Elements and rationale for a common approach to assess and report soil disturbance[1]

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ABSTRACT

Soil disturbance from forest practices ranges from barely perceptible to very obvious, and from positive to nil to negative effects on forest productivity and / or hydrologic function. Currently, most public and private land holders and various other interested parties have different approaches to describing this soil disturbance. More uniformity is needed to describe, monitor, and report soil disturbance from forest practices. We describe required elements for attaining: (1) more uniform terms for describing soil disturbance; (2) cost-effective techniques for monitoring or assessing soil disturbance; and (3) reliable methods to rate inherent soil susceptibility to compaction, rutting, mechanical topsoil displacement, and erosion. Visual disturbance categories are practical for describing soil disturbance. Soil disturbance categories for the Pacific Northwest are described in detail to illustrate essential elements for attaining Element One. A number of potential products are listed to meet the other elements. Completion of these will facilitate collecting comparable data and sharing research and training information. Coordinated efforts will also ensure a more seamless process for assessing and reporting for sustainability protocols, and responding to third-party certification protocols. Additionally, these products will improve operational relevance of research results.

Key words: soil disturbance, forest productivity, hydrologic function, monitoring, Montréal Process, risk ratings for soils, soil compaction, soil displacement, soil erosion, sustainability protocols, third-party certification

RÉSUMÉ

La perturbation du sol au cours des travaux forestiers varie de presque imperceptible à très évidente, accompagnée d'effets positifs, nuls et négatifs sur la productivité forestière ou encore sur les fonctions hydrologiques. Actuellement, la plupart des propriétaires de terrains publics ou privés, ainsi que les groupes de personnes intéressées soutiennent différentes approches de description de la perturbation du sol. Une plus grande uniformité est requise pour décrire, surveiller et faire état des perturbations du sol suite à des travaux forestiers. Nous décrivons les éléments requis pour obtenir (1) des termes plus uniformes pour décrire les perturbations du sol, (2) des techniques efficaces en terme de coût pour surveiller ou évaluer les perturbations du sol et, (3) des méthodes fiables pour classer la susceptibilité inhérente du sol en terme de compaction, orniérage, de déplacement mécanique du sol de surface et d'érosion. Les catégories visuelles de perturbation sont utiles pour décrire les perturbations du sol. Les catégories de perturbation du sol pour le Nord-Ouest du Pacifique sont décrites en détail afin d'illustrer les éléments essentiels requis pour atteindre le Niveau Un. Plusieurs détails supplémentaires sont énumérés dans le cas des autres niveaux. Ces mesures faciliteront la collecte de données comparables et le partage d'information reliée à la recherche et à la formation. Des efforts concertés permettront également d'établir un processus continu d'évaluation et d'état de compte dans le cadre des protocoles de durabilité et de répondre aux protocoles de certification par des tiers. De plus, ces produits accroîtront l'importance opérationnelle des résultats de recherche.

Mots clés : perturbation du sol, productivité forestière, fonction hydrologique, surveillance, Processus de Montréal, classes de risque pour les sols, compaction du sol, déplacement du sol, érosion du sol, protocoles de durabilité, certification par des tiers

[1]Cited in our recently published related papers as "A strategy for more uniform assessment and reporting of soil disturbance for operations, research, and sustainability protocols."

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log landings, and borrow pits. Many of these may be designed as permanent structures. Poorly constructed or maintained forest roads are often the primary source of management-related sediment on forest lands; road surfaces and ditches produce sediment that can be delivered to streams if drainage systems are not properly maintained, and roads in steep terrain can cause landslides if improperly located or constructed (Furniss *et al.* 1991). In addition, the landbase dedicated to the access network is not available to grow trees or forage. For these reasons, most public jurisdictions not only have limits on the amount of permanent access but also prescribe construction and maintenance best practices. Other temporary roads, landings, and even logging trails may be part of the access network during active harvesting of an area but these are subsequently restored to hydrologically stable conditions, and preferably ameliorated to a productive condition.

While definitions of access networks may be reasonably similar amongst jurisdictions, differences exist for how road areas are measured and what limits for percent coverage are set. There may be reasons for having different limits (e.g., terrain constraints); however, it is desirable that limits be applied to the same unit of measure, most commonly the gross harvested area of a cutblock (activity area). It is also desirable to have a similar approach to other aspects of access management, as provided below.

Provisional disturbance definitions for access road networks

Permanent access may include roads, landings, and borrow pits, and any harvesting or yarding trails that will be frequently used or that are permanent. Permanent access typically is considered a permanent loss from the productive landbase and may require tracking under international sustainability protocols or third-party certification standards for wood products. To compare area occupied by roads, we need common protocols for width measurement because berms and sidecasts typically feather off over considerable distance (e.g., 20-cm fill depth is used in B.C. as per Fig. 1).

- Temporary access includes roads, landings, or trails that are not needed until the next rotation. Temporary access is often rehabilitated and reforested to restore hydrologic function and soil productivity.
- Rehabilitated roads are increasingly an operational objective to reduce maintenance costs and risk of stream sedimentation. Criteria should be established to judge completed (successful) mitigation.

Dispersed (in-block) disturbance

Some internal access is required within a given cutblock being harvested or site prepared, prescribed burned, or managed as rangeland. This access may include parts of the permanent road network that will be required for other activities nearby or for repeated entry activities like grazing or partial-cut harvesting. In addition, temporary access may be required for thinning, or other mechanical operations. In the example of harvesting, a very small or large amount of the harvested area may be disturbed depending on the method of harvest, site conditions, and access constraints. Helicopter or skyline harvesting may result in minor gouging and scalping of the surface soil. Cable or grapple yarding may result in deeper gouging on some yarding corridors, and ground-based harvesting may create soil rutting, compaction, and displacement from heavy equipment operating on trails or elsewhere across the site.

It is difficult to relate specific soil disturbance at the time of an activity like harvesting to long-term hydrologic and productivity consequences. This is because our knowledge base is incomplete and climatic events, revegetation, natural amelioration, and site conditions vary tremendously. However, there is a need to manage and minimize the potential for negative effects. Monitoring the severity and extent of soil disturbance at the time of harvest can be used to track progress towards this goal, but it is critical to have data to validate which disturbance classes actually impact hydrologic function, productivity, or other ecosystem functions of concern.

In many jurisdictions, regulation of in-block soil disturbance is based on quantified changes in soil properties and / or visually identifiable categories of disturbance. These systems are based on best available information, ranging from peer-reviewed research to expert and practitioner opinion. Visual systems usually have specified conditions that must be met before a disturbance "*counts*" towards a cumulative total within the area to be reforested. To reduce uncertainty, visual systems and "*counted*" disturbance classes should be validated by research that relates visual observed conditions to soil property thresholds and forest productivity and hydrologic function within given soil and climatic areas.

Following development since the 1980s in B.C., machine traffic and displacement disturbance types have been defined primarily on visual characteristics and dimensions (Fig. 1 and Table 1) (B.C. Ministry of Forests 2001). These definitions were embodied in regulation under the *Forest Practices Code Act* in 1995; however, hardwiring definitions in legislation does little to encourage their evolution over time. Consequently, the new *Forest and Range Practices Act* refers to them as well, but in a way that provides for their revision over time based on research and scientific literature. The threshold conditions (e.g., dimensions) at which disturbance types are counted as detrimental are based on assessing site-specific susceptibility ratings for compaction, displacement, or erosion at that location. This *counted disturbance* is considered potentially detrimental to tree growth or site hydrology. To prevent anticipated negative effects, allowable area for this dispersed, counted disturbance is limited by some jurisdictions. In B.C., this currently ranges from 5% of the activity area on sensitive soils to 10% on less-sensitive soils.

Weyerhaeuser Company (Scott 2000, as referenced in Heninger *et al.* 2002) has developed and used another visual approach to classify soil disturbance (Fig. 2). The classification system is based on the type and degree of disturbance (compaction, puddling, and displacement) to topsoil and subsoil in traffic lanes caused by machine traffic. A similar system tested on the Wallowa-Whitman National Forest includes more displacement definitions and only four traffic disturbance classes. This enables focus on the more severe disturbance classes considered "counted" (Table 2).

In other Canadian provinces and internationally, ruts appear to be the most common disturbance type recognized by various agencies and researchers; however, a number of provinces (e.g., Alberta, Saskatchewan, and Ontario) are currently reviewing their approaches to soil disturbance. Some jurisdictions set critical threshold levels for various soil properties (Powers *et al.* 1998). For example, criteria for compaction focus on absolute or relative changes in bulk density, porosity, or soil strength. One concern with these measure-

Table 1. Soil disturbance definitions from the previous B.C. Forest Practice Code Act, Operational Planning Regulations[a] (still in use today and abbreviated for this paper with clarification provided in [square brackets]).

Compacted area – an area of soil that [requires rehabilitation]:

- (a) is greater than 100 m^2 in area and greater than 5 m wide;
- (b) has a moderate, high or very high soil compaction hazard[b] or the assessment of its soil compaction hazard was not done [such as cable-harvested areas];
- (c) has been compacted by equipment travelling over it, and;
- (d) has one or more of the following attributes:
  - (i) altered soil structure or increased density relative to the surrounding undisturbed soil,
  - (ii) soil puddling,
  - (iii) compacted deposits of forest floor, fine slash / woody debris overlaying or crushed into the mineral soil.

Dispersed disturbance – areas of soil occupied by dispersed trails, gouges and scalps.

Excavated or bladed trail – constructed trail that has [requires rehabilitation]:

- (a) an excavated or bladed width greater than 1.5 m, and;
- (b) mineral soil cutbank height greater than 30 cm.

Dispersed trail – an area that is not a compacted area but that, due to equipment traffic on the soil, has the following attributes:

- (a) impressions or ruts in the soil that are at least:
  - (i) 30 cm wide, 2 m long and a minimum of 15 cm deep where depth is measured from the surface of the undisturbed forest floor to the deepest point in the cross-section over the entire length of 2 m, or,
  - (ii) if the area has a high or very high soil compaction hazard, 30 cm wide, 2 m long and a minimum of 5 cm deep where depth is measured from the surface of the undisturbed mineral soil to the deepest point in the cross-section over the entire length of 2 m;
- (b) has the same attributes as Compacted Area (d) on an area of soil at least 1 m × 2 m that has a moderate, high or very high soil compaction hazard.

Gouge – an excavation into the mineral soil that is:

- (a) deeper than 30 cm;
- (b) deeper than 5 cm where it covers:
  - (i) at least 80% of a 1.8 m × 1.8 m area, or
  - (ii) an area of at least 1 m × 3 m, or;
- (c) to the depth of the underlying bedrock.

Scalp – an area in which the forest floor has been removed from:

- (a) over 80% of a 3 m × 3 m area or:
  - (i) over 80% of a 1.8 m × 1.8 m area if the area,
  - (ii) has a very high soil displacement hazard,
  - (iii) has a very high soil compaction hazard or soil erosion hazard.

[a]The general BCFS Web site where these and other FPC or FRPA information can be located is http://www.for.gov.bc.ca/
[b]Hazard refers to the susceptibility or vulnerability of the soil to undergo significant compaction.

inconsistent application of standards and muddled public perceptions. Soil specialists may thoroughly assess soil conditions within proposed activity areas before prescribing soil management objectives, but application of this information is ineffective when contract administrators and operators lack the understanding and ability to identify disturbance categories. Consequently, undesirable soil conditions often result from misunderstandings or miscommunication, or from a lack of training.

Government agencies also must deal with disparate groups having different perceptions about soil disturbance and its effects on productivity and ecosystem functions. The likelihood of effectively resolving potentially adversarial situations will increase if all participants use the same terms and definitions, and there is sound research to support the recommendations.

Uniform definitions and procedures for describing, monitoring, and reporting disturbances would also assist communication across jurisdictions. Efficiency of limited budgets and resources for soil disturbance assessments, research, and extension could all be improved by sharing the development of training materials, brochures, monitoring protocols, and the research that supports these products. National and international reporting, such as under the Montréal Process criteria and indicators, would be more consistent and improve understanding of each member nation's efforts to improve soil management and conservation.

What disturbance is detrimental?

Not all soil disturbances are detrimental. One general definition of soil disturbance is "any disturbance that changes the physical, chemical, or biological properties of the soil" (Lewis *et al.* 1991). Note that the direction or consequences of these changes are not specified. Site preparation is commonly prescribed for planting and establishing seedlings. Disturbance related to these activities is usually not considered detrimen-

Table 2. Interim severity classes for soil disturbance in the Wallowa-Whitman National Forest (Modified from USFS 2001)

Class 0: Undisturbed Natural State

Soil surface:

- No evidence of past equipment operation.
- No depressions or wheel tracks evident.
- Litter and duff layers present and intact.
- No soil displacement evident.

Class 1: Low Soil Disturbance

Soil surface:

- Faint wheel tracks or slight depressions evident and are <6 inches deep.
- Litter and duff layers present and intact.
- Surface soil has not been displaced and shows minimal mixing with subsoil.

Soil resistance to penetration with tile spade or probe:

- Resistance of surface soils may be slightly greater than observed under natural conditions. Concentrated in top 0–4 inch depth.

Observations of soil physical conditions:

- Change in soil structure from crumb or granular structure to massive or platy structure, restricted to the surface 0–4 inches.

Class 2: Moderate Disturbance

Soil surface:

- Wheel tracks or depressions are >6 inches deep.
- Litter and duff layers partially intact or missing.
- Surface soil partially intact and may be mixed with subsoil.

Soil resistance to penetration with tile spade or probe:

- Increased resistance is present throughout top 4–12 inches of soil.

Observations of soil physical conditions:

- Change in soil structure from crumb or granular structure to massive or platy structure, restricted to the surface 4–12 inches.
- Platy structure is generally continuous.
- Large roots may penetrate the platy structure, but fine and medium roots may not.

Class 3: High Disturbance

Soil surface:

- Wheel tracks or depressions highly evident with depth being > 12 inches deep.
- Litter and duff layers are missing.
- Evidence of topsoil removal, gouging and piling.
- Soil displacement has removed the *majority* of the surface soil. Surface soil may be mixed with subsoil. Subsoil partially or totally exposed.

Soil resistance to penetration with tile spade or probe:

- Increased resistance is deep into the soil profile (> 12 inches).

Observations of soil physical conditions:

- Change in soil structure from granular structure to massive or platy structure extends beyond the top 12 inches of soil.
- Platy structure is continuous.
- Roots do not penetrate the platy structure.

The objective of most management strategies is to limit the amount of detrimental soil disturbance and prevent cumulative detrimental effects. Ultimately, management strategies—whether thresholds for unacceptable disturbance or best management practices—should be based on actual, confirmed effects on tree growth, site hydrology, and other resource values. Similarly, national and international reporting, such as under the Montréal Process' new indicator 4.2.b, "Area and percent of forest land with significant soil degradation" (Montréal Process Working Group 2006), should be based on consideration of these site-dependent effects, and not simply on uniform application of specified thresholds for degraded soil density or organic matter content, since these may or may not "count" as detrimental to soil functions and productivity. More specifically, validated, site-specific criteria are needed for defining soil degradation or hydrologic function disruption rather than using generalized criteria, such as percent change in soil density or organic matter content, since these changes would likely affect soil functions and productivity differently across a range of sites.

Recommendations: Review existing soil disturbance classifications. Decide on common themes and simple categories that are operationally relevant and convenient for reporting results. Develop uniform definitions or descriptions to facilitate meaningful comparisons and learning from well-planned research studies and soil-disturbance monitoring. Suggested requirements for common definitional terms include categories for required (permanent) access, as discussed above, and for dispersed disturbance that meet the following criteria:

- Types and severity of disturbance are clearly defined and effects on off-site soil movement, site productivity, or hydrology are under test or validated using a research-quality strategic database.
- Categories span the range of soil disturbance likely to occur with current and future forest practices.
- Disturbance category definitions can be understood and easily recognized by laypersons (i.e., categories are clear and unambiguous).
- Disturbance categories are visually discernible and readily recognized by equipment operators in the field.
- Distinctions are made among soil/climate types when determining those disturbance categories that are "counted" (detrimental) and those that are not.
- Consistent definitions are provided for both permanent and temporary access, and for acceptable rehabilitated disturbance.

It is recognized that what is considered detrimental will vary depending on the site conditions. Technical committees currently operating or proposed for regional, national, and mate of the parameter in question (e.g., small bias and reasonable precision), and strike a balance between cost and enforceability.

The total amount of soil disturbance in an activity area can be composed of many small polygons, a few large polygons, or, more commonly, a combination of these two extremes. Therefore, pattern and distribution of disturbance should be documented in monitoring reports. Areas of soil disturbance can remain undetected when the survey area is large and sampling intensity is low. It is possible to stratify areas based on the susceptibility of soils to detrimental disturbance (e.g., region, soil type, climate zone). One solution is to allocate the highest proportion of quantitative or detailed disturbance monitoring in areas with sensitive soils, but it is important that all strata have some sampling intensity to assess the entire activity area.

Sampling intensity

Desired levels of confidence and acceptable uncertainty in statistical estimates must be set before establishing sampling intensity. These will depend on the decisions being made from the data and on the risks deemed acceptable by those conducting (requiring or approving) the survey. In addition, one should consider the consequences of making a wrong decision (based on the sampling data). More precise information may be needed (hence a larger sample size) if: (1) a decision is to be made about contract violation or rule infraction, (2) information is to be used in court proceedings, (3) environmental consequences are potentially severe, or (4) effects of new equipment are being evaluated. In contrast, less precise information may suffice for: (1) assessing performance relative to broad standards and guidelines, (2) internal evaluations of operations or planning for restoration, or (3) environmental consequences are inconsequential. Sample sizes are always dependent on how precisely one needs to estimate the mean, the population variability, and the level of confidence one desires. But with any sampling design, there is a point at which the marginal benefits (increased accuracy or precision) do not out-weigh the marginal costs of sampling.

Weyerhaeuser's sampling intensity was developed from several field trials where a predetermined acceptable margin of error was set. For compliance or enforcement monitoring decisions, surveys are required to specify confidence limits and levels. For example, if survey data indicate that 18% of the cutblock was detrimentally disturbed, does this exceed the 15% standard? In British Columbia, the 90% confidence limit is used for compliance (B.C. Ministry of Forests 2001). If the mean and 90% confidence limits were 18 ± 5% in our example, then a standard of 15% was not exceeded because the lower confidence limit would be 13%.[11] This is consistent with a statement by McMahon (1995), in his summary of a study of two survey methods on small areas: "…where single (*sic*; non-replicated) surveys are being used to assess site disturbance, it is necessary to recognize the inherent variability in estimated results. This is particularly important when using the assessment results to determine compliance with a quantitative standard."

[11]In this case a one-sided confidence interval also may be appropriate to calculate if one wants to know with known confidence that the population mean is either at least or no larger than some computed number (Siegel 2003).

To avoid the expense of formal surveys, informal methods can produce rapid evaluations of active operations or for an overview assessment at final harvest inspection. Informal surveys may provide the screening basis for recommending or requiring formal surveys. Several protocols have been developed for visual walk-through estimation of disturbance; these often involve pacing or hip-chaining along transects to estimate average coverage and to locate concentrations of disturbance. In the past, these methods have been considered to provide acceptable levels of precision for this task; however, computation of confidence intervals is not appropriate for informal assessments. With the widespread availability of electronic maps, photos, and GPS, some of this field checking will likely be replaced by more random walkthrough assessments (to discrete GPS points) or remote sensing- based assessments. In BC, informal methods are used on hundreds of cutblocks annually and have been incorporated into the Soil Resource Stewardship Monitoring Protocol for B.C. (Province of B.C. 2005).

What is recorded?

Some protocols document all soil disturbances, while others count only disturbances that are deemed detrimental. To ensure comparability of results, documenting all disturbance categories is preferable. This allows for maximum use of the data for comparisons as well as for tracking beneficial disturbance. Moreover, counted disturbance can be derived when the consequences of disturbance types is known or assessed through longer-term research studies.

Which disturbance is "counted" varies greatly across jurisdictions, partly in response to regional differences in soil resistance and resilience, and how various guidelines evolved. Operational staff in the Pacific Northwest Region (USFS) have struggled to determine what patterns of disturbance (size and shape) should be considered "detrimental" to soil productivity when conducting assessment surveys. Currently, there is a minimal or threshold size limitation for counting soil displacement as detrimental (i.e., 9.3 square meters and 1.5 meters wide). It is most important to assess disturbance classes known or expected to be detrimental based on the information available. Current guidelines for this USFS Region state that no more than 20% of an activity area may have soil in "detrimental" disturbance classes, including permanent and temporary access roads (USFS 1998). Each Region of the Forest Service has developed its own policy and standards that can be found in various locations within their directives system. One consideration would be to indicate which disturbance types are confirmed to be detrimental and which are tentative until validated by research.

Current B.C. guidelines (standards) limit permanent access roads and landings to 7% on a cutblock basis. In-block limits for counted soil disturbance were defined under the previous Forest Practices Code and these definitions still apply for the new Forest and Range Practices Act. Two main types of disturbance are recognized: machine tracks and displacement. The definitions of these disturbance types are summarized in Table 1, with diagrams in Fig. 1. Machine tracks include excavated and bladed trails (skid roads), and disturbance from skidding logs. Excavated and bladed trails (skid roads) are considered temporary access that must be rehabilitated and their area, in combination with that of dispersed disturbance (displacement), must not exceed a speci-

Table 3. Hazard key for soil compaction and puddling (B.C. Ministries of Forests and Environment 1995)

Soil Texture[a] (0–30 cm)		Hazard Rating[b] *moisture regime*	
		Xeric-subhygric[c] (H horizons <20 cm)	*Subhygric-subhydric*[d] (H horizons ≥ 20 cm)
Fragmental Coarse fragments > 70%		L	M
< 70% Coarse Fragments	Sandy S, LS	L	VH[e]
	Sandy Loam SL, fSL	M	
	Silty/Loamy SiL, Si, L	H	
	Clayey SCL, CL, SiCL, SC, SiC, C	VH	

[a]Use dominant soil texture and coarse fragment content of the upper 30 cm of mineral soil to assess compaction hazard. If a pronounced textural change occurs within the upper 30 cm (e.g., silty over sandy soil), then use the more limiting soil texture, providing it amounts to 5 cm of the top 30 cm.
[b]L = Low; M = Moderate; H = High; VH = Very High.
[c]Use this column for subhygric sites with forest floor H-horizons < 20 cm thick.
[d]Use this column for subhygric sites with forest floor H-horizons ≥ 20 cm thick.
[e]Organic soils composed of more than 40 cm of wet organic material or forest floors > 40 cm (including Folisols < 40 cm) are susceptible to rutting due to their very low load-bearing strength materials. Consequently, these organic materials have a high soil displacement hazard and a very high soil compaction and puddling hazard.

The B.C. key does not consider moisture status of the site or depth of surface soil (depth to dense subsoil), because wet soil conditions occur on all sites in some period each year, and most soils in B.C. have dense subsoils close to the surface. This approach may be too simple for other regions where soils remain moist much of the year or where no winter season enables low-impact harvest. In application, hazard (susceptibility) ratings need to be tempered with consideration of on-site moisture conditions by the logging supervisor or equipment operator.

Textural classes, as defined by the Canadian System of Soil Classification (Day 1983) or the USDA-NRCS are weak indicators of soil resistance to mechanical stress. There are at least two problems with using textural classes. First, in textural analysis, it is not uncommon that some of the soil minerals influencing *in-situ* behaviour are removed from the sample before texture determination (e.g., organic matter, calcareous material, iron and aluminum oxides). Second, some texture classes have a very large range in clay content (e.g., 0 to 28% for silt loam). Some clay-size minerals respond differently to mechanical forces, exhibiting different cohesive properties like plasticity and stickiness. Therefore, to predict soil behaviour, we need to supplement soil textural classes.

Soil consistence (degree of cohesion and adhesion) as defined in the Canadian System of Soil Classification (Day1983) provides useful interpretations for harvest planning in relation to addressing risk of soil compaction (Curran 1999, Curran *et al.* 2000). Moreover, a test group of college students more accurately and consistently estimated moist consistence (plasticity) than textural classes. As expected, "plastic" soils varied in actual clay content, presumably because their clay minerals differ. Content of sand and silt also affected plasticity. Siltier soils were plastic at clay contents as low as 12% (Curran, unpublished data). Although use of soil consistence classes currently does not change soil compaction ratings, it alerts users to soil conditions that are more likely to lead to compaction and rutting. Fig. 3 relates plasticity to the texture triangle (note that silt loam encompasses three plasticity classes).

Tree performance and compaction

Excessive soil compaction and puddling are of particular concern in timber-harvesting operations because of their immediate effects on soil properties and roots of residual trees and subsequent effects on regeneration and tree growth. Compacted soils may impede root growth due to greater penetration resistance, lower aeration porosity, and slower rates of infiltration and hydraulic conductivity. Aeration porosity is a reliable indicator of compaction. Lowered aeration porosity reduces gas exchange, which in turn affects oxygen and carbon dioxide concentrations in the soil; this may reduce physiologic functions of roots and lead to root mortality during wet conditions. Compacted soils remain wet longer. This can reduce seedling growth due to lower soil temperature and poorer aeration under some conditions.

In coarse-textured soils, compaction may increase water-holding capacity and increase tree growth (Powers and Fiddler 1997, Stone *et al.* 1999, Gomez *et al.* 2002, Ares *et al.* 2005). Coarse-textured soils typically have lower compaction-hazard (risk) ratings. Tree growth on rehabilitated landings (Bulmer and Curran 1999, Plotnikoff *et al.* 1999) and haul-roads (Curran, unpublished) demonstrate that sandier soils appear repairable following compaction. Finer textured soils typically have higher compaction-risk ratings, but may be amendable to rehabilitation. For example, tree growth on rehabilitated skid trails on silty clay loams in the Oregon Cascades was not different from trees on undisturbed soil (Heninger *et al.* 2002). Other textures require further study.

not uncommon for the forest floor to contain over 50% of the total soil nitrogen and 80% of the phosphorus. Because many B.C. forest sites are nitrogen-deficient, conservation of the forest floor is important. Curran *et al.* (1990) developed a process for rating forest floor displacement susceptibility to be used when planning harvest and site preparation operations in B.C.

Soil factors affecting both forest floor and topsoil displacement risk include depth of fertile soil materials, mineral soil texture and coarse fragments, slope, and topography. Topsoil displacement is the lateral movement of mineral soil caused by moving equipment and logs and is recognized in soil disturbance classifications in B.C. (Fig. 1), the various classifications of the USDA Forest Service (e.g., Table 2), and in DC3 and DC4 of the Weyerhaeuser disturbance classification system (Fig. 2). Displacement includes excavation, scalping, exposure of underlying materials, and burial of more fertile surface soils.

Three effects of displacement can compromise soil productivity and site hydrology: (1) exposure of unfavourable subsoils (dense, gravelly, or calcareous soil with high pH); (2) redistribution and loss of nutrients; and (3) alteration of slope hydrology, which can lead to the hydrologic effects discussed previously with compaction. In addition, exposure of mineral soil can lead to erosion and displacement of fertile topsoil on steep slopes and is more prevalent with certain soil textures and geologic / topographic formations. This is the subject of watershed analyses and erosion ratings that are not discussed here.

Topsoil depth is the key indicator of topsoil-displacement risk as used by Weyerhaeuser's risk-rating system. In more northern temperate forests, the soils that have developed on glaciated terrain are often shallow. In these and other forests throughout the world, many nutrients are concentrated in the forest floor and the top 20 cm of mineral soil. Therefore, managers need to avoid displacing fertile topsoil too far from seedlings, and maintain the volume of topsoil available for rooting. The presence of unfavourable subsoils or water tables also warrants a high risk rating. Under other climatic conditions and with older soils, soil displacement is of more or less concern, depending on total soil depth and the characteristics of the subsoil. For example, detrimental productivity or hydrologic function changes are more likely on a soil with a shallow A horizon (e.g., 2-cm depth) and a high water table than one with a very deep A horizon (e.g., 40 cm) enriched in organic matter without a perched water table.

Tree performance and forest floor/soil displacement

We need better understanding of the effects of organic matter removals, the role of coarse woody debris, and the impacts of site preparation (tillage and/or vegetation control) on long-term site productivity (Stone *et al.* 1999, Fleming *et al.* 2006). Increasing intensity of organic matter removal decreased both diameter and height growth of aspen on sandy soils in the Lake States region of the U.S.A. Stone *et al.* (1999). Displacement of topsoil has reduced tree growth when high pH subsoils are exposed (Smith and Wass 1979), and when rooting volume is largely restricted to subsoils of poor fertility or limited moisture-holding capacity (Clayton *et al.* 1987). Currently, more studies are yielding further information including the LTSP (Powers *et al.* 2005) and some university/industry/agency collaborative studies (Kelting *et al.* 2000, Ares *et al.* 2007).

Recommendations: Existing methods for risk rating soils should be reviewed, and reliable methods and criteria identified.

Although soils can be mapped at a variety of scales and with a variety of objectives, we encourage detailed soil mapping (1:24 000 scale or larger) and representative descriptive data for each mapping unit. Soils mapped in the USA as part of the National Cooperative Soil Surveys are mapped at the land type or land type–phase level of a hierarchy of ecological units; map scale is usually 1:24 000. This is the level at which most direct soil risk-rating methods have been developed. One still needs on-site inspection to confirm accuracy of the mapping and hence the actual soil series to be rated. In the absence of detailed soil mapping, each area proposed for harvest requires its own soil assessment as part of harvest planning, which is the procedure used in B.C. (Curran *et al.* 2000). Other bases for soil risk rating should be considered. Burger and Kelting (1998), for example, noted a clear relationship between Least-Limiting Water Range (LLWR) and productivity on various disturbance types. This characteristic should be evaluated for a range of soils. Further research is warranted on both LLWR and moist-soil consistency (plasticity).

We currently have methods for risk rating soils as to their likelihood for being negatively impacted by equipment traffic. We should now further test their validity by measuring the effects of operational practices on soil characteristics and, ultimately, on productivity and hydrologic function. Results of this validation monitoring may warrant changes in rating systems and guidelines.

Summary and Final Recommendations

We discussed and recommended development of more uniform and effective: (1) soil disturbance categories and their relationship to productivity; (2) monitoring protocols that facilitate comparison and transportability of operational and research results within and across geographic regions and jurisdictions; (3) ratings of soils for risk of compaction, rutting, and displacement.

To support this initiative, a wealth of completed and current work needs synthesis. Products and deliverables include:

- State-of-the-art reviews and position papers about soil disturbance categories, alternative monitoring methods, and risk-rating systems.
- Common definitions of potentially detrimental soil disturbance types for specified areas based on reviews of hydrologic and tree response to soil disturbance.
- Coordinated training and extension materials for forest workers and lay persons.
- Effective methods for converting operational and research information into periodically updated soil management guidelines and BMPs.
- Common soil disturbance guidelines for similar soils and climate.
- Continued involvement with forest certification and sustainability protocols to ensure their operational relevance.

These products and actions will not only promote collection of more comparable data by states, provinces, USFS regions, and private ownerships, but also ensure a more seamless process for reporting at national and international

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