INDICATORS OF SOIL/LAND QUALITY – EXAMPLES

The following examples provide an overview of the history and approaches of soil and land quality assessment. They are not a comprehensive list of all efforts in this area.

United States

The Land Capability Classification represents one of the earliest systems of land quality assessment (Helms 1992). The purpose of this classification system was to provide farmers and government agencies with a tool to determine land that was capable of supporting permanent agriculture, particularly with respect to potential soil erosion. The system consists of eight categories ranging from class 1 soils that have little or no limitations restricting their use for crop production, to class 8 soils that cannot be used for commercial crop production. Four letters are used as subclasses to represent the major hazard or limitation that contributes to the soil occurring within the capability class: (e) erosion, (w) excess wetness, (s) problems in the rooting zone, and (c) climatic limitations. Inputs for the classification system are based on properties that cannot be altered due to technical or economic constraints and include landscape location, slope of the field, depth, texture, reaction of the soil, climate, erosion and risk of flooding. Criteria for classification are somewhat subjective due to the flexibility required for the wide range of cropping systems, climates and soils present in the United States (Davidson 2002).

The classification was applied at the national scale during survey efforts conducted from the 1930s through the 1950s (Helms 1992). The originators of the system realized their land classifications were not permanent and a reappraisal might be necessary due to changes in the land or cropping practices. They hoped "merely to establish a national basis of classification which would be good for a generation or two" (E.A. Norton 1940, as cited by Helms 1992).

Due to environmental concerns, the National Resources Inventory (NRI) was developed to provide a statistically robust survey of natural resource conditions and trends on non-federal land in the United States (Nusser and Goebel 1997). The NRI was conducted in 1977 for the first time, then every five years until 1997. Data have been collected every year since 2001, but for slightly less than 25% of the same sample sites (NRCS 2003). Prior to 2001, data were collected from about 800,000 sample sites contained within 300,000 primary sampling units. Primary sampling units consist of 40 to 160 acre land segments. In a typical county, two primary sampling units (160 acres) are selected for each 6 x 2 mile area, an approximate 4% sampling rate (Nusser and Goebel 1997).

Three sample points are typically obtained within each primary sampling unit (Nusser and Goebel 1997). At each sample point, information is collected on variables such as land cover/use, soil classification, soil properties, erosion factors and related information. For each primary sampling unit, information is collected on climate factors, urban areas, water bodies and related information. Data are collected using photo-interpretation and remote-sensing methods or from available databases (e.g., climate, soil survey), USDA field office records and local NRCS personnel (NRCS 2003). All sample sites were field visited in 1982, about one quarter of sample sites were field visited in 1992 (Nusser and Goebel 1997), and sites where aerial photography was unavailable or unsuitable were visited in 2001 (NRCS 2003). Results are presented for a number of issues relevant to soil functions:

Erosion: for all sample points, water erosion is estimated by the Universal Soil Loss Equation (USLE) and wind erosion is estimated by the Wind Erosion Equation (WEQ). Estimates of both types of erosion (total tons of soil eroded per year, tons eroded per acre, total acres with erosion greater than tolerable, etc.) are available for cropland at the national, state and sub-state scales since 1982.

Urbanization: conversion of all types of rural land (prime farmland, cropland, grazing land, etc.) to developed land is available for cropland at the national, state and sub-state scales since 1982.

Water quality: watersheds with the greatest risk of non-point pollution are identified based on leaching and runoff vulnerability indices calculated for pesticides and nutrients. For example, vulnerability indices for nutrients are obtained from estimates of excess nutrient levels (manure or commercial fertilizer sources) combined with estimates of leaching (based on precipitation and hydrologic factors) or estimates of runoff (based on precipitation and USLE curve numbers) (Kellogg et al. 1997).

Soil quality: Future Annual NRI results will present long-term trends of a Soil Condition Index value for each NRI sample site (NRCS 2003). The Soil Condition Index quantifies the effects of cropping sequences, tillage and other management inputs on trends in soil organic matter content, which will be used as an indicator of soil quality. Climate and soil data will also be used in the assessment.

In addition to these efforts conducted at a national scale, efforts to derive meaningful representations of specific or multiple soil functions have occurred at state and regional scales. One of the early motivations for soil ratings was equitable tax assessment. Huddleston (1984) provides a thorough review of the development and use of soil productivity ratings in the United States until the early 1980s. In general, relative rating systems based on relations to soil and climatic properties were preferred due to the lack of sufficient yield data for different soil types. Rating systems aggregate variables controlling yield outcomes by the use of multiplication, addition or a combination of the two. For example, the Storie Index Rating is determined by multiplying together separate ratings for profile morphology, surface soil texture, or slope, and modifying factors, such as depth, drainage, or alkalinity. Rating systems have successfully estimated productivity for soils lacking yield data, provided the rating systems were adequately validated for the conditions in which they were used. Huddleston (1984) concluded the following steps should be used to derive soil productivity ratings:

- Assignment of numerical values to all soil properties, landscape characteristics and weather conditions that influence plant growth and yield

- Use of both additive and multiplicative processes to formulate factor ratings and combine factors into final productivity ratings

- Use of available yield data, either directly or indirectly, to develop and validate the ratings

- Precise specification of all criteria used to assign numerical values, derive factor ratings, and combine factors in the model

Another motivation for soil assessment was an interest in quantifying the economic benefits and sustainability of conservation measures (Pierce et al. 1983; Popp et al. 2002). Pierce et al. (1983) estimated the impact of soil erosion on crop productivity using a soil productivity index modified from Kiniry et al. (1983). The approach used in these studies was to estimate the sufficiency of soil conditions for root growth, relative to that expected in an ideal soil:

$$\mathrm{PI} = \sum_{i=1}^{r} (A_i x C_i x D_i x WF_i)$$

where PI is productivity index, A_i is sufficiency of available water capacity, C_i is sufficiency of bulk density, D_i is sufficiency of pH, WF_i is weighting factor for each horizon and r is the number of horizons in the depth of rooting. A reasonable fit was obtained with corn yields in Minnesota for several soil series (Pierce et al. 1983). Using this equation, Pierce et al. (1983) showed that certain subsoil characteristics caused some soils to be more vulnerable than others to loss of crop productivity due to soil erosion. Popp et al. (2002) modified the above equation by adding a term representing the sufficiency of organic matter. Based on expected differences in soil quality among several soils with different conservation practices and comparison to yields determined using the EPIC (Erosion-Productivity Impact Calculator) model, they concluded their soil quality indicator outperformed the index by Pierce et al. (1983).

Since the early 1990s, there has been a considerable effort in the United States to develop soil ratings based on measured soil properties for the comparison of land management systems (Karlen et al. 2001). In this approach, soil quality is considered an inherent property of the soil that can be determined from measurable soil attributes (Larson and Pierce 1994). When a soil quality parameter declines below an acceptable limit, an appropriate response is required to increase soil quality. Acceptable limits depend on land use, soil characteristics, landform and climatic conditions.

Many potential parameters of soil quality, measurable at various scales of assessment, have been proposed (Table 2). In a 10-year study of crop residue effects conducted in Wisconsin, a soil quality index was estimated by weighting factors related to water infiltration (aggregate stability, surface porosity), water absorption (porosity, total C, earthworms), degradation resistance (aggregate stability, microbial processes) and plant growth (parameters affecting rooting depth, water relations, nutrient relations and acidity) (Karlen et al. 1994).

Table 2. Potential biological, chemical, and physical indicators of soil quality, measurable at various scales of assessment (from Karlen et al. 2001).

Biological	Chemical	Physical
	Point-scale indicators	
Microbial biomass	pH	Aggregate stability
Potential N mineralization	Organic C and N	Aggregate size distribution
Particulate organic matter	Extractable macronutrients	Bulk density
Respiration	Electrical conductivity	Porosity
Earthworms	Micronutrient concentrations	Penetration resistance
Microbial communities	Heavy metals	Water-filled pore space
Soil enzymes	CEC and cation ratios	Profile depth
Fatty acid profiles	Cesium-137 distribution	Crust formation and strength
Mycorrhiza populations	Xenobiotic loadings	Infiltration
	Field-, farm-, or watershed-scale indicators	
Crop yield	Soil organic matter changes	Topsoil thickness and color
Weed infestations	Nutrient loading or mining	Compaction or ease of tillage
Disease pressure	Heavy metal accumulation	Ponding (infiltration)
Nutrient deficiencies	Changes in salinity	Rill and gully erosion
Growth characteristics	Leaching or runoff losses	Surface residue cover
	Regional-, national-, or international-scale indicators	
Productivity (yield stability)	Acidification	Desertification
Species richness, diversity	Salinization	Loss of vegetative cover
Keystone species and ecosystem engineers	Water quality changes	Wind and water erosion
	Air quality changes (dust and chemical transport)	Siltation of rivers and lakes
Biomass, density and abundance		

An adapted form of the index from Karlen et al. (1994) was used to evaluate the soil quality from an 8-year tillage study in southern Illinois (Hussain et al. 1999). Based on soil samples obtained from 36 farm fields under conventional tillage, no-tillage and non-disturbed management, Wander and Bollero (1999) concluded that particulate organic matter, mean wet weight diameter of aggregates, bulk density and penetration resistance may be good indicators of soil quality because they are sensitive to management and environmentally relevant.

Islam and Weil (2000) concluded that total microbial biomass, active microbial biomass and basal respiration per unit of microbial biomass showed the most promise for inclusion in an index of soil quality, based on soil samples of contrasting management systems obtained from long-term replicated field experiments and pair field samples in mid-Atlantic states. Brejda et al. (2000) found that the most sensitive indicators of soil quality among land uses were total organic C and total N in the Central High Plains, and total organic C and water stable aggregate content in the Southern High Plains. Andrews et al. (2002) calculated a soil quality index based on bulk density, DTPA-extractable Zn, water stable aggregates, pH, electrical conductivity and soil organic matter in an on-farm study with various organic amendments in California's Central Valley.

Other examples of the development and use of soil quality indices are provided by Karlen et al. (2001), who concluded that there is no ideal or universal index for soil quality. Rather, utilization of the soil quality concept requires that the following steps be followed (Figure 4):

- Identify critical functions
- Select appropriate indicators
- Develop appropriate scoring or interpretation guidelines
- Combine the information into index values to determine if the resource is being sustained, degraded, or aggraded.

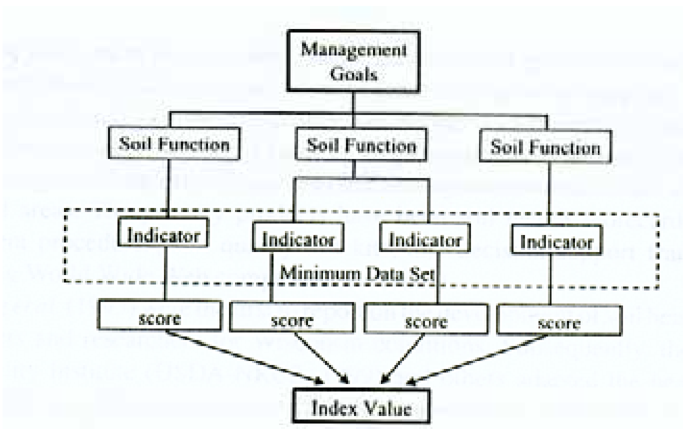

Figure 4. A generalized framework for developing soil quality indices (from Karlen et al. 2001)

Canada

The Canada Land Inventory (CLI) was established in 1963 to provide a comprehensive survey of land capability for the purposes of agriculture, forestry, recreation and wildlife (Canada Land Inventory 1970). The Soil Capability for Agriculture (SCA) classification system is similar in approach to the Land Capability Classification system in the United States. It is an interpretative system based on expert knowledge that classifies soils into seven classes based on their suitability for sustained production of annual field crops (Canada Land Inventory 1965). Class 1 soils are the most suitable (least limitations) for sustained production of annual field crops, while Class 7 soils are unsuitable (most limitations) for sustained production of annual field crops. Classes 1 to 3 are deemed capable of sustained production of annual field crops, while Classes 4 to 6 are recommended for different agricultural uses, such as perennial forage crops, improved pasture and native grazing. Limiting factors included in the classification system include climate (temperature and precipitation), soil structure and/or permeability, erosion, fertility, pH, depth to consolidated bedrock, topography, stoniness, salinity, and risk of flooding, drought or excess water. The inventory was assessed at a large spatial scale (1:30,000+) with limited resolution at local scales. The inventory was designed to be valid for a long time period, although it was recognized that changes in class ratings would occur due to land improvement or degradation. The SCA classification system reflects actual land use, which may serve as one type of validation for the system. In southwestern Ontario, the SCA classification system was significantly correlated with gross returns and gross margin per acre for grain corn production (Patterson and Mackintosh 1976).

The Land Suitability Rating System (LSRS), a revised version of the SCA classification system, was developed in 1995. The LSRS was designed to be more quantitative and better documented, and to encompass organic as well as mineral soils (Agronomic Interpretation Working Group 1995). The overall framework and class ratings from the SCA classification system are preserved, but rating factors are specified for spring-seeded small grain crops (wheat, barley, oats); other crops may be included in the future. The LSRS estimates the suitability of land for crops based on separate ratings for climate, soil, and landscape. Ratings for each component may range from 0 to 100, and the overall land rating is simply the lowest of the three ratings.

Pettapiece et al. (1998) used the LSRS in a pilot project to estimate possible changes in soil quality due to soil erosion or organic matter depletion. Changes in soil properties were estimated from 30-year simulations of EPIC for various combinations of soil landforms, crop rotation, tillage intensity and climate in 15 ecodistricts in Alberta. The project allowed assessment of soil quality trends at regional scales.

The Agri-Environmental Indicator Project developed indicators of the environmental sustainability of Canadian agriculture (McRae et al. 2000). Many of the indicators developed as part of this project are directly or indirectly related to soil quality (Table 3). Indicators are calculated by integrating information on soil, climate, and landscape from *Soil Landscapes of Canada* polygons with information from the *Census of Agriculture* and custom data sets (from provincial agencies, the private sector and other sources). The information is integrated using existing or modified mathematical models selected or developed by scientists and analysts with expertise in the subject. For example, the risk of soil erosion by water is estimated using the Revised Universal Soil Loss Equation, with land use and tillage practice information obtained from the *Census of Agriculture,* and rainfall, soil and slope characteristics obtained from *Soil Landscapes of Canada* and other sources. Indicators are calculated once every five years based on the availability of *Census of Agriculture* data. Most indicators are calculated at the soil polygon scale (3123 soil polygons), and are aggregated to ecodistrict (386), ecoregion (70) and ecozone (7). In some cases, indicators could only be calculated at the provincial or ecozone scale. The indicators are best suited to communicate information of broad changes in environmental impacts over time and among regions.

Table 3. Canadian agri-environmental indicators (from McRae et al. 2000).

Indicator Group	**Agri-environmental indicator**	**Description**	**Frame-work Element**	**Coverage**
Environ-mental Farm Management	Soil Cover by Crops and Residue	Number of days per year when soil is left exposed under specific crop and land management regimes.	Driving Forces Response	National
	Management of Farm Nutrient and Pesticide Inputs	Adoption of best management practices for handling fertilizer, manure, and pesticides.	Driving Forces Response	National
Soil Quality	Risk of Water Erosion	Potential for soil loss in surface runoff under prevailing landscape and climatic conditions and management practices.	Outcome	National
	Risk of Wind Erosion	Potential for soil loss under prevailing landscape and wind conditions and management practices.	Outcome	Prairie Provinces
	Soil Organic Carbon	Estimate of change in organic carbon levels in soils under prevailing management practices.	Outcome	National
	Risk of Tillage Erosion	Potential for soil redistribution under prevailing landscape conditions and tillage and cropping practices.	Outcome	National
	Risk of Soil Compaction	Potential for change in degree of compaction of clay-rich soils estimated from inherent soil compactness and cropping system.	Outcome	Ontario, Maritime Provinces
	Risk of Soil Salinization	Potential for change in the degree of soil salinity estimated from land use, hydrologic, climatic, and soil properties.	Outcome	Prairie Provinces
Water Quality	Risk of Water Contamination by Nitrogen	Potential for nitrogen levels in water leaving farmland to exceed Canadian drinking water standard.	Outcome	Humid Ecozones
	Risk of Water Contamination by Phosphorus	Potential for phosphorus to move off farmland into surface waters.	Outcome	Quebec
Agroeco-system GHG Emissions	Agricultural Greenhouse Gas Budget	Estimated emissions of nitrous oxide, methane, and carbon dioxide from agriculture production systems; summary balances expressed in carbon dioxide equivalents.	Outcome	National
Agroeco-system Biodiversity	Availability of Wildlife Habitat on Farmland	Number of habitat-use units for which habitat has increased, remained constant, or decreased.	Outcome	National
Production Intensity	Energy Use	Energy content of agricultural inputs and outputs.	Driving Forces	National
	Residual Nitrogen	Difference between the amount of N added to farm soils and the amount removed in harvested crop.	Driving Forces	National

New Zealand

In New Zealand, soil quality indicators were developed to meet an environmental requirement to monitor potentially detrimental effects of human activities on the environment (Sparling and Schipper 2002). Environmental requirements are the responsibility of 17 autonomous regional authorities since the Resource Management Act was passed in 1991. Efforts to monitor soil health were initiated in the late 1990s to augment the monitoring of soil erosion that was being conducted by most of the regional authorities. The goal for the program is the use, by 2010, of critical thresholds of soil quality indicators and an associated monitoring system at the regional scale (Manaaki Whenau Landcare Research 2004).

The objective of the program is to monitor the soil quality of 500 soils distributed throughout New Zealand using a three-year sampling frequency (Manaaki Whenau Landcare Research 2004). Soil selection is based on a combination of soil type and land use, and on the perceived risk of soil type/land use to the environment (Sparling and Schipper 2002). Soil type is based on the New Zealand classification of soil order, and 12 of the 15 soil orders are included in the initial sampling program. Land use is divided into nine categories including cropland (arable and mixed), pasture (three types), orchards, grassland, plantation forest and indigenous vegetation. A wide range of soil type and land-use combinations is sampled, but there is a bias toward those of greatest concern with regard to degradation.

Samples are collected for chemical, biochemical, physical and profile characteristics at each location (Sparling and Schipper 2002). Of the original soil properties measured, seven were selected for monitoring soil quality: soil pH, total C, total N, anaerobically mineralizable N, Olsen P, bulk density and macroporosity. These soil properties are combined into four primary factors describing soil quality: (1) fertility based on Olsen P, (2) acidity based on soil pH, (3) organic resources based on mineralizable N, total C and total N, and (4) physical status based on bulk density and macroporosity. The wide diversity in soil types and land uses in New Zealand contributed to the early recognition that the relation of soil properties to the fitness of soil for production and environmental objectives depends on soil type and land use (Manaaki Whenau Landcare Research 2004). Thus, for each of the seven soil properties retained for monitoring soil quality, response curves or target levels were developed by experts for different land use and soil order combinations, based on both environmental and production criteria (Manaaki Whenau Landcare Research 2004).

During development, a pragmatic approach was used to reduce the number of soil properties to a manageable level (Sparling and Schipper 2002). Measures that do not contribute to improved understanding for the goals of the program are dropped, although their potential value for other uses is indicated. For example, unsaturated hydraulic conductivity was dropped because high variability meant an impractical level of replication would be required to detect changes. Particle size distribution and CEC were dropped because they were not responsive to land use. Soil microbial biomass and soil respiration were dropped because these measures could not be interpreted, and because they were reasonably correlated with anaerobically mineralizable N. Base saturation was dropped because it was highly correlated with pH and it was more difficult to measure than pH. Total porosity was dropped because it was less responsive to land use than macroporosity and it was also inversely related to total C. The exclusion of certain measures was supported by observations and theoretical considerations that were relevant for conditions in

New Zealand. However, there is a danger that relevant information might not be obtained, particularly if a soil property is only important for specific land uses, soil types or soil functions.

Aggregation of soil quality information for regional assessment is ongoing (Manaaki Whenau Landcare Research 2004). However, quite a number of useful products are already available from this work. For example, web-based tools allow users to evaluate soil quality for their samples using the approach developed by the program (http://sindi.landcare.cri.nz/). Maps provide information on the vulnerability of different soils to various types of soil degradation and environmental risks, including structural degradation, acidification, N seepage, salinization, potassium deficiency, and microbial transport to shallow groundwater or waterways (McLeod 2003; Stephens et al. 2003; Manaaki Whenau Landcare Research 2004).

Europe Union

Countries within the European Union have made considerable efforts to develop agri-environmental indicators. In contrast to North America, most efforts have focused on environmental impact rather than on production, particularly for water quality as affected by excess nutrients or pesticide use. Another area of considerable interest in Europe is the conservation of agricultural lands for biodiversity, wildlife habitat and aesthetics. Examples of relevant agri-environmental indicators are provided in Table 4.

FAO

The Food and Agriculture Organization (FAO) and International Institute for Applied Systems Analysis (IIASA) developed an agro-ecological zoning (AEZ) methodology to assess potential sustainable food production, including meat and milk, at regional and national scales (Fischer et al. 1999). The methodology limits the type of agricultural land use to ensure that sustainability, environmental, social and economic goals are met. The methodology was first used in 1983 and has since been extended, refined and utilized at the sub-national and national scales in various developing countries. The methodology is based on the following principles that are considered fundamental to any sound evaluation of land resources:

- An interdisciplinary approach is required, with inputs from crop ecologists, pedologists, agronomists, climatologists, livestock specialists, nutritionists, economists, GIS specialists and sociologists.
- Land evaluation is only meaningful in relation to specific land uses.
- Suitable land uses must be sustainable, i.e., no degradation beyond tolerable limits in erosion, salinization, etc.
- Potential production depends on availability of agricultural inputs and technology.
- Different kinds of land use are required to meet demands for products.
- Different kinds of livestock feed resources may be suitable.
- Land use patterns must be constructed to optimize land productivity in relation to political and social objectives, taking into account physical, socio-economic and technological constraints.

Table 4. Examples of different types of agri-environmental indicators related to soil quality that are proposed or used in the European Union.

Type	United Kingdom	France	Germany	OECD*
Soil quality	Concentration of organic matter in topsoil Acidity Concentrations of certain heavy metals Soil management techniques	Number and intensity of severe incidents of soil erosion	Nitrogen balance	Risk of soil erosion by water and wind Mismatch between land capability and land use
Water quality	Trends in N use Nitrate and phosphate losses to freshwater Proportion of soils at different phosphate levels	Phosphate loading from fertilizers and effluents Average duration of cover crops Nutrient surplus of nitrates Contribution of agriculture to annual pollution by phosphates	Nitrogen balance Nitrate in soil in autumn and in leaching water Phosphate and pesticides in eroded matter Total erosion	Proportion of ground and surface water with high nitrate or phosphate levels Area of land potentially vulnerable to water contamination by nitrate and pesticides Quantity of water storage
Land use & conservation	Losses and gains of agricultural land	Land in agricultural use Progress in land planning		
GHG	Emissions of methane and nitrous oxides from agriculture	Emissions of methane, CO_2, and nitrous oxides from agriculture		
Biodiversity, habitat & landscape	Number of threatened species Number and diversity of bird, mammal, and butterfly species Area under commitment to environmental conservation Area under specific land uses	Number of threatened species Trends in wetland areas Areas under environmental protection	Biodiversity indicator (five criteria based on estimated value for natural species)	Area covered by semi-natural agricultural habitats Key species indicators
References	(Baldock 1999)	(Baldock 1999)	(Dabbert et al. 1999; Meudt 1999)	(OECD 1998)

*Organisation for Economic Co-operation and Development

The basic approach of this methodology is to describe both the requirements for different land uses and land attributes, and then to match them in order to determine suitable crops and potential productivity. Multiple land use types are considered. Land attributes are based on (1) climatic factors, (2) internal soil properties (temperature regime, moisture regime, fertility, effective depth, pH, EC), and (3) external soil properties (soil slope, occurrence of flooding and soil accessibility).

The methodology has other components. Maximum biomass production is determined based on climatic conditions, and attainable yields are based on the expected yield losses due to soil and management factors. Algorithms are used to eliminate land uses that are ecologically unsuitable, too risky, environmentally unacceptable or much inferior to other suitable land uses. The methodology also includes algorithms to assess livestock systems. Inputs for the method are obtained from available databases, models and expert opinions. Outputs of the method are estimates of potential, sustainable and acceptable levels of food production, which are obtained for a range of scenarios.

Overview

Table 5 summarizes differences among soil and land evaluation systems.

Objectives: The earliest systems of land evaluation were designed to provide extensive spatial coverage on land suitability for agricultural production or relative productivity (for taxation purposes). Due to increasing environmental and sustainability concerns, recent efforts in land evaluation are primarily designed to monitor land degradation over time.

Spatial scale: Most soil and land evaluation systems have a framework that is useful at large spatial scales, providing coverage at regional to national scales. However, evaluation systems for relative productivity or comparing land degradation among management practices were developed and are generally used within limited regions. The smallest resolution for assessment is at either the field or regional scale. Although all evaluation systems could theoretically be used at the field- or farm-scale, most serve their main purpose when used at regional or larger scales, and they may not be applicable at smaller scales because of insufficient data.

Complete coverage is achieved in most evaluation systems by assessing all land units. Some evaluation systems assess only a small fraction of land units based on statistical sampling (e.g., the National Resources Inventory in the United States) or benchmark sampling (e.g., New Zealand). Remote sensing techniques were not used in the soil/land evaluation systems reviewed in this paper, but they have the potential to increase the spatial coverage, resolution and/or integrated volume of assessments (Nizeyimana and Petersen 1998).

Temporal scale: Land suitability assessments are based on land and climatic variables that are slow to change, and therefore are valid for long time periods (e.g., >30 years). These assessments have only been conducted once in most cases. Evaluation systems to monitor land degradation are determined every one to five years, depending on data and resource availability. Simulation models are increasingly used to increase the integration volume and temporal coverage of assessments. For example, soil erosion models are used to estimate annual rates (increased integrated volume) of soil erosion for previous and future time periods (increased temporal coverage).

Table 5. Comparison of approaches to evaluate soil/land quality.

Primary objective	**Country & references**	**Spatial scale**	**Temporal scale**	**Multiple objec-tives**	**Multiple contexts**	**Inputs**	**Output**	**Output validation**
Land suitability and productivity	USA, Canada (Canada Land Inventory 1970; Helms 1992)	Field to national, 100% coverage	>30 y Single assessment	Built-in	Flexibility	Climate Landscape Stable soil properties	Simple classification system based on relatively simple algorithms	Fit with actual land use and erosion estimates
	Canada (Pettapiece et al. 1998)	Regional, 100% coverage	>30 y Single assessment	Built-in	Flexibility	Land use & management Climate Landscape Stable soil properties	Change in land suitability using model and simple algorithms	Based on data quality assessment, peer review, and model verification
	FAO (Fischer et al. 1999)	Regional to national, 100% coverage	>30 y, Single assessment	Built-in	Flexibility	Climate Crop Landscape Stable soil properties	Potential sustainable productivity based on model outputs	Based on model verification and data quality assessment
	USA (Huddleston 1984)	Field to regional, 100% coverage	>30 y Single assessment	Not applicable	Limited context	Climate Landscape Stable soil properties	Relative productivity based on simple algorithms	Fit with actual crop yields
Monitor degradation and environmental impacts of agricultural lands	USA (NRI) (Nusser and Goebel 1997; NRCS 2003)	Sub-state to national, 4% sample rate	Decades Assessment every 1 to 5 years	Dash-board	Context-indepen-dent indicators	Land use & management Climate Landscape Stable soil properties	Trends in many variables related to soil quality, based on simple algorithms and model outputs	Based on data quality assessment, peer review, and model verification

Primary objective	**Country & references**	**Spatial scale**	**Temporal scale**	**Multiple objec-tives**	**Multiple contexts**	**Inputs**	**Output**	**Output validation**
Monitor degradation and environmental impacts of agricultural lands (continued)	Canada (McRae et al. 2000)	Regional to national, 100% coverage	Decades Assessment every 5 years	Dash-board	Context-indepen-dent indicators	Land use & management Climate Landscape Stable soil properties	Trends in selected indicators related to soil quality, based on simple algorithms and model outputs	Based on data quality assessment, peer review, and model verification
	Europe (Brouwer 1995; OECD 1998)	Regional to national	Decades Assessment every 1 to 5 years	Dash-board	Context-indepen-dent indicators	Land use & management Climate Landscape Stable soil properties	Trends in selected indicators related to soil quality, based on simple algorithms and model outputs	
Monitor soil degradation	USA (among management options) (Karlen et al. 2001)	Field to regional, parametric sampling	Years to decades Variable assessment periods	Aggre-gated	Limited context, flexibility	Management-affected soil properties	Relative aggregated estimate of soil functional capacity	Based on responsiveness and peer review
	New Zealand (Sparling and Schipper 2002)	Regional to national, bench-mark sampling	Decades Assessment every 3 years	Dash-board	Flexibility	Management-affected soil properties	Ratings of different aspects of soil quality	Based on data assessment and peer review

*Multiple objectives***:** Methods to account for multiple objectives are necessary because factors contributing to the achievement of one objective may be negatively correlated to the achievement of other objectives. For example, nutrient availability is positively related to crop productivity and negatively related to water quality. Other factors may be related to multiple objectives in a similar way, but may have a greater impact on one objective than another. For example, soil erosion degrades both crop productivity and surface water quality, but tolerable levels of soil erosion may be lower for one objective than for the other. Three basic methods or approaches are used to account for multiple objectives of soils:

1) <u>Dashboard approach</u>: Multiple indicators are developed for different objectives or issues related to soil or land quality. For example, the current New Zealand system has four factors to describe the quality of a soil (fertility, acidity, organic resources, and physical status) and does not aggregate the factors beyond this level. The agri-environmental indicators system developed in Canada has six indicators describing the status of different soil degradation processes. This approach can often be shown using spider diagrams. The dashboard approach has considerable merit because more information is available from non-aggregated indicators, and appropriate aggregation of dissimilar or contradictory factors is extremely difficult to achieve.

2) <u>Aggregation approach</u>: In some situations, highly aggregated indicators are desirable. For example, communication to the general public through the media is improved using highly aggregated information because people do not have the time or interest to delve into the details of every issue (Jesinghaus 1999). Several approaches might be used to achieve this level of aggregation:

    a. Select one indicator to represent soil or land quality, e.g., the proposed use of trends in soil organic C as an indicator of soil quality, by the NRI in the United States (NRCS 2003).

    b. Select and weight multiple indicators using expert opinion (e.g., Karlen and Stott 1994).

    c. Obtain relative or absolute values (monetary or relative weighting) for all land outcomes (positive values for desirable outcomes, negative values for undesirable outcomes) and sum values for all outcomes of land management (Jaenicke and Lengnick 1999).

    Highly aggregated indicators are challenging to develop due to the requirements for valuation, output validation and communication. *Valuation* is the value or weight given to different components of the issue (e.g., productivity vs. environmental impact), and is strongly dependent on personal beliefs and values (Jesinghaus 1999). *Output validation* refers to the soundness of an indicator to supply reliable information on an outcome, but relations between proposed indicators and outcomes are difficult to ascertain with a high degree of confidence for large, complex systems.

Communication of highly aggregated information for a broad audience is inherently more difficult than site- or issue-specific information to a limited audience of practitioners or industry stakeholders.

3) Built-in constraints approach: Information is provided for the objective of greatest interest, but the role of other objectives is built in by including constraints that affect the output from the primary objective. For example, in the FAO evaluation system, potential food production is limited by the objective to limit erosion rates by not allowing certain cropping systems on land that is susceptible to erosion (Fischer et al. 1999). An advantage of this approach is that linkages between different objectives are explicit and quantifiable. The major challenge for this approach is ensuring all the important objectives are appropriately included in the evaluation system.

Multiple contexts: Due to the large effects of crop type, technology, inputs and landform on potential crop productivity and environmental impact, these factors must be accounted for in any system designed to evaluate soil or land quality. Soil characteristics or management systems that lead to desirable outcomes (high crop productivity, low environmental impact) in a humid climate may not be beneficial in a semi-arid climate. Similarly, soil characteristics or management systems that lead to desirable outcomes for certain crops, landforms (e.g., hillsides vs. level land), or management strategies (e.g., low input vs. high input) may not be beneficial for alternative options. Several approaches have been used to account for the effects of these factors on soil or land evaluation systems:

- Limit the scope, or context, of the evaluation system. For example, many of the productivity indices are only designed for a specific crop in a specific geography.

- Design flexible systems. For example, desirable conditions for soil properties are defined for different land use types in the FAO system or for different land use/soil type combinations in the New Zealand system.

- Develop indicators that are less dependent on context, e.g., use trends rather than absolute values.

Inputs: The inputs used for soil/land evaluation systems reflect the purpose and scale of the objectives. Evaluation systems designed to assess land suitability are based on the most important factors controlling crop growth that cannot be ameliorated by short-term measures. Thus, inputs for these systems include climate, landscape and stable soil properties that are obtained from extensive soil surveys and long-term climatic records. Evaluation systems designed to assess land degradation either utilize measurements of management-dependent soil properties or infer land degradation from known relations of land degradation to management, climate, landscape, and soil variables.

The difference between management-dependent soil properties and stable or inherent soil properties is not absolute. As mentioned previously, soil properties vary at temporal scales ranging from seconds to centuries and at spatial scales ranging from millimetres to hundreds of kilometres. Over a sufficient time period, practices that affect dynamic soil properties will also affect stable soil properties, and stable soil properties will change.

Soil functions depend on both stable and dynamic soil properties, and the decision to limit assessment to either stable or dynamic soil properties is primarily a product of objectives. For example, an objective to compare potential crop productivity at different locations will focus on stable soil properties (e.g., topsoil depth, pH, texture) because these can account for much of the difference in potential crop productivity, while dynamic soil properties (e.g., soil water or nitrate concentrations) would need to be monitored much more intensively. In comparison, an objective to compare potential crop productivity as affected by management practices that influence dynamic soil properties, such as irrigation or fertilizer addition, will focus on the dynamic soil properties affected.

Output: The output from soil/land evaluation systems consists of ratings or trends based on algorithms used for system inputs. In almost all cases, the output provides information of the outcome of soil functions. Algorithms range from simple (e.g., weighted average of several measurements) to complex (e.g., simulation model using daily time steps for many soil processes).

Output validation: Validation of the outputs from the evaluation systems is required to ensure that correct messages are being communicated. In many cases, it is very difficult to determine how well an evaluation system has been validated. Earlier evaluation systems for land capability and productivity were validated through use and improvement of the system until the experts developing the system considered outputs reasonable. Improvements were guided by actual observations of land use, land degradation and crop yields. Simulation models are increasingly used because they are more quantitative and less dependent on user assumptions, but considerable care is required to ensure that they are used for purposes, contexts and scales for which they were intended (Addiscott 1993). As far as possible, outputs from evaluation systems should be validated by comparison with relevant observations or related variables (Bockstaller and Girardin 2003).