Soil Quality Monitoring: Examples of Existing Protocols

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Abstract—Many forestry and agricultural agencies and organizations worldwide have developed soil monitoring and quality standards and guidelines to ensure future sustainability of land management. These soil monitoring standards are typically developed in response to international initiatives such as the Montreal Process, the Helsinki Ministerial Conference, or in support of Best Management Practices program development and Code of Forest Practices regulations. This paper describes international (Australia, New Zealand, Canada, and the European Union) and U.S. efforts and perspectives on soil quality monitoring, and offers suggestions on how to use the existing USDA Forest Service standards and modify them for future relevance.

Introduction

International Approaches

The 1990 Helsinki Ministerial Conference began the process for developing management guidelines and criteria to ensure conservation and sustainable management of forests in Europe and elsewhere (Helsinki 1994). In 1993, the United Nations convened an international seminar in Montreal, Canada, on the sustainable development of temperate and boreal forests. This conference led Canada and nine other nations to form the Working Group on Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forest. This working group soon became known as the "Montreal Process." The Montreal Process was a parallel, but independent, initiative to the Helsinki Process that developed similar criteria (Anon. 1995). Criterion 5 of the six Helsinki Process criteria is to maintain and develop the role of forests in water supply and protection against erosion. Criterion 4 of the Montreal Process is to conserve and maintain soil and water resources. The latter Criterion includes the conservation of soil and water resources and the protective and productive functions of forests. Since the chemical, physical and biological characteristics of aquatic systems are excellent indicators of the condition and sustainability of the lands around them (Breckenridge and others 1995), key conditions of soil and water resources were selected as indicators of sustainability.

The original Montreal Process countries met in Santiago, Chile, in 1995 to endorse a statement of commitment, known as the "Santiago Declaration," along with a comprehensive set of seven criteria and 67 indicators for the conservation and sustainable management of temperate and boreal forests. This new set of criteria and indicators added to the growing body of type-specific measurement and assessment systems already underway through the Helsinki Process in Europe and elsewhere. Eight out of 67 indicators selected in the Montreal Process and endorsed by the nations that drafted the

Santiago Declaration in 1995 pertain to Criterion 4. Following are those indicators that specifically concern soil impacts:

> (18) Area and percent of forest land with significant soil erosion;
>
> (19) Area and percent of forest land managed primarily for protective functions, *e.g.*, watersheds, flood protection, avalanche protection, riparian zones;
>
> (20) Percent of stream kilometers in forested catchments in which stream flow and timing has significantly deviated from the historic range of variation;
>
> (21) Area and percent of forest land with significantly diminished soil organic matter and/or changes in other soil chemical properties;
>
> (22) Area and percent of forest land with significant compaction or change in soil physical properties resulting from human activities;
>
> (24) Percent of water bodies in forest areas (*e.g.*, stream kilometers, lake hectares) with significant variation from the historic range of variability in pH, dissolved oxygen, levels of chemicals (electrical conductivity), sedimentation or temperature change.

The Montreal Process criteria are distinguished from those developed by other sustainability efforts in that they recognize a fundamental connection between forests and people. The criteria function on the assumption that a nation cannot achieve forest sustainability without the support and understanding of its public. The criteria and indicators provide a common understanding and implicit definition of sustainable forest management. They are to be considered tools for assessing trends in forest conditions, and they provide a framework for describing, monitoring, and evaluating progress toward sustainability. An important consideration is that the Criteria and Indicators should not be confused as performance standards for certifying management or products.

Criteria are envisioned as a national-scale consensus of public values. They are meant to communicate an overview of what participating countries want to see in the conditions of their forests. Indicators provide the means for assessing forest conditions and for tracking trends. The Indicators are intended to be flexible components of resource monitoring protocols that can be adjusted to provide the most accurate assessment of environmental, economic, and social trends.

Sustainability is the stewardship goal of forestry, but a more specific definition of its goals and attributes is often complex and open to considerable interpretation (Moir and Mowrer 1995). Many ecologists have attempted to answer the "what," "what level," "for whom," "biological or economic," and "how long" questions of sustainability. Allen and Hoekstra (1994) discussed the emergence of the concept of sustainability and the difficulty in defining it. They clearly pointed out that there is no absolute definition of sustainability, and that it must be viewed within the context of human conceptual frameworks and societal decisions on the type of ecosystem to be sustained and the spatial and temporal scales over which attainment of sustainability is to be judged. Sustainability is also defined in terms of society's needs, the experiential frame of reference of ecosystem managers, and the ecological models that are used to predict future conditions for natural resources. However, our ability to predict future ecosystem conditions is confounded by the uncertainties of increasing encounters with extreme events, poorly understood ecological processes and linkages, surprises by the law of unintended consequences, the development of critical thresholds, and chaotic system behavior. Another approach to the definition of sustainability is to define the conditions that warn of or mark ecosystem deterioration into unsustainability (Moir and Mowrer 1995). Although the goals of the Montreal Process and Santiago Declaration are to ensure management of forest lands for sustainability, the Criteria and Indicators are in essence warning flags to obtain the attention of land managers before ecosystems decline into unsustainability.

Soil compaction, erosion, and organic matter losses are the chief factors that affect decline of ecosystem productivity (Burger 2002; Powers and others 1990). These factors can alter ecosystem carbon allocation and storage, nutrient content and availability, water storage and flux, rhizosphere processes, and insect and disease dynamics. The chief disturbances that affect these three factors are wildfire, insect and disease outbreaks, climate extremes, vegetation management (wood harvesting and stand tending activities, grazing, prescribed fire, chemical weed control, and manual removal of plant species), and recreation (foot traffic and vehicles) (Hart and Hart 1993). Management activities that eliminate natural disturbances (*e.g.*, fire suppression, insect control) or alter ecosystem properties can also affect ecosystem sustainability.

Why Soil Monitoring?

Soil quality monitoring was developed as a means of evaluating the effects of management or harvesting practices on soil functions that affect site productivity (Doran and Jones 1996). Specific reasons might include elevating general awareness of soil condition, education, evaluating specific practices, problem solving, and comparing the effects of alternative management practices and techniques. A number of soil physical, biological, and chemical parameters, which have linkages to soil productivity, have been proposed as forming the minimum data set for screening the condition, quality, and health of soils (Doran and others 1998). Evaluation of soil conditions develops a time-trend analysis that can then be used to assess the sustainability of land management practices.

Soil monitoring developed as a natural outcome from the Helsinki and Montreal Process efforts on sustainability. Codes of Forest Practice, which then were developed, sought to incorporate Best Management Practices and soil monitoring into up-front operations planning rather than post-operation environmental assessment. The approach to soil monitoring varies by country and consists of combinations of self-assessment, independent agency monitoring or combinations of the two approaches. Since soils are vital resources for both natural ecosystems and human endeavors, and they are not easily restored, monitoring of soil conditions and trends is viewed as a necessary activity to maintain their functions and quality (Morvan and others 2007).

In Ireland, the Code of Best Forest Practices has a focus on achieving sustainable forest production by implementing safe and environmentally sound forest harvesting practices. A component of that effort involves routine soil monitoring to verify that acceptable practices are followed and that they do not adversely affect the soil resource (Ireland Forest Service 2000).

The U.S. Forest Service direction on protecting the soil resource is detailed in its Forest Service Manual 2554, Soil Quality Monitoring. The Agency's stated purpose in soil monitoring is to (1) meet direction in the National Forest Management Act of 1976 and other legal mandates, (2) ensure management of National Forest lands under ecosystem management principles without permanently degrading land productivity, and (3) maintain or improve soil quality (O'Neill and others 2005; U.S. Forest Service 2009).

In Australia, State Forestry Practices Codes have been established to provide legally enforceable guidelines and standards to ensure reasonable protection of the natural resources such as soils (Grove 2007). Soil monitoring takes the form of self-monitoring by forestry agencies and companies as well as selected audits by the State Forest Practices Authorities. The belief in soil and other monitoring by the Forestry Consultative Committee is that it will improve forestry operations as well as ensure long-term sustainability.

Curran and others (2005) discussed requirements for sustainable management of forests in Canada and elsewhere. They noted that maintenance of the biological, chemical, and physical properties and processes of soils was crucial for long-term sustainability. A key component for improving the understanding of site productivity and predicting the consequences of forest disturbances and practices was a reliable soil monitoring system.

Concepts and Basis for Monitoring

Characteristics

Soil monitoring must be both logistically effective and scientifically sound in order to achieve the objectives of land management agencies and regulatory authorities. Lovett and others (2007) discussed the important characteristics of monitoring programs in their treatise "*The Seven Habits of Highly Effective Monitoring*." They recommended that effective monitoring programs should

- be designed around clear and compelling questions;
- include review, feedback, and adaptation components;
- choose measurements carefully and consider future uses;
- have systems to maintain data quality and consistency;
- incorporate plans for long-term data accessibility;
- have internal checks and controls to ensure careful examination, interpretation, and delivery of the monitoring data; and
- incorporate an integrated research and development program or strong linkages to other existing research programs.

Another important characteristic of an effective soil monitoring program is a statistically sound protocol for location selection and sampling procedure design. Soil monitoring can be conducted separate from other monitoring programs or within existing programs such as the U.S. Forest Service's FIA Program (O'Neill and others 2005).

Location and Design

The location and design of soil quality monitoring projects are discussed in more detail by Doran and Jones (1996). Sampling locations and designs vary widely depending on the country, state, or province conducting the monitoring. Basic designs fall into the categories of simple random sampling, stratified random sampling, and systematic sampling (Elzinga and others 2001). Examples include random sampling on line transects, random sampling on Cartesian coordinate grids (fig. 1), stratified sampling of stand components (*e.g.*, old-growth, pole stands, sapling clusters, clearings, coarse woody debris piles). Systematic sampling would include evenly spaced sample points on grids established on the monitoring area. This analysis does not compare and contrast soil monitoring location and design techniques. The purpose of this effort is to examine the basic approaches used in a selected number of locations in the world.

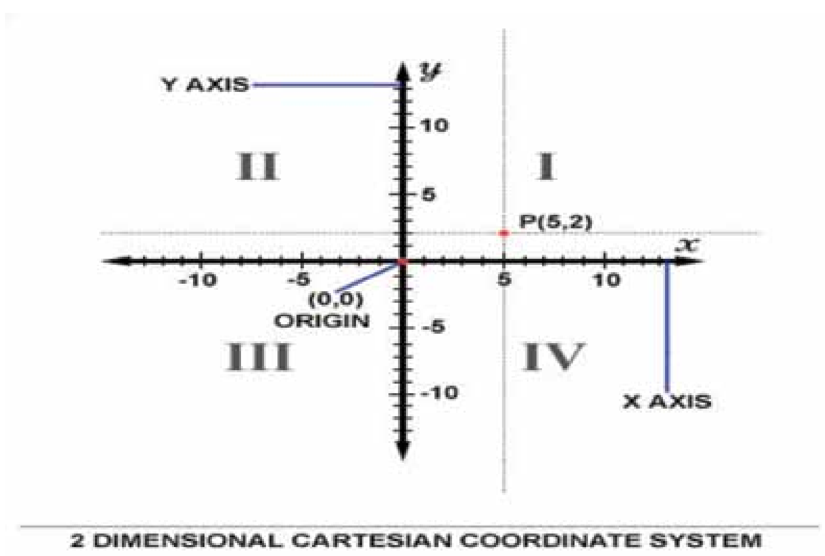

Figure 1. Cartesian coordinate sampling system (adapted from Johnson and Curtis 2001).

Existing Approaches

A number of soil monitoring approaches and systems have been implemented worldwide with mostly similar objectives but sometimes different perspectives. Specifically, the approaches of New Zealand, Australia, Canada, the European Union, and the new Forest Soil Disturbance Monitoring Protocol developed for use within the U.S. Forest Service will be examined.

New Zealand

Forest Code of Practice—New Zealand's 27 million ha of land consists of pasture and arable land (52 percent), native forests (23 percent), and plantation forests (5 percent). The remaining 20 percent is mountains, water, and urban areas. Planting of exotic species plantation forests began in the 1920s. These forests now account for 19 percent of New Zealand's forests but they produce 99 percent of the country's wood requirements. A Forest Code of Practice was established in 1990 (Vaughan and others 1993). The New Zealand Government passed the Resource Management Act of 1991 (RMA) to promote sustainable management of natural resources. The RMA is an effects-based resource law that focuses on land management activities that cause adverse environmental effects. The Forest Code of Practice sets out guidelines to maintain and protect forest values such as soils, water, scenery, recreation, cultural sites, site productivity, and off-site impacts. The Code focuses on both planning and operations to achieve sustainable forest management.

The key components of the planning process in the Code, before any operations are conducted, are (1) identifying important site values, (2) identifying operations that could have significant impact, (3) selecting low impact techniques and methods, (4) establishing protocols to check on compliance to the Code and obtaining approvals, and (5) monitoring actual performance during and after operations. Inputs to the planning come from both external and internal sources (fig. 2). Monitoring then uses an operations database, a rating system, checklists, an operations self appraisal, and finally a compliance check with District and Regional rules.

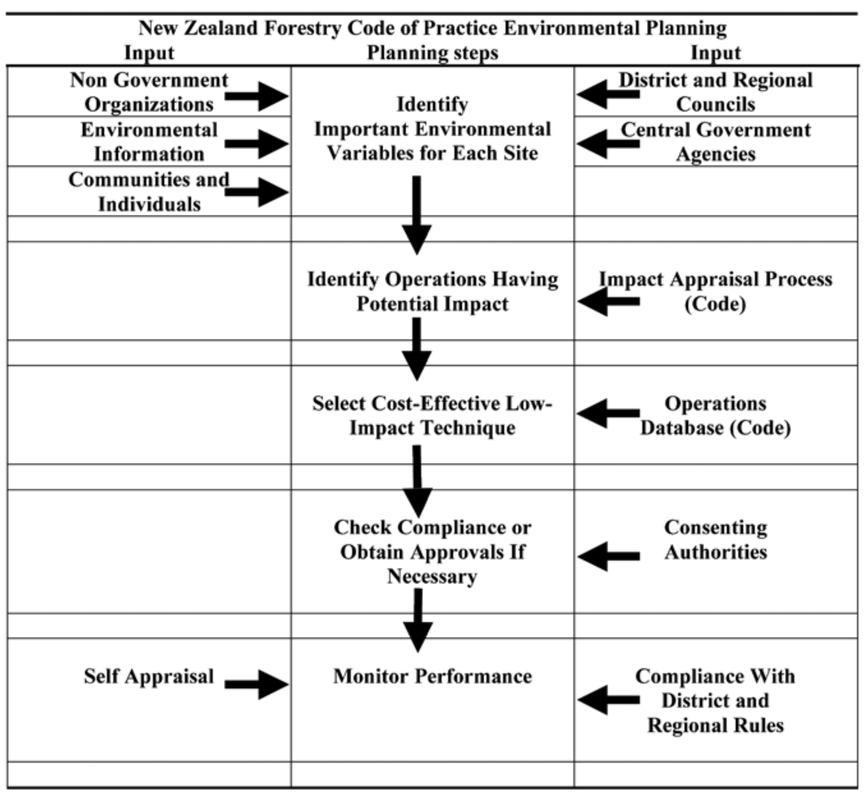

Figure 2. New Zealand Forestry Code of Practice environmental planning flow chart (adapted from Vaughan and others 1993).

Table 1—New Zealand Forest Code of Practice monitoring rating system and symbols (adapted from Vaughan and others 1993).

New Zealand Forestry Code of Practice monitoring rating system

Time	Risk	Impact	Symbols
Short-term	Minor	Minimal	
Long-term	Minor	Low	+/-
Short-term	Major	Intermediate	++/--
Long-term	Major	High	+++/---

Table 2—Example planning checklist for a Wairarapa, New Zealand, woodlot (adapted from Vaughan and others 1993).

	Identified environmental values				
Operation	**Water quality**	**Wetland areas**	**Slope stability**	**Erosion**	**Water supply**
			Access		
Roading	-	•	- - -	- -	- -
			Land preparation		
Herbicides	- -	•	•	•	- -
Oversowing	+ +	•	+	+	•
Tracking	- -	•	- - -	- -	- -
Grazing	- -	- - -	- - -	- - -	- -
			Establishment		
Planting	+	•	+ + +	+ + +	+ +
Releasing	•	•	• •	•	- -
Grazing	- - -	- - -	- - -	- - -	- -
Fertilizing	- -	•	+	+	- -
			Tending		
Pruning	+	•	•	+ +	•
Waste thin	+ +	+	+ + +	+ + +	•
			Protection		
Animal control	•	•	•	•	- -
Roads	- -	•	- -	- -	-
Weed control	- -	- -	•	•	•
			Harvesting		
Roading	- - -	• •	- - -	- - -	- - -
Landings	- - -	•			•
Felling	•	+ +	+ +	•	•
Processing	+ +	•	•	•	•
Extraction	- - -	- -	- -	- - -	- -
Stream cross	- -	-	-	- -	•
Transportation	•	•	-	-	•

The rating system utilizes a four-level risk rating system involving both short- and long-term impacts, minor or major risks, and categories of minimal, low, intermediate, or high (table 1). Symbols that correspond to each are then used on the planning forms. An example checklist from a Wairarapa woodlot near Wellington is shown in table 2 (Vaughan and others 1993). Forest managers are then required to develop mitigation plans based on the pre-harvest assessment. The Forest Code of Practice database provides detailed information on identifying risks and planning mitigation measures. Activities that can potentially have a significant impact on the environment require planning review and consent by District or Regional Councils. Post-operational self-monitoring and regular, periodic monitoring and maintenance are required to achieve the desired outcome of maintaining sustainable management of forest lands.

National Soil Quality Survey—New Zealand conducted a national-scale soil quality monitoring program between 1995 and 2001 at 222 sites in five regions of New Zealand (12 soil orders and 9 land-use categories) (Sparling and Schipper 1998, 2002). Land uses in the survey included arable cropping, mixed cropping, pasture, grassland, plantation forests, and native forest. Sampling of the topsoil (0–10 cm) was done and the properties measured were total carbon (C) and nitrogen (N), potentially mineralizable N, pH, Olsen phosphorus (P), cation exchange capacity, bulk density, total porosity, macroporosity, and total available and readily available water. Seven of these soil parameters (total C, total N, mineralizable N, pH, Olsen P, bulk density, and macroporosity) explained 87 percent of the total variability. Some of the issues that arose during the soil quality sampling were minimum data set, how to stratify, level of precision, cost, centralized data and sample management, re-sampling for trends, and sampling strategy. Important recommendations that came out of the survey were that (1) a precision of 10 percent was impractical due to cost, (2) a precision of 25 percent was more realistic, (3) central storage of data and samples was essential to success of this type of survey, (4) re-sampling needs to be over a 3- to 10-year time period with some being done every year, and (5) current financial constraints prohibit random sampling.

Following are the key findings from the New Zealand Soil Quality Survey:

- Soil Order had a strong effect on the results.
- Land use accounted for only 21 percent of total C variability.
- There was no evidence of acidification under exotic tree species.
- Changes in soil quality between land uses can be detected.
- Biochemical and total C indices are more sensitive to land management differences than physical parameters.
- Soil quality of mature pine plantations before and after logging were similar to native forests or low-productivity pasture.
- Many research needs were identified to make a national-scale soil quality survey a viable management tool.
- Changes in soil quality characteristics can be detected, but there is a general lack of a scientific framework to define acceptable and unacceptable ranges of soil quality parameters.

Australia

Australian Forestry—The total area of native forest reported in the latest *Australia's State of the Forests Report* (National Forest Inventory 2008) is estimated at 162.7 million ha, which is about 21 percent of Australia's land area. Some 75 percent of native forest estate was on public land, and the remainder was private land or unresolved tenure. About 70 percent of Australia's native forests were privately managed. Australia's plantation estate continues to expand, reaching 1.8 million ha in December 2006, an increase of 78,000 ha (4.5 percent) over the prior year 2005. The proportion of hardwood species has increased to 44 percent of the total, with softwood species making up the remainder. About 95 percent of the softwood plantations are *Pinus radiata* and other introduced pines. *P. radiata* is grown on a 30 to 40 year rotation and supplies about 50 percent of the domestic wood demand. Nearly all of the hardwood plantations are native eucalypts, including Tasmanian blue gum (*Eucalyptus globulus*), shining gum (*E. nitens*) and flooded gum (*E. grandis*).

A diverse range of ownership arrangements exists in the Australian plantation industry, including a variety of joint venture and annuity schemes between public and private parties. For several years, most investments in new plantations have been by the private sector. The proportion of public and private plantations was equal (46 percent) in 1999; however, privately owned plantations now account for 59 percent, far exceeding public plantations at 36 percent. This difference is especially pronounced for hardwood plantations, about 86 percent of which are privately owned compared with 36 percent of softwood plantations.

Australian Codes of Forest Practice—In Australia, Codes of Forest Practice are State-based and tied to sustainable yield. Except in Tasmania and Victoria, the Codes are applicable to only public lands. There are 14 State and territory Codes that began development in 1978. They all put an emphasis on quantitative performance standards

Table 3—Topics addressed in four Australian Codes of Forest Practice (adapted from McCormack 1996). Soils-related ones are in *italics.*

Tasmania	New South Wales	Victoria	Western Australia
Design & Planning	Design & Planning	Design & Planning	Design & Planning
	Tree Marking		Tree Marking
	Tree Felling		Tree Felling
Log Skidding/Tracks	*Log Skidding/Tracks*	*Log Skidding/Tracks*	*Log Skidding/Tracks*
Log Landings	*Log Landings*	*Log Landings*	*Log Landings*
Wet Weather	*Wet Weather*		
Water Quality		*Water Quality*	*Water Quality*
Slope Limitations		*Slope Limitations*	
Landscape Values		Landscape Values	Landscape Values
Wildlife habitat		Wildlife habitat	Wildlife habitat
	Fire		Fire
Plant Diversity			Plant Diversity
		Site Rehabilitation	
		Fuel Dumps	
	Licensing		
Cultural Resources			
Geomorphology			
		Crop Trees	

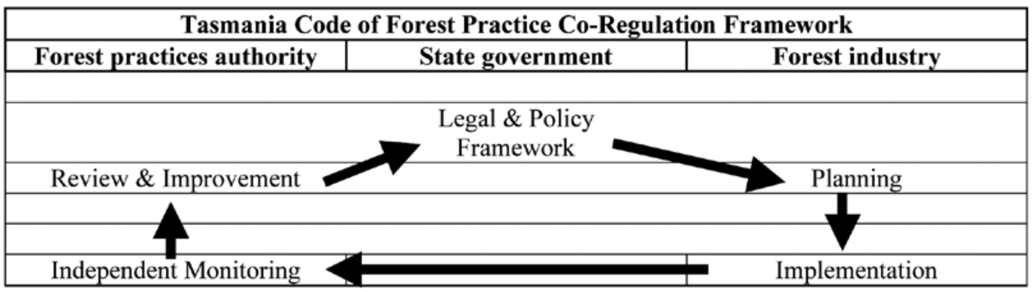

Figure 3. Tasmania adaptive management framework (Code of Forest Practice 1985).

that are keyed into sustainable timber yield and timber harvest planning (McCormack 1996). Old growth and rain forests were the critical issues that lead to these Codes. While soils and soil quality are not directly mentioned as major concerns (table 3), they are inherent in a number of the topics of concern to Australian Codes of Forest Practice.

Tasmanian Code of Forest Practice—The Tasmania Forest Practices Act 1985 was the first Australian Code of Forest Practice (McCormack 1996; Tasmanian Forestry Commission 1993). It deals with a number of issues that relate to soils and soil quality (table 3). First and foremost, the Tasmania Code focuses on proper designing and planning prior to tree harvesting. The Code is administered by the Forest Practices Authority (FPA) but is a co-regulatory adaptive management process in nature (fig. 3). The first level of monitoring is provided by each forest owner, with random independent monitoring conducted by the FPA through Forest Practices Officers (FPO). The FPOs have regulatory powers and can insist on remedial work being done through court actions and fines. However, the main emphasis of FPOs is placed on education and demonstration of Best Management Practices rather than regulatory enforcement.

The Tasmanian FPA employs specialists in forestry, soil science, botany, zoology, geology, hydrology, and archeology whose research and monitoring supports the Code of Forest Practice. The FPA trains and provides advice to forest industry personnel and also conducts the independent audits of forest industry operations (fig. 3).

Canada

Canada has 404 million ha of forested land, accounting for 10 percent of the world's forests and 30 percent of the boreal forests (Natural Resources Canada 2009). Less than 1 percent of Canada's forests are harvested each year, and all Public forests must be successfully regenerated by natural (50 percent) or planting and direct-seeding techniques.

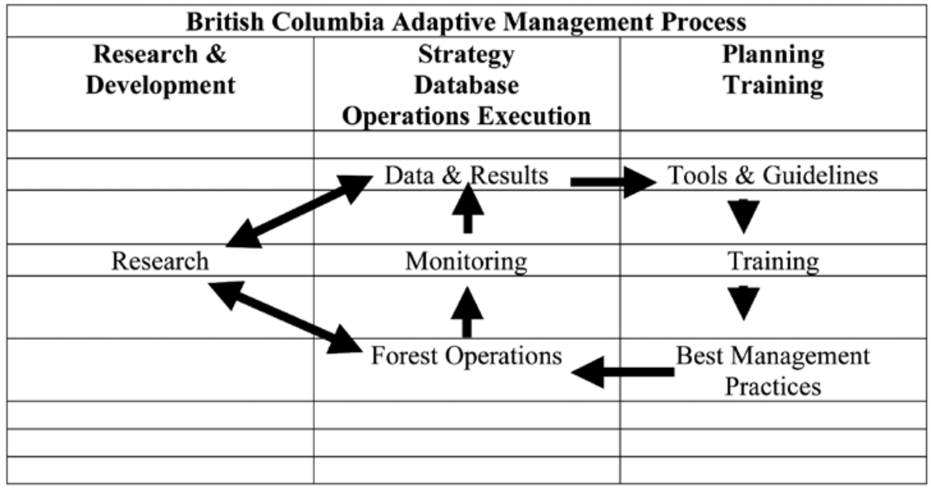

Figure 4. British Columbia soil monitoring adaptive management process (adapted from Curran 2007).

About 36 percent of the country's forests have been certified as being sustainably managed by globally recognized certification standards. Codes of Forest Practice are in place in Nova Scotia, Ontario, and British Columbia. Canada's forest laws and regulations are considered to be among the strictest in the world.

British Columbia has led Canada in developing procedures to ensure forest sustainability. The "Forest Practices Code of British Columbia" of 1996 established the legal framework for monitoring soil disturbances caused by forest operations. It has since been augmented by the "Forest and Range Practices Act of 2002." The Province has an iterative adaptive-management process that provides constant feedback to forest operations and research to improve Best Management Practices and operations planning and execution (fig. 4).

The Soil Conservation Guidebook (British Columbia Ministry of Forests 2001) provides an overview of post-harvest monitoring inspection procedures, the current requirements, and definitions for Soil Conservation Surveys; it also provides instructions on how to conduct surveys. Silvicultural prescriptions define the maximum percent of the net area to be reforested that may be occupied by disturbed soils and the extent to which that area of disturbance can be temporarily exceeded. The operations site plans identify sensitive soils and spell out the maximum percentage of the total harvest area that can be permanent access roads, temporary roads and skid trails, and roadside work areas. Visual Soil Conservation Survey reports are required to verify that prescription limits were not exceeded. If they are, then a formal survey is required. The Surveys focus on disturbance to soil caused by roads and skid trails and the amount of forest floor displacement or damage. In order to "standardize" what can be recognized as soil disturbance by equipment operators, contractors, inspectors, the public, or research scientists, a set of representative visual examples is provided (figs. 5a,b).

A transect survey is installed if a formal Soil Conservation Survey is warranted. Methods are specified in the Soil Conservation Guidebook (British Columbia Ministry of Forests 2001). This type of survey is usually completed as soon as possible after the operations disturbance and it requires site familiarity. The survey transects are documented in case follow-up measurements are needed (fig. 6)

European Union

Forests cover 160 million ha within the European Union, or about 42 percent of the 27-member Union. Six countries account for two-thirds of the forest area with Sweden and Finland alone accounting for 30 percent of the total forest area (Eurostat 2009). Official protocols exist in most member States of the European Union (EU) for soil monitoring (Morvan and others 2007); however, there is a lot of variation in the methodologies used and the intensity of sampling. The EU Monitoring Network has been active for 20 years using a 50 by 50 km grid with variable re-measurement periods. Parts of the

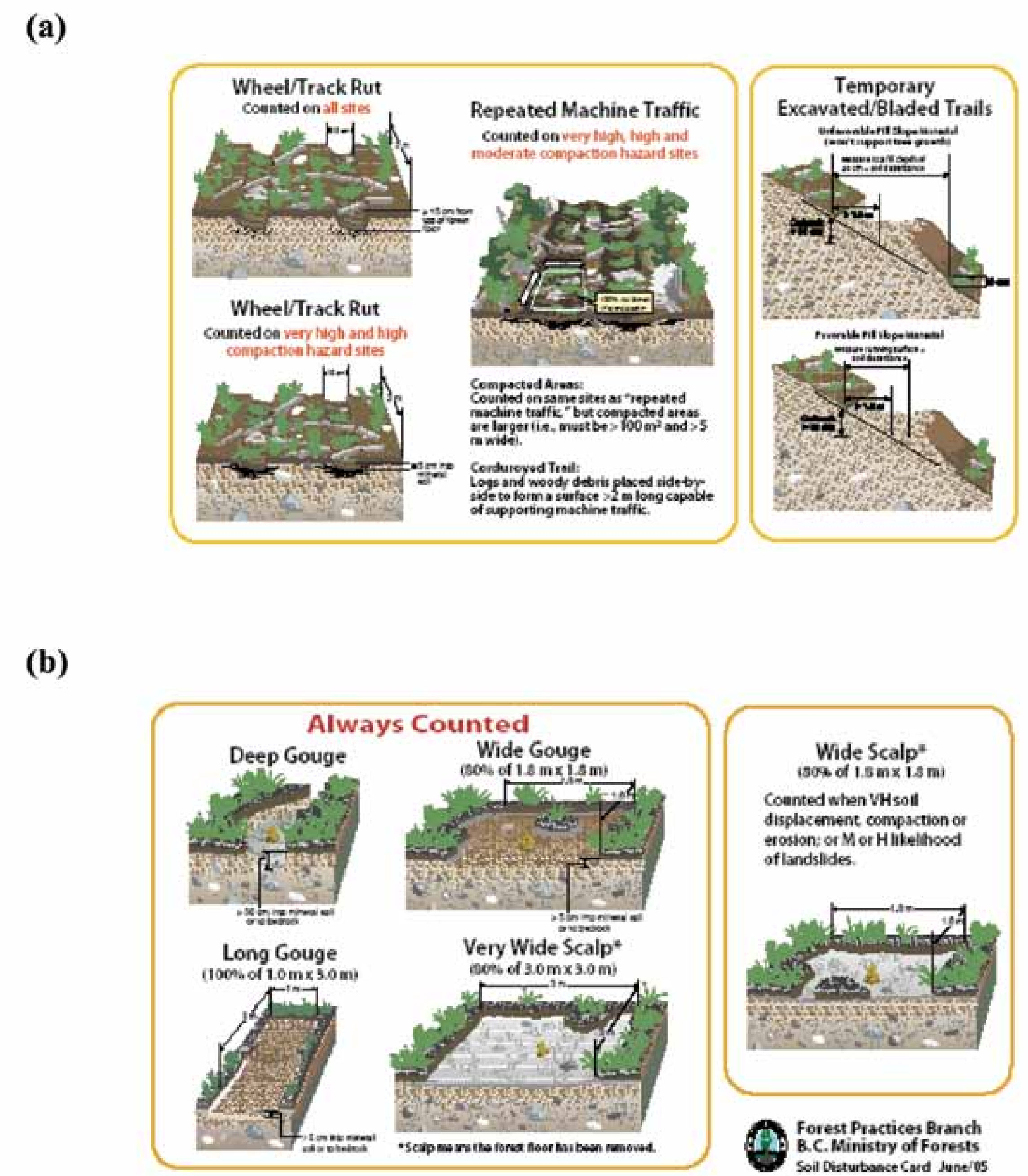

Figure 5. British Columbia Forest Practices Branch, Ministry of Forests visual soil disturbance indicator cards for (a) wheel ruts, machine traffic, and bladed trails; and (b) gouges and scalps (from Curran and others 2005 and British Columbia Ministry of Forests 2001).

EU Network contain dense established sampling grids (*e.g.*, United Kingdom, Ireland, Austria, Denmark) while in other areas the network is still sparse (*e.g.*, Spain, Italy, Greece) (fig. 7). About 90 percent of the EU soils and the land cover classes have at least one monitoring site. However, the density of soil monitoring sites within the European Soil Database units is highly variable. Some units (7 percent) do not have any monitoring sites. Pasture lands have the highest density of soil monitoring sites, but arable land and forests, while slightly less, are comparable in density. A grid of 16 by 16 km has been established for forest soils (ICP 2004).

The key soil parameters being monitored in the EU include erosion risk, compaction risk, the presence of peat, heavy metals, desertification, and presence of livestock. Other indicators being measured are texture, pH, organic matter, bulk density, cations,

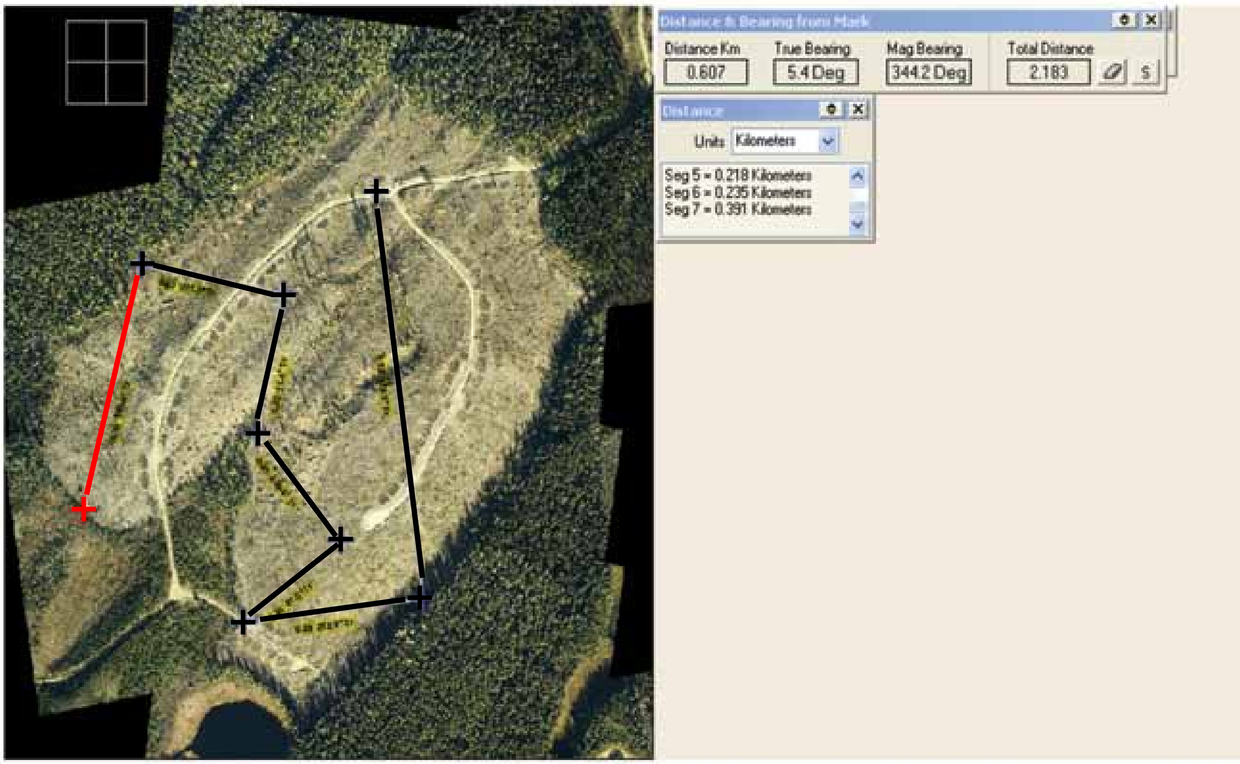

Figure 6. Example of a British Columbia formal soil conservation survey site documentation.

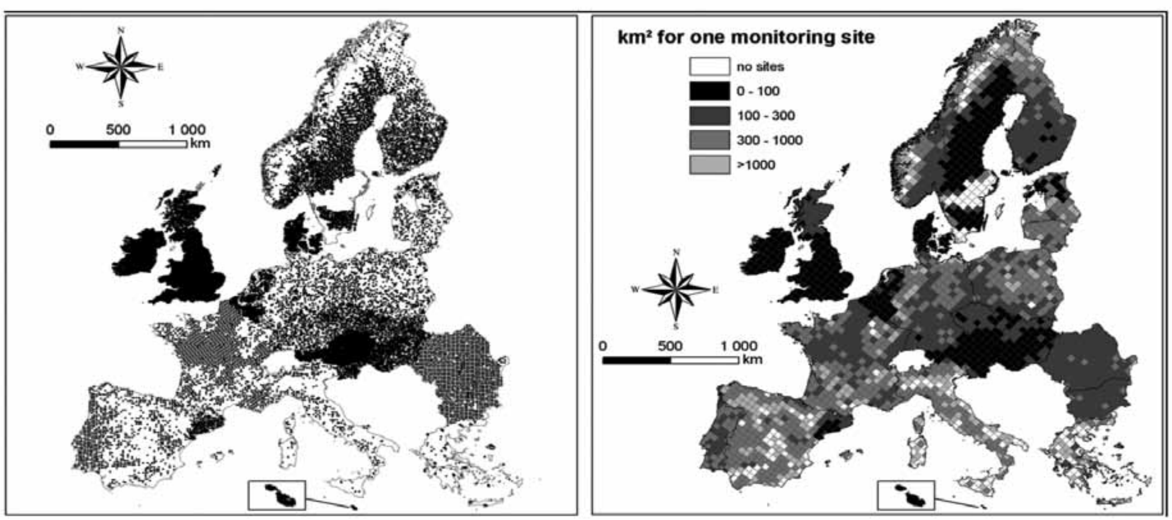

Figure 7. European Union soil monitoring network, GIS repartition (right) and actual density (left) in km[2] for one monitoring site in the 50 by 50 km Cooperative Program for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP) grid of the soil monitoring sites in Europe (Moran and others 2007).

and earthworm activity (Morvan and others 2007). The EU Soil Monitoring Network is simply an inventory system, does not have any interaction with land management entities, and does not have any regulatory power. Soil Network needs include adding 4,100 sites in the lower density part of the network and standardizing sampling and analytical methods. Of the countries with mandated soil monitoring (table 4), Sweden requires measurements of soil physical conditions, coarse woody debris, and soil chemistry. Ireland requires measurements of soil condition, soil fertility, erosion, and other

Table 4—European Union countries with conventional forestry and forest bioenergy monitoring standards and requirements.

Country	Harvest code of forest practices	Bioenergy guidelines	Monitoring Required	Monitoring Type	Monitoring Soil
Denmark	Yes	No	No	None	No
Netherlands	Yes	No	Yes	Operations	No
Finland	Yes	Yes	Yes	Operations	No
Sweden	Yes	Yes	Yes	Multiple	Yes
Germany	Yes	Yes	Yes	Inventory	No
Ireland	Yes	No	Yes	Operations	Yes
United Kingdom	Yes	Yes	No	None	No

Table 5—Ireland forest soil monitoring impacts assessment, example from County Roscommon (adapted from Forest Service 2000).

Ireland Code of Best Forest Practice Soil Impact Assessment

County	Roscommon
Site	Coillte 529
Operation	Whole-tree harvesting
Timeframe	Long-term

Value	Impact factor	Severity VH	Severity H	Severity M	Severity L	Mitigation action
Soil	Fertility		X			NPK fertilizer
	Condition				X	None
	Erosion				X	None
	Other					

parameters as needed. Although the United Kingdom does not require soil monitoring at the present time, changes of Codes of Forest Practice will mandate this activity in the future (Hall 2008, personal communication).

Ireland—Over 70 percent of Ireland's 636,164 ha of forests are owned by the Irish Forestry Board (Coillte Teoranta). Soil monitoring in Ireland is contained within the country's Code of Best Forest Practice and is based on EU and National laws (Ireland Forest Service 2000). Like a number of other countries, the Irish Code is focused on planning, monitoring, and adaptive management rather than regulatory punitive actions. Monitoring is performed to evaluate the performance of the Ireland Code of Best Forest Practice as well as the skills of individual forest harvesting operators. It consists of a self-evaluation impact appraisal by the individual operators and an external assessment by the Irish Forestry Board.

The Ireland impact appraisal evaluates environmental, economic, and social impacts of forestry operations. The focus is on assessing potential impacts in terms of their level, likely consequence, importance, and length of time that the impacts will occur. Potential impacts are evaluated descriptively or on a "points" system on the basis of four subjective severity levels (very high, high, moderate, and low), and follow-up mitigation actions are then planned (table 5). Soil fertility was evaluated at being at high risk because of the soil type and the whole-tree harvesting planned for the cut block. So the mitigation technique prescribed for this stand was the addition of a nitrogen-phosphorus-potassium fertilizer. The other potential soil impacts were evaluated as being low so no mitigations were planned.

United States

Natural Resources Conservation Service and the Agricultural Research Service—Both the Natural Resources Conservation Service (NRCS) and the Agricultural Research Service (ARS) conduct research and development activities related to soil

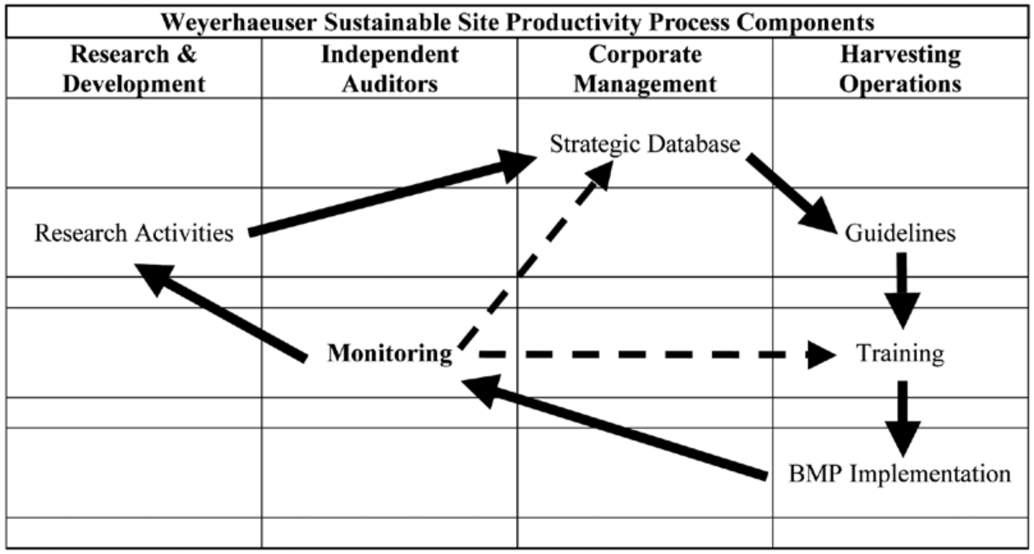

Figure 8. Weyerhaeuser sustainable site productivity process components (adapted from Heninger and others 1998).

quality and soil monitoring (Doran and Jones 1996; Doran and Parkin 1994; Doran and others 1998; Karlen and others 1997; USDA NRCS 2001). Additional information can be found at http://www.ars.usda.gov/main/site_main.htm?modecode=36-25-15-10 and http://www.usda.gov/sqi/. The ARS has also developed and standardized methods for monitoring grassland, shrubland, and savanna ecosystems (Herrick 2005a, b). These manuals deal with vegetation, soil, hydrologic, and geomorphic monitoring methods

U.S. Forest Service: Forest Inventory and Analysis—The U.S. Forest Service conducts soil monitoring as part of its Forest Inventory and Analysis (FIA) Program. Soil monitoring conducted by the FIA is discussed in detail in the following chapter by Amacher and Perry (Amacher and Perry 2010) and by O'Neill and others (2005a,b).

Weyerhaeuser—The Weyerhaeuser Company is committed to soil productivity by using a two-step strategy (Heninger and others 1997, 2002). First, Company operations use equipment and operations practices that are appropriate to the soil, topography, and weather to minimize erosion and harmful soil disturbance. Secondly, Weyerhaeuser employs forestry practices and technology to retain organic matter and soil nutrients on site. The components of the process to achieve sustainability are shown in figure 8 (Heninger 1997) and include (1) a research database; (2) common goals and standards leading to management guidelines; (3) education, training and teaming; (4) selection and use of Best Management Practices (BMPs); (5) independent monitoring of performance and compliance with BMPs; and (6) continuous feedback to the operations side of the organization, and implementation of adaptive experimentation where warranted. Guidelines and BMPs have been developed to minimize detrimental soil disturbance as indicated in figure 9. The key components of this system are the strategic database on soil disturbance impacts, the classification system described in figure 9, a soil operability risk rating system, and a close working relationship between the Research and Development and Operations units to develop BMPs. A key component of this process is monitoring soil impacts of operational practices by independent contractors to assess performance against specified standards. The monitoring provides feedback and information to the corporate soils database, Research and Development, and Operations training programs to continuously improve BMPs to meet Weyerhaeuser's sustainable site productivity strategy (fig. 8).

United States: Forest Soil Disturbance Monitoring Protocol

Background—At the end of the 20th Century, about 33 percent of the U.S. land area or 302 million ha was forest land, 71 percent of the area that was forested in the latter part of the 17th Century (Smith and others 2001). The U.S. Forest Service (USFS) manages around 59 million ha in the National Forest System (NFS) including 39 million

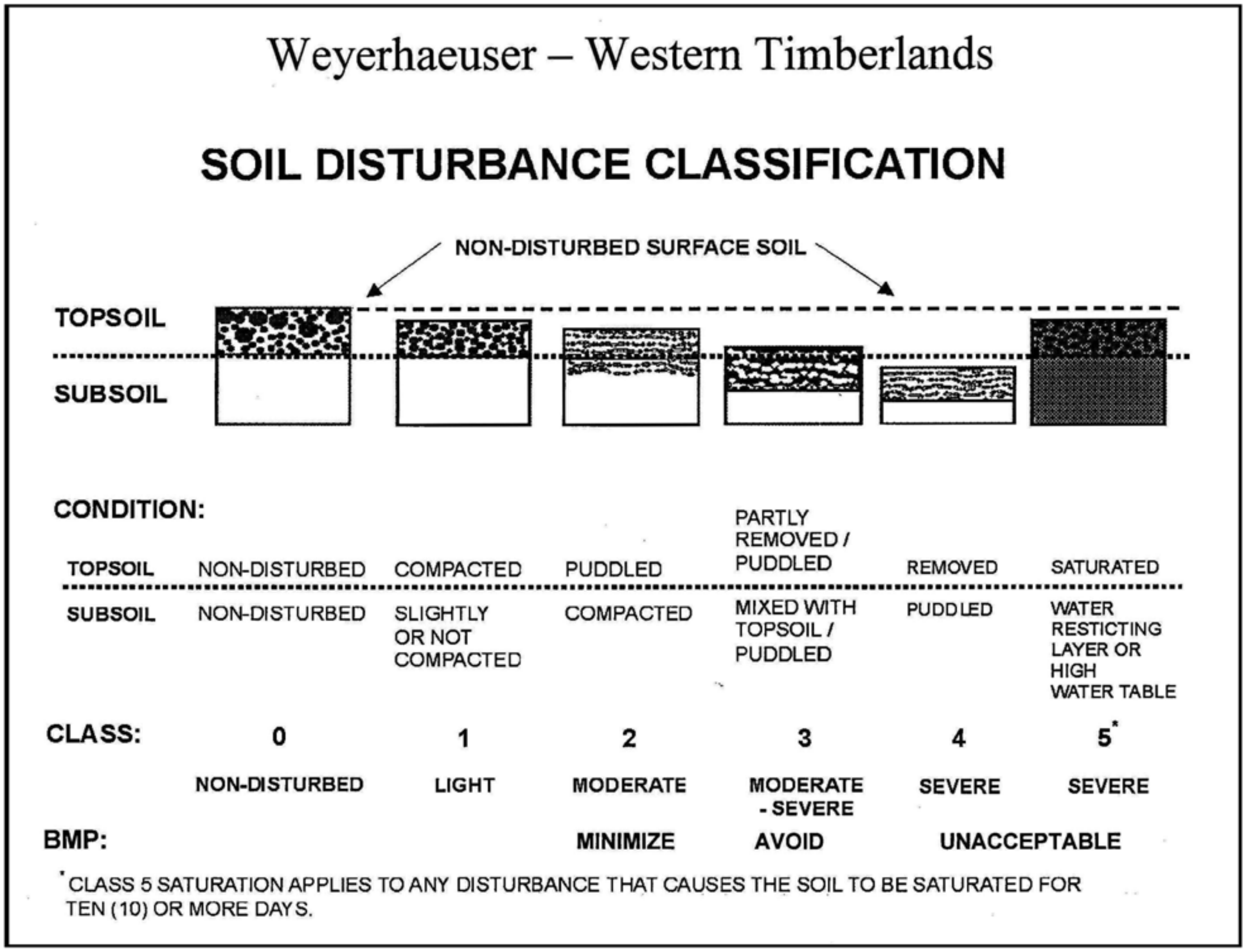

Figure 9. Weyerhaeuser soil disturbance classification system for Western Timberlands (adapted from Heninger and others 1997 and Curran and others 2007).

ha that are classified as capable of producing 1.4 m^3 ha^{-1} yr^{-1} of industrial wood and not legally reserved from timber harvest. Four Acts of Congress important to the issue of resource sustainability, and the soil resource in particular, provide enabling legislation for NFS lands (U.S. Forest Service 1993): (1) The Organic Administration Act of 1897, (2) The Multiple-Use Sustained-Yield Act of 1960, (3) The Forest and Rangeland Renewable Resources Planning Act of 1974 and amendments, and (4) The National Forest Management Act of 1976 (Cline and others 2006; U.S. Forest Service 1993). This legislation sets forth three points that support the need for a long-term soil monitoring program. First, land management should not produce substantial and permanent impairment of site productivity. Second, trees should be harvested only where soil, slope, or other watershed conditions will not be irreversibly damaged. Lastly, tree cutting should occur in a manner that ensures protection of soil, watershed, fish, wildlife, recreation and esthetic resources, and the regeneration of the tree resource. The essence of these key statements of land ethics is a legislative mandate that the USFS conduct research, monitoring, and other assessments to evaluate management effects and to manage for sustained site productivity in a manner that assures protection of all resources and values. The monitoring provisions caused considerable concern among field soil scientists in the NFS with regard to determining baseline soil productivity and what parameters might be used to measure management effectiveness in maintaining soil productivity (Cline and others 2006).

USFS Regions were directed to develop soil quality standards based on Agency guidelines in Forest Service Handbook (FSH) 2509.18: Soil Quality Monitoring. In Chapter 2 of FSH 2509.18, the soil quality monitoring program is spelled out as a systematic process in which data are collected to determine if soil management objectives of maintaining long-term soil productivity and development of operational standards are achieved. It was clearly the policy of the USFS to

- design and implement Best Management Practices,
- maintain or improve long-term site productivity,
- plan and conduct soil quality monitoring,
- evaluate the results of management actions, and
- recommend mitigation measures for measured soil changes.

Responsibilities were delegated to Regional Foresters, Forest Supervisors, District Rangers, and Soil Scientists to develop the soil quality monitoring program. Soil Scientists were specifically given the charge to conduct and supervise effectiveness and validation monitoring, to report management results and recommend changes in actions, and to coordinate validation monitoring with research units. However resources and time were not provided to adequately achieve these directions.

Chapter 2 of FSH 2509.18 went on further to list some "example" soil quality standards. These included increase in bulk density >15 percent, reduction in porosity >10 percent, forest floor removal along with 25 mm (1 inch) of mineral soil, macropore space reduction >50 percent, and erosion losses exceeding 2.2 to 4.4 Mg ha^{-1} (1-2 tons ac^{-1} yr^{-1}). A footnote on a table that listed these "standards" indicated that these were examples only and not intended to be actual soil quality standards; regional soil scientists were charged with that task. Chapter 2 in FSH 2509.18 also discussed topics such as establish threshold values causing significant changes, allowable area extent of disturbance, monitoring projects and plans, sample size and variability, sample design, data collection, and data analysis

The net result for USFS was that Washington Office guidance in FSH 2509.18 was carried forward and detrimental soil disturbance on greater than 15 percent of an activity area was selected as the soil quality standard for many of the Forest Service Regions.

Detrimental soil disturbance was defined as compaction >15 percent, rutting, soil displacement, severely burned areas, surface erosion, and soil mass movement. In essence, an "example" in FSH 2509.18 became the Region 1 "standard" and every other Region went its own way on setting standards. Region 1 issued a Manual supplement to describe its soil monitoring program (U.S. Forest Service 1999). However, it did not take long for problems to develop. There was inconsistent use of the standard with regard to soil type, soil properties, and across jurisdictional (Regional) boundaries. None of the Regional standards were really validated in cooperation with USFS Research and Development, except for the Long-Term Site Productivity Study (Powers and others 2005). Eventually, the original soil monitoring program was challenged in Federal District Court in Montana. This situation led to the development of the new Region1 Soil Monitoring Protocol prototype, and it soon became a National Forest soil monitoring protocol, because it describes a consistent approach and common language for soil monitoring within forested ecosystems.

New Soil Monitoring Protocol—A reliable monitoring protocol has been identified as a critical component of any adaptive management process for forest and rangeland soil conservation programs (Curran and others 2005). Uniform and unambiguous definitions of soil disturbance categories must also relate forest productivity and hydrologic function (Curran and others 2007). A soil monitoring protocol must incorporate a statistically rigorous sampling procedure and firm definitions of visually observable soil disturbance categories

The Protocol, first developed by USFS Region 1 and the Rocky Mountain Research Station, incorporates soil quality monitoring efforts pioneered in the Pacific Northwest (Region 6) (Howes and others 1983). The Protocol is a multi-faceted approach to the soil disturbance and forest sustainability issue (fig.10). The Protocol uses visual soil disturbance classes (Howes and others 1983; Page-Dumroese and others 2006), and a standard inventory, monitoring, and assessment tool. It employs common terminology and has an accessible database. The visual disturbance considerations are soil resilience, degree of disturbance, duration, distribution, and location in relation to other resources.

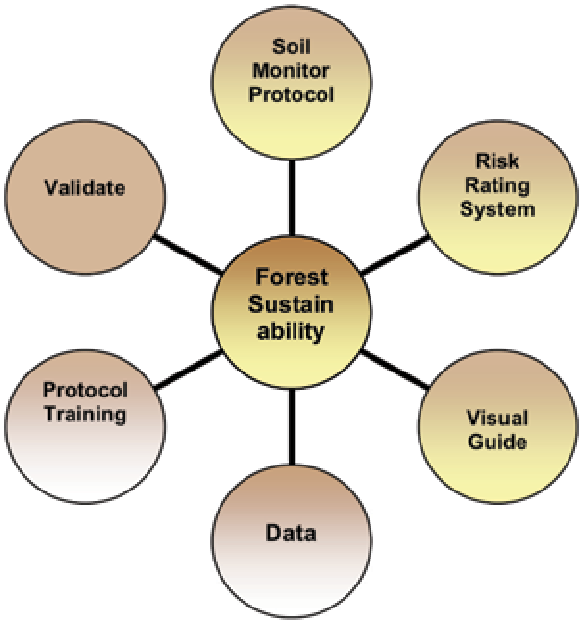

Figure 10. USFS Region 1 Soil Monitoring Protocol multi-faceted approach to forest site productivity.

Table 6—Forest Soil Disturbance Monitoring Protocol pre-harvest soil disturbance class definitions (Page-Dumroese and others 2009a, b).

Class 0—Undisturbed natural state

Soil surface:

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

Class 1—Low soil disturbance

Soil surface:

- Faint wheel tracks or slight depressions evident and are <15 cm deep.
- Forest floor layers present and intact.
- Soil surface has not been displaced and shows minimal mixing with subsoil.
- Some evidence of burning impacts include a mosaic of charred and intact forest floor layers to partially consumed surface OM with blackened surface soil. Root crowns and surface roots of grasses are not consumed.

Class 2—Moderate disturbance

Soil surface:

- Wheel tracks or depressions are >15 cm deep.
- Forest floor layers partially intact or missing.
- Surface soil partially intact and may be mixed with subsoil.
- Burning consumed forest floor, root crowns, and surface roots of grasses. Surface soil is blackened.

Class 3—High disturbance

Soil surface:

- Wheel tracks and depressions highly evident with depth being >30 cm deep.
- Forest floor 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.
- Burning consumed the forest floor, root crowns and surface roots of grasses. Evidence of severely burned soils (mineral soil red in color).

Descriptions of the disturbance classes pre- and post-harvest are listed in tables 6 and 7. Full details of the Forest Soil Disturbance Monitoring Protocol can be found in Volume I and Volume II of the technical guides (Page-Dumroese and others 2009a, b).

In order to reduce monitoring variability, a visual guide of soil disturbance is being developed by the U.S. Forest Service's San Dimas Technology and Development Center with a draft title of *Soil Disturbance Field Guide* (Napper and others, 2009). The guide

Table 7—Forest Soil Disturbance Monitoring Protocol post-harvest/burn disturbance class definitions (Page-Dumroese and others 2009a, b).

Class 0—Undisturbed natural state

Soil surface:

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

Class 1—Low soil disturbance

Soil surface:

- Faint wheel tracks or slight depressions evident and are <15 cm deep.
- Forest floor layers present and intact.
- Soil surface has not been displaced and shows minimal mixing with subsoil.
- Some evidence of burning impacts include a mosaic of charred and intact forest floor layers to partially consumed surface OM with blackened surface soil. Root crowns and surface roots of grasses are not consumed.

Soil resistance to penetration with tile spade or probe:

- Resistance of surface soils may be slightly greater than observed under natural conditions. Concentrated in the top 0-10 cm.

Observations of soil physical conditions:

- Change in soil structure from crumb or granular structure to massive or platy structure, restricted to the surface 0-10 cm.

Class 2—Moderate disturbance

Soil surface:

- Wheel tracks or depressions are >15 cm deep.
- Forest floor layers partially intact or missing.
- Surface soil partially intact and may be mixed with subsoil.
- Burning consumed forest floor, root crowns, and surface roots of grasses. Surface soil is blackened.

Soil resistance to penetration with tile spade or probe:

- Increased resistance is present throughout top 10-30 cm of soil.

Observation of soil physical condition:

- Change in soil structure from crumb or granular structure to massive or platy structure, restricted to the surface 10-30 cm.
- 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 and depressions highly evident with depth being >30 cm deep.
- Forest floor 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.
- Burning consumed the forest floor, root crowns and surface roots of grasses. Evidence of severely burned soils (mineral soil red in color).

Soil resistance to penetration with tile spade or probe:

- Increased resistance is deep into the soil profile (> 30 cm)

Observations of soil physical conditions:

- Change in soil structure from granular structure to massive or platy structure extends beyond the top 30 cm.
- Platy structure is continuous.
- Roots do not penetrate the platy structure.

displays the same four classes of disturbance (none, low, moderate, and high) described in the Forest Soil Disturbance Monitoring Protocol across a range of forest ecosystems in the United States. It is meant for use as a guide to train field crews, a means to provide a high level of consistency, and a focal point for discussions to improve communication among professionals interested in assessing soil disturbance. Two examples for a class 2, low soil disturbance, are shown in figure 11 for lodgepole pine and ponderosa pine.

A standardized data sheet is part of the protocol to ensure that the same data are collected on each site (SoLo 2008). The form header contains basic site data, location, and general sampling details (table 8). The remainder of the table contains the specific soil descriptive and disturbance information (table 9). This protocol takes the first steps in describing how forest management alters soil surface conditions from a pre-harvest condition. Local specialists are charged with defining how those alterations might affect

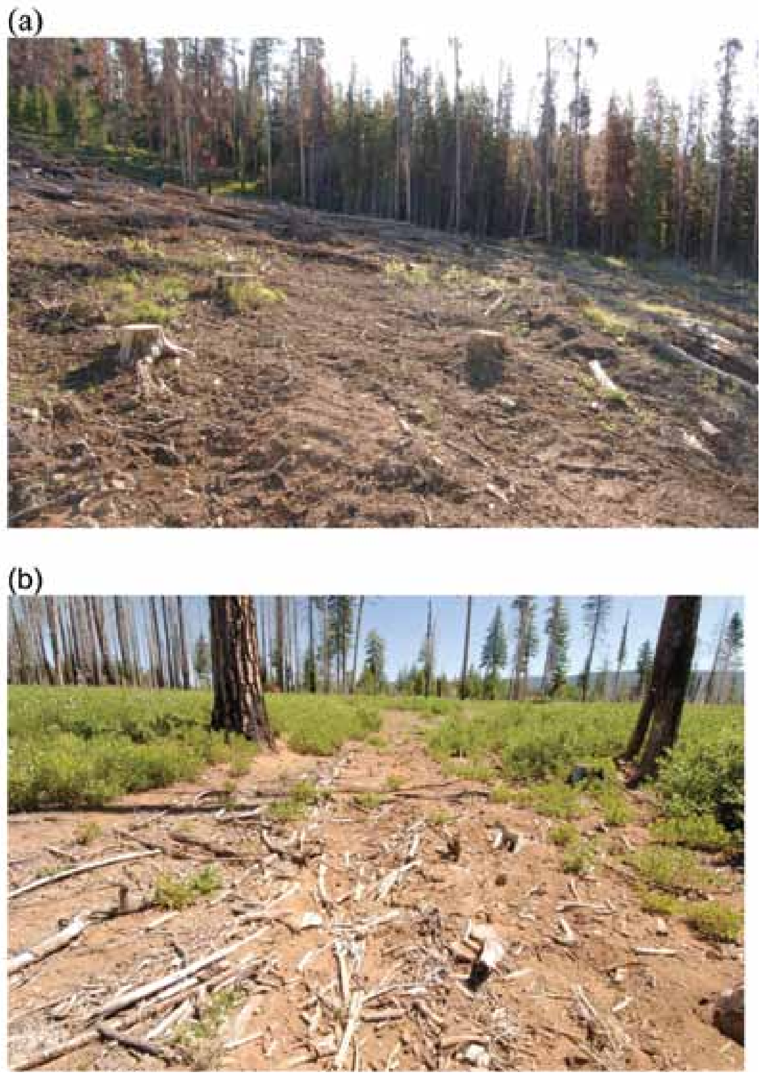

Figure 11. Soil disturbance class 2, low, from the San Dimas Technology Development Center Soil Disturbance visual Guide for (a) lodgepole pine, and (b) ponderosa pine (Napper and others, 2009).

Table 8—SoLo soil disturbance monitoring form basic site data (adapted from SoLo 2008).

SoLo soil disturbance monitoring form header data		
General details	**Location information**	**Sampling details**
Project	GPS start point	Date
Unit identification	Latitude/Longitude	Monitoring type
Observer	UTM coordinates E & W	Point spacing
	UTM zone	Confidence level
		Minimum required Samples
		Interval width

long-term soil productivity and forest sustainability. As with the British Columbia Ministry of Forests project, these disturbance classes need to be locally validated to ensure visual classes and forest growth are appropriately defined.

An integral component of the Protocol (figure 10) is the soil risk rating system (Curran and others 2005; Reynolds and others, in preparation). Its function is to predict the degree of risk of environmental degradation from detrimental soil disturbance. It accounts for variations in soil texture, rock content, organic matter, and vegetation. Like a lot of other soil monitoring systems in the world, the risk rating system is meant to provide

Table 9—SoLo soil disturbance monitoring form detailed soil data (adapted from SoLo 2008).

Direction:							
Sample point	1	2	3	4	5	6	7
f. floor depth (cm):							
Forest floor impacted?							
Live plant?							
Invasive plant?							
Fine woody? <7 cm							
Coarse woody? >7cm							
Bare soil?							
Rock?							
Topsoil displacement?							
Erosion?, comment!							
Rutting? <5cm							
Rutting? 5-10cm							
Rutting? >10cm							
Burning light							
Burning moderate							
Burning severe							
Compaction? 0-10 cm							
Compaction? 10-30 cm							
Compaction? >30cm							
Platy/massive/puddled structure 0-10 cm							
Platy/massive/puddled structure 10-30 cm							
Platy/massive/puddled structure >30 cm							
N Needed (round UP)							
#DIV/0!							
Estimated soil disturbance class							
Detrimental? Enter 1 if Yes, 0 if No							
Comments							

input to Project planning to ensure that adequate Best Management Practices are employed during the operations phase of projects. One attempt at "soil Best Management Practices" has been described by Page-Dumroese and others (2010).

Another important component of the soil monitoring Protocol is training to ensure uniform evaluations of soil conditions by different field crews across the country. As part of this effort, work is in progress to develop a "standardized" training curriculum and materials as well as preparation of a task book similar to those used for Incident Team positions to ensure mastery of key elements. Future web site development will involve additional training modules.

Summary and Conclusions

This paper has reviewed a number of approaches to soil monitoring in Australia, New Zealand, the European Union, Canada, and the United States. Specific cases were evaluated in Tasmania, New Zealand, Ireland, British Columbia, Weyerhaeuser, and the U.S. Forest Service. These States, Companies, and Agencies all have guidance directives from Codes of Forest Practice, Company policy, or National management that focus on soil disturbance. They rely on adaptive management, co-regulation between forest operations and government regulatory authorities, operations planning, and Best Management Practices. The scientific basis for soils monitoring comes from the involvement of Research and Development organizations. Constant feedback from monitoring results and Research and Development efforts results in the type of soil management that will maintain future forest site productivity.

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