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

by Mike Curran[2], Doug Maynard[3], Ron Heninger[4], Tom Terry[5], Steve Howes[6], Doug Stone[7], Tom Niemann[8] and Richard E. Miller[9]

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."

[2]B.C. Forest Service, Forest Sciences Program, 1907 Ridgewood Rd., Nelson British Columbia V1L 6K1. (also, Adjunct Professor, Agroecology, University of B.C.) Corresponding author. E-mail: mike.curran@gov.bc.ca

[3]Natural Resources Canada, Canadian Forest Service, 506 West Burnside, Victoria, British Columbia V8Z 1M5.

[4]Weyerhaeuser Company, P.O. Box 275, Springfield, OR, USA 97478-5781.

[5]Weyerhaeuser Company, Box 420, Centralia, WA, USA 98531.

[6]USDA Forest Service - Pacific Northwest Region P.O. Box 3623, Portland, OR, USA 97208-3623.

[7]USDA Forest Service, North Central Research Station, Forestry Sciences Laboratory, 1831 Hwy 169 E, Grand Rapids, MN, USA 55744.

[8]B.C. Ministry of Forests, Forest Practices Branch, P.O. Box 9513, Stn. Prov. Govt., Victoria, British Columbia V8W 9C2.

[9]Emeritus Scientist, Pacific Northwest Research Station, Forestry Sciences Laboratory, 3625, 93rd Avenue S.W., Olympia, WA, USA 98512-9193.

Introduction

Physical disturbance from some forest practices can affect soil physical, hydrologic, chemical, and biological properties. It is possible to classify disturbance into generally applicable, readily identifiable, and operationally relevant categories even though soil disturbance occurs in a continuum from barely perceptible to obvious. Soil disturbances of concern include excessive compaction, puddling, rutting, displacement of forest floor and topsoil, and disruption of soil drainage. These disturbances, may affect soil capacity for water infiltration and storage, long-term productivity of trees or forage, soil erosion, propagation of invasive plant species, and aesthetics. Consequences may range from no effect to detrimental and will likely depend on the severity and extent of the disturbance, and on the soil and climate where disturbance occurs.

Elucidating cause and effect relationships can be difficult due to interactions amongst growth-limiting factors, and variation in climate and site. For example, soil disturbance that impairs hydrologic function may cause seedling mortality and reduce tree growth in neighbouring areas due to resulting changes in hydrologic regime. Off-site concerns include erosion, sedimentation, and slope stability. Soil disturbance is identifiable and can be managed. It is desirable to describe, monitor, and relate soil disturbance and its longer-term effects on and off-site in an adaptive management process (Curran *et al.* 2005a).

Calibration of soil disturbance schemes, comparisons of results from research and operational monitoring, and comparisons of guidelines and standards have all been hampered by a lack of common language and the resulting proliferation of protocols for assessing soil disturbance. Moreover, reporting of monitoring data within individual organizations, across different jurisdictions, and to third-party certifiers has often been inconsistent and ineffective. To achieve common language and monitoring protocols, however, requires integration of considerable information and peer collaboration.

Our objective is to provide and discuss elements and rationale for a more uniform approach to assessing and reporting all types of soil disturbance, particularly those with potentially detrimental consequences to site productivity or hydrologic functions. We do not impose value judgements about disturbance types, nor do we prescribe adherence to specific measurement protocols or risk-rating systems in our discussion. We do advocate more uniform disturbance definitions and sound assessment approaches. Our role as scientists is to provide technical direction that enables effective communication and comparison of operational and research results. In recent papers, we have described progress towards a common approach in the Pacific Northwest (Curran *et al.* 2005b), and an adaptive management approach for soil conservation (Curran *et al.* 2005a).

In this paper, we provide more detail about common approaches by providing a problem statement with background rationale and our recommendations for each of the following elements: (1) more uniform terms for describing soil disturbance; (2) cost-effective and statistically sound techniques for monitoring or assessing soil disturbance; and (3) reliable methods to rate soils for susceptibility to compaction, rutting, mechanical topsoil displacement, and perhaps erosion. Our views largely draw on experience and examples in British Columbia and the states in the Pacific Northwestern U.S.A, collectively referred to herein as the Pacific Northwest. However, our elements, problem statements, and recommendations are intended to encourage interest and collaboration among peers in other forested areas as well.

The Montréal Process' initial list of criteria and indicators of sustainable forest management included three indicators (4.a, 4.d and 4.e) related to soil disturbance, that focused on erosion, changes in organic matter and/or other chemical properties, soil compaction and other physical properties (Montréal Process 1999). These indicators were explicitly noted as requiring new data, new monitoring programs and/or more basic research. Experience since their initial publication in 1995 prompted the development of a new set of Montréal Process indicators that replaced the three soil indicators with two new soil indicators, focused on (1) meeting best management practices or legislation, and (2) soil degradation (Montréal Process Working Group 2006). Soil disturbance, and our discussion of it in this paper, is closely tied to both of the new indicators. Our recommendations are pertinent to constructive interpretation and use of these indicators, so that they constructively contribute to reporting on progress towards sustainable forest management.

Element One: More Uniform Categories and Definitions of Soil Disturbance

We need clear, unambiguous definitions of disturbance that: are related to effects on forest productivity and hydrologic function; enable precise, consistent, statistically sound, and cost-effective monitoring; and effectively communicate operational and research results.

Problem statement

Many classification systems exist for characterizing soil disturbance. Most define severity of rutting; many also have some definition of compaction; and some define some severity of soil displacement in terms of gouging, scalping, or mixing. The various schemes are based on visual or quantitative criteria, or both. This variety of approaches makes it difficult to compare guidelines, standards, or operational and research results. There is a need for definitions or descriptions of visually observable compaction, puddling, rutting, and scalping (displacement) that are more uniform and, most importantly, relate to forest productivity and hydrologic function.

Background rationale

Soil disturbance results from construction of access roads, harvesting, and site preparation that leaves various patterns of disturbance from machine actions and transported logs or trees. Some sites after intensive site preparation can have disturbed soil on nearly 100% of their area (Robert Campbell, Weyerhaeuser Co., personal communication). We advocate considering soil disturbance in two main categories: (1) the *access road network* that is necessary for permanent travel amongst managed forest areas, and (2) the *dispersed (in-block) disturbance* that occurs on the area to be reforested.

Access road network

Forest harvesting and other activities of forest management require a basic level of access. This access, often referred to as permanent access (e.g., B.C. Ministry of Forests 2001), represents a large investment in construction and maintenance costs. Required access includes roads and drainage structures,

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-

Fig. 1. Field card showing disturbance types counted under B.C. Forest Practices Code and Forest and Range Practices Act.

ments is that they are time-consuming and difficult to measure on a routine basis. Relating these criteria to visually observed disturbance may provide verification of visual classification. Visual criteria should always be validated by detailed assessment of soil properties in the research phase of developing these criteria. Thus, a combination of visual and physical assessment tools may be necessary in some situations.

Why improve uniformity of terms?

Improved communication within individual organizations, between forest scientists and workers, and with regulatory bodies, customers, and other stakeholders may be the most important reason for developing common language for sharing information about soil disturbance. Poor or incomplete understanding of soil disturbance categories can lead to

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-

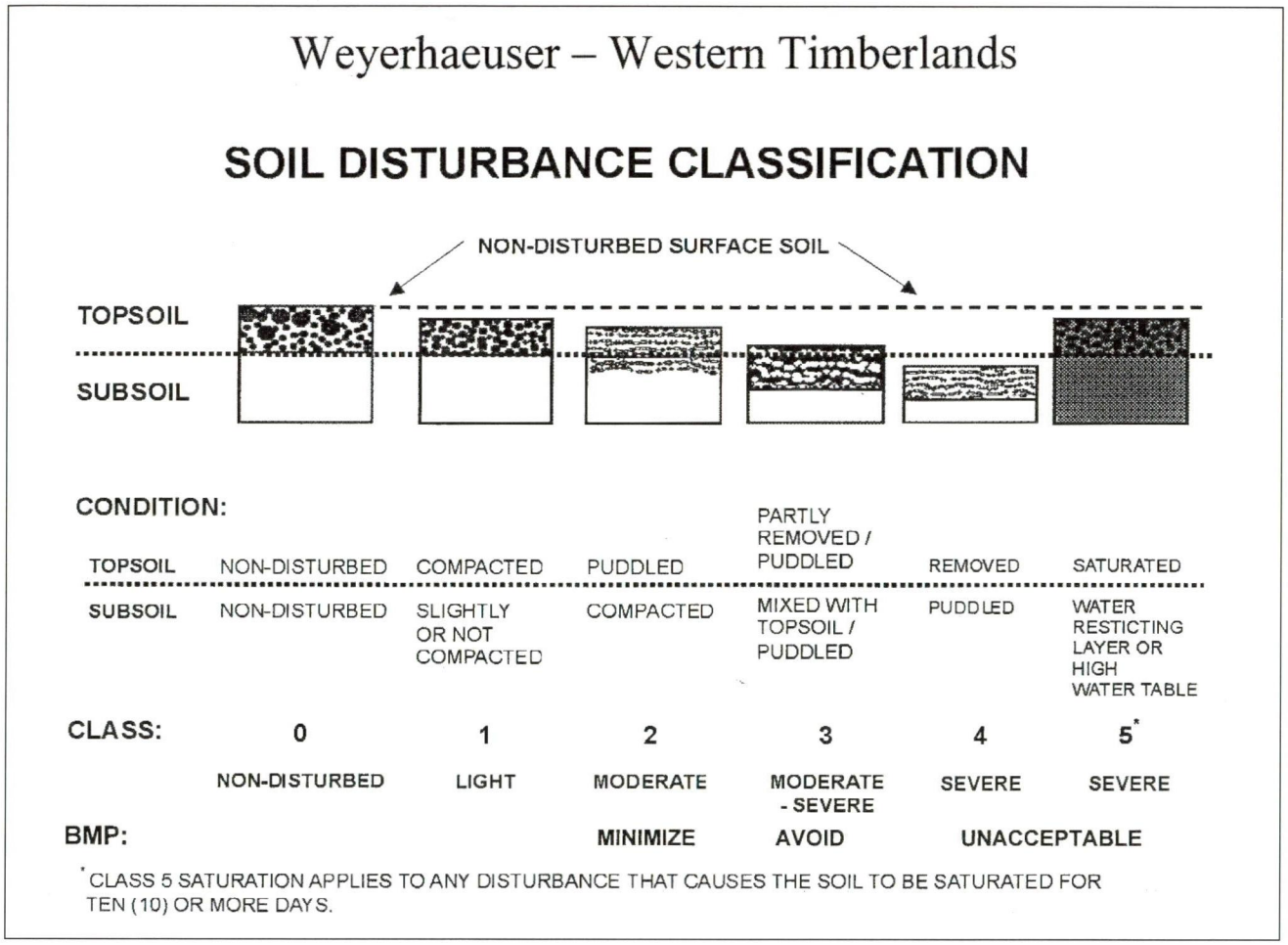

Fig. 2. Soil disturbance categories used by the Weyerhaeuser Company in western Washington and Oregon (Scott 2000), with BMP interpretations added.

tal or counted as disturbance by various jurisdictions' soil-disturbance guidelines.

Some rationale is needed for deciding when a given type or severity of disturbance is counted as detrimental. Soil- and climate-specific studies should be used to determine the types of disturbances that affect tree growth or hydrologic functions. Some disturbance types are obviously of concern for hydrologic function and may not require much study (e.g., excavated and bladed trails in the B.C. system in Fig. 1 and Table 1). The actual effect of a given disturbance and severity on tree growth at a given site will depend on factors that are growth-limiting and how they change over a rotation. Common growth-limiting factors in the B.C. Interior include: soil moisture (drought or excess), extremes of soil temperature, summer frost, limited rooting volume, soil nutrition (e.g., calcareous soils), competing vegetation, and root rot. The consequence of disturbance for tree growth is the net effect of soil disturbance on the original and the new limiting factors. For example, compaction initially can reduce soil aeration, but concurrently it can reduce competition from vegetation. Long-term effects depend largely on which factor is most limiting and how these interacting effects change over time and may be confounded by climatic trends.

Rehabilitation of detrimental soil disturbance should be recognized as a desirable strategy where soil conditions are suitable (Terry and Campbell 1981, Curran 1999). Tillage cannot always ameliorate compaction and improve soil conditions for growth (e.g., under very wet or saturated soil conditions), and it is likely not an adequate treatment where topsoil has been displaced and not replaced. Prevention or other treatment options may be more appropriate under such conditions.

Regardless of their effects on tree growth, some types of soil disturbance are of concern because of their potential consequences for on-site hydrology and associated downslope (off-site) impacts. The primary reason for soil disturbance guidelines in some jurisdictions is to protect water quality and fish (Lock 2001). Erosion and sedimentation are readily visible; but other hydrologic changes are more difficult to discern. Hydrologic effects may also influence tree growth by altering drainage or by exporting water normally available to trees during dry weather. Kuennen *et al.* (1979), in a study of compaction, inferred that because summer drought is generally one of the most growth-limiting factors in the Pacific Northwest, these on-site hydrologic effects may impact productivity on an entire harvested area and also may confound comparisons of tree growth on apparently undisturbed versus disturbed microsites.

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

international levels should compare soil management procedures and tools, and should explore opportunities for improving consistency among approaches.

A first step is to evaluate several existing disturbance classifications for use as soil quality indices. Specifically, one might examine how each classification scheme relates to changes in key soil functions (e.g., nutrition, gas exchange, soil strength, water-holding capacity, infiltration). A second step could be to determine how the scheme will vary with local soil properties that relate to specific soil functions that limit productivity or hydrologic functions. Disturbance categories should represent a justifiable mix of quantitative evidence and assumed or *a priori* relationships between soil factors and tree or hydrologic response.

Concurrently, disturbance categories should be revised under an adaptive management process (Curran *et al.* 2005a), as results become available from monitoring, operational trials, and research studies like the Long-Term Soil Productivity (LTSP) network (Powers *et al.* 2005). Consistent categories would enable those defining best management practice guidance (BMPs) and thresholds for severity and extent of disturbance to maintain soil productivity and hydrologic integrity to be consistent with disturbance category definitions.

Soil restoration practices must be evaluated to determine their effects on productivity and hydrologic function. Criteria are also required for defining soil rehabilitation objectives and for determining when rehabilitated soils are no longer counted as disturbed.

Element Two: Develop Cost-Effective Monitoring Techniques That Facilitate Reliable Comparisons of Operational and Research Results among Regions

The purpose of monitoring soil disturbance is to estimate the extent of an area (often as a percentage) in specified disturbance categories. Sampling methods should provide representative coverage of an activity area (or of strata or subareas), and allow for statistically valid and cost-efficient estimates.

Problem statement

Numerous methods exist for surveying or sampling soil disturbance in operational units and research trials. Although some methods have been developed, tested, and selected based on statistical principles, their precision, accuracy, and cost should be documented and evaluated. Cost-effective protocol options need to be described to meet specific monitoring objectives. A critical review of methods for assessing or monitoring soil disturbance and consultation with statisticians are needed before a reliable system is implemented. Because the amount and severity of soil disturbance is often used as a proxy for longer-term growth impacts and hydrologic functions, it is essential that soil disturbance types are calibrated as to their impacts on tree growth and hydrologic functions based on research studies (Curran *et al.* 2005b).

Background

Sampling designs

In developing early guidelines to reduce soil disturbance, a number of monitoring methods and sampling designs have been used to estimate the amount of disturbance. Formal surveys range from traverse surveys of defined disturbance features (e.g., roads and landings) to line transects for more dispersed features (e.g., equipment trails and localized rutting). Traverse surveys involve either completely traversing (i.e., pacing or hip-chaining) a feature (e.g., a landing) or measuring its length and then repeatedly sampling widths to estimate mean width (e.g., roads, skid roads, or skid trails), and calculate the area of the disturbance feature. For line- transect methods, which may include point-sampling along each transect (McMahon 1995), or measuring line-intercept distances (Smith and Wass 1976), the transects need to be randomly located or systematically located with a randomly selected starting point. For continuous-line transects, the length of the distance intercepted by each disturbance type is recorded and its percentage of the total transect length is calculated. Random, continuous-line transects are handled as cluster-samples (two-stage sampling) by the USDA Forest Service (Howes *et al.* 1983). Thus, each transect is considered as an observation. In some applications, each point sample on the transect is treated as the sampling unit and the point is classified as the disturbance type it falls within (B.C. Ministry of Forests 2001). In this case, the number of points within disturbance types is divided by the total number of sample points to calculate the percentage of disturbed area. B.C. Forest Service efforts led initially to a combination of both traverse and transect techniques (Curran and Thompson 1991), and later to simpler, equally spaced parallel transects with point samples (B.C. Ministry of Forests 2001). In both the continuous-line and point-sampling cases, the survey can be conducted quickly when visually defined disturbance types or classes are used. Sampling should occur soon after harvesting, particularly in areas where natural re-vegetation will rapidly obscure disturbance.

Other approaches to quantify disturbance have used aerial photos (e.g., as in use in Quebec[10] and B.C. (Province of B.C. 2005)) or even global-positioning systems mounted on harvesting equipment (Partington *et al.* 2005). Combinations of such methods might be used to assess landings, temporary roads, and skid trails.

When guidelines are based on visual classes, surveys of soil disturbance can provide reasonably efficient monitoring, reporting, and enforcement of soil disturbance standards. Costs increase markedly when guidelines are based on quantitative disturbance criteria, such as percent change in bulk density or aeration porosity, or when disturbance for transect segments or points are described in detail (e.g., gouge, 5 to 10 cm deep into mineral soil, 55 cm wide, and 155 cm long). These require sampling of soil physical properties and measurement of disturbance features. Cost associated with quantitative measures may be prohibitive. For example, the Pacific Northwest Region of the USFS developed such procedures based on soil physical properties (Howes *et al.* 1983), but implementation was expensive and often cost-prohibitive. As budgets declined, the amount of monitoring has dropped to almost nil, making more cost-effective protocols a necessity.

For assessing regulatory compliance, chosen method(s) must fit the intended use, provide a statistically sound esti-

[10]Jette, J-P. Protecting forest soils through an adaptive management approach. Research note (describing Quebec soil disturbance standards and monitoring results). Tabled at the XII World Forestry Congress, Quebec, Canada, 2003.

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-

fied percentage of the cutblock area that will be reforested (e.g., 15% before rehabilitation and 10% after, on less sensitive soils). On more sensitive sites (those with High and Very High Compaction Susceptibility, more disturbance types are counted (e.g., 5-cm deep ruts and impressions, as opposed to 15 cm on less sensitive soils) and the limit is lower (e.g., 10% before rehabilitation, and 5% after).

Inferences from disturbance monitoring

Monitoring estimates severity and extent of soil disturbance. From these data, estimates can be inferred on the potential consequences to tree performance or hydrologic functions. This approach is used because collecting direct evidence (measuring tree growth or hydrologic functions) is time-consuming and costly. Clearly, operational monitoring should be supported by concurrent research to relate productivity and hydrologic function to visual disturbance classes and associated soil physical properties as referred to in Element One. Such research supports local estimates of productivity declines or gains that are used to predict long-term yields, and to set harvest levels.

In some jurisdictions, specified disturbance types require immediate stoppage of operations and amelioration, or require rehabilitation after harvesting. In Eastern Canada, where water quality for fisheries is a major concern, rut depths and lengths that are not permitted are specified, regardless of an apparent low risk for sediment delivery to streams (Lock 2001).

Recommendations: Principal requirements of soil disturbance surveys should be specified after review of existing systems and the literature.

Critical reviews of monitoring methods for assessing soil disturbance and of proper statistical sampling designs are needed. This would identify advantages and disadvantages of various methods, and facilitate integration of ideas into several alternatives to fit specified objectives, sampling accuracy, and risk tolerance. The desired outcome should be consensus on a visual classification system (Element One) and several optional methods for monitoring disturbance (Element Two) to meet the specified objective. A reliable soil-disturbance monitoring system should address the following sampling considerations:

- The sampling design should provide impartial coverage over the entire area being monitored. Stratification with unequal allocation of samples is acceptable.
- Sampling units should be positioned randomly to ensure that systematic bias does not occur. The confidence interval around estimated population means should be reported and the confidence level should be specified.
- The system should be cost-effective and provide meaningful data that are accurate and repeatable for the parameter being estimated.
- The total (base) area to which disturbance limits (standards) apply needs to be specified when reporting percentages of disturbed soils. Permanent-access disturbance (roads) represents a loss from the timber-harvesting landbase and is often calculated as a percentage of that landbase (gross area). In contrast, in-block disturbance is often calculated as a percentage of what is referred to in B.C. as the net area to be reforested. It is important to make these distinctions to avoid confusion.

Element Three: Develop Reliable Methods to Rate Soils for Their Relative Vulnerability to Compaction, Rutting, Displacement, and Erosion

Problem statement

Various methods exist for rating soils for their vulnerability to specified disturbance processes. Each method was developed for a specific geographic area. The merits of alternative methods across geographic areas should be assessed, and comparable risk-classes developed that are: (1) useful for soil disturbance guidelines, and (2) validated by operational and research results.

Background

Soil-disturbance risk ratings focus on the inherent vulnerability of a given soil to soil-degrading processes such as compaction, rutting, and displacement relative to other soils. Interpretations are normally based on descriptive information for each mapping unit identified in detailed soil survey. Wherever ratings are based on soil maps, actual soil conditions must be verified on the site. By various means, soil mapping units are rated for their susceptibility for detrimental soil disturbance to occur. In the absence of detailed soil classification and mapping, interpretations are based on site-specific data. Five soil-disturbance processes originally defined for forest management in B.C. (Curran *et al.* 1990 and Lewis *et al.* 1991) are still used in harvest planning and operational monitoring. These are soil compaction, soil displacement, forest floor displacement, surface soil erosion, and mass wasting. Currently in B.C., "sensitive soils" are defined based on higher soil compaction, displacement, or erosion hazard ratings, which are referenced in legislation that defines soil disturbance limits for sensitive and non-sensitive soils.

Soil disturbance risk ratings can be useful in planning forest operations. The operational challenge is to minimize the area of detrimental disturbance. To meet this challenge, the manager needs to consider both inherent site factors and manageable factors that can mitigate disturbance. Manageable factors include timing of harvest, avoiding wet soils, designating equipment, laying out harvest areas, and operating techniques with the equipment.

A research challenge is to validate soil disturbance risk ratings or predictions of soil vulnerability and, more importantly, to quantify the linkage between change in soil properties and consequences for tree growth, erosion, and hydrologic processes. For example, under what conditions does compaction reduce tree growth or increase erosion?

Because compaction, puddling, and displacement are of particular concern in the Pacific Northwest, each will be discussed in detail as to: (1) their effects on soil properties and processes, (2) factors used to predict soil risk, and (3) the ultimate goal of relating the ratings to consequences for tree growth.

Soil compaction and puddling

Risk ratings to minimize compaction focus on soil physical properties (e.g., texture, coarse fragments, organic layers), often combined with site factors such as drainage or moisture regimes.

Soil disturbance risk factors

The B.C. Forest Service's compaction-hazard (susceptibility or vulnerability) key is an example of a simple key based mainly on soil texture and coarse fragment content (Table 3).

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.

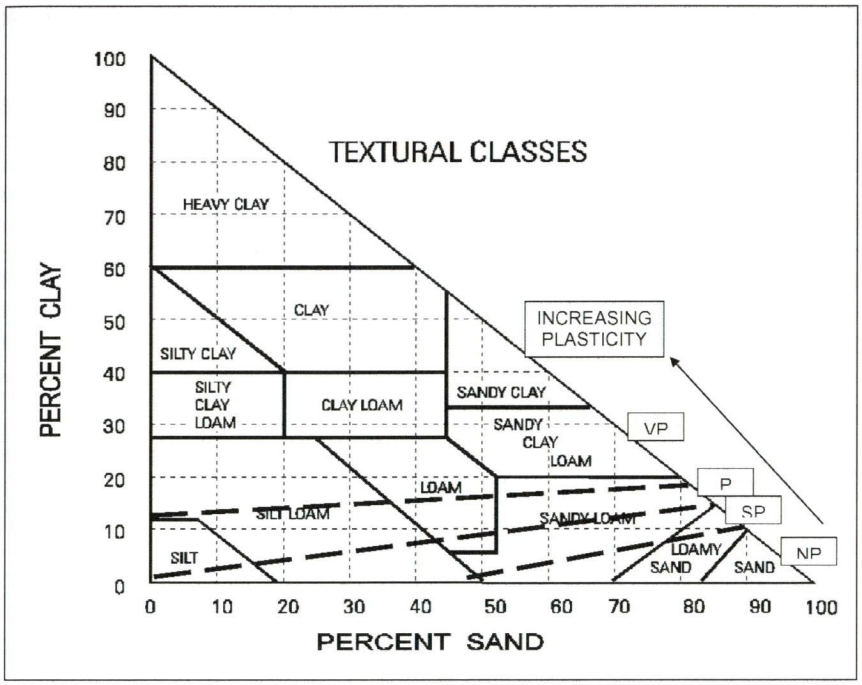

Fig. 3. Demonstration of how soil consistence (plasticity) categories fall into the soil texture triangle, based on 48 samples of varying clay and sand content. The three thick dashed lines delineate, from the bottom right corner: non-plastic (NP), slightly-plastic (NP), plastic (P), and very plastic (VP), respectively (Curran, unpublished data).

Texture classes may be too broad to be a precise predictor of impacts on tree performance after disturbance. For example, in a 15-year-old stand with soil disturbance from a harvest and stump removal in southern B.C., Wass and Senyk (1999) found that tree growth was reduced on a soil with 12% clay (Gates Creek soil), but not significantly affected on soil with 4% clay. Both soils were classified as gravelly sandy loam texture, but their moist consistencies (plasticity) are different, demonstrating that this may be an additional criterion to be used along with texture.

A further example of the variable nature of tree growth after soil disturbance was reported for aspen regeneration and growth in the Lake States (Stone 2001). Much lower density of suckers was measured on heavily disturbed and rutted soil, and a highly significant negative relation existed between first-year height growth and an area-weighted index of soil disturbance (Stone and Elioff 2000). The site with the greatest reduction in aspen sucker density, however, was compacted in spring when suckers were emerging. Thus, timing of the operations confounded response across sites. In other situations, differences among reported growth response can be explained by differences in soil resistance or in severity and extent of compaction among study sites or replicates within a site. Therefore, valid inferences about cause and effect require reliable data and careful consideration of treatments, site conditions, and species of concern.

Slower rates of moisture infiltration and hydraulic conductivity in compacted or puddled soil can increase runoff during rainfall and snowmelt. Increased runoff from a cutblock can affect downslope sites, natural drainage features, and other resource values due to erosion and sedimentation. Increased runoff also means less water is likely stored on-site for tree growth during summer drought. Puddled and ponded areas can also cause seedling mortality due to impeded drainage and lack of adequate soil aeration. These hydrologic effects are most likely the consequence of concentrated disturbance associated with skid trails, and they could be severe enough to count as detrimental disturbance types. Effects of more dispersed traffic are difficult to isolate and clear relationships have not always been elucidated (D. Toews, Research Hydrologist, BCFS, Nelson, personal communication, 1999).

Weyerhaeuser's soil-disturbance risk key is designed to rate soils on their potential to exceed Disturbance Class (DC) 2 (Fig. 2) when machines travel on them. Disturbance Class 2 is moderate disturbance that results in puddled topsoil and compacted subsoil (Scott 2000). The primary driver in risk-rating soil is the depth to topsoil, defined as the A- or AB-horizon. If a soil has shallow topsoil (< 28 cm), it is rated very high risk of exceeding DC 2 (or being detrimentally displaced). High-, moderate-, and low-disturbance risks are functions of topsoil texture and coarse fragment content of both top- and subsoil. Depths to water table and subsoil texture are used to determine if soil has risk to become saturated.

The impacts of skid-trails on Douglas-fir growth in Coastal Washington and the Oregon Cascades have been investigated (Miller *et al.* 1996 and Heninger *et al.* 2002). The coastal Washington soils are deep, loams to clay loam, with high organic matter, moderate risk to compaction/displacement, and intermediate summer rainfall. Seedlings were planted in ruts of DC 1 (light disturbance with compacted topsoil) and DC 2 (Fig. 2). Seedling growth was reduced in the first and second year following planting; however, by year 7 or 8 after planting average height and volume did not differ from seedlings planted in undisturbed soil. In the Oregon Cascades, soils were less deep, had silty clay loam texture, less organic matter, and are rated high and very high risk to compaction/displacement. Extended summer dry periods are the norm. Seedlings again were planted in ruts of DC 2 and 3 (moderate to severe disturbance). Height growth on skid trails averaged 24% less than on undisturbed soil in year 4 after planting and decreased to 6% less in year 7. For years 8 to 10, mean height growth was similar for both disturbed skid trails and undisturbed soil. Reduced height growth lasted about seven years compared with two years for coastal Washington. Soils, climate, and species vary and interact; thus, generalizations about the effects of skid trails on tree growth have limited geographic-climatic scope.

Forest floor and topsoil displacement

Risk factors

Forest floor displacement is likely of greatest concern in regions and sites where much of the organic matter and nitrogen capital (or even much of the rooting zone) exists in the forest floor. In northern forests of the B.C. Interior, it is

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

levels. Additionally, incorporation of the assembled information into an adaptive management framework will improve operational relevance of research results.

Organizations and jurisdictions need to consider how their science and technology programs can contribute to achieving a common approach to soil disturbance assessment. We suggest that regional working committees complete these products. For example, some regional issues could be addressed by the newly created "Soil Disturbance Working Group" of the Northwest Forest Soils Council, the "National Working Group on Forest Soil Disturbance" in Canada, and the Soil Quality Standards working group for the USDA Forest Service. Internationally, umbrella organizations such as the International Union of Forest Research Organizations (IUFRO), the International Energy Agency (IEA), or the organizers of North American Forest Soils Conferences could provide leadership. Although it is more realistic to start regionally (such as in the Pacific Northwest), potential co-operators at all levels should be engaged early to ensure general acceptance of a common language and congruent approaches to assessing and reporting soil disturbance at the local and international level, such as under the Montréal Process.

This work is timely because regulatory and certification / international protocol requirements are increasing the need for demonstrating reliable soil management systems. Given adequate support by sponsoring jurisdictions, initial products (e.g., disturbance types, risk-rating systems, and monitoring methods) for reporting research and monitoring results could be drafted in a relatively short period of time. Other products (e.g., an adaptive soil management process, operational reporting to satisfy certification requirements, or comparison of guidelines) are beyond the scope of technical committees and would involve other interests. The authors plan to pursue the three elements presented in this paper in the Pacific Northwest and participate in and encourage similar efforts in other regions and at the national and international levels.

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