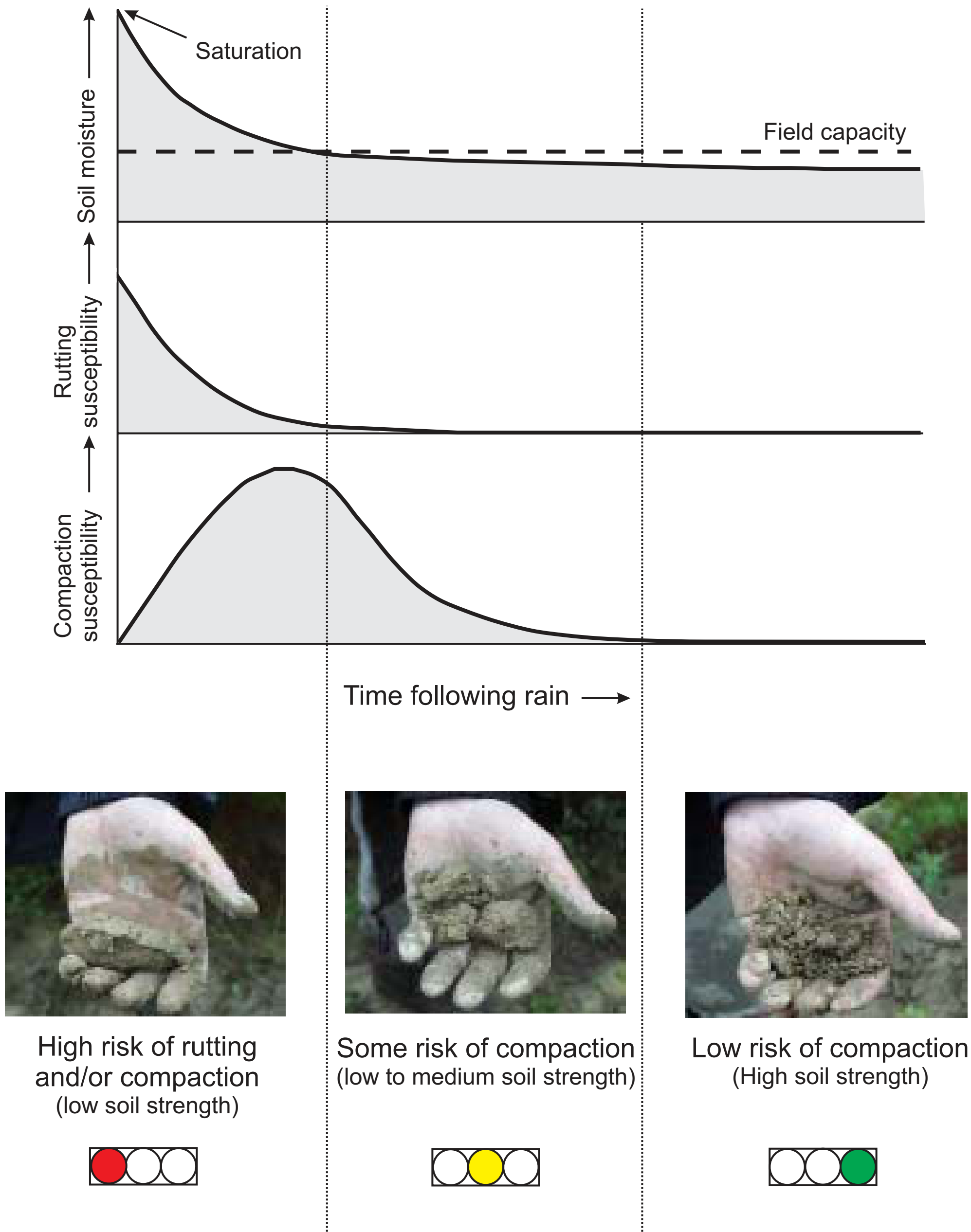
1. Use a hand shovel or auger to obtain a soil sample down to a depth of 30 cm. Break a clod and inspect broken surface for mottles. Mottles indicate frequently saturated soils. Feel texture to verify that soil is fine and not grainy feeling.
2. Hand consistency test: This checks the firmness of the soil by feel. Select a handful of soil from wettest zone within the 30 cm depth. Mold this into a clod and observe the following:
   a) When squeezed or flattened by force, clod does not crumble. This means that the soil is wetter than field capacity and is at a *high risk of compaction and rutting* for both standard or wide tires. Soils at, or slightly drier than, field capacity are of most concern for compaction.

   b) If soil is relatively easy to mold, but breaks when squeezed or flattened, there is *some risk of compaction if soil moisture is close to field capacity* for wide tires and *high risk* for standard tires. When the mold is easier to break, the sample is drier and below field capacity, and the risk of compaction is reduced.

   c) If soil cannot be molded by hand, then it will not be deformed and there is a *low risk of compaction or rutting* for wide tires and some risk with standard tires.

Photos courtesy of Andrei Startsev, Alberta Research Council.

Following heavy rains, the susceptibility of soils to compaction and rutting changes over time as the soil drains (prepared by Andrei Startsev, Alberta Research Council). Note: assumes wide tire use only.



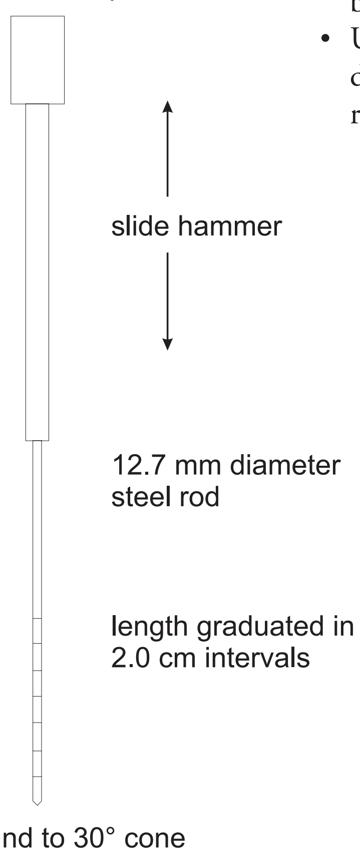
Appendix III

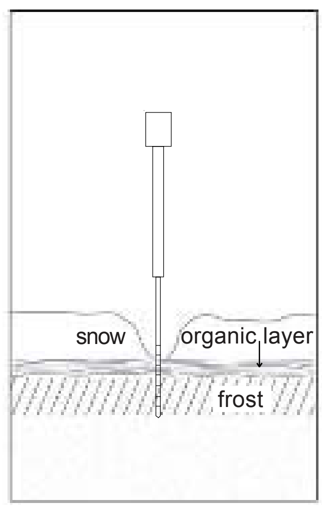
Using a frost probe to estimate the depth of frost penetration

A simple frost probe can be used to estimate the depth of frost in soil, as follows.

- Using the slide hammer, the probe is hammered into the frozen ground until it breaks through to unfrozen soil.
- Using the scale along the probe and discounting the organic layer thickness, record the depth of frozen soil.

Home-made frost probe





Example of a home made frost probe
total weight = 7 kg

Photo courtesy of D.Stone, United States Dept. of Agriculture Forest Service, North Central Research Station, Grand Rapids, Minnesota.