Policies and practices to sustain soil productivity: perspectives from the public and private sectors[1]

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Abstract: The USDA Forest Service, the Canadian Forest Service, and US and Canadian forest products industries are committed to the principles of sustainable forestry with a major focus on protecting soil productivity. The USDA Forest Service has developed and adopted soil quality standards to evaluate the effects of forest use and management activities on forest soils and, if necessary, prescribe remedial or preventive actions to avoid adverse impacts on soil productivity. Similarly, the Canadian Forest Service has adopted a series of criteria and indicators with which to monitor the impacts of management on soil resources. The policies of both public agencies reflect the recommendations of the Montréal Process Working Group (1999). Many forest industries have adopted the Sustainable Forestry Initiative developed by the American Forest and Paper Association (2000). Standards of the Sustainable Forestry Initiative clearly state the vision and direction for achieving sustainable forest management, goals, and objectives to be attained and performance measures for judging whether a goal or objective has been achieved. However, both public and private entities recognize that current standards, criteria, and indicators represent first approximations. Continuing revision and adjustment based on information from long-term research studies are vital to protecting soil productivity while deriving optimum public benefits from our forest-based resources.

Résumé : Le service des forêts du département de l'agriculture des États-Unis, le Service canadien des forêts et les industries canadiennes et américaines des produits du bois adhèrent aux principes de la foresterie durable avec une attention particulière pour la protection de la productivité des sols. Le service américain des forêts a développé et adapté des normes de qualité des sols pour évaluer les effets de l'utilisation de la forêt et des activités d'aménagement sur les sols forestiers et, si nécessaire, pour prescrire des actions préventives ou correctives afin d'éviter les impacts négatifs sur la productivité des sols. De la même façon, le Service canadien des forêts a adopté une série de critères et d'indicateurs pour le suivi des impacts de l'aménagement sur les ressources du sol. Les politiques des deux organismes gouvernementaux reflètent les recommandations du Groupe de travail du Processus de Montréal (1999). Plusieurs industries forestières ont adopté le programme « Sustainable Forestry Initiative » (SFI) développé par l'« American Forest and Paper Association » (2000). La norme SFI énonce clairement la vision et l'orientation pour réaliser un aménagement forestier durable, les buts et les objectifs à atteindre et les mesures de performance pour juger si un but ou un objectif a été atteint. Cependant, ces deux entités, tant privée que publique, reconnaissent que les normes, critères et indicateurs actuels constituent une première approximation. Une révision et des ajustements continus basés sur les résultats de travaux de recherche à long terme sont vitaux pour protéger la productivité des sols tout en tirant le maximum de bénéfices de nos ressources forestières pour le bien-être de la population.

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Introduction

Public recognition of the vital role that forests play in sustaining life on our planet (Krishnaswamy and Hanson 1999) has increased pressure, both domestic and international, for forest landowners producing and exporting forest products to demonstrate that they manage forests in a sustainable way. Sound management of the forest soil resource is essential to sustainable forest management and the delivery of ecological, social, and economic goods and services provided by forested ecosystems. Information concerning the impacts of forest uses and activities on soil productivity is sought by a range of jurisdictions for use in guiding best management practices at local and (or) national levels and for third party certification of sustainable forestry.

This paper describes the actions and activities of two public forestry organizations, the United States Department of Agriculture, Forest Service (USDA-FS), Natural Resources Canada, Canadian Forest Service (CFS), and the US and Canadian forest industries that subscribe to the Sustainable Forestry Initiative (SFI) of the American Forest and Paper Association (AF&PA). These organizations are committed to developing policies and practices that meet the challenges of maintaining soil productivity while simultaneously providing the goods, services, and resource values demanded by society for the lands they administer.

USDA Forest Service

Background and mission

In 1997, approximately one third of the US land area or 302×10^6 ha was forest land; 71% of the area that was forested in 1630 (Smith et al. 2001). About two thirds (204×10^6 ha) of US forest land is classed as timberland, which is defined as forest capable of producing 1.4 m^3 industrial wood·ha^{-1} annually and not legally reserved from timber harvest. The USDA-FS manages ~59×10^6 ha in the National Forest System (NFS) including 39×10^6 ha that are classified as timberland (Smith et al. 2001). The general requirements under which NFS land is managed are set forth in enabling legislation. Four legislative acts are especially important to the issue of resource sustainability and the soil resource in particular (USDA Forest Service 1993). These acts constitute the legal policy that governs USDA-FS activities. An increasing concern with the soil–forest productivity relationship is reflected in the increasing specificity of the legal mandates set forth in this legislation (USDA Forest Service 1993).

(1) The Organic Administration Act of 1897. This landmark act created the NFS and specified that "No national forest shall be established, except to improve and protect the forest within the boundaries, or for the purpose of securing favorable conditions of water flows, and to furnish a continuous supply of timber for the use and necessities of citizens of the United States;...".
(2) The Multiple-Use Sustained-Yield Act of 1960. This law directed management to consider resource values but "not necessarily the combination of uses that will give the greatest dollar return or the greatest unit output...without impairment of the productivity of the land".
(3) The Forest and Rangeland Renewable Resources Planning Act of 1974 and the amendment.
(4) The National Forest Management Act of 1976 (USDA Forest Service 1993).

The last two acts will be referred to collectively as NFMA. This legislation sets forth three points that bear on the need for a long-term soil productivity monitoring program:

(*i*) Section 6g3C requires that guidelines in land management plans "insure research on and (based on continuous monitoring and assessment in the field) evaluation of the effects of each management system to the end that it will not produce substantial and permanent impairment of the productivity of the land".
(*ii*) Section 6g3Ei: "insure that timber will be harvested from National Forest System lands only where soil, slope, or other watershed conditions will not be irreversibly damaged".
(*iii*) Section 6g3Fv: "insure that clearcutting, seed tree cutting, and other cuts...are carried out in a manner consistent with the protection of soil, watershed, fish, wildlife, recreation and esthetic resources, and the regeneration of the timber resource".

NFMA, in section 13, also specifies that the "Secretary of Agriculture shall limit the sale of timber from each National Forest to a quantity equal to or less than a quantity which can be removed from such forest annually in perpetuity on a sustained-yield basis". The essence of these landmark statements of land ethics is a legislative mandate that the USDA-FS conduct research, monitoring, and assessments to evaluate management effects and to manage for sustained-yield in perpetuity and in a manner that assures protection of all resources and values. This is a tall order because it demands, on the part of USDA-FS managers, a level of resource background and knowledge that does not reside in any single individual. In fact, NFMA requires that NFS management plans be developed by interdisciplinary teams and with public participation. This requirement makes research, monitoring, and assessment critical for the preparation of plans that are workable and will withstand public review.

The monitoring provision in NFMA caused considerable concern among field soil scientists in the NFS with regard, in particular, to how to determine baseline soil productivity and what parameters might be used to monitor management effectiveness in maintaining it.

The approach to monitoring soil quality

The desirability of soil-based indicators of potential productivity has generated discussions of the concept of soil quality (Rodale Institute 1991; Doran et al. 1994). Both the National Research Council (National Research Council 1993) and the Soil Science Society of America (Karlen et al. 1997) define soil quality in terms of its relation to the functions that soils perform and noted its historic relationship to soil productivity. Both describe conceptual approaches to monitoring and suggest parameters that might be used to determine soil quality. But neither provides many useful specifics, especially for forest environments. Karlen et al. (1997) concluded that the variety of conditions existing across ecosystems make it unlikely that the same or similar set of measures of soil quality would be appropriate for all conditions.

Forest managers involved in the issue expressed the desire for the simplicity of nationally consistent metrics, although a number of authorities pointed out that single parameters, values, or measurement methods are not appropriate in all cases (Knoepp et al. 2000; Page-Dumroese et al. 2000; Schoenholtz et al. 2000). But the body of law mandating resource protection, including soils, encouraged USDA-FS scientists to develop operational measures of soil quality, examples of which are shown in Table 1. When viewed on a national scale, these first attempts to define soil quality standards were inconsistent, usually reflected best professional judgment rather than documented evidence, and were intended as early warnings rather than absolute limits (Powers et al. 1998). A task group assigned to review the situation recommended that Forest Service Research be asked for assistance. This assistance came in the form of the nation wide Long-Term Soil Productivity (LTSP) study (Powers et al. 1990; Powers 2006). To date, 62 replications of the LTSP study have been established in the United States and Canada. In addition, forest industry and university cooperators have established a network of affiliated studies that contribute to the detailed ecological database that is a part of the LTSP protocol.

The committee that conceived and designed the LTSP study concluded that the two soil parameters governing soil productivity that were most likely to be impacted by forest management and use were soil organic matter and soil porosity (Powers et al. 1990; Powers 2006). Thus, organic matter and soil porosity (or soil compaction) are the two principal soil parameters being monitored in the LTSP and affiliated studies. The importance of these two indicators of soil quality is also recognized in the Montréal Process Working Group (1999) agreements, Criterion 4 (Soil and Water Conservation), which lists diminished organic matter or changes in other soil chemical properties and changes in soil strength (compaction) or other physical properties as key indicators of sustainability.

The USDA-FS is committed to bringing sound scientific principles to bear on management decisions. Toward this end, two policy development roundtables were sponsored by the Deputy Chiefs for Research and NFS. The results of these efforts were published to assist the agency in making best use of its management and scientific skills. The first was held in 1994 and the resulting publication (USDA Forest Service 1995) defined the various players in the management decision-making process and their roles and responsibilities. A subsequent roundtable was held in 1996 (USDA Forest Service 1997) that produced a set of guidelines designed to assist the agency in obtaining the maximum benefit from science–management collaboration. Mills et al. (2001) also described principles of science-based natural resource decision-making and suggested a set of guidelines to focus the science contribution in the decision-making process.

The establishment of soil quality standards based on research such as the LTSP study is firm evidence of the successful collaboration between USDA-FS scientists and managers to help meet the sustainability mandates of NFMA. Workable field monitoring and assessment programs are equally important and need ongoing review and modification as new assessment technology and information on the implications of soil disturbance on productivity becomes available.

Canada: a forest and forestry nation

Forests cover ~310 × 10^6 ha of Canada's landmass and 145 × 10^6 ha are subject to forest management activities (Natural Resources Canada 2004). Forest industry provides one of every 15 jobs and generates 30% of all manufacturing investment. In 2001, forestry contributed $28.5 billion to the GDP and $44.1 billion as value of exports or 19% of world exports of forest products (Natural Resources Canada 2004). But the value of the goods and services provided by Canada's forests, commercial and otherwise, far exceeds that measured in dollars or cubic metres of wood. Canada's forests are central to the social and spiritual well being of all Canadians and especially the aboriginal people. Furthermore, Canada's forests are an integral part of the world's ecological cycles. Fully 10% of the world's forests are located within Canada and about 20% of the world's freshwater flows from her watersheds. The forest provides habitats for an estimated 200 000 species of plants, animals, and microorganisms (Natural Resources Canada 2004).

Most of Canada's forest land is under public ownership; 16% is owned by the federal government and 77% by the various provincial governments, with the remaining 7% privately owned (Natural Resources Canada 2004). The federal government's role in forestry is restricted to federal lands. There are no national guidelines or regulations for nonfederal forestland; however, individual provinces have forest practice codes and guidelines to promote the conservation of the soil and water resources. These codes and guidelines vary among the provinces.

Moving towards sustainable forest management

Forestry policies and practices in Canada have evolved continually since the time of European settlement. Forestry had its beginnings in unregulated exploitation but eventually gave way to policies that, in turn, focused on revenue, conservation, timber management and to those of the current age dealing with sustainable forest management (Y. Hardy, Sustainable forest management: the mark of a society. Unpublished paper delivered to the University of Gembloux, Belgium, September 1997). The Rio Earth Summit of 1992 focused world attention on the importance of forests in achieving sustainable development. Following the United Nations Conference on Economic Development, a subsequent meeting in Montreal, Canada, on Sustainable Management of Temperate and Boreal Forests led to the development of criteria and indicators of sustainable forest management (Montréal Process Working Group 1999).

The criteria and indicators are intended to provide a common understanding of what is meant by sustainable forest management. Taken together, the set of criteria and indicators suggests an implicit definition of the conservation and sustainable management of forest ecosystems. No single criterion or indicator is an indication of sustainability but should be considered in the context of other criteria and indicators (Montréal Process Working Group 1999). The "criteria" are seen as defining the essential components of sustainable for-

Table 1. Selected soil quality standards for USDA Forest Service regions.

	Threshold values			
Forest Service region	Soil displacement	Rutting–puddling	Compaction	Organic matter
Northern Rocky Mountains	Loss of 2.5 cm or half of A horizon	Soil puddling present	Bulk density increase 15% (20% volcanic soils)	<30% litter retention, ref. habitat type
Central Rocky Mountains	Soil loss from continuous area >9 m^2		Bulk density increase 15% or exceed 1.25–1.60 $g \cdot cm^{-3}$ depending on soil texture	<90% retained fine logging slash clearcut, 50% shelterwood
Southwest			Bulk density increase 15% or 50% increase soil strength or soil structure criteria	Litter absent or not evenly distributed, large wood <11–16 $Mg \cdot ha^{-1}$
Intermountain	Removal >50% A or 5 cm soil from 1 m^2	Ruts of hoof prints in mineral soil or Oa horizon of organic soil	Reduce >10% soil porosity or double soil strength	Large wood and litter insufficient to maintain productivity
Pacific Southwest	OM upper 30 cm <85% of natural		Reduce 10% soil porosity area large enough to affect productivity	Litter and duff <50% area, <12 decomposing logs per hectare and diameter at least 50 cm, length 3 m
Pacific Northwest	Removal >50% topsoil or humus rich A from 9.3 m^2 >1.5 m wide	Ruts at least 15 cm deep	Bulk density increase 15%, macropore reduction 15% — measure by permiameter, 20% andic materials	See soil displacement
Southeast	Removal >50% topsoil or humus rich A from 5.6 m^2 >1 m wide	Ruts exceed 15 cm deep >15 m length, 30 cm >3 m or 46 cm any length	Bulk density increase 15%, 20% decrease macroporosity	Soil OM <85% of upper 30 cm undisturbed soil or losses enough to degrade nutrient cycle
Northeast	Removal half thickness of A from 5.6 m^2 >1 m wide	Ruts 30 cm deep >3 m length or 46 cm any length	Bulk density increase 15% over undisturbed	
Alaska	Removal of forest floor and >50% topsoil from 9.3 m^2 >1.5 m wide	Ruts or hoof prints in mineral soil or Oa horizon of organic soil	Bulk density increase 15% over undisturbed	

Note: Adapted from Powers et al. (1998). The text of criteria is not always complete or exactly as stated. The purpose is to illustrate the variance of criteria to suit conditions.

Table 2. Criteria of sustainable forest management established by Canadian Council of Forest Ministers (2003) compared with those of the Montréal Process Working Group (1999).

Canadian Council of Forest Ministers	Montréal process
Biological diversity	Conservation of biological diversity
Ecosystem condition and productivity	Productive capacity of forest ecosystems
Soil and water	Forest ecosystem health and vitality
Role in global ecological cycles	Soil and water resources
Economics and social benefits	Contributions to global carbon cycles
Society's responsibility	Long-term multiple socioeconomic benefits
	Framework for forest conservation and sustainable management

est management, whereas "indicators" are seen as the means to measure, or describe, a criterion (Wijewardana et al. 1997) and over time to allow for the reporting of trends. In 1995, 10 Montréal Process countries signed the Santiago Declaration for the conservation and management of temperate and boreal forests. The Montréal Process (Montréal Process Working Group 1999) describes seven criteria (Table 2) and 67 indicators. One of the seven criteria addresses the conservation and maintenance of soil and water resources.

In 1992, the Canadian Council of Forest Ministers (CCFM), made up of federal, provincial, and territorial ministers responsible for forest resources, released a national forest sector strategy addressing sustainable forest management. This was followed in 1995 by a Canadian framework for criteria and indicators entitled "Defining sustainable development: a Canadian approach to criteria and indicators". There was little reported in the last national status report on the soil and water criterion (Canadian Council of Forest Ministers 2000) for two main reasons. There was a lack of data with only a limited number of sites currently being monitored for soil disturbances and there was no clear definition of significant soil disturbance (e.g., not all soil disturbances result in a negative effect on productivity).

In 2003, the CCFM criteria and indicators were revised to improve the ability to report on and assess progress towards sustainable forest management (Canadian Council of Forest Ministers 2003). The CCFM national criteria and indicators parallel those found in the Montréal Process but reflect a common understanding by Canadians of sustainable forest management. A common criterion of both frameworks addresses the conservation of soil and water resources (Table 2): criterion 3 of the CCFM and criterion 4 under the Montréal Process. A comparison between soil and water indicators from the two systems is shown in Table 3. The revised CCFM criteria and indicators framework consists of six criteria and 46 indicators (Canadian Council of Forest Ministers 2003). The criteria remain unchanged but the number of indicators has been reduced. In addition, indicators have been identified as core indicators (36) or supporting indicators (10). The core indicators relate to values, issues, or concerns of great interest to Canadians, while supporting indicators provide more detailed information (Canadian Council of Forest Ministers 2003).

Although the CFS does not have a regulatory responsibility for nonfederal lands, the agency contributed to the development and updating of the CCFM criteria and indicators and is responsible for reporting on the Montréal Process on a national level. The rates of compliance to the locally applicable soil disturbance standards (e.g., provincial regulations) are used as proxies for national reporting on the soil and water criterion and are collected through the provincial and territorial agencies responsible for forest management in Canada.

A forest industry perspective on sustaining site productivity

In 1997, 58% (118×10^6 ha) of US timberlands were nonindustrial private forests and these forests produced an equal proportion of annual harvest removals (Smith et al. 2001). Forest industry owned 13% (27×10^6 ha) of US timberlands, but industrial forests provided 30% of the volume harvested. The NFS accounted for 19% (39×10^6 ha) of timberland ownership but supplied <5% of harvest removals. Between 1987 and 1997, harvests from NFS declined by >60% (Smith et al. 2001). Over the same period, harvesting from private nonindustrial forests increased dramatically to meet the demands for forest products, but harvests from forest industry lands held steady, indicating that these lands were already being harvested at their capacity (Smith et al. 2001).

Forest industry and sustainable forestry

The public, in general, and forest product customers, in particular, place considerable emphasis on sustainability and environmental values, and private forests possess many of the same environmental and social values as public forests. Customers buying forest products expect that forest sustainability be attained in both the narrow and broad sense. Narrow-sense sustainability refers to maintaining the potential productivity of the soil, while broad-sense sustainability refers to sustaining all social and economic values of forest resources including soil productivity, clean water, wildlife, and fish habitat, biodiversity, and aesthetic values. Forest product companies are expected to have clearly defined stewardship goals and to provide assurance that these goals are met. George J. Harad, former Chairman and CEO, Boise Cascade Corporation, recently stated that the forest products industry has two great challenges. One is to dramatically improve its ability to consistently earn its cost of capital and show a profit so it can justify the new investment that it will need to meet customer requirements. The second challenge is to win the confidence of customers and the general public by showing that our management is appropriate and sustainable (O'Brien 2001).

Hence, there has been a major movement towards developing certification systems with criteria and indicators to give assurance to the public and forest product customers that their concerns about sustainability and forest steward-

Table 3. Criteria and indicators related to the soil resource under the Montréal Process Working Group (1999) and Canadian Council of Forest Ministers (2003).

Montréal Process criterion 4, soil and water resources indicators	Canadian Council of Forest Ministers criterion 3, soil and water indicators
Area and percentage of forest land with significant soil erosion	Rate of compliance with locally applicable soil disturbance standards (core indicator)
Area and percentage of forestland with significant compaction or change in soil physical properties resulting from human activities	
Area and percentage of forestland with significantly diminished soil organic matter and (or) changes in other soil chemical properties	
Area and percentage of forest land with significant soil erosion	Rate of compliance with locally applicable road construction, stream crossing, and riparian zone management standards (core indicator)
Area and percentage of forest land managed primarily for protective functions, e.g., watersheds, flood protection, avalanche protection, riparian zones	
Percentage of stream kilometres in forested catchments in which stream flow and timing have significantly deviated from the historic range of variation	
Percentage of water bodies in forest areas (e.g., stream kilometres, lake hectares) with significant variance of biological diversity from the historic range of variability	
Percentage of water bodies in forest areas (e.g., stream kilometres, lake hectares) with significant variation from the historic range of variability in pH, dissolved oxygen, levels of chemicals, sedimentation, or temperature change	
Percentage of stream kilometres in forested catchments in which stream flow and timing have significantly deviated from the historic range of variation	Proportion of watersheds with substantial stand-replacing disturbances in the last 20 years (supporting indicator)

ship are being addressed. Environmental conservation and responsible ecological practices make good business sense, and industrial forestry in the United States has taken significant steps to ensure an environmentally conscious, sustainable forestry ethic.

Commitment to soil stewardship

In 1994, the SFI was adopted by the AF&PA whose membership accounts for ~84% of paper production, 50% of solid wood production, and 90% of industrial timberland in the United States (American Forest and Paper Association 2000). There are currently 61.5×10^6 ha of forestland enrolled in the SFI program, making it one of the world's largest sustainable forestry programs (American Forest and Paper Association 2005). The SFI standard requires participants to have stated performance measures showing how the objectives (goals) and principles are being followed to meet SFI targets. The standard comprises principles that clearly state the vision and direction for achieving sustainable forest management, objectives defining goals to be attained, and performance measures for judging whether an objective has been achieved. Companies participating must demonstrate that they are adhering to the principles and meeting the performance measures outlined in the program. There is a uniform process for conducting verification audits, and all auditors must meet rigorous educational and professional criteria. In addition, there is a group of 15 experts representing conservation, environmental, professional, academic, and public organizations that comprise an independent multistakeholder Sustainable Forestry Board, which manages the SFI program standards and verification procedures and SFI program compliance. The mission of this panel is to provide a framework to conduct an independent review of the SFI program and annual report of implementation status.

The importance of soil stewardship is evident in the SFI definition of sustainable forestry: "Sustainable forestry means managing our forests to meet the needs of the present without compromising the ability of future generations to meet their own needs by practicing a land stewardship ethic which integrates the growing and nurturing of trees for useful products with the conservation of the soil, air, and water quality, and wildlife and fish habitat". This is further emphasized in one of the program objectives: "Ensure long-term forest productivity and conservation of forest resources through prompt reforestation, soil conservation, afforestation, and other measures".

Performance measures are required to ensure that program participants will implement management practices to protect and enhance forest and soil productivity. AF&PA members will meet or exceed all established "best management practices (BMPs)" approved by the US Environmental Protection Agency and all applicable state and federal water quality laws and regulations applicable to forest land. In addition, program participants are required to "...broaden the practice of sustainable forestry by cooperating with non-industrial landowners, wood producers, consulting foresters, and program participants' employees who have responsibility in wood procurement and landowner assistance programs". A key performance measure in this area is how participants promote among other forest landowners sustainable forestry practices that are economically and environmentally responsible. An example of this is that 92% of the raw material used by SFI program participants to make paper and wood products in 2003 was delivered by loggers trained in the following areas: AF&PA sustainable forestry principles, BMPs

Table 4. Examples of soil management decision support tools and their applications used by selected forest products companies.

Decision support tools	Application objectives
Soil survey – land classification within a geographical information system that links to soil management interpretations and BMPs	Provide access to latest soil management interpretations and BMPs; BMPs are updated periodically based on performance monitoring and new research findings
Soil operability ratings for ground-based harvesting operations linked with geographical information systems	Aid harvest planning to minimize detrimental soil disturbance from harvesting operations
Soil disturbance classification system that is simple to understand, visually discernible, biologically relevant, and easily communicated	Provide a consistent regional approach for describing harvesting-related soil disturbance to aid monitoring and communication of research results and BMPs
Soil tillage guidelines and BMPs for regional soils/landforms	Refine site-specific recommendations for bedding, mounding, subsoiling, and tillage to ameliorate soil physical properties that limit optimal root growth
Nutrient demand and supply models based on tree growth potential, soil nutrient capital, and organic matter management practices	Derive fertilizer needs and potential gains for applying nutrient amendments to intensively management plantations
Enhanced fertilization diagnostic tools based on foliar nutritional levels, leaf area index, nutrient demand, and soil nutrient supply	Refine fertilizer rate and application timing prescriptions and volume response predictions
Organic matter management BMPs	Protect or enhance nutrient supply and cycling and carbon sequestration
Vegetation management BMPs based on site resources (soil moisture, nutrient availability and cycling, and light interception)	Enhance tree growth and protect other forest resources (wildlife habitat, water quality, and biodiverstity) at both the stand and landscape level
Easily applied, statistically valid performance monitoring and tracking methods	Allow cost effective BMP compliance and soil quality monitoring

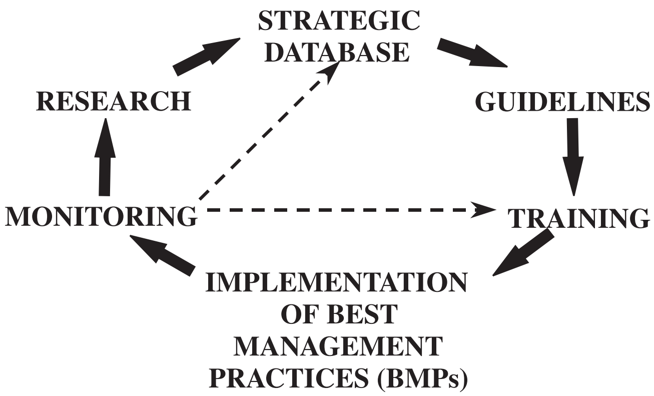
pertaining to road construction and retirement, site preparation, streamside management, regeneration and forest resource conservation, awareness of responsibilities under the Endangered Species Act and other wildlife considerations, logging safety, and other related topics.

Improving forest operations

SFI requires that factors critical to sustaining soil productivity be identified and monitored. Powers et al. (1990) concluded the forest practices most likely to impact long-term soil productivity are those practices that induce changes in soil organic matter and soil physical properties such as porosity. Allen et al. (1998) pointed out the critical importance of optimum stand nutrition in meeting forest productivity objectives. Harvesting and site preparation are the management practices with the greatest potential to directly impact soil organic matter, soil physical properties, and nutrient resources (Powers et al. 1990; Fox 2000). Examples of decision support tool developments and actions taken by forest industry to address these important factors are outlined below.

(1) Soil operability risk-rating systems: rating systems linked to a soil survey insure "higher-risk" soils are harvested during "lower-risk" times of the year using the appropriate equipment. (Steinbrenner 1975; Morris and Campbell 1991; Aust et al. 1995; Heninger et al. 1997).
(2) Soil disturbance guidelines and soil management BMPs: site-specific prescriptions to (*i*) limit equipment traffic on sensitive soils, (*ii*) designate equipment traffic lanes, (*iii*) use operational BMPs and monitoring processes, and (*iv*) ameliorate adversely impacted areas.
(3) Equipment operator education and training: training modules for employees and contractors on forest soil management principles and BMPs to meet forest productivity and soil stewardship objectives (Heninger et al. 1997; Curran 1999; Logan 1999).
(4) Use of low ground pressure equipment: machines with high-flotation tires or low ground-pressure tracks are used in most ground-based harvesting and site preparation operations (Beets et al. 1994; Smidt and Blinn 1995; Arnup 1998; Logan 1999).
(5) Postharvest tillage and amelioration: tillage of heavy traffic areas and temporary roads to mitigate possible detrimental effect of ground-based equipment (Bulmer and Curran 1999; Plotnikoff et al. 1999).
(6) Forest fertilization: optimizing nutrient supplies for increased stand growth and value (Allen 2001).
(7) Reductions in broadcast burning: burning of logging slash is decreasing owing to (*i*) harvesting younger stands with high utilization levels resulting in less logging slash and debris, (*ii*) liability issues and air quality concerns, (*iii*) concerns about nutrient and carbon losses, and (*iv*) high costs of burning.
(8) Improvements in mechanical harvesting: using machines that lift logs and swing them to the landing or roadside with much less ground disturbance than skidding and dragging logs and cut-to-length harvesters that delimb trees and forwarders that move through the forest on a freshly created bed of slash with less soil compaction than conventional felling and skidding (Powers et al. 1999).
(9) Redistributing logging residues: chipping slash and bark on the logging site and distributing chips to the skid trails, thus reducing soil compaction, retaining nutrients and carbon, and improving planting conditions.
(10) Vegetation management: vegetation management treatments that enhance tree growth while protecting water

Fig. 1. Reliable process component framework to achieve sustainable site productivity.



quality, riparian zones, biodiversity, and wildlife habitat at the landscape level (Wagner 2000).

(11) Decision support tools: science-based information to forest manager in achieving stewardship goals (Table 4).

Reliable process framework to achieve sustainable site productivity

Forest industry frequently uses "reliable processes" that follow total quality management principles (Deming 2000) to insure that the most appropriate management practices are employed (Fig. 1). Some essential components of a proposed reliable process framework to achieve sustainable site productivity are as follows: (*i*) collaborative regional research programs that develop the strategic database and determine the implications of treatments on soil physical and chemical properties and tree growth, (*ii*) subsequent development of soil management guidelines (BMPs) and decision support tools by companies and cooperative research programs, (*iii*) development of training modules to communicate cause-and-effect principles, soil management expectations, and BMPs, (*iv*) operational implementation of BMPs and monitoring to measure performance and provide feedback, and (*v*) continuous improvement by monitoring feedback links that help set research and strategic database priorities and update guidelines and training modules.

All components of this process must be in place regionally to achieve sustainable site productivity objectives. Organizational structures also must be compatible with the process components so that the process is functional, timely, and aligned with long-term sustainability strategies.

Forest management systems that provide responsible land stewardship and sustain soil productivity require detailed planning, careful execution, and wise allocation of resources. Road- and stream-side management zones, wetlands protection, species diversity, habitat protection for threatened or endangered species, and similar practices of good land stewardship must be accomplished within a cost structure that maintains the forest industry's competitiveness in a global economy. Restricting management in some areas to achieve ecological resource protections will likely have to be counterbalanced with increases in productivity on lands most suitable for intensive culture if overall yields are to be maintained. Powers (1999) and Fox (2000) concluded that intensive forest management can be sustained on many soils, but this is not a static process. Continuous improvement of our database and decision support tools is necessary and this requires that forest industry, universities, the USDA-FS, and other agencies and organizations continue to collaborate within a reliable process framework if we expect to meet soil and forest stewardship objectives in a sustainable manner.

A common need: better tools

In forestry, as in a number of public arenas where there is a link between science and public policy, science must be translated into tools that can be used and understood by a broad audience. While it is fair to say that the science is still in its infancy, a number of tools have been developed, some with a broader application than others. Traditional studies related to site productivity, pre- and postharvest, were focused on nutrient impoverishment and replacement through fertilization. This work has been focused on the soil as a medium for the production of biomass before and after harvesting. Soil productivity has been traditionally linked with tree growth. However, growth usually is confounded by factors other than those related to soil (Burger 1996; Burger and Kelting 1999). Even historic measures of site productivity such as site index are a summation of climate, aspect, slope, geology, and soil influences. Using a bioindicator, a tree crop, to measure soil quality can be problematic, since growth rate is a function of genetics, stocking, environment, pests, diseases, and cultural practice (Powers 2001). Additionally, use of a productivity index focuses on the forest systems as producers of wood and ignores their larger role as producers of ecological goods and services. It is not difficult to imagine a scenario where commercial yield could be higher over the short term at the expense of soil quality and long-term site productivity (e.g., mobilization and loss of nutrient capital). This scenario has been described in agricultural systems where improved hybrid crops, improved fertilization, and pest control have resulted in increased crop production, while measures of soil quality, such as soil organic matter content, have indicated a deterioration in soil quality (Burger 1996; Kneeshaw et al. 2000).

Powers et al. (1998) suggested a more encompassing evaluation of soil quality based on an in-depth knowledge of soil properties and their variability developed through soil inventory, mapping, and repeated monitoring of integrated indices of physical quality, nutrient supply, and soil faunal activity. The authors also pointed out that indices must reflect processes that are important to potential productivity, integrate a variety of properties and processes, and be broadly applicable and practical in an operational monitoring program. The significance of monitoring is not so much in absolute values as in trends emerging over time.

Modeling approaches linked to spatially specific outputs have been developed by Burger and Kelting (1999) and Kelting et al. (1999). These approaches are elegant and hold considerable promise for the development of science-based monitoring systems. Other simulation approaches driven by nutrient budgets, water availability, temperature, and other variables are currently being investigated in Canada, the United States, and elsewhere (Kneeshaw et al. 2000; Landsberg et al. 2001; Powers 2001). There is no doubt that modeling efforts will continue to make significant contributions to our understanding of this area, but models can also suffer from certain shortcomings. They can be complex, data intensive, and difficult to parameterize. Increases in complexity decrease the likelihood that they will be adopted and implemented at the operational scale. However, the value of models may be a function of the harvesting practice (intensive versus extensive), land ownership, and available information. All of these approaches are helping to shape thinking on the implications of practices on the soil environment, what hypotheses to test, and potential applicability of soil quality parameters as sustainability indicators.

Development of useful indicators of soil quality will continue to be tied to intensive investigations at long-term research sites, such as the LTSP program and the many productive university–industry–agency research cooperatives in the United States and Canada. Results from these programs can lead to the development of indicators of "best practices", which are then used to adapt and report on practices on a broader scale. Several authors (Heninger et al. 1997; Powers et al. 1998; Burger and Kelting 1999; Kneeshaw et al. 2000) have identified necessary attributes for ecological standards or indicators of sustainable forest management including soils. These include (*i*) scientifically sound, (*ii*) operationally feasible, (*iii*) socially responsible and credible, (*iv*) standard methodology for measurement, (*v*) easily interpretable, sensitive, and responsive to changes by forestry practice, (*vi*) integrated, (*vii*) linked to silvicultural prescriptions, and (*viii*) easily measured and cost effective.

Consideration of these, or similar attributes, when determining indicators of soil quality may lead to their integration at a higher level and adoption operationally. Lessons learned in agriculture also should be carefully considered. Recently, Vance (2000) reviewed long-term agricultural studies and concluded that the following key findings had implications for forest management and research direction: (*i*) soil organic matter is the link between most management systems and sustainable site productivity, (*ii*) nutrient deficiencies can be corrected, (*iii*) soil texture is a key variable affecting soil organic matter and site productivity, (*iv*) return of crop residues enhances soil organic matter and site productivity, and (*v*) productive cropping systems have environmental benefits.

The continuing need for research

As science advances and new understandings are developed, management methods must advance in response. The USDA-FS, CFS, and the forest products industry are dedicated to meeting this challenge through close coordination between science and management. Within Canada and the United States, there is a broad range of forest types, developed in different environments, under different disturbance regimes, and across a range of soil types. It is more than a little presumptuous to assume that the same indicators and practices will be suitable for use across the range of forest and soil conditions. But if they are to gain support, our objective should focus on the development of principles and tools that can be broadly applied.

Our desire to understand the impacts of forestry practices on the sustainability of soils at regional and national levels has led us to an examination of the information that supports our current position and to the development of indicators or measures of soil quality at the stand level. The LUCID project (Wright et al. 2002) and Sustainable Forest Management (SFM) Network (Kneeshaw et al. 2000) advocate an adaptive approach at the forest management unit scale. An adaptive management approach to preserving soil productivity requires a continuing flow of information concerning management impacts and soil system response. Our need for scientific information to support forest management decisions has never been more urgent than it is today.

Our knowledge of factors affecting soil productivity is advancing steadily, but further progress will not be made globally without continued investment in, and commitment to, long-term integrated studies. The work initiated in the United States and later in Canada under the LTSP study is instrumental to filling of information gaps. In Canada, the Forest Ecosystem Research Network of Sites (FERNS), an affiliation of government, university, and industry research, is carrying out work aimed at extending our knowledge of the impact of forestry practices and best management practices across a range of ecozones (Mitchell and Lee 1999). The Model Forest Network (Canadian Forest Service 2005) has undertaken an extensive examination of indicators of sustainable forest management at the local level. The Natural Sciences and Engineering Research Council of Canada funded SFM Network has proposed two types of indicators, one type for the planning of SFM and another type for monitoring to assess whether management yielded the projected results (Kneeshaw et al. 2000).

In the United States, the forest products industry and the USDA-FS along with universities and other agencies have initiated a number of collaborative research programs to understand the implications of intensive management treatments on tree growth and soil–plant relationships and processes. Some examples are (*i*) the LTSP study, (*ii*) multiagency cooperative databases on stand management such as the North Carolina State University and Virginia Polytechnic Institute and State University Forest Nutrition Cooperative in the southern United States and the University of Washington Stand Management Cooperative in the western United States, (*iii*) the Southeast Tree Research and Education Site in North Carolina, (*iv*) collaborative work led Virginia Polytechnic Institute and State University involving industry and government agencies to determine how management impacts soil and forest productivity on Atlantic Coastal Plain wetlands, and (*v*) operational variants of the North American LTSP program, such as those in loblolly pine led by Louisiana State University and those in Douglas-fir installed by industry cooperators with the USDA-FS PNW Research Station, Olympia Forestry Sciences Laboratory, University of Washington, and Oregon State University.

Common features of these research programs are (*i*) they have multiple sponsors, (*ii*) they are designed to provide quantitative information to develop and test process-based tree growth response models, (*iii*) they contribute to regional databases for developing site-specific soil management guidelines, and (*iv*) they involve teams of interdisciplinary scientists.

Within these programs, integration of tree improvement, soil science, silviculture, pathology, geographic information systems, remote sensing, and other disciplines is now the research program norm rather than the exception. Priority research opportunities for enhancing and sustaining tree growth include (*i*) assessing the implications of altering soil quality parameters on stand performance and validating soil quality thresholds that affect productivity, (*ii*) assessing stand performance parameters accurately and efficiently, (*iii*) developing inexpensive and accurate monitoring methods, (*iv*) developing landscape-level planning and remote sensing technologies to more precisely prescribe treatments and monitor treatment performance, (*v*) integrating knowledge into easily used decision support and training tools, (*vi*) optimizing site resource allocation to crop trees (water, nutrients, solar radiation, etc.), (*vii*) optimizing tree nutrition (fertilization) regimes, and (*viii*) developing breakthrough concepts and technologies to reduce management costs while meeting sustainability objectives (Terry et al. 2004; Fisher et al. 2005).

Summary and conclusions

The USDA-FS, the CFS, and the forest products industry share a common goal and commitment to practice ethical stewardship and sustainable management of the forest resources for which they are responsible. Each is constrained by unique social, economic, and political factors in addition to an array of climatic and ecological variables. Each of the three entities has adopted a somewhat different approach and each is at a different stage of implementation. All are addressing, albeit somewhat differently, the processes for achieving sustainability goals within their operating framework, and each is committed to achieving the desired results. All agree that achieving the goal of sustainable forestry is an iterative process, and the development of best management practices and the indicators and criteria for monitoring and assuring effectiveness will require continuing inputs of new and more precise information from interdisciplinary and collaborative research programs.

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