SOIL QUALITY ASSESSMENT IN LAND RECLAMATION

by

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ABSTRACT

The development and application of quantitative soil quality assessment (SQA) concepts involve calibrating soil quality indicators (SQI), such as soil organic carbon (SOC), to soil management goals such as yield or biomass productivity to create soil quality-scoring functions (SQF). Currently, SQA is used primarily to evaluate agronomic land use, but the concept could easily be applied to other land uses such as reclamation. To do so, the robustness and transferability of predictive SQI and SQF must be demonstrated considering baseline variations between natural and reclaimed soils. The indices must also be responsive to and meet the design criteria and objectives of reclamation covers. Calibrating more complex, bi-directional and time sensitive relationships between SQI and performance measures such as forest soil productivity will also require defining SQF concepts needed to support a healthy forest stand, since that is often the goal for reconstructing and revegetating disturbed soils. The objective of this research was to develop quantitative, calibrated, justifiable and validated SQF within a SQA framework that would be suitable for assessing, monitoring and managing land reclamation. An existing SQI database and measures of ecosystem performance compiled over the last 30 years for Alberta oil sand reclamation was used to develop SQF relationships that were validated for both site specific and regional SQA scenarios. Accuracy and transferability of SQF were assessed based on their ability to reproduce known or specific treatment effects from independent sites. Baseline SOC variation was used as the main predictive indicator to identify functional management units and define boundary conditions for SQF. Both analytical (GYPSY) and process-model (BIOME-BGC) options were used to calibrate SQF for effects of time and available water holding capacity on forest productivity. Generally, SQF developed from natural soils were transferable and justifiably rated the quality of peat-mineral mix covers in reconstructed soils. Although high spatial and temporal variation in SOC was observed at the regional scale, SOC values were useful for defining and delineating functional management zones ($p < 0.05$) for further SQA applications. Based on those soil management zones, critical SQF thresholds and metrics for optimizing reclamation cover design were developed and evaluated based on their capability to supply soil nutrients such as nitrogen (N) as a measure of their performance. Both the GYPSY and BIOME-BGC models provided pre-validated outputs suitable for calibrating SQF. Finally, in seven application scenarios completed within this study, integrated soil quality ratings generally resulted in expected non-significant or significant ($p < 0.05$) treatment effects. The ratings appeared to be more realistic than simply testing for changes in predictive soil quality indicators in response to management goals for reclaimed soils. SQF also proved to be useful for quantitatively defining equivalent capability functions for reclaimed soils, assessing quality of both dry- and wet-land reclaimed soils and are suitable for monitoring the quality of reclamation covers through all phases of restoration.

PREFACE

This dissertation is an original work conducted by Abimbola Akinyele Ojekanmi. A version of chapter 2 has been published as Ojekanmi, A.A. and Chang, S.X., 2014. Soil quality assessment for peat mineral mix cover soil used in oil sands reclamation. Journal of Environmental Quality, 43, 1566-1575, and a version of chapter 4 has been submitted for publication in Soil Science Society of America Journal. Chapters 1, 3 and 5 are also being reformatted for submission to various peer reviewed journals. Eighty percent of the soil quality data used in these studies was compiled by the author from various sources published by the Forest Soil Laboratory of the Department of Renewable Resources, University of Alberta, Canada. This included a large number of Alberta oil sands reclamation studies completed under the direct supervision of Dr. Scott X Chang. The remaining data was approved for use by Alberta oil sands industry partners participating in the Cumulative Environmental Management Association (CEMA) within the Athabasca oil sands region of northern Alberta.

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AOSR: Athabasca oil sands region
AWHC: available water holding capacity
CEC: cation exchange capacity
CV: coefficient of variation
EC: electrical conductivity
FC: field capacity
FF: forest floor
LFH: litter, fibric and humic mix
LSUB: lower subsoil
MAF: multi-indicator assessment framework
MS: mineral soils
N: nitrogen (N)
P: Total soil phosphorus
PMM: peat mineral soil mix
PWP: permanent wilting point
SAR: sodium adsorption ratio
SMAF: soil management assessment framework
SOC: soil organic carbon
SOM: soil organic matter
SQ: soil quality
SQA: soil quality assessment
SQAF: soil quality assessment framework
SQF: soil quality-scoring functions
SQI: soil quality indicators
SQMAF: soil quality management and assessment framework
TSOIL: topsoil
USUB: upper subsoil

Chapter 1 Soil Quality Assessment and Application in Land Reclamation: A Review

1. Introduction

Soils are an integral part of a complex, inter-related and functional ecological system that influences ecosystem health based on their physical, chemical and biological properties. The capability of soils to support environment quality, plant productivity and other direct or indirect functions within a land use or ecosystem boundary is defined as soil quality (Doran and Parkin, 1994; Karlen et al., 1997). Various stakeholders view soil quality based on the soil's capacity to provide ecosystem services; for example, farmers know the section of their field producing the best yield possesses the best soil quality (Allievi et al., 1993).

Quantifying soil quality (SQ) is challenging considering the need to integrate diverse measures of multiple functionalities supporting the relevant agronomic, environmental and anthropogenic management goals (Karlen et. al., 1997). The definitions of SQ also suggest the need to quantify soil quality will be relevant to other land use and management operations beyond agronomy, such as in watershed management, environmental conservation, land reclamation and remediation, linear structure developments, among others. These land use options also have similar end goals such as maintaining environmental quality and restoring plant productivity. Therefore, there is the need to comprehensively examine the historical, current, regulatory and recent advances in the understanding and applications of concepts of soil quality, with emphasis on potential applications in disciplines such as in land reclamation.

The objective of this review is to examine current advances in multi-indicator SQ assessment and identify potential applications in land reclamation. This includes demonstrating the development of a quantitative and adaptable SQ assessment framework for application in land reclamation operations, with emphasis on the use of numerical and quantitative SQ scoring functions. Using Alberta oil sands land reclamation as a case study, this review examines potential adaptation of these recent advances and applications of SQ assessment framework within phases of land reclamation operations while also identifying critical research gaps required to implement such framework.

1.1. Historical perspective of soil quality

Historically, SQ was viewed from a very narrow perspective as the medium that supports crop productivity based solely on its fertility. Subsequent events that led to the loss of soil function and ecosystems drove the need to broaden the SQ perspective toward managing environmental and human impacts while acknowledging the multifunctional, renewable and non-renewable nature of soils. Landmark events that demonstrate loss of soil functionality and ecosystem services include the permanent disappearance of the Tikal rainforest and the southern Mesopotamia grasslands (Lowdermilk, 1953). These examples represent the consequences of both abandonment and continuous use of soil resources for agriculture, urban and mining developments without recognizing that soils support numerous functions beyond crop productivity (Hillel, 1991; Diamond, 2005). The severe natural resource disaster associated with the Dust Bowl within the US Great Plains occurred shortly after the periods when soils were thought to be an "immutable and indestructible resource" (Whitney, 1909). Such claims led to intensive tillage throughout the US Great Plains and ultimately to that environmental disaster (Baumhardt, 2003).

The historic worldwide loss of SQ with resultant environmental and human impacts, led to a better understanding of land use on environmental effects and ecosystem health. It became clear that sustaining soil capability to perform specific ecosystem functions required reliable, science-based soil management tools for assessing impacts of land use. Therefore, the SQ concept was introduced with emphasis for guiding allocation and use of soil resources based on the sensitivity of various soils to degradation processes such as erosion, compaction, topsoil loss and other factors (Warkentin et al., 1977). Soil quality assessment (SQA) was also recognized a complicated process because of the diverse, multiple functions and indicators required to explain the concepts (Borggaard, 2006). This complexity combined with opinions of various stakeholders, such as environmental regulators, farmers and researcher's, resulted in a series of SQ definitions with broadening perspective over time.

Soil quality was initially perceived as a soil's capability with emphasis on its natural attributes such as fertility and erodibility (SSSA, 1987), then expanded to include its ability to support crop or plant growth (Power and Myers, 1989). In 1991, SQ was further defined to capture the concepts of soil functions needed to support and maintain crop productivity while improving environmental, floral and faunal health (NCR-59 Madison, USA). Larson et al. (1991)

refined the definitions even further as a soils capability to function within a defined ecosystem boundary. Pierce et al. (1993) then introduced "fitness for use" as a concept to define SQ, laying the foundation for an objective SQA protocol.

Carter et al. (1996) clarified differences between objective and subjective definitions of SQ. They stressed that objectivity relates to definitions of SQ based on its current state and use, while subjective definitions captured personal and social values conferred on soil resources. In 1994, SQ was defined as the capacity of soils to perform specific functions within natural or managed ecosystems boundary, to support flora and fauna's productivity, maintain or enhance water and air quality while supporting ecosystem and human health (Karlen et. al., 1997; Harris et al., 1994). This definition indirectly points to the three types of soil function: properties and processes within the soil, direct effects on soil processes affecting plant productivity, and indirect effects on ecosystem and human health. The definition also suggested the SQ concept was adaptable to land use options beyond agriculture. Broader operations such as engineering, mining and construction industries also need constant emphasis on ecosystem restoration to ensure they do not negatively affect environmental sustainability.

1.2. Soil functions and quality

Differences and diversity among soil physical, chemical and biological properties are the main reason soils vary in their capacity to perform multiple functions. Soil properties along a chronosequence or toposequence usually reflect the impact of unique combinations of local and regional factors of soil formation. The effects of those factors result in soils with unique physical, chemical and biological configurations that ultimately determine their ability to perform specific ecosystem functions.

The diversity of soil mineralogy, structure, texture, hydraulic properties, color and other pedogenetic features has been a focus of SQ research (Arshad et al., 1996). Soil physical functionalities relate to its resilience to mechanical stress and capability to return to dynamic equilibrium (Seybold et al., 1999). Soil physical properties often regulate functions such as water storage in aquifers, plant water uptake, and transport of solutes and gasses. They also support contaminant filtration, stability of engineered structures, and provides physical resistance and/or support for plants roots.

Soil quality in relation to its chemistry encompasses the ability to support carbon sequestration, and transform contaminants into non-toxic and/or immobile forms. Soil chemical functions can mitigate contaminant leakages into surface and groundwater resources (Brus et al., 2005), while also supporting nutrient cycling, storage, and availability to plants. Soil chemistry also influences the transformation of organic matter, nitrogen, phosphorus and other elements through its effects on pH, cation exchange capacity, and redox potential. Collectively, soil chemical quality generally provides an indication of soil fertility status and its ability to support plant productivity and further enhance development of a healthy ecosystem.

Soil biological functions primarily reflect the vast soil microbial diversity and its potential to carry out or support numerous functions including soil respiration, nutrient fixation, nitrogen dynamics, enzymatic catalysis, and bioremediation of contaminants. Productive soils are also known as suitable source of energy and water for soil microbes, thereby enhancing their capability to support various fundamental processes related to many soil functions.

Soil functions can also be broadly classified into utility, environmental and cultural or social functions (Bezdicek et al., 1996). Utility functions are those related to plant productivity, including the capability to support long-term biomass production and provide materials for engineering operations. Environmental functions are in-situ functions such as water storage and transport, elemental transport, transformation, and contaminant buffering. Social or cultural functions of soil include its ability to conserve history of natural and anthropogenic influences such as the identification of maximum water depth based on profile mottling and redox signatures. Figure 1 presents a diagrammatic summary of soil functions that integrates into measures of soil quality.

Appreciation of soil functions is sometimes limited by its current use and the current state of scientific understandings of how soils affect ecosystem processes. Translating this general knowledge for specific soils and its potential for local, regional, national and global scale applications is highly desirable and would be beneficial to the scientific community. Furthermore, the need to quantify soil functions based on differences in biogeochemical configuration and the impact of land management practices is widely recognized irrespective of the extent or type of land use. Quantifying soil functions and quality is also relevant for land-based industries other than agriculture. This includes industries such as mining, engineering, construction, watershed management and ecosystem conservation. For each, however, a clear and consistent SQA approach needs to be defined using management frameworks consistent with public regulatory systems in order to ensure compliance with specific environmental requirements.

1.3. Soil quality and environmental regulations

Land-based industries creating significant disturbance to soil systems and the ecosystem will require adequate regulation to ensure effective reclamation of impacted soils to baseline quality or better. Such land-use regulations need to carefully guide industrial reclamation operations while providing a clear, consistent and adaptable framework to support SQA and management (Powter et al., 2012). Using an assessment framework will ensure consistency among various industry stakeholders in demonstrating environmental sustainability of their respective land use operations.

A science-based, quantitative and validated soil quality assessment framework (SQAF) is necessary to quantify soil function and/or calibrate how soil function influences ecosystem performance. Such a framework would be useful for regulatory and land use industries to analyze the ecological or soil functional impact of various land use operations. The need for a SQAF also becomes imperative when compliance with public regulations needs to be documented. Regulated land-based industries also like to quantify performance of reconstructed soils in order to demonstrate economic benefit associated with their land reclamation scenarios. Both needs could be enhanced by having a consistent SQA framework.

Ensuring a balance between ecosystem conservation operations and profitable land use is a major regulatory challenge of the 21st century. A good example is the need to construct engineered structures without compromising soil and water quality. To maintain balance, a reliable, consistent, justifiable, and quantitative SQAF is needed to quantify loss or gain in multiple functions related to SQ, thus providing a defendable and publicly regulated strategy for managing land-based industry operations. Such a framework should allow for identification of SQ indicators related to environmental quality and productivity, while also demonstrating the quantitative implications of effective soil quality management (Harris et al., 1994). It is also important to recognize that land use regulations are meant to prevent, restore or manage potential SQ loss due to the impact of salinization, erosion, compaction, excessive fertilizer application, leaching, loss of soil organic carbon (SOC), nutrients and plant regenerative propagules. Those potential losses further justify the need for a regulated land restoration or reclamation process to maintain balance in ecosystem health.

1.4 Importance of soil quality in land reclamation

Land reclamation involves the reconstruction of a disturbed or degraded landscape with the goal being to return the soil, vegetation and biodiversity to a pre-disturbance land capability. This operational process ensures environmental sustainability of the natural resource industry while maintaining societal or ecosystem health. Historically, land reclamation has been an integral part of natural resource development operations. Therefore, a critical objective is to restore the soil processes, functionality and inherent capabilities required to sustain soil biogeochemical processes, plant productivity, environmental and human health removed by either anthropogenic or natural factor (Naeth, 2012; Powter et al., 2012).

Anthropogenic degradation due to soil disturbances in agriculture, mining operation, acidic or excessive nutrient depositions due to emissions from extraction plants, waste treatment operations, and road or pipeline construction is a real problem. Soil disturbances can be a consequence of excessive fertilizer or manure application, tillage, contaminant leakage, soil compaction, and other factors. Natural degradation can also result due to salinization, soil drying or caking due to drought, excessive carbon loss, and soil erosion. These processes fundamentally inhibit or remove the ability of a soil to perform specific biogeochemical functions. Therefore, an objective of SQA and monitoring in a land reclamation operation is to identify and quantify soil capabilities or functionalities that have been lost, and to design corresponding mitigation techniques for restoring and quantitatively or qualitatively monitoring recovery of those functions in spatial and temporal dimensions. Restoration of those functions is best justified using selected soil quality indicators (SQI) that demonstrate long-term, stable correlations to specific measures of ecosystem performance such as an increase in plant biomass, improvement in nutrient supply and enhanced soil biodiversity.

The critical role of soils in land reclamation and ecosystem restoration is widely acknowledged (Asensio et al., 2013; Bodlak et al., 2013; Chun et al., 2001). Soils provide the medium containing biological, physical and chemical indicators of functional change that can be impacted by previously discussed degradation processes. Changes in SQI usually correspond to either improvements or further degradation in ecosystem capability, as influenced by choice of specific land reclamation technique. Soils also retain the potential for ecological propagation such as in the regeneration of seedling and conservation of plant propagules for re-vegetation operations. Furthermore, land reclamation operations require temporary soil conservation in stockpiles for later use in landscape and soil reconstruction. Therefore, soil is the main conservable component of the ecosystem for later use in land reclamation operation. Soil conservation is possible with minimal cost in comparison to other essential elements associated with a functional ecosystem such as air, animals, vegetation and water.

2. Advances in soil quality evaluation

Soil quality assessment requires a comprehensive view of the ecosystem or landscape processes. Therefore, a complete set of biological, physical and chemical properties of soils defined as SQI are required, while capturing the effect of various soil and landscape management practices. SQA involves making direct and indirect inferences based on changes in SQI. Bezdicek et al. (1996) discussed two approaches to SQA based on the differences in interpretation and analysis of soil quality indicators.

The first approach to SQA involves the use of inherent and assumed static attributes to infer SQ. This involves, i) defining the objectives of SQA, ii) selecting a relevant SQI, iii) determining the baseline conditions and the critical limits of the indicators, iv) determining the effect of soil degradation processes or anthropogenic stress on the selected indicators, and v) finally, comparing the absolute values of the indicators to the baseline, thresholds and critical limits to determine if there is a significant impact of land use or not (Martel et al., 1980; Saini et al., 1980; Ketcheson, 1980; Acton, 1991; Coote, 1991). The advantage of this approach is the ease of incorporating both qualitative and quantitative measures of soil functions. An example is the comparison of soil bulk density between reclaimed and natural soil to determine the effect of mechanical compaction during soil replacement operations. Another example is qualitative assessment and comparison of soil pedogenetic properties using visual indicators such as soil color and structure to determine and compare the extent of profile oxidation or reduction, horizon maturity, extent of organic matter accumulation and decomposition in reconstructed soils, when compared to natural, pre-disturbance or baseline soils.

The disadvantage of this SQA approach is that reference or baseline conditions as expressed using SQI parameters are not quantitatively static parameters. SQI vary in spatial and temporal dimensions. Baseline conditions are usually chosen assuming ideal soil characteristics within the same proximity. Comparing pre-disturbance or baseline parameters of soil quality with others as impacted by management practices cannot be justified when there is change in soil management from forest to agronomic or reclaimed systems, and vice-versa. Reclaimed soils could sometimes perform better than natural soils, leading to a false conclusion when comparing reclaimed soil quality to that associated with natural soil. For example, soils in lower slope positions could have higher nitrate concentrations than natural soils in upper slope positions simply because of difference in soil moisture, water movement and nitrification rates, even though soil type and pedology are similar.

A major lesson here is that pre-disturbance, baseline functionalities should be related to land use management types, and analyzed along temporal or spatial dimensions. Land reclamation currently emphasizes the use of equivalent pre-disturbance capability as the minimum goal for reconstructed soils. Reconstructed or reclaimed soils are also expected to function as well or better than pre-disturbance natural soils. This expectation is only valid when factors influencing both soil type and functionality are similar and analyzed for equivalent landscape, temporal and spatial dimensions, with a clear understanding of baseline variation in SQI for both systems.

Another weakness of using of inherent and assumed static attributes is the assumption that quantitative thresholds and critical limits reflect the effect of all the possible factors affecting SQI. This may or may not be true, and therefore could invalidate comparisons between natural and reconstructed soil parameters. Another implication of this approach to land reclamation is the need to account for temporal dynamics of SQI. It takes years to form natural or baseline soil conditions; therefore reclaimed soils may also need years for some characteristics to emerge. In other words, monitoring SQ improvement in reconstructed landscape is desirable, especially when the long term objective involves the recreation of commercial forest. Therefore, there is a need to identify reliable measures of performance (baseline function) from early to late stages of land reclamation, rather than comparing a single baseline indicator such as a mature and developed forest system, with no clear idea of systemic variations between the two systems.

The second approach to SQA is more recent and builds on identified weaknesses of the first approach (Bezdicek et al., 1996). This SQA approach is based on the capacity of a soil to perform specific functions such as sustaining productivity and environmental health in natural or managed ecosystem (Karlen, 1997; Pierce et al., 1993; Acton and Gregorich, 1995). The approach identifies and uses soil relations to calibrate relationships between relevant SQI and specific measures of ecosystem performance. Those relationships are then built into quantitative or numerical frameworks with potentials for analyzing SQ in spatial, temporal and landscape dimensions.

This SQA approach is implemented by the design and calibration of soil quality-scoring functions (SQF), to capture variability in baseline conditions and effects of site specific management factors on selected indicators. This approach also provides better guidelines on the use of soil physical, chemical and biological properties as quantitative and functional indicators of SQ. There is an emphasis on developing a clear understanding of soil relations based on the existing body of research and need for calibrating SQI values using relevant quantitative measures of soil function and/or defined measures of ecosystem performance (SSSA, 1996; Doran and Parkin, 1994). One example is development of the soil management assessment framework (SMAF) which involves indicator selection, interpretation and integration in a quantitative framework using defined soil functional indicators that capture site specific variation (Andrews et al., 2004). A major advantage of this approach is that variations in baseline systems are easily captured. This provides greater confidence in SQI comparisons and quality ratings from reclaimed or disturbed soils to baseline, natural or undisturbed soils.

Quantitative and process based SQF can be further validated for other site specific uses. This is feasible because the fundamental process relations driving the soil functions, as expressed numerically in calibrating SQI to specific measures of ecosystem performance, are the same at different spatial scales, stages of land reclamation, or ecosystem development. This approach further recognizes that SQI vary from relatively static parameters to highly variable or dynamic SQI. It encourages the use and integration of multiple indicators in a quantitative framework using widely accepted and characterized functional relations between selected measures of performance and related SQI (Pierce et al., 1993; Acton and Gregorich, 1995; Karlen et al., 1997). The remainder of this review focuses on the details of this SQA method with emphasis on its application within land reclamation or soil reconstruction operations.

2.1 Indicators of soil quality

Soil quality indicators (SQI) are qualitative and quantitative properties that respond to changes in management practices at different temporal and spatial scales (Andrews et al., 2004). Table 1.1 presents common land and soil management objectives such as maintaining plant productivity, reconstructing natural ecosystems, and conserving environmental processes. Each objective is further related to supporting soil functions and a corresponding suite of representative physical, chemical and biological indicators.

Doran and Parkin, (1994) discussed the desirable attributes of a SQI, including strong correlation with ecosystem process and selected measures of performance. SQI values are expected to adequately capture soil physical, chemical and biological processes or functions to be considered integrative. They must be able to serve as primary input for estimating other soil quality parameters that are costly and difficult to measure in the laboratory or field. SQI values should incorporate conventional or routine measures applicable for field assessment and also be sensitive to management and climatic variations while capturing both short and long-term changes in soil processes, functions, and management goals. SQI values are desired to be a component of existing and readily available databases, compiled within the range of 5 to 10 years, or more.

Examples of such SQI values include measures of soil organic matter, soil reaction, texture, moisture, and nutrient content. The measures include parameters such as soil organic carbon (SOC), pH, textural fractions, water content and N concentrations. Indicators of soil function and quality can be predictive or direct measures of performance (Wander et al., 2002). Predictive indicators include SOC, pH, and electrical conductivity (EC). Direct indicators or measures of performance quantify the extent of achieving important management goals. For example, a direct indicator of available soil nutrient pools and nutrient cycling potentials will include quantitative measures of available soil nitrogen, phosphorus, and other nutrient elements.

Predictive indicators are soil properties that have significant control on multiple processes and are measured routinely, e.g. soil reaction which is measured using pH probes. Soil pH is an indicator of nutrient availability, nutrient retention and cation exchange capacity. Direct measures of performance or management goals quantify the extent to which soils perform a particular function and might require intensive, non-routine analytical technique, e.g. soil respiration measured by examining the amount of carbon-dioxide produced in a chamber experiment. Predictive indicators such as total SOC or measures of oxidizable fractions of SOC can be used as an alternative indicator of soil's potential for respiration (Wander et al., 2002). In other words, there is a quantifiable relationship and correlations between predictive and direct indicators of soil functions, termed soil relations in this review.

2.1.1 Selection of soil quality indicators

The large numbers of soil functions and related indicators call for an objective SQA with clearly defined goal or rationale for such assessment. The multi-functional nature of soil processes also relates to the need to carefully select a minimum group of relevant indicators that meet the defined objective of SQA (Doran and Parkin, 1994). SQI features that will influence their choice as suitable indicators for specific soil management goals include the SQI's stability, sensitivity, ease of measurement and potential for use in monitoring within a specific time or spatial scale (Table 1.2). Literature agrees on the static and dynamic nature of SQI (Larson and Pierce, 1994; Andrews et al., 2004; Varvel et al., 2006; Bell and Raczkowski, 2008). SQI values include dynamic and highly sensitive indicators that capture changes in SQ at fine temporal and spatial scale. Some examples include biological respiration and enzymatic activities in soil processes. Other SQI values can be stable, less sensitive and static indicators responding only to major degradation processes over an extended period. This group of SQI includes soil textural composition and bulk density which change primarily in response to processes such as erosion and sedimentation.

Dynamic SQ indicators include soil physical, biological and chemical properties that are highly variable and sensitive but may be useful only for short period or daily monitoring. Those indicators reflect a soil's potential to respond to, short- or medium-term stress or degradation factors. The static SQI values are relatively unchanging when analyzed using their absolute values over a short period. A careful observation of subtle changes in the static indicators such as soil bulk density, when calibrated against specific measures of performance over an extensive period, could show some significant effects with respect to defined SQ management goals, even though the absolute values seem relatively static.

A common management objective associated with SQA for land reclamation is the analysis of soil resilience to mechanical compaction. Soil resilience infers the capacity to restore its physical features such as structure, stress tolerance, and ability to return to structural equilibrium after mechanical soil compaction. The choice of suitable indicators to determine the potential for inter-particule and structural recovery will depend on the time scale required for the processes to occur, indicator sensitivity, ease of measuring resilience, indicator stability, and potential for use as a SQI monitoring parameter.

2.1.2 Methods of selecting indicators

There are several methods for selecting indicators or reducing large databases to indicators presented in the literature. This includes use of multivariate statistical analyses, expert opinion in site-specific approach and local judgment (Andrews et al., 2004). Local judgment is based on visual assessment and expert advice. This approach for selecting indicators involves site-specific knowledge of correlations between SQI and specific measures of performance. An example of local judgment in land reclamation is the extent of organic or litter horizons development in reclaimed forest soil, creating an organic carbon and nitrogen pool, that supports mineralization and corresponds to increasing nutrient availability to support biomass development. This relation indicates restoration of nutrient cycling processes in reconstructed soils and demonstrates a trajectory toward vibrant soil nutrient cycling processes in reconstructed soils during reclamation operations.

Multivariate statistical analysis involves selection of data from an extensive database of SQI based on their correlation and discriminate structure. The selection is implemented using statistical reductionist methods such as factor analysis, principal component analysis and partial least square analysis (Brejda et al., 2000a; Brejda et al., 2000b; de Lima et al., 2008; Zvomuya et al., 2008). The technique is very reliable for analyzing large regional datasets of SQI. Reliability of selected SQI will further depend on the level of understanding of fundamental or ecological processes that link the selected variables.

Expert opinion approaches such as in Andrews et al. (2004) select relevant indicators from existing databases using a series of decision rules developed using meta-analysis of relevant indicators. The databases contain multiple indicators of ecosystem process and functions related to the defined SQA objectives. The decision rules are designed based on soil quality management goals, related soil functionalities, and site - specific factors affecting soil functions of interest. Andrews et al. (2002a) further compared the use of expert opinion and principal component analysis and confirmed that neither technique resulted in significant differences in the selection of representative indicators. The non-significant differences suggest the techniques are not mutually exclusive, and that they could be used in a complementary way to increase the level of confidence in indicator choice.

2.1.3 Correlations and ecologically relevant units of indicators

Soil quality indicators are expected to describe ecological processes and functions related to different types of soils at both temporal and spatial scales (Visser and Parkinson, 1992). Measurement units of SQI must reflect field conditions as much as possible, to ensure the values describe relevant ecological processes and functions. For example, this involves the use of volumetric rather than gravimetric measurement units whenever possible, so that the values are adjusted for soil bulk density and horizon depth. Bell and Raczkowski, (2008) reported an error reduction of 7 to 14% in SQ analysis by using volumetric measures of SQI. Using existing SQ databases that contain horizon depth and bulk density data is desirable so that soil nutrient measurements expressed in gravimetric forms (g kg^{-1} of soil) can be transformed to volumetric measures (Mg ha^{-1}).

Ecological units are imperative when comparing integrative measures of SQ that reflect the combined effect of various soil physical, chemical, and biological processes such as SOC, water-filled pore space and pH. SOC status relates to soil microbial diversity, enzymatic activity, nutrient cycling, water retention, carbon sequestration, soil structure, bulk density and others. This integrative nature makes SOC one of the most important SQI because it provides consistent and stable correlations with other measures of ecosystem performance. Water-filled pore spaces also influences soil processes such as biological respiration, soil moisture dynamics, porosity, solute transport and nutrient dynamics, but it is a transient effect. Soil pH reflects nutrient exchange capacity, effect of soil texture and moisture, and organic fraction dynamics. Comparative analysis of these SQI using relevant ecological units is desirable for SQA, especially when there is good knowledge of site-specific factors influencing indicator variation.

An effective SQ indicator must always correlate with measures of soil function or defined measures of ecosystem performance. These relationships can sometimes be expressed quantitatively using mathematical models such as quadratic or sigmoid functions. The preference for non-linear models is generally related to the fact that fundamental soil processes, represented by SQI - measures of performance or soil relations, are not necessarily linear. Examples include soil pH and texture in relation to biomass productivity. The measurement unit for soil pH is in logarithm units, and measures of soil texture are proportional, thereby having a non-linear relationship with biomass productivity. Janzen et al. (1992) emphasized that the absolute values of SQI, e.g. a soil pH value of 7.6, has no meaning regarding SQA except that such a measure is quantitatively calibrated against defined measures of performance or soil functions. Calibration identifies the need to avoid generalization in SQA and focuses on site-specific issues. The requirement for further calibration also suggests the need for a clear understanding of linkages among objectives of SQA, soil quality indicators, soil functionalities and relevant performance measures (Table 1.1).

2.2 Multi-indicator assessment and indexing

Soil functions are best represented by multiple variables as presented in Table 1.1. The selection process for SQI needs to identify the minimum number of variables that best correlates with measures of soil function or determines proper soil relations. This requirement thus justifies a need for a multi-indicator assessment framework (MAF) using ecologically appropriate measures of SQI calibrated with "objective" measures of performance or management goals. The indicators selected as direct measures of performance must be able to delineate effects of soil management practices. An example relevant to land reclamation is the effect of different types of cover, such as peat-mineral mix or litter, fibric and humic mix (LFH), and differences in vegetation types on overall soil quality (Bohanec et al., 2007). Those indicators are further scored using reliable numerical techniques or models, and the SQ scores are combined into an overall index of soil quality.

Various national, regional, and site-specific MAF have been proposed and applied for SQA to specific ecosystem boundaries at different scales. Two national frameworks are the Dutch's MAF which focuses on ecotoxicology and risk assessment (van Straalen and Denneman, 1989; Brus et al., 2009) and the French soil quality monitoring systems (Cornu et al., 2009). Regional frameworks include the Alberta soil quality benchmark (Cathcart et al., 2008) and Wisconsin soil health framework (Romig et al., 1996). Other MAFs include those designed for participatory research using adaptable frameworks such as the soil management assessment framework (SMAF) proposed by Andrews et al. (2004), the comprehensive assessment of soil health (CASH) developed for the Cornell Soil Health Test (CSHT), (Fine et al., 2017) and the micro LEIS décision support system (De La Rosa, 2005). Those MAFs are at different stages of research, development, and application.

Multi–indicator assessment frameworks adopt different numerical techniques of scoring and integration of soil quality scores. Scoring methods include the use of score cards (Romig et al., 1996; Karlen et al., 2003) and pedotransfer functions (De Vos et al., 2005). Recent approaches to SQ scoring involve the use multiple regression functions (Zornoza et al., 2007) and soil process-based models (Wienhold et al., 2006; Karlen et al., 2008). Integration techniques of SQ scores include additive methods, weighted additive, and multiplicative techniques (Andrews et al., 2002a), in spatial or temporal dimensions.

Harris et al. (1996) identified two broad numerical methods of transforming soil relations: functional and mechanistic as well as process – based analytical techniques. The functional, process-based numerical method includes a productivity index using pedo-transfer functions (Larson and Pierce, 1994) and a soil quality index that focuses on regression of SQI and measures of performance/management goals (Doran and Parkin, 1994). Functional techniques also include the use of fuzzy logic theory for soil quality mapping (Ambuel et al., 1994) and standard scoring functions in which standardized mathematical functions are modified based on experimentally derived upper and lower thresholds of indicators (Andrews et al., 2004). The designed soil quality-scoring function (SQF) or SQ models produce unit – less soil quality ratings that ranged between 0 and 1 (Fig. 1-2), thereby enhancing numerical integration and further statistical analysis of SQ ratings. Those techniques also allow for quantitative estimates of weighting factors to determine the relative importance of SQI components used in multi-indicator assessment approaches.

The mechanistic, process – based methods incorporates varieties of specialized numerical models with potential for soil quality simulation. The predictive models include C and N cycling models such as NCSOIL (Molina et al., 1980; Molina et al., 1983), soil –water quality models such as NLEAP (Shaffer et al., 1985), P–index models (Lemunyon and Gilbert, 1993), pesticide attenuation models (Mulla et al., 1996), water erosion model such as RUSLE (Bussacca et al., 1993) and the EPIC model (Williams and Renard, 1985). The advantage of mechanistic techniques is the ability to simulate complex processes and produce SQF that account for other interacting factors without the need for weighting quality ratings. The disadvantage is the need for a sufficient amount of data to calibrate and validate site-specific SQ models.

The development, use, and adaptation of soil process-based soil quality - scoring function is advancement in the effort to adopt and apply quantitative MAFs. These numerical or quantitative functions are referred to in this publication as SQF. Herrick, (2000) discussed five constraints required to validate the functional definition and assessment of soil quality. Those constraints are easily captured and implemented in SQA when SQF are designed and used for SQ ratings.

The constraints include the need for, i) SQI to correlate with ecosystem functions and socio-economic indicators, apart from being able to discriminate between the effect of different management practices, ii) SQA to identify indicators that continue to correlates with ecosystem functions under various ecosystem and disturbance condition, iii) improved soil monitoring systems, iv) encouragement for developing models that allow for feedback between SQI, socio-economic condition, ecosystem performances, and v) capturing soil quality from landscape perspective or spatial dimension. SQF derived from the techniques previously discussed provide justifiable, quantitative and adaptive techniques for achieving the requirements specified by Herrick, (2000).

2.3 Soil quality functions

The development of numerical or analytical techniques for SQI selection, correlation, calibration with defined measures of performance, transformation into SQ index scores, and integration of those scores, has been demonstrated and applied for various agronomic and environmental SQA scenarios (Harris et al., 1996; Andrews and Carroll, 2001; Karlen et al., 2001; Andrews et al., 2002b; Andrews et al., 2004; Karlen, 2004; Weinhold et al., 2006; Bohanec et al., 2007; Jokela et al., 2009). A common feature of those efforts is in the design and use of SQF using various numerical techniques. SQF quantitatively relate SQI values to measures of performance. The most important performance measures depend on what land managers see as the primary need to increase biomass productivity or improve soil nutrient availability for land reclamation. SQF can be expressed as simple or stepwise regression equations, fuzzy logic functions, or process-based models.

As an example of the development and use of typical SQF, a regression equation between soil electrical conductivity (EC) and total soil phosphorus (P) was derived and is shown in Figure 1.2. (Weinhold et al., 2006). This SQF uses cation content to represent P retention and was developed for a coarse-textured mineral soil being salvaged and conserved for reclamation after mining disturbance (Figure 1.2). Electrical conductivity (EC) was selected as the predictive indicator because it represents soil P release from retention by soil cations. Phosphorus concentration, normalized between 0 and 1, was defined as the goal or performance measure and the relationship between EC and total P was fitted using a non-linear curve. This regression curve represents the acceptable trend and published relationship between P retention and potentially available plant P or the extent to which P retention by soil cations controls its availability and release for plant use (Ige et al., 2007). EC not only reflects overall ionic balance in the soil as influenced by concentrations of calcium, magnesium, aluminum, nitrate, phosphate and other ions (Smith et al., 1996), it also reflects the tendency of those ions to control P availability for plant use. Zero designates the lowest SQ score (minimum P availability), while 1.0 represents the highest (maximum P availability) with an assumption that P availability improves the potential for plant P uptake (Figure 1.2). The objective for developing this SQF is to demonstrate the use of a calibrated EC curve as a defendable SQ scoring technique to quantify potential P supplies within a reclaimed soil.

Using the EC correlation function as an example, SQF in its simplest form should be a set of logic functions, with clearly defined boundary conditions (e.g., $0 < EC < 0.4$, dS m^{-1}) to account for site-specific variation in EC. The function should not only be adaptable to similar soil types from different locations or within the same region, it should also fulfill all the required criteria specified by Herrick, (2000). SQF relationships should be valid for specific ecosystem conditions and integrate the most critical processes, preferably a complete set of biological, physical and chemical process relating to a specific soil function, such as phosphorus retention, transformation, or dynamics as in this case. Quality scores produced by SQF are expected to reflect similar significant soil function differences observed in response to different soil management strategies or reclamation practices.

Soil quality functions can be analyzed to define general or critical site-specific SQI thresholds (e.g., EC = 0.4 dS m^{-1} in Fig.1-2). The thresholds are useful for identifying which soils are suitable for land reclamation, especially for planning large scale soil salvage and conservation operations with an emphasis on site-specific soil quality. Another application of SQF in land reclamation is for defining baseline or equivalent soil quality as the basis for evaluating reconstructed soils during the post reconstruction phase of land reclamation. SQF are also useful for low- cost, routine and long term monitoring of SQ by focusing on the use of existing, calibrated and validated SQF, and measuring only predictive SQI values such as EC in this case.

3. Land reclamation operations and soil quality assessment

Many industrial feats and 21st century technology advances are characterized by dependence on development and use of natural resources. Surface oil sands mining within the Athabasca oil sands region (AOSR) in Northeastern Alberta, Canada is one example. A direct consequence of surface mining operations is the need for massive land reclamation that includes soil conservation, landscape and soil profile reconstruction, and revegetation. Reconstruction of soil profile and landscape functionalities requires a soil quality assessment framework (SQAF) to verify and ensure reclaimed soils are actively improving in their ability to perform desired ecological functions. The SQAF will also allow for consistency in assessment and monitoring of SQ during ecosystem re-development. To demonstrate the development and application of such framework with an emphasis on the use of SQF, there is a need to analyze SQA needs associated with all phases of the Alberta oil sands reclamation operation.

3.1 Oil sands reclamation operation and soil quality assessment

There are four major stages of land reclamation related to Alberta oil sands mining operations with significant needs for SQA and monitoring, or potentials for managing soil degradation. The first stage is pre – disturbance assessment during which suitable vadose zone materials for revegetation and geological materials for landscape redesign are excavated and conserved based on SQI defined critical limits and thresholds (Table 1.3). The choice and range of SQI values are bounded by critical limits that optimize a particular measure of ecosystem performance, such as the best SQI range for plant productivity (Alberta Soil Advisory Committee, 1987).

Stage one involves the need to carefully manage moisture in hydric soils to improve access, carryout the excavation and to stockpile suitable soil materials. SQA criteria derived from SQF' thresholds and critical limits are needed to define biological, chemical and physical limits at which soils are suitable for use as cover soil and subsoil at a particular site, thereby meeting the ultimate need for revegetation. The basis for currently adopted criteria in reclamation utilizes generalized, plant specific requirements for cultivated or forest soils (Alberta Soil Advisory Committee, 1987). The generalized criteria are not necessarily suitable for the local plant species such as jack pine (*Pinus banksiana*) and white spruce (*Picea glauca*). Therefore, differences in land use objectives, such as the need to revegetate reconstructed soils with local species, will not allow for efficient use of critical soil limits generated based on agronomic land reclamation needs. In other words, land reclamation objectives and final land use targets, including future revegetation plans, should directly drive which soil functions are defined as critical for the success of the land reclamation and therefore, what is set as the suitable SQI range in stage one.

The initial SQ assessment also needs to develop and test a consistent, transferable and/or adaptable SQAF to define critical, site-specific SQI limits that will be adopted for planning soil conservation operations. One example is the current agronomic assumption regarding the best soil pH for cover soil created using A, B, or C horizon materials, peat or organic materials including forest litter, and/or fibric and humic (LFH) substances. The current pH ranges for LFH materials considered suitable for reconstructing topsoil ranges from 3.5 to 7.5 and from 3.5 to 8 for restoring subsoil, while an optimum pH for supplying nutrients ranges from 6 to 7 (Figure 1.3a). A careful observation of the best range of pH for LFH derived from a dry, coarse textured substrate, growing jack pines on Alberta oil sands ranges from 3.5 to 6. Furthermore, the site-specific, optimum pH range for nutrient supply within these soils ranges from 3.5 to 4.0 based on the potential to exchange cations (Figure 1.3b). These differences point to the discrepancy between SQ criteria defined using generalized assumptions versus actual, site-specific needs. A reliable and consistent SQAF will thus provide greater flexibility in dealing with site-specific SQ issues and complement general SQ guidelines.

Legacy oil sands associated with mines established over decades may need to address material deficit associated with long-term reclamation. Often the volume of earth materials required for full site rehabilitation greatly exceeds what is currently available at the mining site. This potential soil volume deficit may require re-engineering deeper geological substrates as topsoil or ameliorating subsoil materials with the correct organic amendment. This is especially true when parent materials meet the site-specific criteria for either topsoil or subsoil. The soil material deficit also encourages research focused on using geological substrates and overburden

(Pleistocene formation) as components of the reclaimed soil control section or as cover soil, especially when the mines are not prone to acid drainage. The volume of soil material required to meet these legacy mine needs will significantly impact the long term SQA approach. The choice of critical SQI limits for determining the depth and volume of natural soils available for conservation and soil profile reconstruction will be a determining factor. There is also a need to optimize critical limits to ensure the best recovery of suitable soil materials, while also considering site-specific peculiarities. This optimization approach further encourages site-specific SQ management and the need to develop SQ thresholds for dealing with such peculiarities.

The second stage of reclamation involves recreating a healthy soil substrate for revegetation (Table 1.3). This phase uses soil salvaged from the excavation point or segregated stockpiles of LFH, peat, and mineral subsoil for profile reconstruction. The landscape design and relevant cover should target the natural ecosystem which may be upland, wetland or transitional. The design should include an appropriate combination of tree species and surface cover to reproduce the desired ecosystem and consider any potential causes for soil quality degradation during reconstruction and cover placement operations. It should also restore the required hydrological regime needed to develop and sustain the desired ecosystem.

The third stage of mine land reclamation focuses on post-reclamation management to ensure reclaimed landscape, soil, and vegetation are developing toward the required trajectory (Table 1.3). Soil quality monitoring is critical at this phase because reclaimed landscapes are influenced by the same environmental and anthropogenic stresses affecting natural systems. Furthermore, effects of waste streams, such as saline parent material or overburden, sulfur and coke from extraction plants, and soil with bitumen impregnation or tar balls, incorporated into cover and landscape designs on soil functions should be carefully analyzed.

Future land reclamation research and industry applications should include the design and adoption of appropriate SQAF tools to ensure all questions are addressed in a quantitative manner while striving for successful ecological restoration. The critical role of SQA in cover soil design should also be recognized. As an example, an appropriate SQA may be able to delineate the role of soil pH on plant nutrient release and quantify how cover soil roughness affect moisture retention and distribution. Land reclamation specialist with technical knowledge of

SQA will be able to answer those questions by using properly calibrated SQF for design and optimum placement of cover soils to ensure a successful reclamation operation.

The need to identify sensitive, stable and reliable SQI for quantifying the long-term impact of mine waste materials on soil functions is essential (Table 1.2). Critical soil functions, such as nutrient cycling and sorption of heavy metals from waste substrates, are essential at this stage and should be used to develop an appropriate SQAF for long term SQ monitoring within reclaimed landscapes.

The fourth and final stage of reclamation focuses on establishing a functional soil – vegetation system in order to recreate soils with equivalent SQ or capabilities similar to the original, undisturbed natural system. The role of SQA at this stage will be to demonstrate the existence of vibrant soil functions and the vigor required to develop a healthy ecosystem. A well-designed SQ monitoring system, with the capability to demonstrate long term trajectories in SQ improvement during the post-reclamation management stage, will complement current mine closure and certification processes. The SQ improvement based on changes in SQI should also correlate with restoration of soil functions, growth of healthy vegetation or biomass, and ecosystem biodiversity.

3.2 Proposed framework for soil quality assessment in land reclamation

Based on advances in SQA and stages of land reclamation already discussed, a flexible and transferable SQA framework is proposed for the Alberta oil sands reclamation. This tool has also been designed to be adaptable into general land reclamation practice (Figure 1.4). The framework involves a four-step process for defining SQA objectives of SQA, selecting relevant soil functions, indicators and soil relations, determining the numerical design and appropriate indicator transformations for the SQF, and integrating the analyses into a final SQ score. The steps are similar to frameworks previously proposed for other land use applications such as managing forest soil quality (Burger et al., 1999) and agronomic applications (Andrews et al., 2004). The proposed framework provides consistent guidelines for developing SQF and analyzing SQ with an emphasis on the stages of land reclamation presented in Table 1.3.

To design applicable SQF for each land reclamation phase, the first step is to identify the relevant SQI – measures of performance (termed soil relations) for each stage. Table 1.4 presents an objective driven set of land reclamation goals with relevant examples of soil relations. The choice of soil relations will be based on correlation between SQI values and the performance measures. Each SQI should be a routine, measurable, predictive process or property variable identified as a measure of performance for a specific management goal (Figure 1.3).

A SQA example for the pre-disturbance stage is the depth of natural soil which is used to guide excavation and conservation operations, especially for moisture limiting or dry sites. Considering that soil moisture retention is a critical parameter for sites with coarse texture substrates, reclaimed profile designs should reflect the effect of cover soil moisture retention on plant survival and biomass production. SOC, normalized for its moisture retention properties, is a SQI that can be numerically transformed into a baseline function or SQF. The SQF can be validated for site-specific assessment of potential moisture retention. This SOC based SQF, and its threshold parameters, can be used to guide soil salvage or excavation operations based on the quantity of SOC required to maintain a particular moisture level. This SQF can also be used to design reconstructed covers and to analyze long term SQ effects on the potential to retain moisture. Loss of SOC in stockpiled soil due to respiration or oxidation can reduce a soil's capacity to retain moisture. This illustrates a typical scenario and justifies the use of known soil relations when designing SQF to capture site-specific peculiarities.

Guidelines for the proposed SQAF are presented in Figure 1.4, while the existing regulatory framework and data management required for Alberta oil sands reclamation are outlined in Figure 1.5. Once the SQA objective for reclamation is defined, specific soil relations such as pH can be used to provide a site-specific and defendable SQA tool. Baseline data for industrial sites exist in environmental impact assessment documents and can be used as a reliable database for developing such correlation tools. Several other data sources, including the pre-disturbance soil survey and audit programs in the Alberta oil sands industry, also exist within various land reclamation research studies.

Soil quality functions derived from relevant soil relations can be quantified using various numerical transformation techniques (Figure 1.5). Correlating performance measures identified in existing databases can also be normalized to produce SQI values. To further account for site-specific variation in indicators, SQF can be presented as a set of logic functions with defined boundaries. Factors affecting variability in SQI can be identified using soil quality management units based on significantly different groups of indicators, and used to develop SQF for each management unit, provided there is sufficient SQI data to validate each SQF.

Land reclamation provides a unique opportunity for a soil management system, in which data from soils salvaged and analyzed before disturbance can be used to develop SQF that can then serve as the basis for designing soil covers, risk assessment and monitoring the same soil material when subsequently replaced at the same or different landscape position. Those SQF applications are feasible because the fundamental or mechanistic processes driving the soil relations used to develop the SQF are similar before and after disturbance. In other words, the definition of equivalent capability or soil quality is now directly tied to the degree at which reconstructed soils support and reproduce basic fundamental processes such as carbon mineralization, water partitioning, soil moisture retention and nutrient cycling relative to the pre-disturbance condition (Table 1.4).

3.3 Soil quality research gaps in land reclamation

The proposed SQAF in Figure 1.4 emphasizes the development of SQF using simple regression functions or more complex numerical models depending on various factors and complexity of underlying fundamental processes driving the chosen soil relations. Application of SQF for assessment and monitoring of SQ during land reclamation will provide a better scientifically justifiable, quantitative and numerical technique for measuring ecosystem services and rating soil quality. Research gaps that needed to be addressed to adopt the proposed framework include the analysis of SQI and functional relations regarding their variability, stability and the minimum amount of data required to capture all fundamental process that might influence the specific end goal or performance measure.

SQF for different phases of land reclamation operation with the capability to capture relevant ecosystem processes such as nutrient management, moisture retention, vegetative performance and soil resilience need to be developed. SQF using soil to plant productivity relations to define process based equivalent capability functions or baseline SQF as the basis for judging or monitoring reconstructed soils also need to be developed.

Additional research gaps include the need to analyze of soil and landscape effects on SQI and their baseline variation, while defining site-specific, local or regional SQ management units to predict SQF variation. Spatial scale effects in relation to the use of validated SQFs, when adapted to a different site condition with similarity in soil types and fundamental soil processes, should also be researched. Effects of time scale and dynamics on SQI is also critical, especially when biological and microbial indicators are used to design SQF. Quantifying those relationships will support the use of biological indicators to assess the impact of incorporating waste material such as coke and sulphuric materials from mining extraction plants into reclamation covers.

The lack of a comprehensive and consistent SQAF for calibrating soil relations, which sometimes results in the use of different numerical transformation and integration techniques that produce an incomparable and meaningless index of soil quality (Burger et al., 1999), needs to be addressed. Such frameworks need to clearly separate predictive indicators and performance measures (Wander et al., 2002; Bredja et al., 2000a; Bredja et al., 2000b).

Soil quality indexes produced by any numerical transformation technique should be suitable for rigorous statistical analysis while still maintaining their simplicity for defining SQ classes and efficiently integrating multiple functions. SQ indexes need not deviate from the original statistical distribution and interactions that capture relationships between predictive indicators and performance measures. SQF must also account for baseline or site-specific variations in predictive indicators, although this is addressed by developing SQF for delineated soil quality management units. Finally, definitions of critical threshold and limits of SQ should not be generalized or based on expert opinion alone. Such thresholds should quantitatively account for site-specific processes driving all SQA objectives.

4. Conclusions

A major advancement in quantitative SQA is the development and application of numerical techniques within a clear framework for design and use of SQF. The SQF relates predictive indicators of SQ to specific performance measures or management goals. SQF accounts SQI variation and allow for the determination of critical SQA thresholds. Adaptation of quantitative SQ concepts during land reclamation for monitoring and assessment requires a systematic analysis for each stage of land reclamation in order to meet important objectives, functions and soil relations for each phase of the operation. SQF based on widely acknowledged and scientifically validated soil relations between predictive SQI and defined measures of performance need to be carefully designed. Furthermore, a clear, consistent, justifiable and quantitative framework for multi-indicator SQA, SQF will generate SQ ratings with a high level of statistical reliability and thus facilitate comparisons of functionality between natural and reclaimed soils.

Use of SQF derived from baseline or pre-disturbance assessment data will also provide a suitable, quantitative framework for assessing the extent to which land reclamation meet the requirements of equivalent land capability or soil quality. This review regarding the need to develop SQF for various stages of land reclamation operation has identified several research gaps that will require using existing, SQ databases to capture long term trends, variations, and relations in indicators, while defining soil quality management units at regional scales.

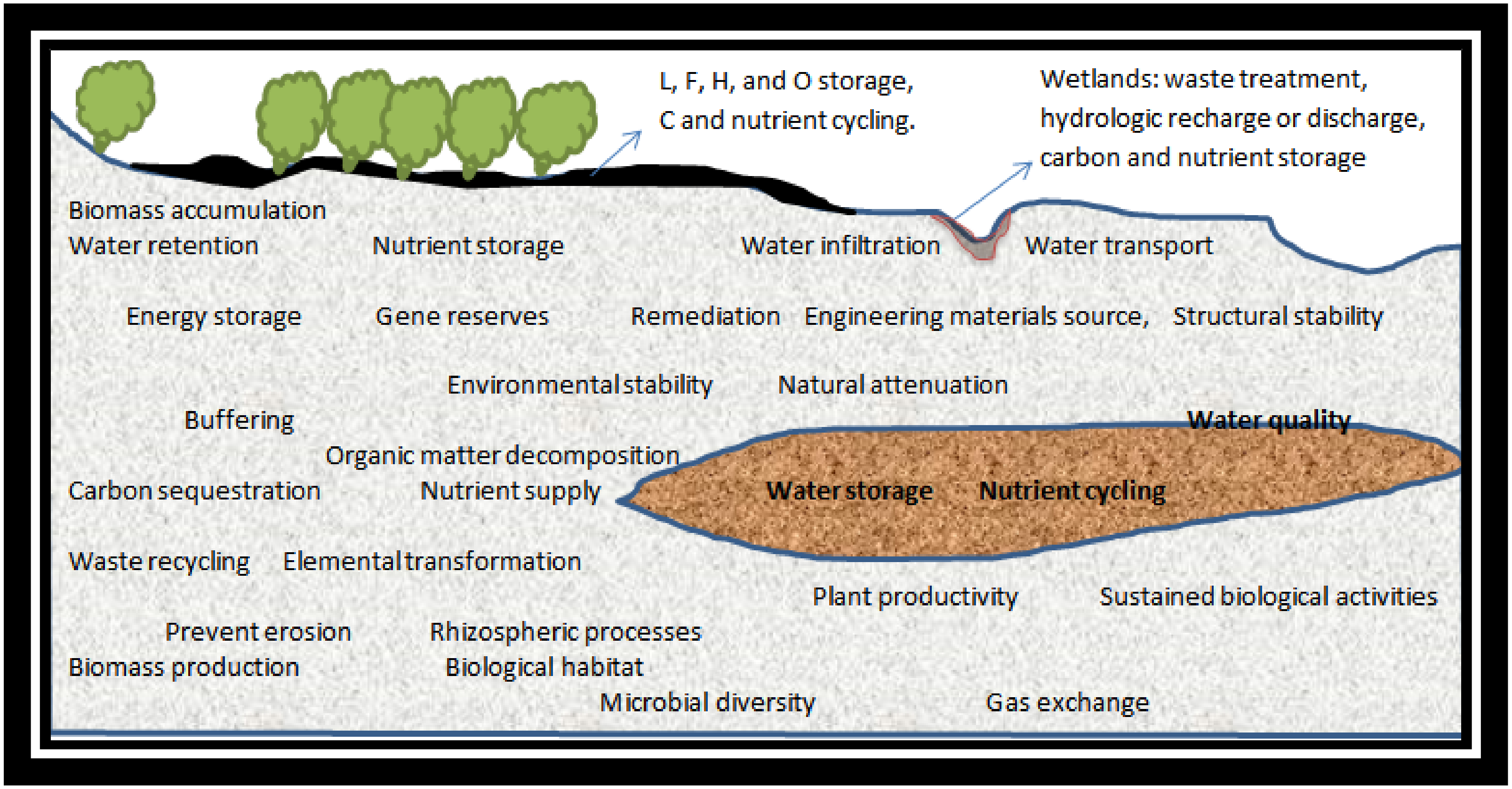

Figure 1.1. Diversity of soil functions in natural and managed ecosystems (Andrews et al., 2004; Saleh et al., 2001; Wasten et al.1997).

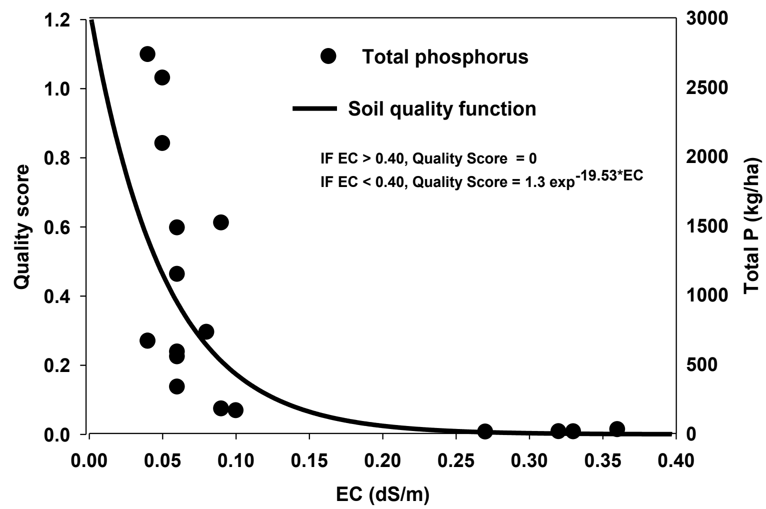

Figure 1.2. A soil quality function designed for assessing site specific potential of phosphorus (P) supply and retention in a coarse textured reclaimed soil using electrical conductivity as predictive indicator of P retention by soil cations to estimate the potential for its release or retention, adapted from Ige et al., 2007 and Macky et al., 2004.

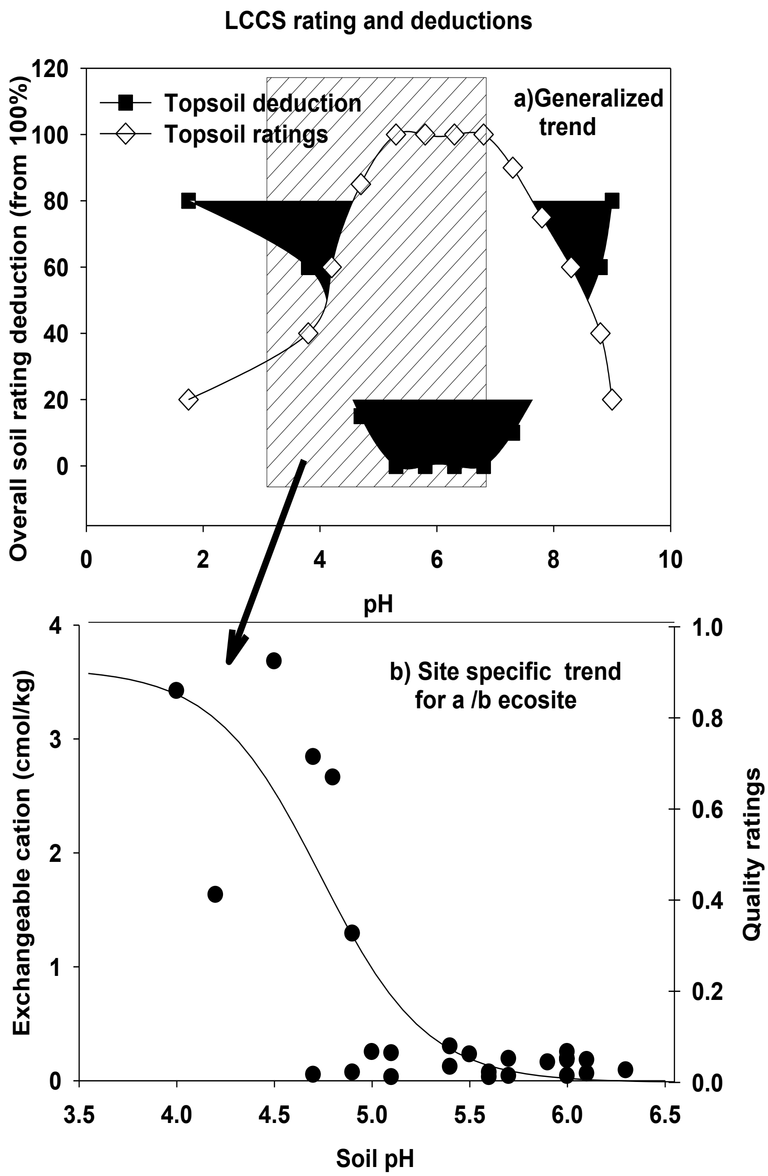

Figure 1.3. Comparison of, a) optimum topsoil (0 to 15-cm) pH range in existing SQ assessment frameworks for oil sands (LCCS rating system), and b) a site specific soil pH analysis for a dry site (a/b ecosites) calibrated based on the potential to exchange cations (Data summarized from Ojekanmi et al. 2012).

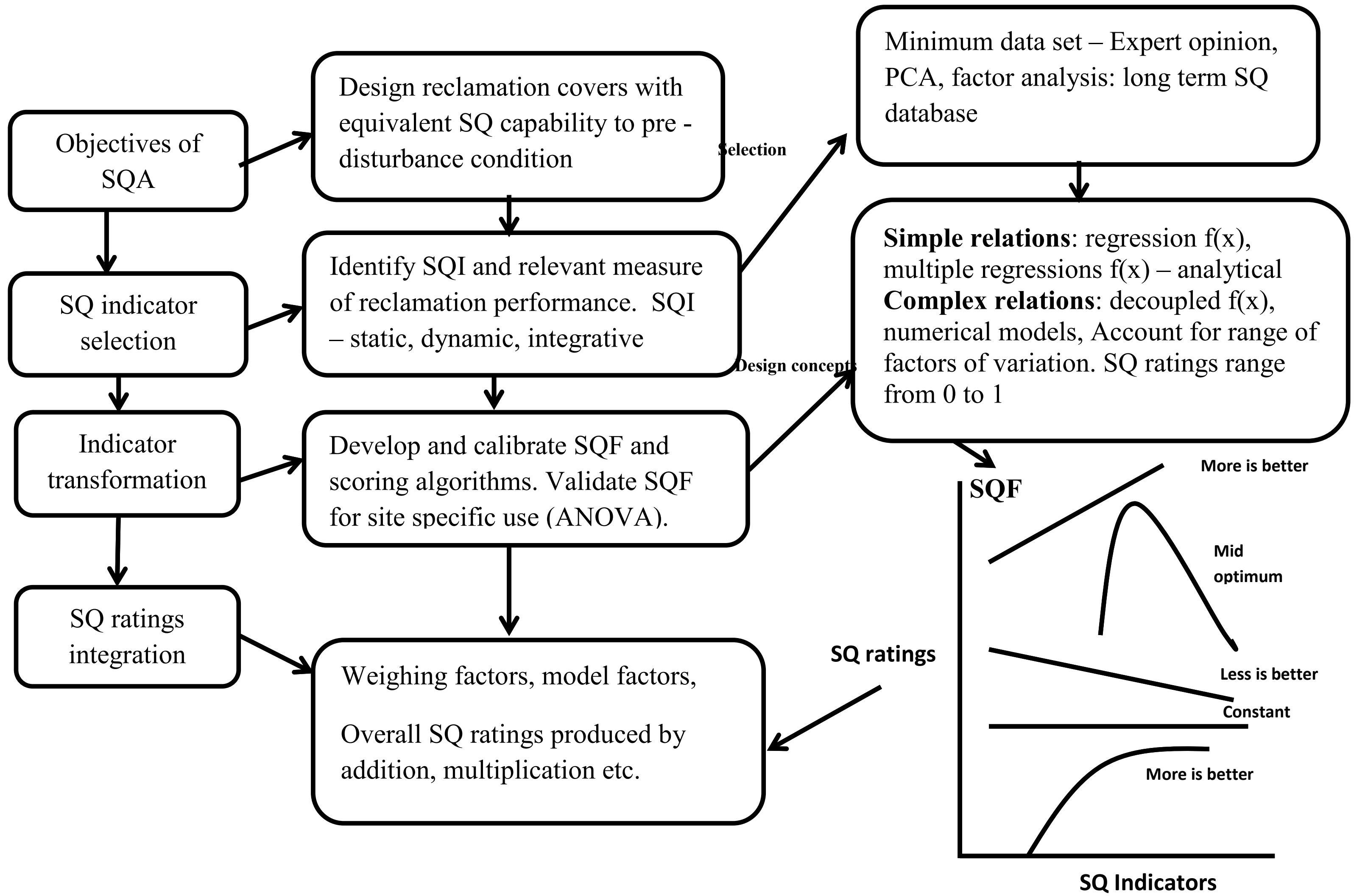

Figure 1.4. Proposed soil quality assessment framework for land reclamation operations.

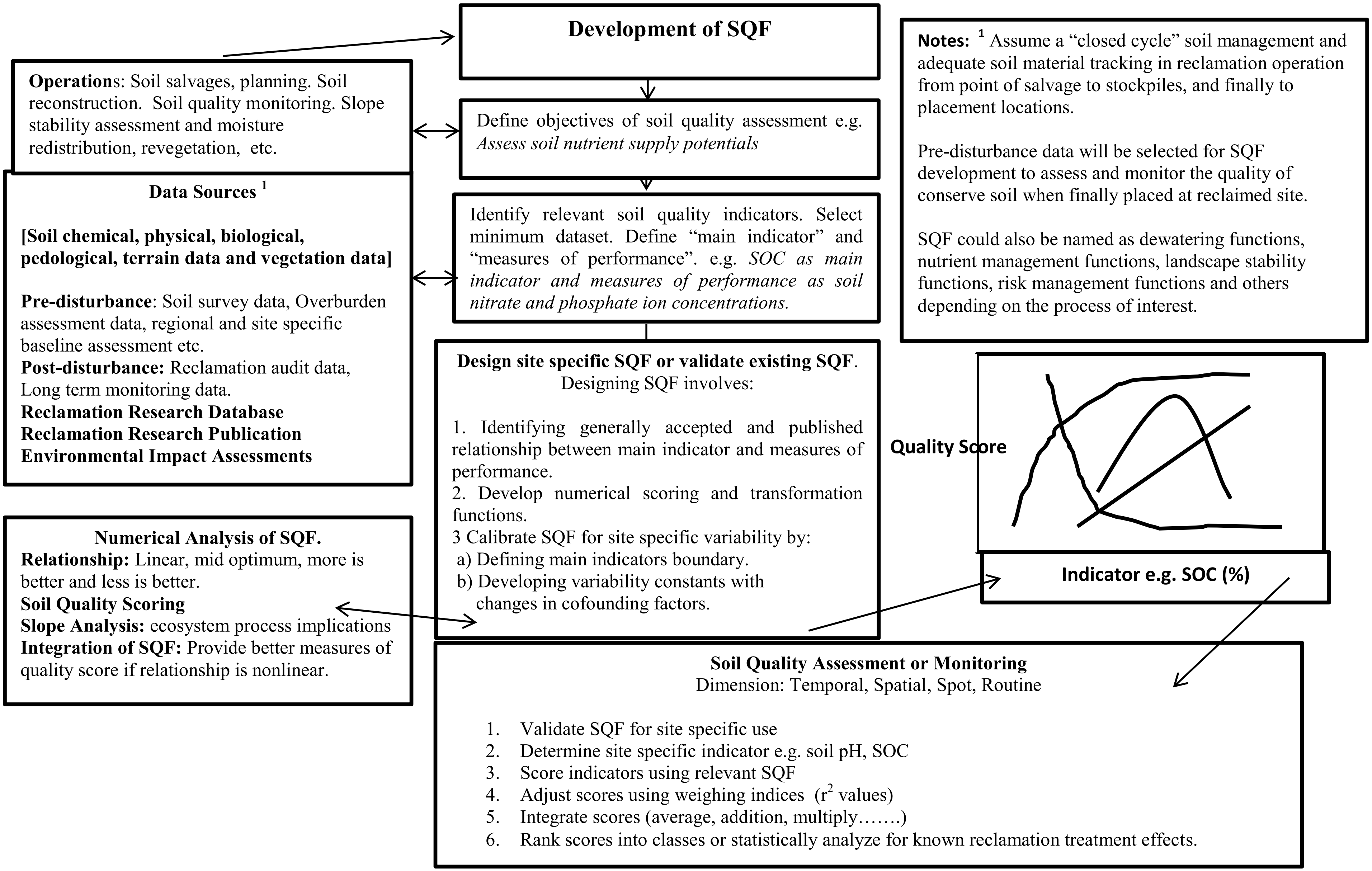

Figure 1.5. Application of the proposed SQA framework based on the existing regulatory framework in oil sands reclamation operation.

Table 1.1. Linkages between soil function and indicators for soil management objectives.

Management objectives	Soil function	Linked SQ indicators	References
Productivity	Nutrient cycling	pH, SOC, nitrogen, phosphorus, cation exchange capacity, bulk density, enzyme activity	Doran and Parkin (1994), Karlen et al. (1996)
	Vegetative productivity	Soil fertility (macro and micro nutrients), plant available water, agro-climatic factors, SOC	Andrew et al. (2002b), Carter (2002)
Ecosystem reconstruction	Landscape process re-establishment	Slope, wetness index, soil texture, water holding capacity, flow path length	Liu et al. (2000) , Sawatsky et al. (1996)
	Engineering material strength and slope stability	Soil texture, moisture content, hydraulic conductivity	Hamner et al. (1999)
Environmental management	Natural attenuation, filtering and buffering of contaminants	Soil texture, bulk density, moisture content, metal and organics , water holding capacity, concentrations, redox potentials, pH, Electrical conductivity	Larson and Pierce (1994), Arshad et al. (1996), Smith and Doran (1996)
	Water quality	Soil chemistry (pH), soil nitrate and metal concentration	Lee et al. (1998), Willis (1995)
	Carbon sequestration and emission	Carbon, nitrogen, soil texture, water filled pore space	Franzluebbers (2009), Andrew et al. (2002b)

Table 1.2. Features of soil properties affecting their selection and use as soil quality indicators. Stability implies comparative measures of variability or repeatability of indicators. Sensitivity implies comparative SQI's response to land use, management practice or a degradation process. Temporal scale implies the time change required to observe a significant change in SQI. Monitoring potential refers to how frequently indicators can be used in temporal soil quality monitoring.

Features of indicators	Soil quality indicators (Probability scale)[a] Dynamic → Static		
	Biological: enzyme activity, microbial biomass, soil biodiversity, soil respiration.	Chemical and soil fertility-related: pH, EC, CEC, Redox condition, Soil C, N and P (kg/ha)[b].	Physical: Bulk density, Porosity, Soil structure, Hydraulic conductivity, Texture, Water filled pore space
Stability or variability	High	Medium	Low
Ease of measurement	More intensive	Very easy	Easy
Sensitivity	High	Medium	Low
Temporal scale	Diurnal	Seasonal	Annual or decades
Monitoring potential	Short term	Medium term	Long term

a The arrangement of soil quality indicators (SQI) in range of biological-chemical-physical only suggest a probability scale of sensitivity of indicators from dynamic to static continuous range. Biological indicators such as respiration have higher probability of reflecting short –term, daily response of changes in SQI, while changes in physical properties also have higher probability of reflect changes as a result of long term and more intense impact of soil degradation processes.

b EC is electrical conductivity, CEC is soil cation exchange capacity and Soil C, N and P implies soil carbon, nitrogen and phosphorus.

Table 1.3. Stages of land reclamation operation and related soil quality assessment needs.

Stages	Reclamation operation	Objectives	Soil quality implications
1	Pre-disturbance soil assessment	Determine suitable soil distribution, volume and depth to support soil salvage	SQA due to chemistry of parent material, hydrology, land use history, wetland and water quality issues etc.
	Landscape water management	Improve soil strength for trafficability and ease of excavation	Loss of dissolved nutrient through drainage. Changes to fen chemistry and nutrient by redirecting water flow.
	Soil salvage	Excavate suitable reclamation materials	Soil compaction, nutrient loss, wet soil issues and drainage, decomposition of organic matter, mixing with unsuitable soil, etc.
	Stockpiling	Temporarily conserve suitable soil before re-placement	Potential for excessive organic deposition, carbon oxidation, nutrient leaching, soil material mixing, saline groundwater intrusion, compaction and soil volume loss, etc.
2	Landscape design	Recreate suitable surface for drainage and geotechnical stable substrate to support reclamation covers.	Compaction, source of salt for diffusion into cover soil, creates hard pan and impermeable layers, slope stability, potential for erosion.
	Soil placement	Replace subsoil and cover soil to required depth	Compaction, salinization, loss of plant propagules, soil nutrient loss, shallow depth for rooting.
	Re-vegetation	Replace forest by planting seedlings	Excessive fertilizer application can change soil chemistry or consequently cause nutrient element loss.
3	Reclamation management	Manage post reclamation issues and audits	Plant mortality, moisture deficiency, erosion, loss of cover soil, impact of process affected water, coke, sulphur on soil and plant response, stress factors.
4	Closure and certification	Landscape and ecosystem integration	Potential for contaminant loading, slope failure, analysis and management of seepage, restoration of groundwater regime, and others.

Table 1.4. Stages of reclamation operation and relevant soil relations that form the basis for the development of soil quality functions. Note that objectives of reclamation operations vary at different stages of reclamation operation. Soil relations also represent "main indicator – measure of performance" relations.

	Stages of reclamation			
	Pre-disturbance	Post-disturbance	Risk management	Closure & certification
Reclamation Operations	Wetland water management. Soil sampling, analysis and quality assessment. Soil salvage and stockpiling. Identify suitable soils.	Landscape design and construction. Cover soil placement. Drainage design. Revegetation.	Soil placement audit and quality monitoring. Slope stability and erosion assessment. Manage salt and contaminant flux	Analysis of long term soil quality and vegetation monitoring data.
Objectives	Dewater hydric soils. Identify suitable soils. Conserve soil quality.	Design stable landscape Design suitable covers Use appropriate plants	Manage soil nutrient and moisture supply, erosion control and remediation of salts and mining wastes affected materials.	Demonstrate long term soil quality improvement accompanied with vegetation performance to equivalent capability
Soil relations and functions	Soil texture, slope – water retention. Soil carbon – nutrient supply. Soil texture – plant available water relations.	Slope position, texture – moisture retention. Soil texture – erosivity, Soil fertility – biomass. Soil moisture - biomass	Soil carbon – nutrient, Soil pH – salt relations, Soil enzyme activity and pH – metal content.	Soil chemistry, fertility – biomass relations. Site index – tree height, volume and biomass.[3]
Fundamental processes	Carbon mineralization, soil moisture partitioning and water retention	Plant water use, water transport, soil moisture partitioning, shear strength-soil moisture relations	Carbon accumulation, decomposition and transformation. Nutrient cycling.	Plant nutrients and water use efficiency.

Chapter 2 Development, Calibration, Validation and Application of Soil Quality Functions in Land Reclamation: Soil Quality Assessment for Peat–Mineral Mix Coversoil Used in Oil Sands Reclamation

1. Introduction

After surface mining, land reclamation operations using conserved topsoils are required to ensure appropriate vegetative growth and long-term sustainable use of land resources. A critical factor affecting the success of environmental restoration or land reclamation initiatives is the quality of conserved soil materials and their capability to sustain healthy plant communities (Alberta Soil Advisory Committee, 1987; Turcotte et al., 2009). Natural soils reflect the historical development of ecosystems, as impacted by factors such as the geology, climate and vegetation that grows on the soil. Therefore, the quality of soils conserved for reclamation operations should to some extent reflect the soil quality (SQ) variables and functionalities that existed pre-mining. As such, reclaimed soils may require further management in its new placement location, assuming a different set of ecosystem factors will be in effect to achieve similar success in ecosystem development (Burton et al., 2011). This suggests the need to develop a cost effective and adaptable SQ management framework to support large scale soil reconstruction operations.

An important soil management practice in oil sands reclamation in Alberta, Canada, is the use of peat-mineral soil mix (PMM) as cover soils for land reclamation (Hemstock, 2008; Moskal, 1999). This involves the mixing of humic, mesic and fibric forms of peat materials with generally sandy mineral soils, collected either from tailings extraction processes or the B horizons of Eluviated Dystric Brunisols (Soil Classification Working Group, 1998), equivalent to a Dystric Cryochrept in the USDA soil classification system (Soil Survey Staff, 1999) or a Dystric Cambisol in the FAO soil classification system (WRB, 2006). Previous studies reported the benefit of PMM in improving soil physical, chemical and biological properties, thereby supporting the nutrient and water demand of various tree species planted on the reclaimed landscape (Shaughnessy, 2010). Improvements in nutrient cycling, water holding capacity, cation exchange capacity (CEC) and microbial activities in the soil after PMM amendment are mostly related to the increase in soil organic carbon (SOC), in comparison to straight sandy or peat soil materials used for land reclamation (Fedkenheuer et al., 1979; Hemstock, 2008; Kong et al., 1980; Moskal, 1999).

The application of PMM in land reclamation has also been found to improve soil moisture retention parameters such as increasing available water holding capacity (AWHC) and soil moisture content. The PMM also influences soil fertility by enhancing soil nitrogen dynamics, thereby increasing forest productivity (Hemstock, 2008; Moskal, 1999). Turcotte et al. (2009) examined soil organic matter quality in northern Alberta's oil sands reclamation area and observed that organic matter status in reconstructed soils were directly linked to time since landscape reconstruction and can serve as a reliable SQ monitoring parameter. Soil organic carbon in peat material stockpiled for reclamation placement was also found to highly correlate with other SQ parameters such as nitrogen content, microbial respiration rate, enzyme activities, CEC, bulk density, pore volume, and soil water retention capacity (Kong et al., 1980).

A requirement for the design of a SQ management and assessment framework (SQMAF) involves the identification of a set of minimum, quantitative and readily available data that represents the soil functions of interest (Carter, 2002; Arshad and Martin, 2002; Doran and Parkin, 1994; Wander et al., 2002).This includes parameters showing measurable responses to changes in management, climate and edaphic factors (Andrews et al., 2004; Doran and Parkin, 1994; Doran and Parkin, 1996). Also of interest are the specific SQ indicators that can be easily measured with minimal cost and have the capability to integrate a variety of other soil physical, chemical and biological processes that affect SQ in different ecosystems (Brejda et al., 2000a and 2000b).

Recent efforts in the development of SQMAF recognized that SQ indicators that correlate with other measures of ecosystem or agronomic performance should be calibrated against specific goal parameters (Janzen et al., 1992). Furthermore, there are emphasis on the establishment of linear and non–linear SQ algorithms which are otherwise called soil quality-scoring functions (SQF), to serve diverse agronomic and environmental objectives (Andrews et al., 2004; Arshad and Martin, 2002; Idowu et al., 2008; Karlen et al., 2001). Soil quality functions integrate soil properties representing desirable soil functionalities into a central indicator and end point measures or measures of performance. The central or main indicator usually correlates strongly with relevant measures of performance, thereby providing the potential for SQ prediction using mathematical models.

Soil quality functions can be focused on relatively static SQ indicators such as those used in land capability assessment with more emphasis on pedological properties, especially factors such as soil texture, which translates to available water holding capacity that are related to soil formation and pedogenesis (Leskiw, 1998). SQF can also incorporate dynamic SQ indicators in typically non-linear scoring algorithms, providing the opportunity to assess SQ changes in temporal and spatial scales (Andrews et al., 2004; Andrews and Carroll, 2001). A major advantage of using SQ assessment and rating algorithms is the ability to conduct a multi-indicator assessment based on the relationship between representative quality indicators, e.g., SOC and a large number of other performance indicators. The SQF can be validated and adapted for other site-specific assessments, with the ability to statistically analyze the quality ratings for new sites, similar to designed experiments that examine treatment effects on measures of SQ indicators.

In order to ensure that reclaimed soils and ecosystems develop towards fully functional ecosystems with healthy soils that support productive vegetation, there is a need to develop SQF or scoring functions from pre-disturbance soil data, validate the SQF for reconstructed soils and eventually use the validated SQF to assess or monitor the quality of reclaimed soils. The objectives of this research are i) to demonstrate the development of non-linear SQF that integrates measures of performance for PMM, using SQ parameters available in datasets established in the oil sands region in Alberta, ii) to validate the SQF on PMM using independent datasets, and iii) to briefly demonstrate a practical application of the SQF in SQ monitoring for land reclamation in the oil sands in Alberta, Canada.

2.0 Materials and methods

The development of SQF is a data intensive process that involves relating measures of performance such as crop yield, tree growth and soil biodiversity to a set of SQ indicators such as soil fertility, nutrient supply potentials, soil moisture retention characteristics and other indicators of environmental quality that best represent a specific ecosystem of interest. Such datasets and their inter-relations is expected to agree with the generally accepted or published relationships between SQ indicators and measures of performance, within randomly sampled data points that sufficiently capture the observed variability in a local or regional ecosystem of interest. In this study, various sources of data that reported soil physical and chemical properties of peat, natural sandy textured soils, tailings sand and PMM materials were compiled from the existing literature on oil sands reclamation research (Moskal, 1999; Macyk et al., 1995; Macyk, 2009; McGill et al., 1980; Logan, 1978).

All data used in the SQF development were derived from a study that examined the effect of PMM on overall SQ in reclaimed oil sands mines. Macyk et al. (1995) investigated the effect of mixing sandy mineral soils from A and B_m horizons of Brunisols (natural soil) and tailings sand with peat materials at various stages of decomposition. Treatment rates of 10, 30 and 50% by mass of peat was mixed with mineral soils and coarse textured tailings sand to determine the effects of the rate of mixing on overall soil physical and chemical properties. The mineral soils, tailings sand and peat were all collected in the Aurora region of the Regional Municipality of Wood Buffalo and in the related mines before disturbance occurred. Soil physical and chemical properties from this study were compiled into a database. The data include SOC and nitrogen concentrations measured using LECO CN-2000 CNS Analyzer (LECO Corporation, 1993). Soil pH (1:1) was measured in saturated water paste (Doughty, 1941). Plant available nutrients were determined using the DTPA-NH_4HCO_3 extraction technique (Soltanpour, 1981), CEC and extractable ions were measured by extracting the soil with a 1 M ammonium acetate solution at pH 7 (Holmgren et al., 1997), with elemental concentrations in the extracts measured using an inductively coupled plasma atomic emission spectrophotometry (ICP-AES). Sodium adsorption ratio (SAR) was calculated based on soluble ion concentrations in saturated paste extracts (USDA, 1954), with elemental concentrations measured using ICP-AES. Electrical conductivity of the saturated paste was measured using an EC meter. Total elemental concentrations in soil samples were further determined using ICP-AES after the samples were digested at 425 °C with 1.5 mL of concentrated HNO_3, 4.5 mL of concentrated HCl and 10 mL of concentrated HF for 10 minutes at 100 percent power in a microwave digestion system (CEM Corporation Systems). Soil physical properties measured include bulk density and gravimetric moisture content. Field capacity (FC) and permanent wilting point (PWP) were determined by measuring the gravimetric moisture content at 0.3 and 15 bar of soil water potential or suction (Mckeague, 1978).

The compiled SQ data from Macyk et al. (1995) were analyzed using Pearson correlation analysis. A selected subset of the compiled dataset was further used to generate nonlinear scoring functions or SQF that relate SOC to various soil properties of interest that represent measures of performance. The measures of performance were selected based on the defined objectives of the soil quality assessment (SQA). McGill et al. (1980), Moskal (1999), Logan (1978) and Macyk et al. (2004) provided additional data on PMM for validating the SQF and to test the applicability in a long term SQ monitoring scenario for oil sands reclamation operations. Moskal (1999) examined the effect of peat-mineral soil mixing on soil FC, PWP and gravimetric moisture content using a combination of pressure plate analysis at 0.1 MPa (FC), 1.5 MPa (PWP) and Walkley-Black digestion technique (Nelson and Sommers, 1986) to determine the SOC content of the PMM. McGill et al. (1980) and Logan (1978) examined the nutrient supply potential and fertility of tailings sand, B horizons of Brunisols and peat materials using similar analytical methods as reported in Macyk et al. (2004).

2.1 Selection of quality indicators and the minimum datasets

In order to select the most important indicators or a minimum number of datasets that capture and explain the responses observed in a typical reclamation operation involving PMM, the objective for the SQA was focused on identifying SQ indicators that integrate PMM capability to supply essential plant nutrients, monitor the potential for increasing the sodium content of the mixed peat and mineral soils, retain essential cations and supply moisture for plants. Datasets related to these objectives were selected and normalized to generate soil quality rating functions.

The SOC was highly correlated ($P < 0.05$) with soil quality parameters of a large group of PMMs (Table 2.1, n =15), confirming that SOC is a very important parameter explaining most of the SQ indicators related to the defined SQA objectives (Brejda et al., 2000a; Brejda et al., 2000b). The relationship between SOC and other quality indicators is widely acknowledged in the literature. In addition, many regional and site-specific SQ studies recognized the critical role of changes in SOC on the overall quality ratings of different types of soils (Chaer et al., 2009; Chatterjee and Lal, 2009; Haynes, 2005; Keller et al., 2004; Zaujec, 2001; Arshad and Martin, 2002).

2.2 Development, calibration, validation and application of SQF

Soil quality algorithms were developed using the method described in Weinhold et al. (2009) by regressing SOC (g kg^{-1}) to properties of PMM that indicate its capacity to i) retain moisture (FC, PWP and AWHC, in %), ii) exchange cations (CEC), iii) monitor sodicity (SAR), and iv) supply essential plant nutrients (total nitrogen and phosphorus, mg kg^{-1} of soil). Curve Expert Professional (version 1.5), a curve fitting and data analysis software with about 300 built-in and custom regression functions was used for regression of SOC to selected measures of performance. Non–linear regression models were fitted to the data to relate SOC to each of the parameters that represent SQ. The SQ indicators were normalized between 0 and 1, where 0 and 1 represent the possible minimum and maximum quality scores for each SQ indicator in this site specific analysis. The regression model with the highest r^2 value and related regression constants (a, b, c, d) were selected as the final SQF parameters. The r^2 value reported for the regression was defined as a z-factor for use as a weighing factor in the quality score integration process.

To assess the validity of the SQF capability in rating SQ, independent datasets from McGill et al. (1980), Moskal (1999) and Logan (1978) were analyzed. Moskal (1999) tested the effects of peat-mineral mixing at mass ratios of 3:1, 1:1, 1:3 and 0:1 of peat to mineral soil on FC, PWP and AWHC. Corresponding SOC for each level of treatment was reported in 3 replications. To validate the SQF, the SOC data was used as input into the soil quality algorithms developed for rating FC, PWP and AWHC, thereby producing the corresponding quality scores. The output quality scores ranging from 0 to 1 and reported value of the original quality indicators data (FC, PWP, AWHC) were both tested for the rate of treatment effect using one way ANOVA. The SQF performance was judged based on its capability to repeat the same mean differences (significant or not significant) observed in the experimental FC, PWP and AWHC data (Weinhold et al., 2009). The overall r^2 value of the ANOVA for the quality scores was defined as the m-FC factor, another weighing factor for the final quality score.

McGill et al. (1980) and Logan (1978) also analyzed the effect of soil material types including peat, B_m horizon of sandy Brunisols and tailings sands on nutrient supply potentials for plants. This study also reported SOC, total nitrogen and CEC data for each of the material types. Similar to the previous validation process, the SOC data was used as an input into the SQF to rate nitrogen supply and CEC. Output scores, reported nitrogen (%) and CEC data were further analyzed for the material type effect using ANOVA. The SQF for rating nitrogen and cation supply potential were further evaluated by the capability of its output ratings to repeat the same mean differences (significant or non-significant) observed in the original experimental data.

Finally, to demonstrate the applicability of the validated SQF in land reclamation, soil quality monitoring data in a long-term database (Macyk, 2004) were rated using the SOC data.

The study reported a maximum of 10 to 20 g kg^{-1} change in SOC over 10-15 years of SQ monitoring for reclamation profiles in oil sands reclamation. A SQ rating for each of the 7 functions was determined using a maximum SOC of 20 g kg^{-1} to produce 7 different ratings for each of the SQA's objectives represented by each of the SQF. The overall rating was determined by averaging the 7 ratings. Potential application of the SQF in the design of reclamation cover with PMM, based on specific criteria required to sustain plant productivity in land reclamation, was further discussed. A concise summary of the SQ analysis, sources of data, rationale for the SQ analysis and references for selected indicators in this study are presented in Table 2.2.

2.3 Statistical analysis

All statistical analyses on the soil quality data were performed in MINITAB 16 (LEAD Technologies Inc. 2011 Version). Pearson correlation between SOC and other measures of soil quality, including FC, PWP, AWHC, CEC, DTPA extractable elements, SAR, EC and total element concentrations, were analyzed. The effect of rates of peat mixing with mineral soil on the physical, chemical and fertility parameters of PMM were tested using the Tukey method of mean comparison. To validate the SQF, one way ANOVAs were conducted to test specific effects of rates of PMM on FC, PWP, AWHC, nitrogen and CEC for the 2 independent sets of validation datasets on quality ratings. In all cases rates of PMM and soil material types were treated as the independent variable while FC, PWP, AWHC, nitrogen, CEC and respective quality scores were treated as dependent variables.

3.0 Results and discussion

3.1 Effects of peat-mineral mixing on soil quality indicators

Physical properties of PMM including its soil moisture retention characteristics improved with increasing proportion of peat or increasing SOC content (Figure 2.1). The FC, PWP and AWHC of peat materials were significantly greater (p<0.05) than that of B_m horizon of Brunisols (natural sandy soil) or tailings sand (Figure 2.1a). Mixing of mineral soil with 10, 30 and 50% peat by weight increased SOC between 5.0 and 35 g kg^{-1}. The FC, PWP and AWHC also increased with increasing SOC content (Figure 2.1b). Bulk density declined from 1.4 to 0.7 with increasing SOC (Table 2.3). Other soil quality investigations have reported similar relationship between SOC and water retention property (Rawls et al., 2003; Zhuang et al., 2008). Rawls (2003) reported significant improvement in the ability of pedotransfer functions to predict soil moisture content when SOC or organic matter content was incorporated into the pedotransfer functions as an independent variable. Dexter (2004) also noticed that organic-clay complexes were influenced by SOC in forest soils which invariably impacted soil water retention capability or available water holding capacity.

Measures of soil fertility such as total soil nitrogen also increased with increasing proportion of peat in the mixture (Figure 2.2). Cation exchange capacity increased from 1.7 to 10.1 by increased mixing of peat from 10 to 50%, while DTPA extractable iron (Fe), phosphorus (P), potassium (K) and sodium (Na) generally increased with increasing SOC (Table 2.3). Exchangeable Ca and Mg also increased with increasing SOC. Electrical conductivity was not affected by mixing with peat, while saturated paste Ca and Mg concentrations increased with increasing SOC. The trend observed here is consistent with other studies in which increasing SOC improve measures of soil fertility (Fu et al., 2011; Lal, 2001; Trinchera et al., 2001).

Mixing of peat with B_m horizons of Brunisols or tailings sand generally increased total nutrient concentrations. Brunisolic B_m horizons are sources for phosphorus based on the DTPA extractable P and total P data, while all other elements were from the peat material. The significant differences observed in the total P and DTPA extractable P concentrations of Brunisols (natural sandy soils), tailing sands and peat are of interest. Soils from the B horizon of sandy Brunisols with high extractable P have a significant advantage over tailings sand in the design of PMM. They can be a significant source of both extractable and total P than tailings sand (Table 2.3). Brunisols also have higher concentrations of P sorption elements such as Ca, Mg, Al and Fe. The reported and summarized pH data show that peat materials and mineral soils had a slightly acidic pH, tailings sands were slightly alkaline and PMM was close to neutral pH (Table 2.3). Mixing peat with mineral soils therefore makes soil nutrients more available for plant uptake, since nutrients increasingly become more available in soils within the neutral range of pH with few exceptions (Smeck et al., 1971; Okruszko et al., 1962; Bray, 1938; Liang and Chang, 2004).

3.2 Soil quality rating functions

To assess the SQ implications of land reclamation practices such as the use of PMM, a sigmoid function between SOC and transformed scores of SQ indicators (selected measures of performance) were fitted and this represents a “more is better” relationship between the SOC and normalized performance measures (Figure 2.3). The functions capture site specific variability between 0 and 35 g kg^{-1} of SOC with increasing SQ scores. This is consistent with the SOC relationships reported by Andrew et al. (2004) in the development of soil management assessment framework, in which the higher the SOC content, the better the SQ within the range of carbon content relevant to a specific site.

Tailings sand could potentially have high sodium concentrations due to the use of NaOH in the oil sands extraction process thereby increasing its SAR. The effect of mixing tailings sand with peat on sodium content of the mixture as measured using SAR seems to be the most sensitive quality function, in which a 10 g kg^{-1} change in SOC of the PMM resulted in the best soil material possible based on quality rating of 0.8, which is close to the maximum possible score of 1 (Figure 2.3). This is best explained by the fact that the tailings sand used in this site specific situation have very low sodium content. Therefore, mixing the soil materials in this case does not result in significantly higher total or exchangeable Na (Table 2.3).The mixing of peat (SAR = 0.6, EC = 2.42 dS m^{-1}) with mineral soil materials (SAR = 0.5– 6.7, EC = 0.09 – 0.49 dS m^{-1}) resulted in a range of EC (0.81 -1.91 dS m^{-1}) and SAR (1.0 - 2.6), thereby reducing the sodicity in the PMM to a range which is better suited for use as a reclamation coversoil (Table 2.3). The range of EC and SAR observed in the PMM materials also correlates with the accepted range required to support a non-saline boreal forest species, with the critical limits for EC and SAR generally considered to be at 4 and 10 dS m^{-1}, respectively, for good quality reclamation materials (Purdy et al., 2005; Macyk et al., 1987; Lilles et al., 2010).

The rate at which SQ improvement occurs with increasing SOC $(\partial(qualityscore)|\partial(SOC))$ was faster with SAR (steeper slope) than with other quality parameters (Figure 2.3). Generally speaking, differences observed in the trend and rate of change in quality scores in relation to changes in SOC suggests that the underlying mechanism for the observed SQ response might be due to the dilution effect of the component soil materials or chemical transformation process due to the changes in soil chemistry (*i.e.*, pH).

The regression equations and related constants in Table 2.4 indicated that most of the non–linear regression functions have an r^2 value ranging between 0.7 and 0.9, except for SAR. The r^2 values represent the extent to which SOC predicts the observed measures of quality performance and therefore can be used as a weighing factor (z) for the output quality scores. Weinhold et al. (2009) and Andrews et al. (2004) also demonstrated the importance of weighing factors in SQ rating conducted using the soil management and assessment framework. This study further demonstrates that weighing index can compensate for the effect of other underlying factors and processes affecting the relationship between SOC and selected measures of performance, as represented by the overall r^2 reported for the SQF validation. In situations where the SQF was designed with its reported r^2 (z factor) during regression or multiple regression analysis and further validated using an independent sets of data, such as using ANOVA with its reported r^2 (m factor), both z and m factors can serve as combined weighing factors for the final quality scores.

Overall, the most responsive SQ change was observed within the mid-range of SOC around 15 to 22.5 g kg^{-1} with the highest around 25 to 30 g kg^{-1} for all the SQF (Figure 2.3). The SQF were applicable only for soils with SOC ranging up to 35 g kg^{-1} while SOC greater than 35 g kg^{-1} was rated 1 for this site. The range of SOC reported in this study was because of the peat materials used in the study which were sourced from Brunisolic soils with dry A horizon and peat overlaying a coarse texture B to C horizon, and growing coniferous species such as jack pine (*Pinus banksiana*).

The SQF designed in this study uses SOC as the main input parameter, providing a numerical framework to model and calibrate soil quality improvement in oil sands reclamation. The SQF will provides a quantitative technique to assess SQ using justifiable weighing factors rather than using weighing factors based on expert opinion. Existing SQA and land capability rating techniques for oil sands reclamation rely mainly on soil nutrient and moisture indicators (Leskiw, 1998). The soil moisture ratings receive a weighing of 80% of the overall score, while soil nutrient ratings for the remaining 20%. The selection and use of these weighing factors was based on expert opinion (Leskiw, 1998) which may create bias in SQ ratings unlike the use and integration of weighing factors generated in SQF development that are derived from statistical models.

3.3 Validation of soil quality functions

Table 2.5 presents the results of the statistical validation of the soil quality models or SQF capturing the changes in SOC as an indicator of changes in soil moisture retention capacity, based on the PMM experiment in Moskal (1999). Increasing peat composition from 0 to 75% of soil total mass resulted in the FC increasing from 8.2 to 39.7% which corresponds to improvement in SQ ratings from 0.1 to about 1 ($P < 0.05$). Both PWP and AWHC also increased ($P < 0.05$) in SQ ratings (Table 2.5). The significant change in moisture retention parameters due to 4 levels of peat mixing was also captured by the corresponding changes in SQ ratings. The SQF performed well in producing statistically justifiable ratings similar to the effect of PMM addition rate on FC, PWP and AWHC. About 78 to 97% of the effects of PMM on soil moisture retention parameters were also captured by the quality rating functions, based on the adjusted r^2 value (Table 2.5). This indicates that SOC is a reliable predictor of SQ and that the quality ratings produced by the SQF are free of bias, confirming the concept that soil organic matter is a crucial soil factor that affects the dynamics of soil water retention (Rawls et al., 2003; Zhuang et al., 2008).

The SQF developed using SOC as an input variable was also able to differentiate among peat, tailings sand and sandy materials in terms of their capability to supply nitrogen and exchangeable cations (Table 2.6). Overall, the SQ ratings explained up to 90% of the effects of the different soil material types on the selected soil fertility parameters.

The m-factor (adjusted r^2) explains the extent to which the designed SQF is suitable in analyzing SQ parameters from other reclamation placements practices with similar soil types (PMM). A high m value (close to 100 %) strongly justifies the use of the SQF developed from natural or pre-reclamation soil data as the basis for assessing the quality of reclaimed soils that have similar pedogenetic history or material types. In other words, changes in SOC of natural soils that were conserved and then used for land reclamation capture the SQ change in moisture retention, soil fertility and cation exchange capabilities. The extent of change in SQ can be determined using calibration curves between SOC and the measure of soil quality. The SQF also enables the calibration of SQ indicators against selected measures of quality, end point measures, or measures of ecosystem services. Using SQF to rate soils has a numerical advantage in its ability to capture variations in pre-disturbance SQ indicators, thereby ensuring that comparison of SQ indicators before and after reclamation captures all the potential variability or effect of other confounding factors in baseline soils.

3.4 Integration and applications of quality functions

Multi–indicator assessment and rating of SQ are usually based on the use of more than one SQ indicator to ensure that all relevant mechanistic processes related to soil functions of interest are captured. This suggests the need for quantitative techniques for integrating SQ scores determined using SQF. Different methods of SQ score integration discussed in the literature include combined averaging and weighing techniques (Andrews et al., 2004). Score averaging techniques can be applied to routine field SQ assessment where there is a need to infer the quality of reclaimed soil for soil management. Weighing techniques that further integrate m, z and other justifiable weighing factors into the final quality scores will be desirable, considering the need to demonstrate a more rigorous and conservative SQ assessment for regulatory compliance.

To demonstrate the practical application of the soil quality models or SQF, the long term study on carbon and nitrogen dynamics in PMM published by Macyk et al. (2004) was used to determine the typical changes in reclaimed SOC. This study reported a 10 to 20 g kg^{-1} decline in the SOC level in PMM over 10-15 years, corresponding to an average of 0.5 reduction in quality ratings based on the SQF established in this study (Figure 2.3).This illustrate the need to effectively manage soil nutrient and moisture availability in land reclamation to ensure overall quality improvement with time, especially during the initial phase of soil placement and re-vegetation.

Soil management practices in reclamation operations such as soil salvage, stockpiling and further preparation for re-vegetation increases carbon loss due to mechanical manipulation and soil exposure, causing oxidation of the reactive forms of carbon in the soil (Drozdowski et al., 2010). This suggests the need for SQ monitoring and management of reclaimed soils to ensure adequate nutrient supply and moisture retention to sustain a productive ecosystem. In a productive ecosystem, the return of plant litter to the soil surface enhances nutrient cycling in the later years of reclamation (Drozdowski et al., 2010; Arevalo et al., 2012). Therefore, monitoring SOC levels and related quality rating will be critical in the initial years of reclamation when there is minimal or no input of carbon through litter fall or lack of active nutrient cycling processes.

One of the potential applications of SQF in land reclamation is to use SOC to identify maximum soil salvage depth for coversoils in soil conservation operations or to design specific type of reclamation covers based on soil SOC and expected quality ratings to be achieved.

4. Conclusion

In summary, this research demonstrated the development, validation and potential application of SQF using SOC as a single and reliable SQ indicator. The use of PMM in land reclamation by mixing B_m horizon materials of Brunisols and tailing sands with peat in oil sands reclamation clearly improves coversoil quality to supply essential plant nutrients, retain moisture and exchange essential cations such as Ca and Mg without any significant risk of increasing the sodicity of the coversoil. The SQF also generated unbiased SQ ratings that can be analyzed using relevant statistical models and weighing factors, thereby addressing the needs for reclamation SQ management and monitoring. The SQF provides a numerical framework for monitoring and managing the quality of reconstructed soils. The assessment framework developed in this study could be applied to other reclamation operations in the study region.

Table 2.1. Correlation coefficients (**r**) between soil total carbon and various soil quality indicators including permanent wilting point (PWP), available water holding capacity (AWHC), electrical conductivity (EC), sodium adsorption ratio (SAR) and cation exchangeable capacity (CEC).

Quality Indicator	**r**	Quality indicator	**r**	Quality indicator	**r**
Bulk density	0.97*	Potassium†	0.86*	CEC	0.99*
Field capacity	0.99*	Magnesium†	0.99*	Total calcium	0.99*
PWP	0.98*	EC	0.74*	Total magnesium	0.98*
AWHC	0.73*	SAR	-0.31	Total sodium	0.90*
Total nitrogen	0.99*	Calcium†	0.87*	Total phosphorus	0.98*

* Implies significance at $P < 0.05$

† DTPA extractable elements. All analysis based on data from Macyk et al. (1995).

Table 2.2. Summary of data sources and rationale for conducting specific SQ analysis with selected indicators.

Data analysis	Rationale	Data source	SQ indicators and references for relevant analytical techniques[†]
The SQ implication of PMM in land reclamation	Understand the impact of PMM on soil quality indicators (physical and chemical properties)	Macyk et al. (1995)	Bulk density (coring method), PWP, FC, AWHC (Mckeague,1978), SOC and soil total nitrogen (Leco Analyzer, 1993), soil pH(1:1), (Doughty, 1941), CEC (Holmgren et al.,1997), EC (EC probe), SAR (USDA,1954), exchangeable Na, Ca and Mg, DTPA extractable Fe, P, K, Mg (Soltanpour,1981), total Ca, Fe, Mg, Na , P (CEM microwave digestion)
Development of SQ functions	Develop a site specific and quantitative framework of soil quality assessment for land reclamation	Macyk et al. (1995)	SOC (Leco CN Analyzer, 1993), PWP, FC and AWHC (Mckeague, 1978), total nitrogen (Leco Analyzer, 1993), total phosphorus (CEM microwave digestion), CEC (Holmgren et al., 1997), SAR (USDA, 1954)[‡]
Validation of SQ functions	Test the applicability and transferability of SQ functions using independent datasets	Moskal (1999)	FC, PWP and AWHC (Mckeague, 1978)
		McGill et al. (1980) and Logan (1978)	Total nitrogen (Leco CN Analyzer) and CEC (Holmgren et al., 1997)

Continue next page

Data analysis	Rationale	Data source	SQ indicators and references for relevant analytical techniques[†]
Application of SQ functions	Demonstrate the application of SQ functions in long term monitoring	Macyk (2009)	SOC (Leco CN Analyzer)

[†] SQ is soil quality, PMM is peat mineral mix, PWP is permanent wilting point, FC is field capacity, AWHC is available holding capacity, SOC is soil organic carbon, CEC is cation exchange capacity, EC is electrical conductivity and SAR is sodium adsorption ratio.

[‡] Selection of indicators for SQF development was based on the defined objectives of the SQ assessment.

Table 2.3. Effects of mixing peat material at rates of 10, 30 and 50% by mass (PMM-10, PMM-30 and PMM-50, respectively) with tailings sand on soil quality indicators including a physical parameter (bulk density), chemical parameters (electrical conductivity (EC), cation exchange capacity (CEC), sodium adsorption ratio (SAR), soil pH (1:1) and exchangeable Na, Ca and Mg) and soil fertility indicators (soil organic carbon (SOC)), DTPA extractable elements representing plant available elements and soil total nutrient elements). Data summarized from Macyk et al. (1995) and values within each column followed by different lowercase letters are significantly different at *P <0.05* using Tukey comparison test.

Treatment	SOC	Bulk density	Exchangeable cations			CEC	DTPA extractable elements			
			Na	Ca	Mg		Fe	P	K	Na
	(g kg^{-1})	Mg m^{-3}	cmol kg^{-1}				mg kg^{-1}			
PMM-10	5.60 d	1.4 b	0.2 a	1.7 d	0.4 cd	1.7 c	62.9 d	0.5 d	2.4 d	34.8 a
PMM-30	15.7 c	1.3 c	0.2 a	4.7 c	0.9 c	4.5 c	164.8c	0.5 d	3.9cd	42.7 a
PMM-50	28.8 b	1.3 d	0.3 a	10.5 b	1.8 b	10.1 b	279.8b	0.8 c	5.7bc	50.1 a
Peat	95.3 a	0.7 f	0.6 a	44.2 a	7.4 a	44.7 a	991.0a	3.1 b	9.0ab	107 b
Natural Sand†	4.20 d	1.2 e	-§	-	0.1 d	2.6 c	138.3c	13.4a	10.4 a	1.03 c
Tailings Sand‡	2.40 d	1.4 a	-	-	0.1 cd	0.5 c	12.4 e	0.04e	1.5 cd	40.4 d

Continue next page

	Saturated paste extract					Total element				
	EC	SAR	Ca	Mg	pH[¶]	Ca	Fe	Mg	Na	P
	dS m^{-1}		mg kg^{-1}			mg kg^{-1}				
PMM-10	0.81 bc	2.6 a	87.2 d	23.7 d	6.7	1438 d	2247 e	143 c	1687 c	56 d
PMM-30	1.46 ab	1.4 a	251.5 c	56.3 c	6.8	2431 c	3280 c	226bc	2005bc	73cd
PMM-50	1.91 a	1.0 a	398.3 b	84.2 b	6.6	3591 b	4254 b	424 b	1975bc	92 c
Peat	2.42 a	0.6 a	602.0 a	130 a	6.3	9728 a	8527 a	1758a	3647a	212 b
Natural Sand	0.09 c	0.5 a	10.7 d	1.8 e	4.1	3700 b	3166cd	483 b	2649ab	581 a
Tailings Sand	0.49 bc	6.7 a	21.9 d	7.5 e	8.3	1218 d	2073de	133bc	1885bc	49 d

† Ae and B_m horizons of a Dystric Cryochchrept (USDA) or a Dystric Brunisol (Canada)

‡ Sandy ejects from the oil sands extraction process

§ Below detection limit.

¶ The pH was measured in saturated water paste following Doughty (1941).

Table 2.4. Algorithms relating y (SQ rating ranging from 0 to 1) to quality indicator x (soil organic carbon in g kg^{-1}) of specific soil functions where a, b and c are constants and r^2 is the regression coefficient between x and y, using selected soil functional parameters including available water holding capacity (AWHC), field capacity, permanent wilting point, cation exchange capacity (CEC), sodium adsorption ratio (SAR), soil nitrogen and phosphorus.

Soil function	Parameter	Quality algorithm	A	b	c	$\mathbf{r^2}$ †
Moisture retention	Field capacity	$\boldsymbol{y = a/(1 + \exp(-(x - c)/b)}$	1.073	0.523	1.750	0.96*
	Permanent wilting point	$\mathbf{y = a + bx}$	-8.828	3.120		0.77*
	AWHC	$\mathbf{y = a/(1 + \exp(-(x - c)/b)}$	1.003	0.464	1.661	0.93*
Cation exchange	CEC	$\mathbf{y = a/(1 + \exp(-(x - c)/b)}$	0.857	0.503	1.998	0.88*
Potential for sodicity	SAR	$\mathbf{y = 1 - (1/(1 + ax)^{\boldsymbol{b}}}$	1.233	1.903		0.23
Supply of essential nutrients	Nitrogen	$\mathbf{y = a/(1 + \exp(-(x - c)/b)}$	1.074	2.023	0.531	0.97*
	Phosphorus	$\mathbf{y = a/(1 + \exp(-(x - c)/b)}$	0.735	0.509	1.380	0.76*

† The $\mathbf{r^2}$ was defined as a weighing factor (z) at the quality score integration stage

* Implies significance of regression at $P < 0.05$

Table 2.5. Effects of peat mineral mixing ratio on soil field capacity (FC), permanent wilting point (PWP), available water holding capacity (AWHC) and corresponding soil quality ratings.

Peat: mineral ratio†	FC		PWP		AWHC	
	Mean§ %	Rating	Mean %	Rating	Mean %	Rating
3:1	39.7 a‡	1.0 a	20.1 a	1.0 a	19.6 a	1.0 a
1:1	19.9 b	0.7 b	6.7 b	0.5 b	13.2 ab	0.7 b
1:3	13.4 bc	0.3 c	6.3 c	0.3 c	7.1 bc	0.3 c
0:1	8.2 c	0.1 d	3.7 d	0.0 d	4.6 c	0.1 d
Adj. r^2 (%)	88.9	97.6	90.2	98.6	78.3	97.6

† Mass ratio of peat to mineral soil.

‡ Means with the same lowercase letter are not significantly different at $P < 0.05$.

§ Number of replicates varied from 2 to 6. Moisture and related soil organic carbon data from Moskal (1999). Ratings are unit less and normalized between 0 and 1. Adj. r^2 is the adjusted r^2 as reported in one way ANOVA for reported means and ratings using replications of 3 samples.

Table 2.6. Material type effect on soil total nitrogen, cation exchange capacity (CEC) and corresponding soil quality ratings.

Material type §	Nitrogen (%)		CEC	
	Mean†	Rating	Mean	Rating
Peat	0.98 a‡	1.00 a	183 a	1.00 a
Natural sand	0.02 b	0.52 b	1.20 b	0.18 b
Tailings sand	0.001 b	0.51 b	1.18 c	0.18 b
Adj. r^2 (%)	98.3	99.9	99.2	100

† The number of replications varied between 2 to 6.

‡ Means in each column with the same lowercase letter are not significantly different at $P < 0.05$

§ Soil fertility and related soil organic carbon data from McGill et al. (1980) and Logan (1978). Natural sands were from B_m horizon of Brunisols. Adj. r^2 is the adjusted r^2 as reported in one way ANOVA for means and ratings.

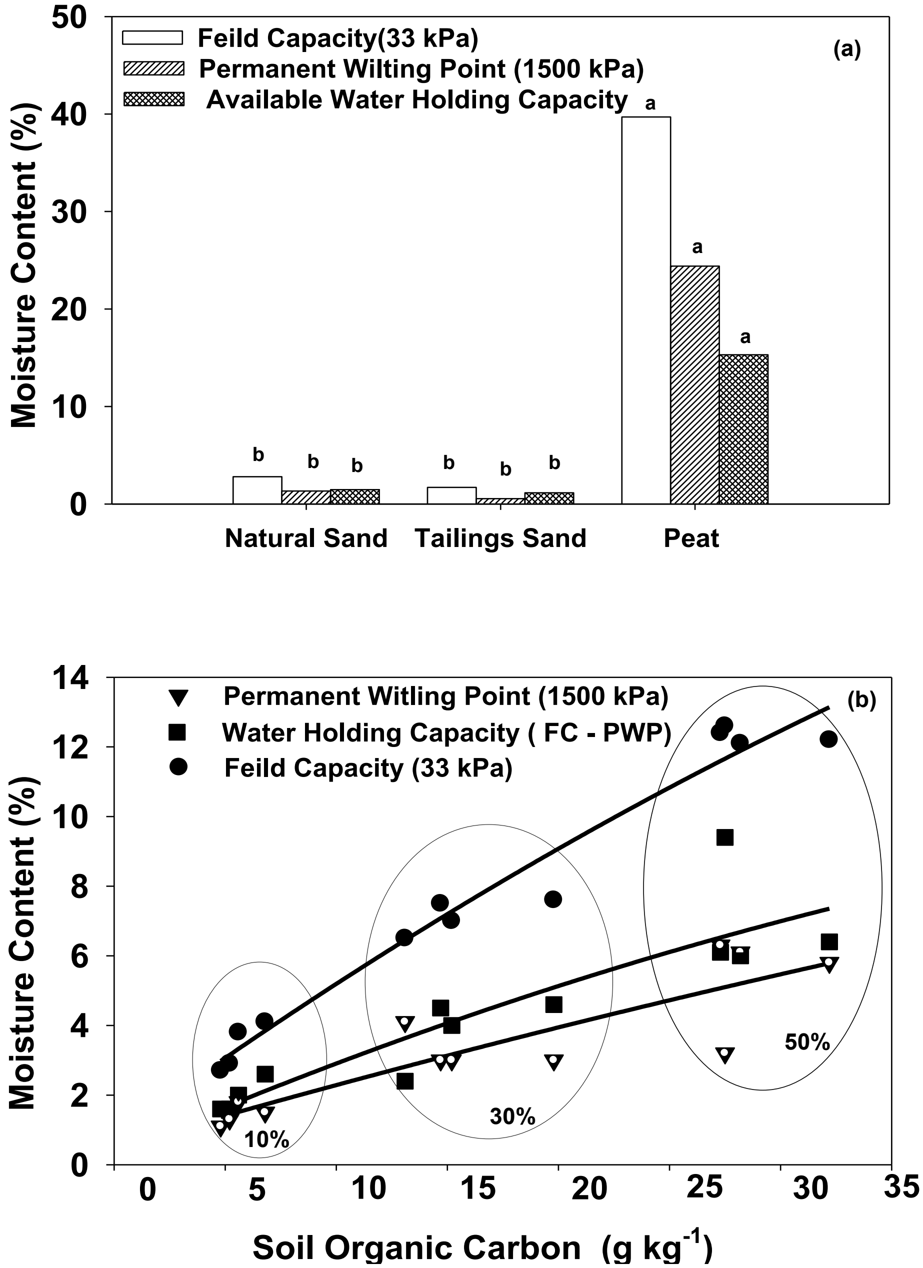

Figure 2.1. Gravimetric moisture content at permanent wilting point (1500 kPa) and field capacity (33 kPa), and available water holding capacity (AWHC) of (a) three different materials including natural sand (B_m horizon), tailings sand, and peat; and (b) peat-sand mix in relation to changes in soil organic carbon as peat composition increased from10 to 50% by weight. Lower case alphabets represent no significant difference in means (n=3) using Tukey test at *P* < 0.05.

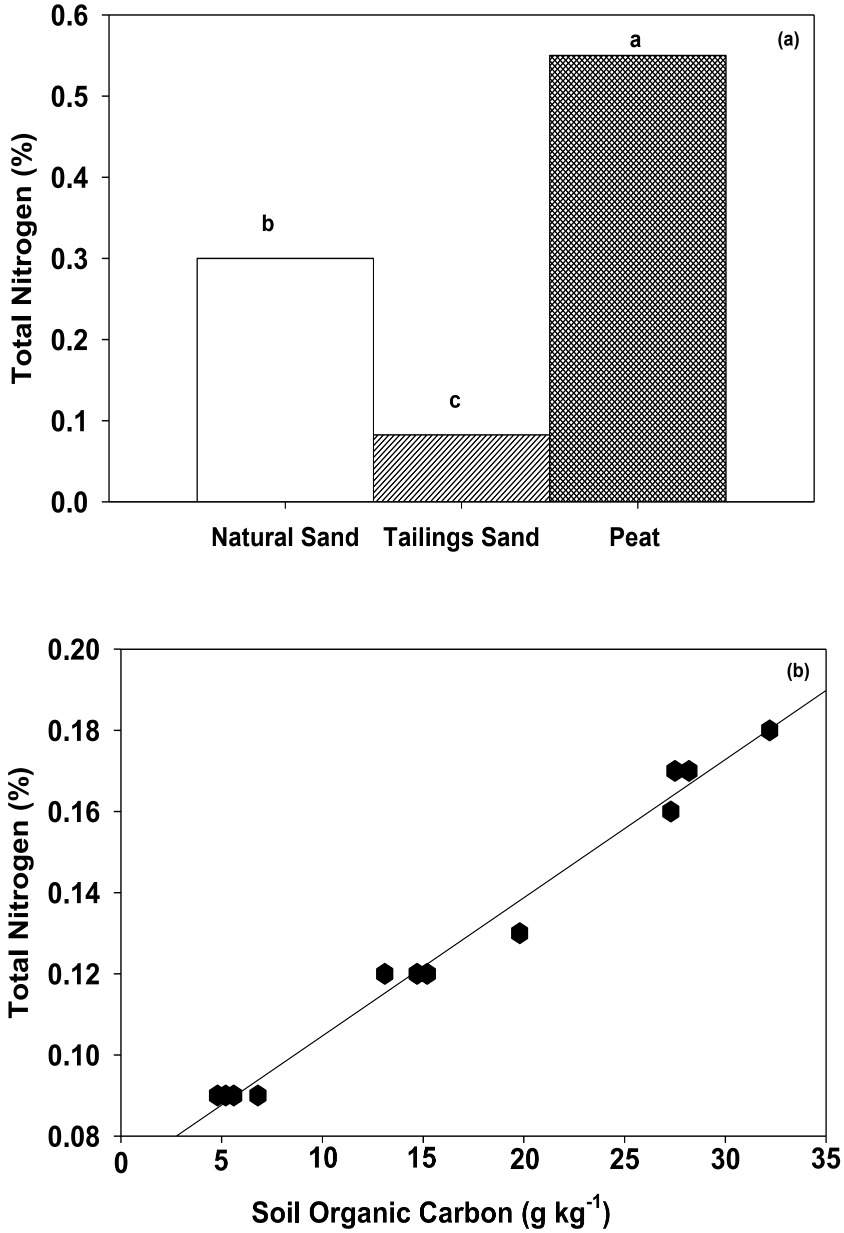

Figure 2.2. Total nitrogen concentrations (%) in (a) three different materials including natural sand (B horizons), tailings sand, and peat; and (b) peat-sand mix in relation to changes in soil carbon content when the peat composition increased in the soil mixture. Lower case alphabets represent no significant difference in means (n=3) using Tukey test at $P < 0.05$.

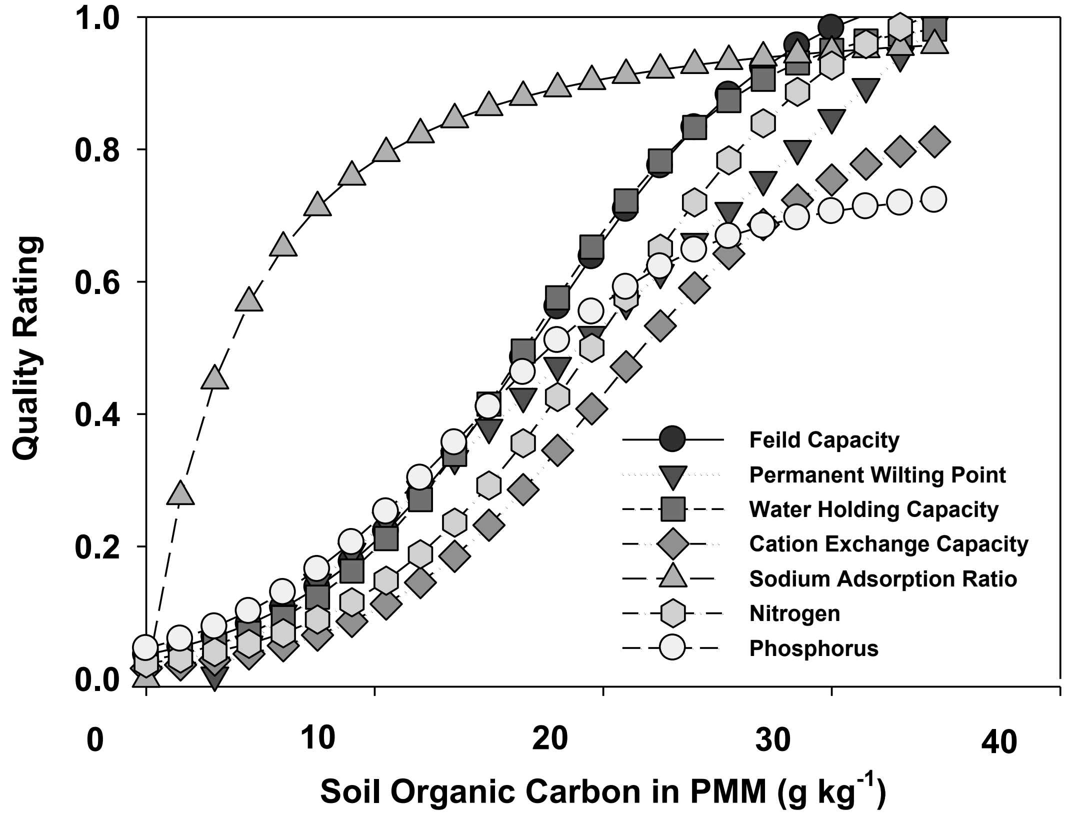

Figure 2.3. Soil quality rating functions developed by relating soil total carbon to soil quality indicators for a multifunctional assessment of reclamation cover soils reconstructed using peat-sand mix material.

Chapter 3 Variation of Soil Organic Carbon in Alberta's Oil Sands Region: Distinguishing Functional Soil Management Units for Soil Quality Assessment in Natural and Reclaimed Soils.

1. Introduction

Soil organic carbon (SOC) measurements reflect soil organic matter (SOM) decomposition and transformation processes. SOM sources include plant litter, root exudates, microbial cells, animal manure, and organic soil amendments (e.g., compost) (Nelson et al., 1996). All influence the amount of SOC in response to their degree of decomposition and other soil physical, chemical and biological factors influencing SOM transformation. Variation in SOC makes it a reliable, robust and quantitative indicator of fundamental processes driving soil functions and thus overall soil quality (SQ). Therefore, having a clear idea of site-specific or regional variation in SOC concentrations will improve soil quality assessment (SQA) for operations such as land reclamation.

The need to quantify SOC change is a core principle of soil quality assessment (SQA), which must also consider soil formation factors such as climate, parent material, organisms, topography and time. Also, since the same factors that directly or indirectly influence the status and dynamics of SOM and therefore SOC composition, the concentration and composition of SOC are recognized as primary and integrative drivers for physical, chemical and biological soil processes. The quantity, composition, distribution and balance of SOC also reflect land use effects (Arevalo et al., 2011), biomass deposition, carbon sequestration (Baah-Acheamfour et al., 2014), soil nutrient status (Zeng et al., 2010) and other long-term effects of soil management practises (Li et al., 2013). Clearly understanding differences and variation in SOC among soil types is essential for identifying functional soil management units.

Soil processes related to nutrient cycling such as nitrogen (N) mineralization, nitrification and ammonification, exchange of cations, transformation of organic forms of phosphorus (P), P release and immobilization, and microbial biomass production are related and sometimes occur simultaneously with SOM transformation or carbon cycling (Chang et al., 1995; Chang et al., 1996; Chang et al.,1997). SOC therefore exhibits strong correlation with both spatial and temporal transformation processes (Yan et al., 2012). SOC measurements are generally inversely correlated with physical properties such as soil strength, resilience and compaction including bulk density and Atterberg limits (Blanco-Canqui et al., 2006). In contrast, they are positively correlated with soil chemical properties such as cation exchange capacity (Kaiser et al., 1997) and indicators of biological processes such as soil respiration, microbial biomass and enzyme activity (Gregorich et al., 1997). The integrative nature of SOC and its correlation with several soil processes makes it a very important SQ indicator and useful for quantitative SQA.

Soil quality infers the ability of a specific natural or reconstructed soil to perform critical functions based on its unique physical, chemical and biological characteristics. SOC provides a reliable and quantitative means for predicting, calibrating and modelling various biogeochemical and functional processes that reflect SQ (Stott, 2009). These functional processes include nutrient cycling, soil moisture retention, moisture transmission, chemical transformation, plant root support, and inhibition of plant toxicity. The processes and their relevant metrics thus form the basis for quantitatively defining performance measures associated with a SQA process.

SOC also demonstrates strong correlations with SQA measures of performance or soil function (Andrews et al., 2004; Stott et al., 2009), thus making it a good predictive indicator. The predictive indicators are required in development of scoring functions or soil quality-scoring functions (SQF) that relate SOC as an independent variable to normalized measures of performance such as nutrient element concentrations or soil moisture content (Fine et al., 2017; Ojekanmi et al., 2014; Stott et al., 2009; Andrews et al., 2004).

Soil quality scores or ratings produced for natural, cultivated, reconstructed and reclaimed soils can be generated using SQF. The SQF can be further validated for site specific, local and regional use. This approach provides a robust, justifiable, quantitative and process-based approach to SQA using acceptable statistical and experimental designs. Ojekanmi et al. (2014) expanded the application of SQF to reconstructed soils in land reclamation and ecosystem reconstruction scenario from typical agronomic applications for site specific applications. This involves the use of natural soils for reconstructing new soil profiles at sites disturbed by surface mining. The SQF was developed from natural or pre-disturbance soil data by selecting SOC as the predictive indicator for multiple functional processes. The SQF was then validated for site specific use with an independent dataset collected from reclaimed soil. After successful validation, the SQF was used to analyze long term SQ variations in similar reclaimed soils using a long term SOC dataset.

Applying SQF requires rating the quality of natural or reclaimed soils within the same biogeoclimatic zones with predictive indicators such as SOC, examining effects of various treatments on SQ and the design of land reclamation covers based on critical SQF thresholds. Use of SOC as the predictive indicator within a multi-indicator SQA framework is clearly defendable based on the integrative nature of SOC to reflect multiple processes and the strong correlations observed with the relevant measures of performance, soil function or management goals (Stott et al., 2009).

This approach to SQA points to the need to carefully examine the baseline or predisturbance variations of SOC in natural or reclaimed systems, while identifying relevant and statistically significant soil and landscape attributes contributing to observed SOC variations. There is the need to quantitatively account for the effect of these factors of SOC variation when SOC is used as a predictive parameter in SQA. These soil and landscape factors are known to significantly influence SOC variation and its correlation to other indicators of soil functions. Therefore, a good understanding of SOC variation will further improve the reliability of SQ scores derived from SQF by identifying the predictive boundary condition of the SQF to minimize error while identifying the range of indicators resulting in optimum SQ performance or SQ thresholds.

Numerous factors affecting SOC variation in both natural and reclaimed soils have been identified. Within forest soils this includes effects of climate, soil texture, parent material, land use types, forest plant species and vegetation dynamics (Boča et al., 2014). Soil moisture, litter turnover rates, profile redistribution and adsorption of dissolved organic carbon were identified by Woldeselassie et al. (2012) as factors affecting SOC variation at the landscape scale. In a temporal study, Wuest, (2014) observed seasonal changes in SOC due to input rates of plant residue and root exudates, SOM decomposition rates, soil temperature fluctuations, and changes in soil management practises. Also, considering SOC measurement techniques and timing of soil sampling in relation to SOM cycles, long terms changes in SOC were observed to occur gradually. Factors of SOC variability in long term experiments include land use types (grassland, pasture, forest), site and soil slope, drainage and effect of measurement scale (Wuest, 2014).

The quantity of SOC in the predisturbance or natural soils used for reconstructing soil in land reclamation is an important factor influencing the quantity and variation of SOC among different types of reclamation cover designs or series. Tian et al. (2009) noticed rapid increase in

SOC due to application of bio solids to reclaimed soils. Akala et al. (2001) studied reclaimed soils with ages ranging from 21 to 30 years and noticed the differences in SOC sequestration rates due to differences in reclamation cover designs by comparing topsoil or no topsoil treatments, horizons (0-15 cm and 15-30 cm) and land use types (forest and pasture). This study also observed a constant and stable SOC pools for 30 year's old reclaimed soils. Kern (1994) observed that soil great groups provide more information on SOC variability than taxonomic order and sub order. Therefore, approaches to soil taxonomy for both natural and reclaimed soils should capture temporal and spatial variation in SOC for natural and reclaimed soils (Naeth et al., 2012).

Land reclamation provides opportunities to reconstruct soils using pre-disturbance SQ as the assessment standard within an ecosite, which are areas with unique and recurring combinations of vegetation, soils, landform and other environmental factors (Beckingham et al., 1996). The typical or characteristic measures of variation and distribution of SOC within an ecosite and over a period will influence its use as a standard for assessing SQ of reclaimed soils. The objectives for this phase of the research project include: (i) an analysis of SOC variation as impacted by landscape and soil factors of the Alberta oil sands regions over 10 years period, (ii) identification of distinguishing soil management units based on statistically significant soil and landscape factors influencing SOC variation for this region, and (iii) an examination of factors influencing SOC variation and its use as a quantitative and predictive SQA indicator for the design and application of SQF.

2. Materials and Methods

2.1 Site description

The Athabasca Oil Sands Region (AOSR) is located northeast of the Province of Alberta, Canada within the boreal forest region. The AOSR southern limit is around (416513.99 mE, 5996830.83 mN, UTM 12) and northern limit extend up to (476902.52 mE, 6650497.17 mN, UTM 12). The climate is continental, typically with long, cold winters and short, cool summers. Mean daily temperatures range from −18.8°C in January to 16.8°C in July. Annual precipitation is 455 mm, falling predominantly as rain (342 mm) during the summer months. Soils within the region are dominantly Luvisols developed from lacustrine deposits and Brunisols from glacio-fluvial outwash. The dominant vegetation within the boreal forest includes white spruce (*Picea glauca)*, black spruce (*Picea mariana*), trembling aspen (*Populus tremuloides*), balsam poplar (*Populus balsamifera*), white birch (*Betula papyfrifera*), and jack pine (*Pinus banksiana*) (McMillan et al., 2007).

According to Alberta Energy Regulators, the AOSR has 4,800 km^2 of mineable surface oil sands, with 767 km^2 already disturbed as of 2012 in support of bitumen deposit developments. Disturbances within the area include tree clearing, soil removal and conservation, changes in landscape and site hydrology. Those challenges created a need for land reclamation activities such as soil conservation, landscape reconstruction, cover soil designs, revegetation and final development of healthy ecosystems. Reconstruction operations require managing a large volume of soil, thus justifying the need for a rigorous SQA framework to make decisions regarding: (1) what soils should be conserved; (2) what type of reclamation covers should be replaced in disturbed soil; (3) what are the critical soil functions or capabilities in the reclaimed soil; and (4) how to monitor this extensive area for two to three decades at a minimal cost to the operations? These questions and others indicate the need for a quantitative soil quality assessment framework to support land reclamation within the AOSR.

2.2 Experimental designs

Data for this study were collected and compiled into a database between 2000 and 2010 by a consortium of industries and industrial stakeholders actively reconstructing the boreal forest's landscape, soil and vegetation within the AOSR as represented by the Cumulative Environmental Management Association (CEMA), in Alberta, Canada. Approximately 116 permanent sampling plots were established within the AOSR of which 50 were natural and 66 were reclaimed areas. Plots with natural soil served as experimental controls and the basis for evaluating reclaimed plots. Each plot was 10 m wide by 40 m long and spatially distributed to capture representative ecosites for natural sites and various reclamation designs within the AOSR (Figure 3.1).

The overall objective for these long-term soil and vegetation monitoring plots was to collect performance data needed to demonstrate SQ improvement due to reclamation and thus provide baseline information for future SQA. Natural plot locations were selected within 10 natural ecosites used as targets for reclamation (Beckingham et al., 1996), while reclaimed plots were selected based on location and reclamation design which reflected the type of soil materials used to construct the cover soil (0 to 0.3 m), upper subsoil (0.3 to 0.5 m) and lower subsoil (0.5 to1.0 m).

2.3 Soil sampling and chemical analysis

Soil sampling followed a completely randomized design within ecosites and reclamation series with a varying number of replicates (N) over 10 years. Soil and landscape data, including detailed soil profile descriptions, vegetation type, horizons, ecosites, parent materials, drainage, slope position, soil series, taxonomic group and subgroup, moisture and nutrient regimes, were collected and organised into a relational database (Day, 1982). Throughout a 10 year period, 94 plots were sampled once between 2000 and 2004, and 74 plots were sampled two or three times between 2005 and 2010. Soil samples were consistently collected between September and October each year. The sampling design for natural plots included recording sampling depth and collecting separate composite samples from the A_e, B_m, B_t, BC and C horizons. The reclaimed sites were sampled by material types and depth ranging from 0 to 0.2 m for topsoil (TSOIL), 0.2 to 0.5 m for upper subsoil (USUB) and 0.5 to 1.0 m for lower subsoils (LSUB). Within those depth ranges, two or more composite soil samples were collected depending on the number of different soil material types within the profile.

Several physical, chemical, biological properties were measured and the data were organised into a relational database for further analysis. Soil organic carbon was analysed using LECO CN-2000 analyser (Wright and Bailey, 2011) and total soil nitrogen (N) was determined using Kjeldahl digestion technique (Bremner, 1996; Mckeague, 1978). Soil bulk density was determined using soil core method with a cylinder that was 0.68 m in height and 0.73 m in diameter (Blake and Hartage, 1986). Soil texture was determined using the hydrometer method (Gee and Bauder, 1986). Soil chemical analyses included pH in water (Thomas, 1996), cation exchange capacity, exchangable acidity (CEC – NH_4OAC at pH 7), sodium adsorption ratio (SAR), and electrical conductivity (EC) measured in soluble extracts as outlined by Mckeague, (1978). All data were stored in a reclamation database for the entire 10- to 12-year period.

2.4 Data retrieval, computations and statistical analysis

A database query was designed and run to retrieve soil and landscape parameters which include horizons, ecosites, parent materials, drainage, slope position, soil series, taxonomic groups and subgroup, moisture and nutrient regime for both natural and reclaimed soils. Parameter subclasses were chosen to define unique soil quality management groups with significantly different SOC composition within the AOSR. This enabled the sites to be grouped into soil management zones within the Canadian land classification system (Day, 1982). The database included soil quality data compiled from 2000 to 2010. Soil parameters queried included horizon depth, bulk density, SOC and nitrogen (N) concentrations. Measures of SOC and N reported in gravimetric units such as mg kg^{-1} were converted to volumetric units such as Mg ha^{-1} using the reported bulk density and horizon thickness, to ensure the use ecologically representative units.

2.5 Development and analysis of SQF

To independently analyse and then compare the SOC - N dynamics of natural or forest soils (> 30 years of forest stands) and reclaimed soils (0 – 12 years of forest stands) with emphasis on soil quality relations (SOC – N) in each soil type, a different SQF was developed for the natural and reclaimed soils. Using a proposed SQA framework for reconstructed ecosystems as shown in Figure 3.2 (Ojekanmi et al., 2014; Stott et al., 2009; Andrews et al., 2004), the SQA objective was to define and assess soil capacity to supply N for plants while also using SOC changes as a predictive SQ indicator (*i.e.*, capacity to supply nutrient for plant use using N as representative nutrient). Therefore, SOC (Mg ha^{-1}) was selected as a predictive SQ indicator and corresponding N as a measure of ecosystem performance or management objective.

The SOC – N relation had been previously characterised as a typical “more is better” relation, in which increasing SOC implies better quality for functions such as moisture retention and nutrient cycling with related enzyme activity (Stott et al., 2009; Andrews et al., 2004). Increasing SOC is due to various SOM transformation processes including direct addition caused by decomposition of plant litter and other anthropogenic effects that result in simultaneous increase in N input (Andrews et al., 2004). Nitrogen concentrations (Mg ha^{-1}) were normalized between 0 and 1 by dividing by the maximum reported N concentration and regressed with SOC to derive SQF. The best fit for each regression was determined using Curve Expert Pro Software

(Daniel Hyams, 2012) which contains a database of about 200 in-built and customized numerical functions. Differential analysis of the SQF to determine the rate of change in N supply with change in SOC content based on δ(N)/δ(SOC) were completed for both natural and reclaimed soils. This is to clearly identify the optimum SQ thresholds based on range of SOC content that exhibits the highest rate of change in N input with changes in SOC content. The δ(N)/δ(SOC) analysis also allows for the understanding of the general trends of rates of changes in N to changes in SOC, or N cycling with increasing SOC.

The trends of δ (N)/δ (SOC) for natural soils were defined as the pre-disturbance function or equivalent N supply capability function, which forms the basis for assessing N supply potential or defining the target SQ for reclaimed soils. Annual average rate of N - SOC cycling was defined by the slope of a linear regression function on SOC – N relation, (Δ(N)/Δ(SOC) per year. Mean annual trend of (Δ(N)/Δ(SOC) was captured for years with adequate data points between 2000 and 2010 to further describe the SOC – N relations.

2.6 Validation and application of soil quality functions

To test the applicability of SQF designed from natural soils data and ability of SQ ratings generated using SOC as predictive indicators of N supply trends at other independent sites within the AOSR, the SOC and N (Mg ha^{-1}) data reported by Yan et al. (2012) was selected and examined for effectiveness as a soil N index for predicting forest productivity within the AOSR. The study compiled SOC and N (Mg ha^{-1}) data for both forest floor (FF) and mineral soils (MS), while demonstrating significant ($p < 0.05$) differences between FF and MS in terms of N supply potential for plant use. We selected those data for SQF validation by examining the ability of SQ ratings generated using SOC to demonstrate expected significant differences in N supply potential of FF and MS. Nitrogen (Mg ha^{-1}) reported by Yan et al. (2012) and SQ ratings generated using SOC (Mg ha^{-1}) reported in the same study as the input parameters into SQF were analysed separately for effects of soil material types (FF and MS), using a two-sample t-test at a probability of 0.05.

To further demonstrate the application of SQF in land assessing quality of reclaimed soils, N supply ratings were generated for various natural and reclaimed soils based on SOC (Mg ha^{-1}) data reported by Macyk et al. (2005) for soils within the AOSR of the boreal forest zone. The SOC (Mg ha^{-1}) data were input into the SQF to generate relevant SQ ratings. The SQF was further validated by testing the capability of the SQ ratings generated to repeat similar and statistical trends observed in N composition for different types of soil material used for land reclamation within the AOSR.

2.7 Statistical analysis

Summary statistics including mean (μ), standard deviation (δ), minimum (Q0), first quartile (Q1), third quartile (Q3), maximum (Q4), coefficient of variation (CV), range (Δ), skewness (α) and kurtosis (β) of SOC ($Mg\ ha^{-1}$) as impacted by slope, horizon, soil texture, parent material, nutrient regime, soil drainage, ecosites, soil series and group were determined using MINITAB statistical software (Alin, 2010). Effects of soil and landscape factors were tested using ANOVA to identify the significant ($p < 0.05$) factors for SOC variation. Mean SOC values for each factor were compared using Fisher's protected LSD test. To ensure that normality assumptions were met, logarithm transforms of SOC were used to normalize the data before running an ANOVA using Anderson-Darling test of normality as well as Bartlett and Levene's test to ensure variance equality among residuals.

To test the pre-disturbance SQF' capability for differentiating N supply potentials between forest floor (FF) and mineral soils (MS), we used a two-sample t–test at $p < 0.05$ to distinguish the effect of FF and MS on the reported N data and SQ ratings generated using SOC as input into the designed SQF. To further validate the pre-disturbance SQF for its applicability among different types of reclamation materials [e.g., peat-mineral mix soils (peat-mix), Luvisols, secondary materials (mix of B and C horizons from natural soils), Brunisols, overburden (soil materials below C horizons with suitable pH and EC to support revegetation) and tailings (clean sandy extracts from oil-sands extraction plants)], ANOVA was conducted and a Tukey test was performed to separate SOC means into significant groups within the five types of reclamation materials. SOC values were used as input into the SQF and SQ output ratings were compared using a Tukey test. The ability of SQ scores to repeat similar, mean differences among the materials as reported using the original SOC ($Mgha^{-1}$) data was the basis for the validating the applicability of the SQF in rating the quality of the reclaimed soils. Mean differences among the significantly different ($p < 0.05$) subclasses of factors influencing SOC variation were also used as the basis to group each of the subclasses of soil and landscape attributes into management units, putting into consideration the definitions of each subclass according to the Canadian land classification system (Day, 1982).

3. Results

3.1 Soil organic carbon variation in natural soils

The natural soils analysed in this study are from boreal forest stands with trees greater than 30 years of age. This provides an ideal reference that represents well-developed forests, with stable sources of plant litter for organic matter and nutrient cycling. Generally, SOC data collected within AOSR were not normally distributed as reflected by measures of skewness (lateral dispersion, α) or kurtosis (vertical dispersion, β), (Tables 3.1, 3.2 and 3.3). Many estimates for α and β are close to zero using thresholds of ± 2 standard deviations for skewness and ± 3 for kurtosis, with exception that the dataset does have a significant number of outliers (Tables 3.1, 3.2 and 3.3). Normalizing the datasets at probabilities greater than 0.34 resulted in homoscedasticity assumptions also being met at $p > 0.05$. Natural soil horizons within the AOSR generally exhibited non-significant variation ($p < 0.05$) in SOC (Table 3.1) with means ranging from 18.61 Mg ha^{-1} in the A horizon to 29.44 Mg ha^{-1} in the B horizons. C horizons are rarely sampled and analysed for SOC except in soils with organic matter at depths greater than 1.0 m. SOC content of the organic soils is greater than the maximum range reported for A, B and surface organic layers of litter, fibric and humic materials (O-fmh) horizons in this study. The minimum concentration of SOC is 0.49 Mg ha^{-1} in the A horizon while the maximum is 162.43 Mg ha^{-1} for the O-fmh or LFH soil materials (Table 3.1). Measures of SOC dispersion, including standard deviation (22 – 26 Mg ha^{-1}) and co-efficient of variation (86 -126%), also reflect similar non-significant differences among horizons within natural self-sustaining forest soils (Table 3.1).

Ecosite classes (a to e) generally increased significantly ($p < 0.05$) in SOC content and variability (Table 3.1). SOC in ecosites a and b, which are characterised by coarse textured substrates growing dominantly jackpine species (*pinus banksiana*), had mean SOC concentrations ranging from 6.88 to 13.70 Mg ha^{-1}, while ecosites d and e, which had finer textured substrates supporting aspen (*populous tremuloides*) and white spruce (*picea glauca*) as the dominant vegetation had SOC concentrations ranging from 24.59 to 52.78 Mg ha^{-1}. All the measures of SOC variation such as range, standard deviation and coefficient of variation (CV) also increased from ecosites a to ecosites e. Soil parent materials classes within the AOSR including aeolian, fluvial, and lacustrine and moraine till do not reflect any significant difference ($p < 0.05$) in mean SOC concentration (Table 3.1).

Drainage class significantly ($p < 0.05$) influenced SOC concentration with very rapid, rapid, poorly and well drained soils being significantly different from moderately-well and imperfectly drained soils. This increase in mean SOC ranged from 6.78 to 35.24 Mg ha^{-1} with the standard deviation and CV following the increasing trend from 4.67 to 23.61 Mg ha^{-1} and 66 to 100%, respectively (Table 3.2). The xeric, subxeric and submesic moisture regimes have significantly different in SOC content compared to hygric, mesic and subhygric regimes. This classification of long-term moisture supply also shows an increasing mean SOC from 7.91 to 45.42 Mg ha^{-1}, with a statistical SOC range from 18 to 159 Mg ha^{-1}. The CV among moisture regime classes increased from 63 to 88% and standard deviation of mean of SOC from 5 to 40 Mg ha^{-1}. Slope positions, however, show non-significant differences in SOC content and variation (Table 3.2).

Soil nutrient regime significantly ($p < 0.05$) increased as mean SOC increased from poor (9.07 Mg ha^{-1}) to rich (38.87 Mg ha^{-1}) classes. The standard deviation followed the same trend, increasing from 5.6 to 25.78 Mg ha^{-1} of SOC (Table 3.3). Mean SOC among soil textural classes increased from 7.55 Mg ha^{-1} for loamy sands to 72.14 Mg ha^{-1} in heavy clay soils. The CV and statistical range of SOC by soil texture classes from dominantly coarse to dominantly fine textured soil also follows the increasing trend with increasing SOC content (Table 3). Soil order and subgroups as defined by the Canadian soil classification system also demarcate SOC increasing among Brunisols (9.69 to 10.14 Mg ha^{-1}), Luvisols (25.84 to 27.72 Mgha^{-1}) and Regosols (40.30 to 74.30 Mgha^{-1}) as shown in Table 3.3. Similar increasing trends were observed in SOC range and CV for each soil class (Table 3.3).

3.2 Soil organic carbon variation in reclaimed soils

Reclaimed soils in the AOSR are generally less than 30 years of age, with many plots being within the 5 to 15 year range. Tree species are also in juvenile stages, actively developing their canopies with less SOM cycling than mature stands on natural soils. There are also major differences among oil sands reclamation operators in terms of soil reconstruction practices. For example, a few of the reclaimed sites have a history of fertilizer application while others have not received any form of nutrient amendments.

The log transformed SOC data for reclaimed soil fit into assumptions of normality required for the analysis of variance model. The reported values of α and β, the vertical and lateral dispersion from the mean which are closer to zero are within the relevant thresholds discussed earlier. There are few data outliers; therefore the use of log transformed SOC data increased the confidence in mean comparison test (Table 3.4 and 3.5). Further test of equality of variance of residuals for the log transformed dataset improves the extent to which the dataset meets the assumption related to equality of variance of residual required for ANOVA.

Soil horizons in reclaimed sites showed significant ($p < 0.05$) SOC differences (Table 4) with mean values increasing from 82.78 Mg ha^{-1} in the USUB to 172.41 Mg ha^{-1} in the LSUB. The minimum SOC was 1.03 Mg ha^{-1} for the USUB, while the maximum was 899 Mg ha^{-1} within the LSUB. This distribution is mainly attributed to reclamation cover design, targeted reclamation ecosites, differences in SOC content of soil materials, and volume of soil materials used for reconstructing a soil horizon. The CV ranged from 72 to 143%, while the mean SOC ranged from 540 to 898 Mg ha^{-1} among reclamation horizons.

Slope position did not significantly influence mean SOC in the reclaimed soils (Table 3.4). Meanwhile, soil moisture class had a significant ($p < 0.05$) impact that ranged from 50 to 132 Mg ha^{-1} of SOC among the different classes. Specifically, the submesic, mesic and subhygric classes were significantly different from subxeric soils. Measures of SOC variation including CV (76 to 104%) and statistical range (65 to 892 Mg ha^{-1}) also increased with increasing mean SOC content (Table 3.4).

Soil nutrient regime, drainage and different reclamation or soil placement designs significantly ($p < 0.05$) influenced mean SOC content in the reclaimed soils (Table 3.5). Nutrient rich soils are significantly different from medium and nutrient poor soils. SOC content increases from 62 Mg ha^{-1} in nutrient poor soils to 146 Mg ha^{-1} in nutrient rich soils. The moderately well, well and imperfectly drained soil classes have different SOC content than rapidly drained classes. Soil drainage classes also increased in SOC content from 50 Mg ha^{-1} in imperfectly drained soils to 134 Mg ha^{-1} in moderately well drained soils. SOC distribution among the various placement or cover designs was strictly a function of soil material type and combinations. The SOC ranged from 38 to 285 Mg ha^{-1} among different cover designs. The range of SOC content also follows the same increasing trend from cover design N which is a peat – mineral mix material placed on sandy substrate having 38 $Mgha^{-1}$, to cover design J which is a peat –mineral mix material only within the control section of 1.0 m having 285 $Mgha^{-1}$ (Table 3.5).

3.3 Comparing natural and reclaimed soils

There were seven distinguishing soil and landscape factors that demonstrated significant ($p < 0.05$) differences in mean SOC in natural ASOR soils that provided the capability to functionally delineate soil quality management zones. This included classes of ecosites, soil texture fractions, soil nutrient regimes, soil moisture regimes, drainage group, and soil classification. Among reclaimed soils there were five factors that accounted for significant variation in SOC content. They included reclamation horizon class, placement design, drainage, moisture and nutrient regime (Table 3.6). The common or similar distinguishing factors for both reclaimed and natural soils based on SOC content are soil moisture regimes, soil nutrient regimes and drainage classes.

Generally, reclaimed soils are designed with greater SOC than in natural soils. The maximum amount of SOC observed in natural soils ranged between 162 to 240 Mg ha^{-1}, while those of reclaimed soils ranged between 600 to 898 Mg ha^{-1} (Tables 3.1 to 3.5). Since the statistical range (difference between maximum and minimum, Δ) of SOC increases with increasing SOC content, it implies that reclaimed soils generally exhibit greater Δ of SOC than natural soils. Both reclaimed and natural soils exhibit very high CV, sometimes above 100%.

Based on mean comparison completed for both natural and reclaimed soil (Table 3.1 to 3.5), we can further identify and group significantly different ($p < 0.05$) factors of SOC variation representing a range of SOC composition into sub classes. This will be very useful in distinguishing natural soils from reclaimed soil, while selecting reliable boundary conditions or inference space for soil quality functions (SQF) to support SQA and management need. In natural soils, ecosites can be grouped into 4 significant difference ($p < 0.05$) classes from ecosites a to ecosites e, soil texture can be divided into 3 groups of clayey, loamy and sandy, and moisture regime can be divided into 3 groups of hygric-subhygric, mesic-submesic and xeric – subxeric. Nutrient regimes can be classed into 3 groups of poor, medium and rich soils. Soil drainage classes can be demarcated into 3 groups of moderately well - well drained soils, very rapid-rapidly drained soils and imperfect to poorly drained soils. The soil types based on Canadian soil classification system can be broadly grouped into Brunisols, Luvisols and Regosols. These classes represent significantly different soil and landscape factors suitable for defining functional soil management zones to improve soil quality assessment at a regional scale.

In relation to mean SOC in reclaimed soils and observed mean differences (Table 3.4 and 3.5), the reclamation horizons can be divided into 3 groups of TSOIL, USUB and LSUB. Nutrient regime is divided into poor, medium and rich groups. Soil drainage classes can be grouped into moderately well, well and rapid drainage classes. The moisture regime into 3 significantly different ($p < 0.05$) groups of submesic, subxeric and mesic. The reclamation or cover design can be grouped into 2 significant different ($p < 0.05$) broad classes of A, B E, H, N series and F, I, J, M, N, O series based on SOC content and variation.

The common or similar factors of SOC variation in both natural and reclaimed soils each have 3 significant different classes or groups based on SOC content. A careful examination of the physical description of these groups based on Day (1982) indicated that natural soils encompassed extreme and broader classes in each group than reclaimed soils. For example, the soil moisture regime and drainage groups for natural soils include the extreme classes of very rapid – xeric soils, and the imperfectly drained - hygric soils which are not readily identifiable in reclaimed soils. Soil nutrient regime classes also have 3 similar groups based on SOC content of both natural and reclaimed soils.

3.4 Soil quality assessment based on SOC – nitrogen relations

Using the proposed framework (Figure 3.2), the objectives of SQA were defined by assessing soil's potential to supply N using SOC as the predictive SQ indicator. SOC – N relation demonstrates a robust, "more is better" relation within the SOC range of 0 to 120 $Mgha^{-1}$ for natural soils (Figure 3.3a). This relation was modelled quantitatively using a normal distributed, regression function (a type of sigmoid function). This formed the quantitative basis for defining a pre-disturbance SQF which is useful for SQA when validated for other similar or site-specific use. This is also important when natural soils are used as the basis for assessing the quality of reclaimed soils. The Pearson correlation coefficient between SOC and N is 0.79, while a regression of the two variables indicates that SOC explains about 62% of the underlying factors responsible for soil N variation (Figure 3.3a).

Reclaimed soils also confirmed a “more is better” relationship between SOC and N within the range of 0 to 400 $Mgha^{-1}$ (Figure 3.3b). The regression model captured the relationship between SOC and N in the reconstructed soils and produces the desired SQF which can be used for comparing the quality of reclaimed soil in the region. The Pearson correlation coefficient between SOC and N is 0.60, while a regression of the two variables indicated that SOC explained about 37% of the underlying factors responsible for soil N distribution (Figure 3.3b).

To compare the rates of SOC – N cycling in the two independent systems at regional scale without consideration for the effect of the functional or management group identified earlier, the rate of changes in soil N in relation to changes in SOC is presented in Figure 3.3c. The SQ threshold for optimum performance for natural soils to supply N was observed between 40 to 60 Mg ha^{-1} of SOC corresponding to range of 0.0100 to 0.0103 Mg of soil N. In other words, 1000 g shift in SOC content per unit ha of soil within the optimum SOC range corresponds to approximately 102 g shift in soil N per unit ha. The maximum rate was observed at 50 Mg ha^{-1} of SOC with about 0.0106 Mg ha^{-1} of soil N.

The soil quality threshold where the best range of N supply was observed in the reclaimed soils is broader in comparison to natural soils, ranging from 120 to 320 $Mgha^{-1}$ of SOC which corresponds to 0.015 to 0.018 $Mgha^{-1}$ of soil N (Figure 3.3c). The maximum or peak N concentration was observed at 260 $Mgha^{-1}$ of SOC with 0.002 $Mgha^{-1}$ of N. In comparing reclaimed to natural soil, there is about 5-fold difference in optimum or peak rates of N supply from 0.002 to 0.01. This difference in the rates of N supply between natural and reclaimed soil is justifiable, when the basis for judging reclaimed system is in relation to natural, self-sustaining system, with mineralization of SOC and N at a regional scale within the AOSR.

3.5 Soil quality assessment: Effect of time on N cycling rate

The annual trends of the SOC – N relation for natural and reclaimed soils is presented in Figure 3.4a and 3.4b, for years with adequate data to represent such relation. Corresponding mean annual rates of N - SOC cycling for natural and reclaimed soils or slope of the N – SOC regression lines presented in Figure 3.4a and 3.4b, are shown in Figure 3.4c and 3.4d, respectively. The time trends in mean annual rate of N – SOC cycling do not suggest an overall cumulative increase in SQ, in respect to capacity to supply N over time. Each year has a peculiar

SQ variation indicating potentially various factors affecting SOC–N dynamics for each year which eventually influences the overall SQ. The rate of N - SOC cycling observed in natural soils ranges from 0.02 to 0.06 while that of reclaimed soils ranges from 0.01 to 0.05. Two sample t-test at $p < 0.05$ between these annual rates for natural and reclaimed soils indicated no significant difference ($t = 1.03$, $p = 0.332$, $df = 9$) in SQ between reclaimed and natural soils, over the 10-year period. This directly questions the use of annual averages of SQ indicators and ratings while comparing natural and reclaimed systems, or the use of linear functions to model mineralization process rather than the use of non-linear functions.

3.6 Soil quality assessment: SQF validation and applications

A unique feature of the pre-disturbance SQF presented in Figure 3.3a is that it captures various ranges of SOC for different types of soil materials within the AOSR. Therefore, its unique strength should be in ability to differentiate and assess SQ of different types of soil material used in land reclamation within AOSR, based on their ability to supply N. Using the data from Yan et al. (2012), there was a significant ($p < 0.05$) difference between forest floor (FF or O-fmh) and mineral soil (MS) in terms of N supply using a two-sample t – test (Figure 3.5).

The SQ scores generated by the SQF using SOC reported by Yan et al. (2012) are also presented in Figure 3.5. The SQ score also confirmed the significant difference between FF and MS, showing that FF materials generate significantly higher amount of N or have better SQ than mineral soils ($p = 0.002$). Further validation of the SQF using data from Macyk et al. (2005) was completed. The SQ ratings produced by the predisturbance SQF effectively captured the known trend of original mean differences reported by Yan et al. (2012), for different types of reclamation materials either organic or mineral (Figure 3.6a and 3.6b).

Application of the SQF confirmed increasing SQ in terms of N supply potentials from Brunisols (0.35) to Luvisols (0.55) and peat (0.85), as reported in Figure 3.7a. No difference in SQ was observed between stockpiled and fresh, directly placed peat material in soil reconstruction operations based on reported SOC content (Figure 3.7b). Overburden and deep geological soil materials sampled below 1.0 m generally have low SQ because of the lower SOC content (Figure 3.7c). Finally, the SQF also reflects the better performance of LFH (litter, fibric and humic) cover soils than peat mineral soil mix in terms of N supply potentials when the materials are used as cover on tailings sand substrate, a common practise in the AOSR reclamation operation (Figure 3.7d).

4. Discussion

The summary statistics and mean SOC content for ecosite classes for natural soils in this study captures the differences in SOM input or accumulation processes such as litter deposition, which indirectly infers forest stand effect on SOC variation within the AOSR. The organic deposition process is one of the main reasons for the trends of increasing SOC variation with increasing SOC content observed in this study (Table 3.1). The significant differences observed within these ecosite groups support the need to emphasize soil and forest stand interactions in explaining SOC concentrations, trends and variations observed within AOSR. Neither of the soil or forest stand factors will alone sufficiently explain SOC variation in the boreal forest of AOSR (Baah-Acheamfour et al., 2014). Future study will carefully examine such interactions and how they affect the soil – plant productivity relations, while using this relation as the basis for SQA.

All the measures of SOC variation and dispersion including Q1, Q2, Q3, Q4, range and CV generally increased with increasing SOC content for both natural and reclaimed soils. These characteristics trend of increase in variability of SOC in natural soils potentially could be viewed as a weakness of SOC as a quantitative soil quality indicator. Meanwhile the increasing variability did not prevent the use SOC as the basis for delineating management zone. This is the case for classes of soil and landscape factors that still demonstrated significant differences in mean SOC concentration within its respective group, despite the high CV. These distinct classes of soil and landscape factors based on SOC content formed the basis for defining functional, soil management units. Factor such as soil`s parent materials did not capture the significant differences in SOC content mainly because SOC input and transformation process are dominantly within the plant rooting zones.

Another reason for the high SOC variation and CV in natural and reclaimed soil reported in this study could also be attributed to spatial variation. The completely randomized soil sampling design within plots is a potential contributing factor to such high variation. Blocked and randomized soil sampling designs potentially could further reduce CV reported. Previous large-scale monitoring of SOC such as in Colombo et al. (2014) showed similar high spatial variation at regional scales. Baah-Acheamfour et al. (2014) noted forest stands as the main SOM input sources for natural forest soils in different types of forested and managed forest system. Therefore, difference in tree species, physiology and potential for producing forest floor litter will also significantly affect the quantity and variation of SOC observed in natural soils of AOSR.

For further emphasis, common factors that accounted for differences in SOC content and variation in both reclaimed and natural soils include soil nutrient regime, moisture regime and drainage classes (Table 3.6). These factors explained the strong and robust process based relations observed between SOC and indicators of soil nutrient supply such as N concentration or soil water status such as gravimetric or volumetric moisture content. This SOC, nutrient status and moisture retention relationship follows similar “more is better” trends irrespective of the differences in soil nutrient management, the rates of nutrient cycling and stage of forest stand development reflecting differences in potentials for input or output of SOC.

Both natural and reclaimed systems are functional in terms of soil moisture and nutrient supply or mineralization to different extents. Meanwhile, this SQ analysis indicated that reclaimed soils lack specific groups or classes of soil moisture and nutrient regimes in comparison to natural soils. Therefore, SQA for land reclamation and mine closure should further focus on the future development of reclaimed soil and ecosystem with very rapid drainage and xeric moisture regime or imperfectly drained soils with hygric moisture regimes. A major land reclamation operation bias observed in the AOSR is the focus on development of well drained ecosites that exclude the practicality of xeric and hygric soils due to operational and machinery constraints. Development of hygric soils in wetlands system or a healthy forest stands with organic litters growing on moisture limiting soils such as coarse textured Brunisols will be additional indicator of long term SQ improvement and ecosystem development.

The non-significant difference ($p < 0.05$) of mean SOC by horizons of natural soils suggests that the natural forest soils are in a dynamic but steady state in terms of balance between input and output of SOC. In other words, the SOC balance in such system is tending towards an equilibrium state in which the rate of SOC input can be balanced by the rate of SOC output. Therefore, temporal or spatial monitoring of SOC in such natural system may reflect a stable and functional SOM or SOC pool in a self-sustaining, mature, natural forest soil. This stability and balance of SOC as impacted by SOC input and output process in reclaimed soils will therefore be a major indicator of long term SQ improvement. This will confirm that reconstructed soils are tending towards a stable nutrient cycling system as observed in natural soils. Similar stable pool of SOC was observed by Akala et al. (2001) in a long term SOC study of reclaimed soil, confirming the potential for use of SOC balance as an indicator of SQ development in land reclamation and restoration of soil to equivalent capability similar to natural soils.

4.1 Implications of SOC variation for soil quality assessment

Reclaimed and natural systems are different in terms of SOC and N content, even though they exhibit similarities in trends of SOC transformation processes such as mineralization. The SOC – N relations and the related SQF as shown in Figure 3.3a and 3.3b indicated similarity in increasing N supply capacity with increasing SOC content for both natural and reclaimed soils. This similarity in trends confirms that SOC transformation process such as mineralization significantly influenced the rate of supply of N in these soils to varying extent, regardless of the differences in approach to soil nutrient management in the reclaimed soils.

To quantitatively analyse and compare the differences in N supply capacity for natural and reclaimed systems to meet our SQ assessment criteria, applicable SQ metrics include the fact that SOC accounts for 62% of variation in N in natural soils and 37% of the N variation in reclaimed soils. This suggests some deficiency with SOC – N dynamics in reclaimed soils and opportunity to further improve the reconstructed soils' N cycling over time, if the natural forest soil's SOC – N dynamics is used as the basis for defining the target equivalent capacity. This difference in dynamics of SOC – N could also be linked to potential loss in nutrient due to stockpiling of reclaimed soils before replacement or less of vibrant carbon and nitrogen cycling system in the reclaimed soils. Further detailed analysis of this SOC variation along the subclasses of the soil and landscape factors demarcated by their significant difference ($p < 0.05$) in SOC concentration will provide better estimates of N supply capacity for comparing both systems at subclass level in a multi-indicator SQA procedure.

The differential analysis of SOC – N relation in Figure 3.3c provided additional quantitative SQ metrics which are useful in tracking the performance of reclaimed soils. The 5-fold difference in maximum or optimum rate of cycling from 0.002 $Mgha^{-1}$ of N in reclaimed soil to 0.01 $Mgha^{-1}$ of N in natural soils suggest that reclaimed system have potential to improve N supply capability over the years. This index will also be useful for projecting SQ into future years to determine if the reclaimed systems are moving towards a self-sustained natural system in terms of N supply potential or if reclaimed systems are improving in SQ when multiple objectives of SQA are defined that includes N supply potentials.

Potential factors responsible for the lower indices in SQ performance of reclaimed soils could include the effect of alternate source of N such as in fertilizer application to supplement soil N which could further discourage the release of organic forms of N by nutrient cycling processes or the N priming effect (Westerman et al., 1973). Another factor is the potential for oxidation of SOC in reclamation stockpiles or temporary storage reducing the initial SOC and N content of the soil in comparison to directly placed soil materials. The impact of reclamation substrates (subsoils)` chemistry such as coke or alkaline overburden materials on the topsoil pH and the need for reconstructed soil to adjust to a new micro - climatic environment, also could potentially affect SQ performance such as N supply capacity of reclaimed soil.

Use of non – linear SQF for SQA allowed for a detailed analysis of SQ while capturing both short term, seasonal and long-term variation in SOC – N dynamics (Figures 3.3a, 3.3b, 3.3c) in comparison to use of annual averages of indicators (Figure 3.4). Similar advantages were noted by Andrew et al. (2014) when comparing the use of linear and non-linear fits for modeling SQ relations. This advantage was clearly demonstrated when rates determined using the non-linear fits are compared to the means of annual rates in SOC – N cycling in Figure 3.4. The non-significant differences in the mean annual rates for natural and reclaimed soils did not account for the subtle seasonal variation in SOC – N dynamics. The fundamental processes of N supply and balance in these soils occur simultaneously with SOM transformation including N aminization, mineralization, ammonification and nitrification. These processes are not necessarily cumulative in temporal dimension considering N output processes such as plant uptake or leaching. Therefore, use of annual average of the rates of N output without accounting for seasonal variations and N balance could potentially produce false SQ metrics. This further discourages direct comparison of SQ indicators with baseline standards without accounting for the cofounding factors and the relevant process relations influencing the defined objectives of SQA. Designed SQF allow for the definition of a non-bias pre-disturbance system to judge reclaimed soils. The SQF also allow for a process based analysis of SQ indicators – measure of performance relation as demonstrated using the SOC – N regression function analysis.

Though not fully examined in this study, SQF will prove to be a valuable tool for planning and designing reclamation covers based on site specific soil properties, with a clear definition of performance targets in land reclamation. Figure 3.3a and 3.3b demonstrated a quantitative algorithm that could also be useful in analysing regional scale SQ variation, mainly to differentiate between soil material types. The major weakness of the SQF, which is a subject of the next study, is the need to fully integrate the knowledge of the effects of the statistically significant subclasses of soil and landscape factors influencing SOC content into the designs and application of SQF. There is the need to fully account for the effects of these factors of SOC variation along subgroups or classes identified in this study using constrained SQF with boundary conditions defined by the upper and lower limits of the SOC concentrations. Focus on the effects of common factors of SOC variation between natural and reclaimed soils such as soil moisture and drainage on reclamation cover design and SQ management is also desirable to enhance comparison of both systems.

5. Conclusion

We demonstrated the need for a clear understanding of SOC distribution and variation in the development of a regional scale SQF for the AOSR. Generally, we identified the significant soil and landscape factors that influence changes in SOC concentrations within the AOSR. Seven factors were identified for natural soils of AOSR and 5 factors for reconstructed soils. The common factors, irrespective of the differences in source, content and input rate of SOC for natural and reclaimed soils are soil moisture regime, nutrient regime and drainage. SOC dispersion and variation as measured using standard deviation, Q1 to Q4 and CV generally increased with increasing SOC content. Though high level of SOC variability was observed, SOC is still very useful in defining functional, soil quality management zones.

Defining the objectives of our SQ assessment based on the ability of the soils within AOSR to supply N, we successfully used SOC to predict N supply potential in both natural and reclaimed soils. Rate of SOC – N transformation determined using developed SQF showed that there are 5 orders of differences between natural and reclaimed soils in terms of potential for N supply through SOM cycling process. Using SOC – N regression analysis, SOC content accounted for 62% of N variation in natural soil and 37% of N variation in reclaimed soil.

To further demonstrate the application of pre-disturbance SQF developed based on the SOC – N relations, we validated the SQF based on their ability to differentiate the N supply potential of FF and MS materials using an independent dataset. We further validate the SQF using another independent dataset by testing the SQF ability to differentiate N supply potentials of different types of materials used for land reclamation within AOSR. After successful validation, the SQF was successfully applied for SQA in 4 different scenarios including the assessment of the SQ of reclamation designs using O-fmh (LFH) and peat –mineral mix as coversoil, and tailings sands as subsoil or substrate. We further demonstrated the advantage of non-linear SQF in SQA in comparison to the use of annual averages or single point indicator comparison.

Table 3.1. Summary statistics (mean (μ),standard deviation (δ),minimum (Q0),first quartile (Q1),third quartile (Q3), maximum (Q4), coefficient of variation (CV), range (Δ), skewness (α) and kurtosis (β)) of soil organic carbon in forest soils of the Alberta oil sands region as impacted by horizons (HR), ecosites (EC) and soil parent materials (PM) after 10 years of soil quality monitoring.

		SOC ($Mgha^{-1}$) ¶		Distribution of SOC ($Mgha^{-1}$)				Measures of Dispersion of SOC				
Soil Properties		μ	δ	Q0	Q1	Q3	Q4	CV (%)	Δ	α	β	N¶
HR†	A	18.16a	22.91	0.49	6.02	18.86	114.35	126.14	113.86	2.79	7.87	65
	O-fmh	23.73a	24.51	3.76	7.52	31.22	162.43	103.27	158.68	3.31	16.04	63
	B	29.44a	25.46	8.14	9.23	46.49	72.14	86.49	64.00	0.90	-0.80	11
EC ‡	a	6.88d	4.94	0.49	3.80	8.04	16.68	71.87	16.19	1.10	0.24	16
	b	13.70c	11.06	2.52	7.52	16.01	48.78	80.77	46.26	2.01	3.96	59
	d	24.59b	20.07	4.38	8.83	32.14	80.30	81.61	75.92	1.29	1.04	46
	e	52.78a	40.87	3.76	28.93	76.70	162.43	77.43	158.68	1.42	1.68	18
PM §	Aeolian	9.89a	7.42	2.38	4.19	14.88	27.63	75.05	25.24	1.32	1.66	12
	Fluvial	21.78a	27.59	0.49	6.56	28.87	162.43	126.67	161.95	2.88	9.80	80
	GL-FLV	21.95a	5.54	18.03	-	-	25.86	25.23	7.83	-	-	2
	Lacustrine	23.37a	15.37	5.12	11.10	38.85	48.78	65.79	43.66	0.76	-0.89	17
	Moraine-till	24.89a	21.49	4.38	9.18	33.39	80.30	86.33	75.92	1.36	1.06	28

† SOC summary by horizons (HR): A horizons includes eluviated (Ae) and organic Ah, B horizons including mottled Bt and gleyed Bm, O-fmh represents fibric, mesic and humic organics overlaying A horizons in forest soils.
‡ SOC's summary by soil profiles in specific natural ecological models or ecosites (EC) as defined by Beckingham et al. (1996). This includes the moisture dry sites or coarse textured soils growing dominantly jack pines such a (lichen) and b (blueberry) sites. There are also moisture rich or fine textured soils growing dominantly white spruce and aspens including the d (low-bush cranberry) and e (dogwood) site types.
§ SOC's summary by profiles of soils formed on specific parent materials (PM). GL-FLV implies glacio-fluvial materials.
¶ The number of data points found in the soil database used to calculate mean. Means with different alphabets are significantly different at $p < 0.005$.

Table 3.2. Summary statistics (mean (μ), standard deviation (δ), minimum (Q0), first quartile (Q1),third quartile (Q3), maximum (Q4), coefficient of variation (CV), range (Δ), skewness (α) and kurtosis (β)) of soil organic carbon in forest soils of the Alberta oil sands region as impacted by drainage (DR), slope position (SP) and moisture regime (MR) after 10 years of soil quality monitoring.

Soil and landscape properties †		SOC ($Mgha^{-1}$) §		Distribution of SOC ($Mgha^{-1}$)				Measures of Dispersion of SOC				
		μ	δ	Q0	Q1	Q3	Q4	CV (%)	Δ	α	β	N‡
DR	Very Rapidly	6.78c	4.67	2.38	3.58	9.51	15.62	68.97	13.23	1.70	3.35	6
	Poorly	8.81bc	0.74	8.28	-	-	9.33	8.43	1.05	-	-	2
	Rapidly	9.95c	7.05	0.49	5.49	13.44	39.74	70.88	39.26	1.97	5.68	51
	Well	21.57b	18.12	3.38	8.07	30.44	72.14	83.99	68.76	1.60	2.80	17
	Mod. Well	31.91ab	31.85	3.76	10.45	43.46	162.43	99.82	158.68	2.17	5.77	46
	Imperfectly	35.24a	23.61	10.94	17.64	42.32	102.57	66.98	91.63	1.68	3.35	17
SP	Crest	14.27a	10.09	4.83	9.19	18.00	34.02	70.68	29.19	1.98	4.60	6
	Middle	14.81a	15.80	0.49	5.45	17.02	72.14	106.69	71.65	2.24	5.54	30
	Upper	21.15a	20.19	3.74	6.14	31.63	72.14	95.48	68.40	1.51	1.98	14
	Lower	23.98a	30.03	2.61	5.35	31.74	102.57	125.22	99.96	2.35	6.07	10
	Level	24.48a	26.67	2.38	8.05	29.88	162.43	108.94	160.05	2.75	9.80	79
MR	Xeric	7.91c	5.02	0.49	3.98	11.47	18.51	63.51	18.02	0.70	-0.66	30
	Submesic	12.42c	9.07	3.10	7.56	21.02	31.97	73.00	28.87	1.08	-0.25	21
	Subxeric	13.51c	9.16	4.76	6.56	16.07	39.74	67.78	34.99	1.85	3.81	16
	Hygric	14.38bc	9.80	8.28	8.54	24.47	28.98	68.10	20.70	1.93	3.75	4
	Mesic	26.29b	20.10	5.12	11.16	35.96	80.30	76.47	75.18	1.17	0.65	45
	Subhygric	45.42a	39.69	3.76	19.88	71.71	162.43	87.37	158.68	1.52	2.22	23

† Based on Day, J.H.1982. Canadian soil information system (CanSIS). Manual for describing soils in the field (Revised, 1982). Land Resource Research Institute Contribution No.82-52. Research Branch, Agriculture Canada Ottawa, Ontario. DR is drainage, SP is slope and MR is moisture regime.
‡ The number of data points found in the soil database.
§ Means with different alphabets are significantly different at $p < 0.005$.

Table 3.3. Summary statistics (mean (μ), standard deviation (δ), minimum (Q0), first quartile (Q1),third quartile (Q3), maximum (Q4), coefficient of variation (CV), range (Δ), skewness (α) and kurtosis (β)) of soil organic carbon in forest soils of the Alberta oil sands region as impacted by soil nutrient regime (NR), soil texture classes (ST), soil series and subgroups (SG) after 10 years of soil quality monitoring.

		SOC ($Mgha^{-1}$) ‡		Distribution of SOC ($Mgha^{-1}$)				Measures of Dispersion of SOC				
Soil Properties		μ	δ	Q0	Q1	Q3	Q4	CV (%)	Δ	α	β	N
NR†	Poor	9.07c	5.60	0.49	4.99	12.43	27.63	61.73	27.14	1.25	1.72	51
	Medium	25.68b	27.19	2.61	8.26	31.22	162.4	105.87	159.8	2.76	10.07	67
	Rich	38.87a	25.78	9.66	20.94	44.01	102.6	66.31	92.91	1.20	0.82	21
ST§	LS	7.55b	3.08	3.375	4.756	9.472	14.58	40.83	11.20	0.62	0.68	14
	S	9.05b	6.65	0.49	2.98	14.24	27.63	73.53	27.14	1.08	1.33	22
	SL	11.99ab	8.64	6.11	7.72	15.33	29.36	72.02	23.26	2.28	5.39	6
	SC	21.00ab	-	21.00	-	-	21.00	-	-	-	-	2
	L	24.54ab	24.1	5.12	11.7	25.12	86.36	98.20	81.24	1.94	3.00	15
	C	33.01ab	11.44	21.04	21.04	46.49	46.49	34.65	25.45	0.29	-1.87	6
	CL	33.70ab	32.9	14.7	14.7	71.7	71.70	97.63	57.00	1.73	-	3
	SiL	38.30ab	69.4	4.4	5.3	86	162.4	181.0	158.0	2.23	4.98	5
	SiC	56.60ab	64.9	10.7	-	-	102.6	114.7	91.90	-	-	2
	HC	72.14a	-	72.13	-	-	72.14	0.00	0.00	-	-	2
SG¶	O.G	8.81cd	0.74	8.28	-	-	9.33	8.43	1.05	-	-	2
	E.DYB	9.69d	6.89	0.49	4.99	13.72	39.74	71.17	39.26	1.98	6.14	53
	E.EB	10.14d	6.77	3.38	7.61	9.47	24.00	66.77	20.63	1.63	1.82	12
	GL.E.DB	19.96abcd	12.76	10.94	-	-	28.98	63.93	18.05	-	-	2
	O.GL	25.84bc	20.19	4.38	10.19	32.77	80.30	78.14	75.92	1.20	0.73	45
	GL.GL	27.72abc	16.21	11.60	12.87	46.49	48.78	58.48	37.18	0.40	-2.21	7
	GL.R	40.30ab	23.30	19.90	22.40	64.60	73.50	57.79	53.60	1.40	2.20	4
	O.HR	42.87a	23.07	22.93	28.73	63.19	86.36	53.80	63.42	1.41	0.57	8
	GL.HR	74.30a	61.40	3.80	22.70	126.40	162.40	82.71	158.70	0.34	-1.56	6

† Nutrient Regime (NR); based on Beckingham et al., (1996).
‡ Means with different alphabets are significantly different at $p < 0.005$.

§ Soil texture (ST) ; including loamy sand (LS), sand (S), sandy loam (SL), sandy clay (SC), loam (L), clay loam (CL), silt loam (SiL), silt clay (SiC) and heavy clay (HC) particle sizes.

¶ Subgroups (SG); based on Canadian Soil Classification System includes eluviated eutric brunisols (E.EB), eluviated dystric brunisols (E.DYB), glaciated grey luvisols (GL.GL), orthic grey luvisols (O.GL), gleyed humic regosol GL.HR), orthic humic regosols (O.HR), gleyed eluviated dystric brunisols (GL.E.DYB), orthic gleysol (O.G) and gleyed regosols (GL.R).

Table 3.4. Summary statistics (mean (μ), standard deviation (δ), minimum (Q0), first quartile (Q1),third quartile (Q3), maximum (Q4), coefficient of variation (CV), range (Δ), skewness (α) and kurtosis (β)) of soil organic carbon in reclaimed soils of the Alberta oil sands region as impacted by soil horizon (HR), slope position (SP) and moisture regime (MR) after 10 years of soil quality monitoring.

Soil Properties		SOC ($Mgha^{-1}$)[4]		Distribution of SOC ($Mgha^{-1}$)				Measures of Dispersion of SOC				
		μ	δ	Q0	Q1	Q3	Q4	CV (%)	Δ	α	β	N
HR[†]	USUB	82.78c	85.36	1.03	34.68	99.57	604.77	103.12	603.74	3.22	15.73	89
	TSOIL	125.68b	90.59	0.60	69.68	166.22	540.54	72.08	539.94	2.08	6.18	131
	LSUB	172.41a	247.45	1.11	20.19	233.39	898.66	143.52	897.55	2.06	3.50	41
SP[‡]	Upper	96.57 a	105.50	1.03	43.25	101.67	604.77	109.25	603.74	3.16	11.93	66
	Level	115.86a	165.30	1.03	42.16	117.88	898.66	142.66	897.63	3.70	15.38	62
	Crest	126.26a	53.64	76.14	87.31	180.59	204.60	42.49	128.46	0.66	-1.68	11
	Middle	129.55a	126.51	0.60	49.25	169.93	793.87	97.65	793.26	2.90	12.05	119
	Lower	178.86a	124.49	81.72	81.72	319.20	319.20	69.60	237.48	1.37	-	3
MR[§]	Subhygric	49.64ab	37.73	16.96	16.96	82.32	82.32	76.02	65.36	0.00	-6.00	4
	Subxeric	75.76b	77.92	1.03	18.13	91.68	356.34	102.86	355.30	1.78	3.86	35
	Mesic	120.08ab	123.00	0.60	54.77	150.74	793.87	102.43	793.26	3.27	13.87	139
	Submesic	132.25a	137.70	5.71	53.88	169.06	898.66	104.12	892.95	3.23	14.45	68

[†] Reclaimed horizons (HR); classified by depth include upper subsoil (USUB, 20-50cm), lower subsoil (LSUB, 50-100cm) and topsoil (TSOIL, 0-20cm).
[‡] Slope position (SP) of reclaimed soils based on Day, J.H.1982.
[§] Moisture regimes (MR) of reclaimed soils based on Day, J.H.1982.
[¶] Means with different alphabets are significantly different at $p < 0.005$.

Table 3.5. Summary statistics (mean (μ), standard deviation (δ), minimum (Q0), first quartile (Q1),third quartile (Q3), maximum (Q4), coefficient of variation (CV), range (Δ), skewness (α) and kurtosis (β)) of soil organic carbon in reclaimed soils of the Alberta oil sands region as impacted by soil nutrient regime (NR), drainage (DR) and reclamation placement design (RPD) after 10 years of soil quality monitoring.

		SOC ($Mgha^{-1}$)[¶]		Distribution of SOC ($Mgha^{-1}$)				Measures of Dispersion of SOC				
Soil Properties		μ	δ	Q0	Q1	Q3	Q4	CV (%)	Δ	α	β	N
NR[†]	Poor	62.16 b	36.85	9.87	35.25	83.71	141.96	59.28	132.10	0.64	-0.33	23
	Medium	110.76b	120.89	0.60	49.54	140.59	898.66	109.14	898.06	3.66	18.48	151
	Rich	146.49 a	153.43	1.03	54.77	184.44	898.66	104.74	897.63	2.78	9.84	87
DR[‡]	Imperfectly	49.64ab	37.73	16.96	16.96	82.32	82.32	76.02	65.36	0.00	-6.00	4
	Rapidly	74.04b	75.23	1.03	15.06	95.58	309.76	101.61	308.73	1.34	1.34	42
	Well	123.61a	133.66	0.60	54.90	149.07	898.66	108.13	898.06	3.45	15.13	116
	Mod. Well	133.86a	142.05	1.03	54.42	166.47	898.66	106.12	897.63	3.17	12.89	99
RPD [§]	N	38.27b	42.92	1.03	1.11	84.82	90.47	112.14	89.44	0.37	-2.22	12
	B	67.13b	35.98	9.87	44.80	82.88	158.46	53.60	148.59	0.91	0.96	34
	H	79.33b	72.64	5.25	11.76	126.50	216.96	91.56	211.71	0.78	-0.65	31
	A	87.93b	61.88	5.71	31.46	129.13	218.76	70.38	213.05	0.53	-0.80	38
	E	97.29b	101.60	0.60	55.27	105.24	604.77	104.43	604.17	3.82	18.11	36
	M	105.81b	96.87	18.06	42.16	140.59	309.76	91.55	291.70	1.42	0.90	15
	F	115.90ab	96.26	16.20	51.42	173.98	319.20	83.05	303.00	1.14	0.17	15
	I	181.15a	152.78	16.96	87.31	227.94	793.87	84.34	776.90	2.38	6.65	68
	O	264.03a	340.00	54.65	65.64	386.91	898.66	128.78	844.01	1.65	1.11	10
	J	285.54a	61.58	242.00	-	-	329.08	21.56	87.08	-	-	2

[†] Soil nutrient regime classes (NR); based on Beckingham et al., (1996). [‡] Soil drainage (DR) classes; based on Day, J.H., 1982

[§] Reclamation placement designs (RPD); based on different combination of topsoil and substrate layers such as A (peat mix/mineral soil/tailings sands), B(direct placements/tailings sands), E(peat mix/secondary/overburden), F(direct placement /overburden), H(peat mix/tailing sands), I(peat mix/overburden), J(peat mix),M(peat mix/secondary/clearwater),N(peat mix/sand), and O(peat mix/mineral soils/coke). Peat mix is a mixtures of organic and mineral soils, secondary are mineral soils salvaged within depth of 1m, overburden are soil materials generally salvaged below 1m with suitable chemistry (pH, EC and SAR) for revegetation while clearwater are soil materials with oil impregnation either as tarballs or sticky forms of oil, due to the oil sands formation in Alberta.

[¶] Means with different alphabets are significantly different at $p < 0.005$.

Table 3.6. Statistical analysis of factors affecting SOC distribution in forest and reclaimed soils of the Alberta oil sands region.

Soil and landscape factors		DF	F Test	P value (< 0.05)	Adj. R^2 (%)
Natural Soil	Slope position	4	1.06	0.380	0.16
	Horizon	6	1.52	0.222	0.75
	Ecosites	3	20.89	< 0.001	30.18
	Soil texture	9	3.51	0.001	22.88
	Moisture regime	5	10.71	0.000	26.03
	Parent material	4	0.87	0.482	0.00
	Soil series	7	10.82	< 0.001	33.25
	Nutrient regime	2	16.44	< 0.001	18.29
	Drainage	5	7.08	< 0.001	18.06
	Soil group	8	11.15	< 0.001	37.05
Reclaimed Soil	Slope position	4	0.86	0.489	0.00
	Horizon	2	7.43	0.001	4.71
	Moisture regime	3	2.14	0.096	1.37
	Placement design	9	6.23	0.000	15.34
	Nutrient regime	2	4.56	0.011	2.67
	Drainage	3	2.58	0.054	1.79

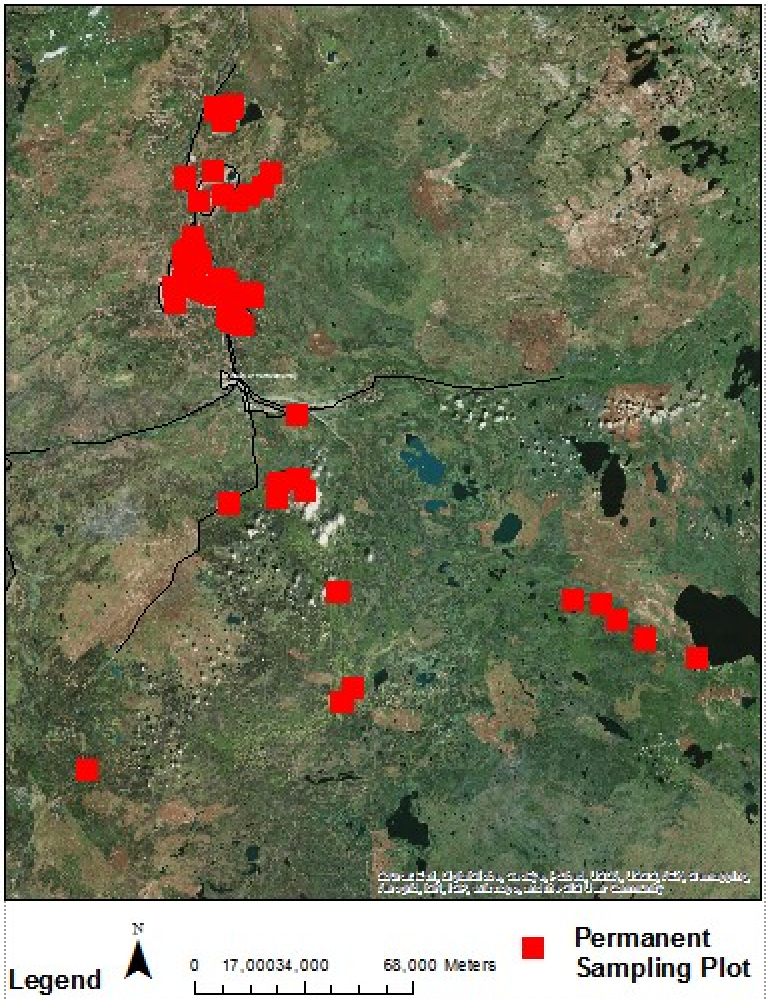

Figure 3.1. Soil sampling location within Athabasca oil sands region, Alberta, Canada.

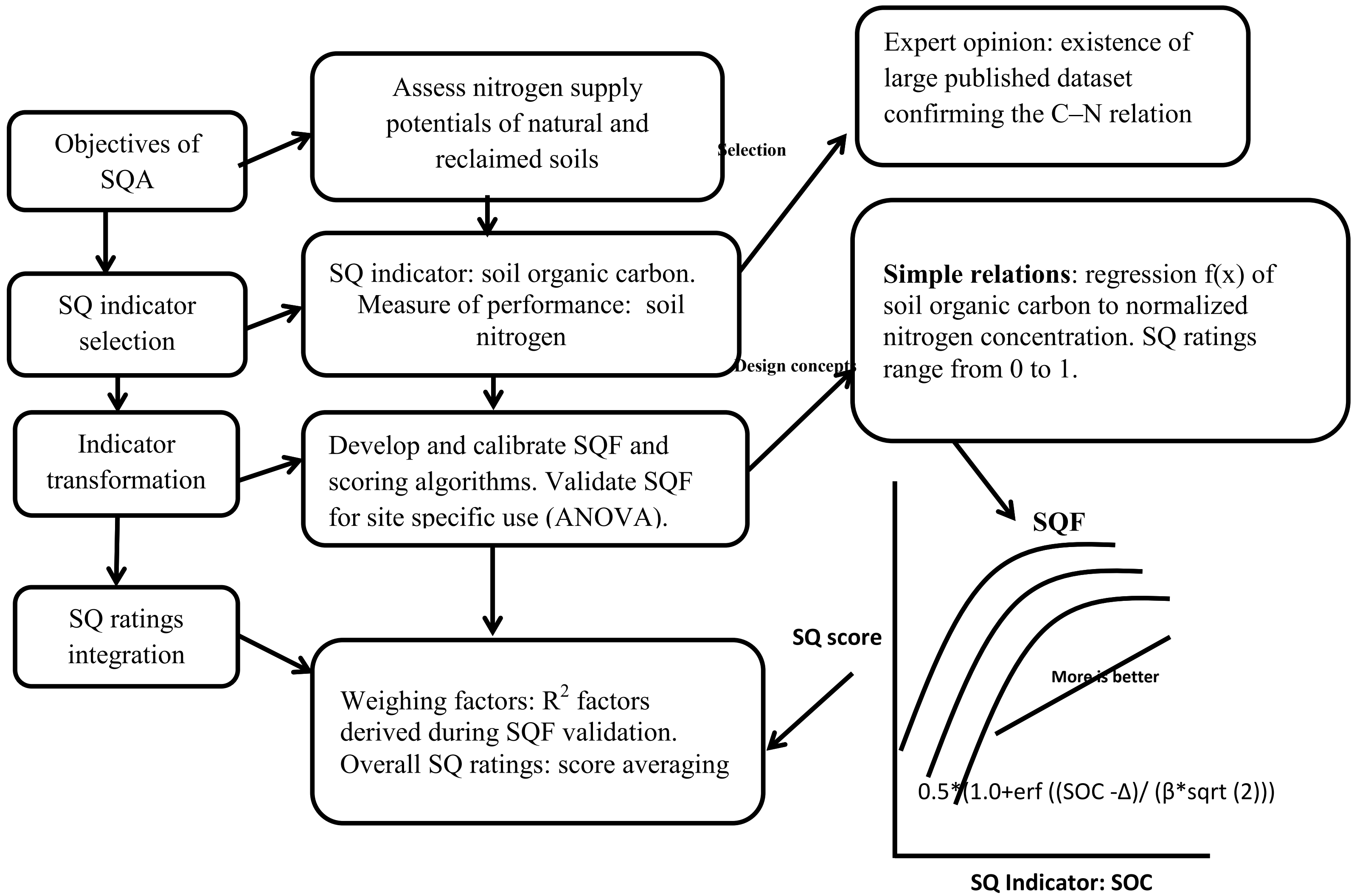

Figure 3.2. Soil quality assessment framework adopted in this study.

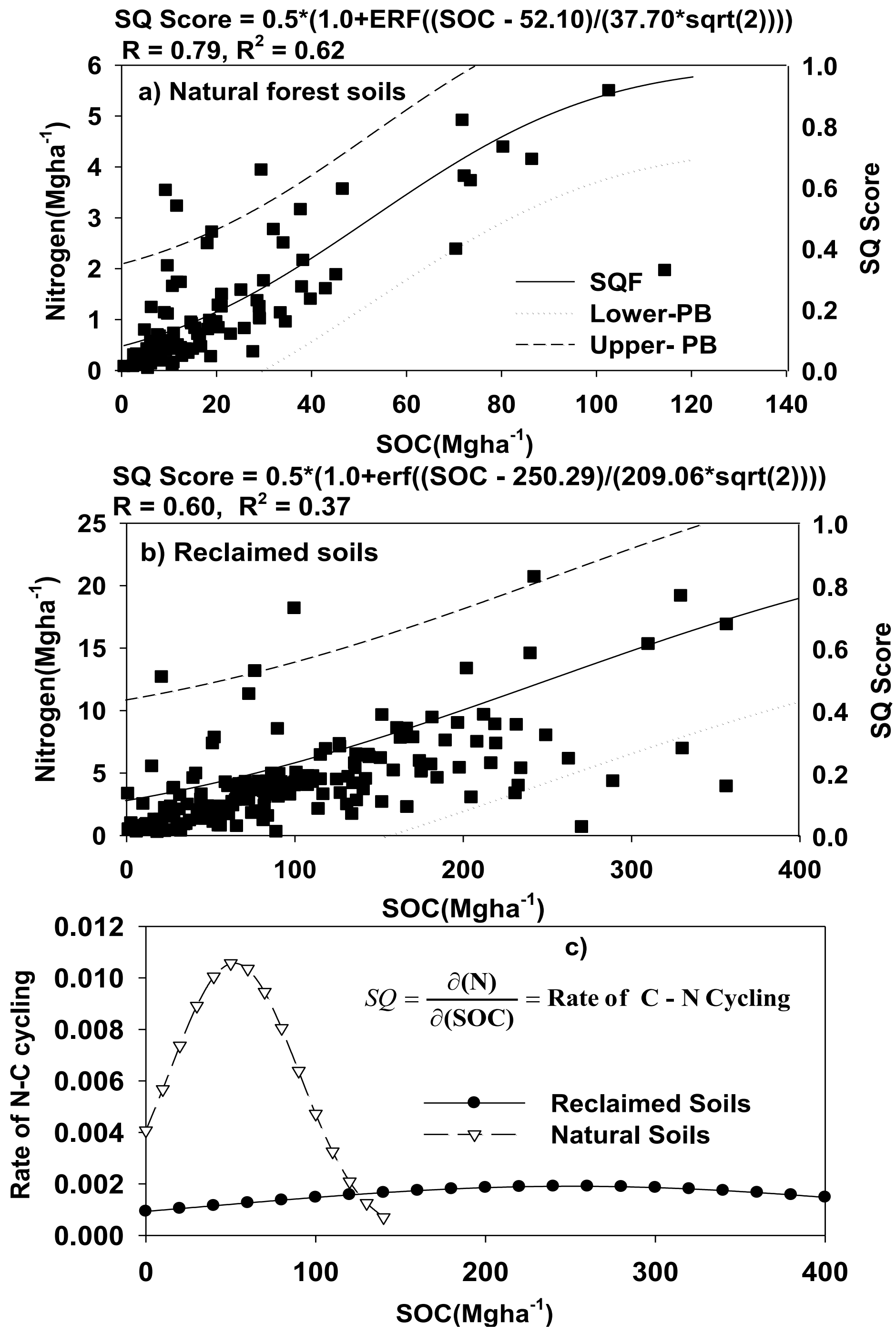

Figure 3.3. Soil organic carbon – nitrogen relations in natural and reclaimed soils.

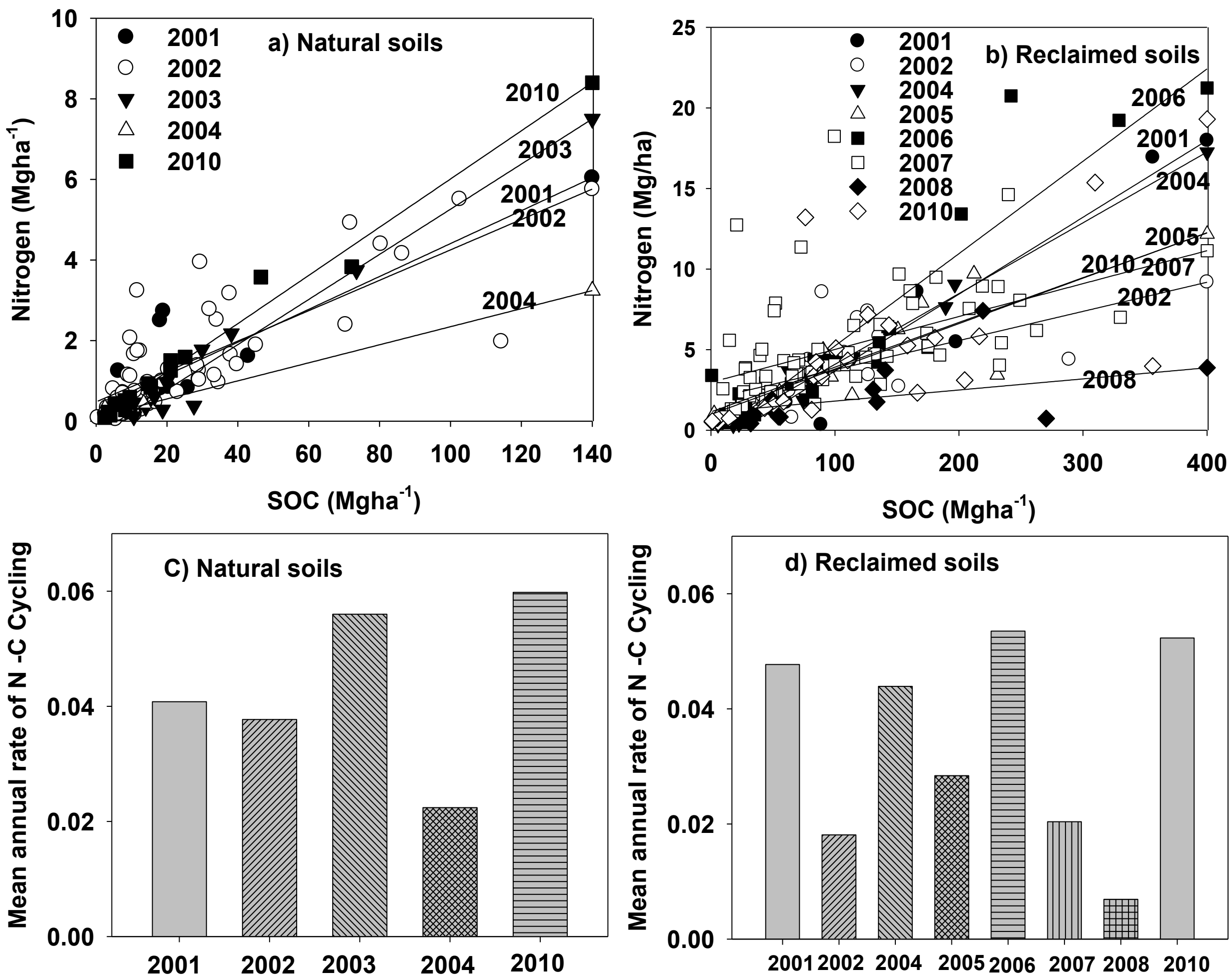

Figure 3.4. Temporal changes in annual rate of C-N cycling for natural and reclaimed soils.

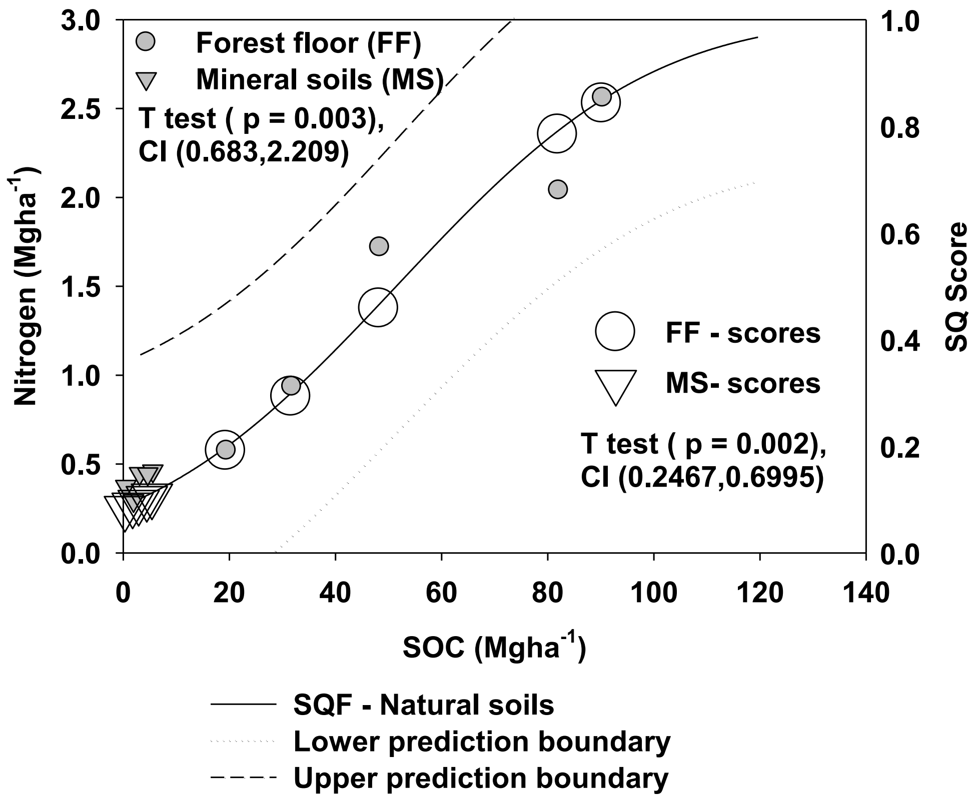

Figure 3.5. Validation of soil quality function based on its ability to differentiate the N supply potential of natural soils including the forest floor (FF) and mineral soils (MS).

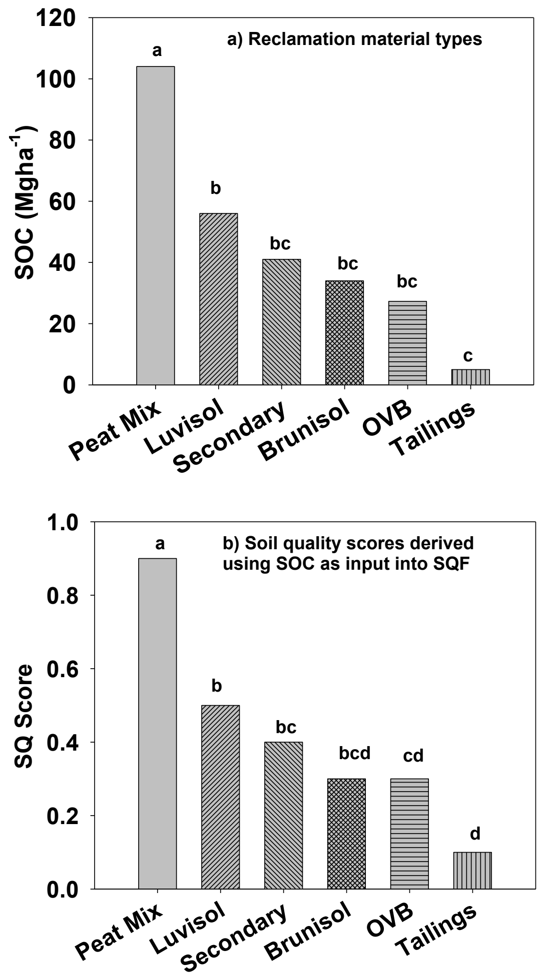

Figure 3.6. Validation of SOF's ability to rate SQ using SOC distribution in typical soils used for land reclamation within AOSR. The soils include Peat-Mix which are peat-mineral mix, Luvisols which are fine textured B and C horizon. Brunisols are coarse textured B and C horizon. Secondary is the name given to B and C horizon soils at reclaimed site, OVB is overburden soil materials below C horizons and Tailings are mainly sandy extracts.

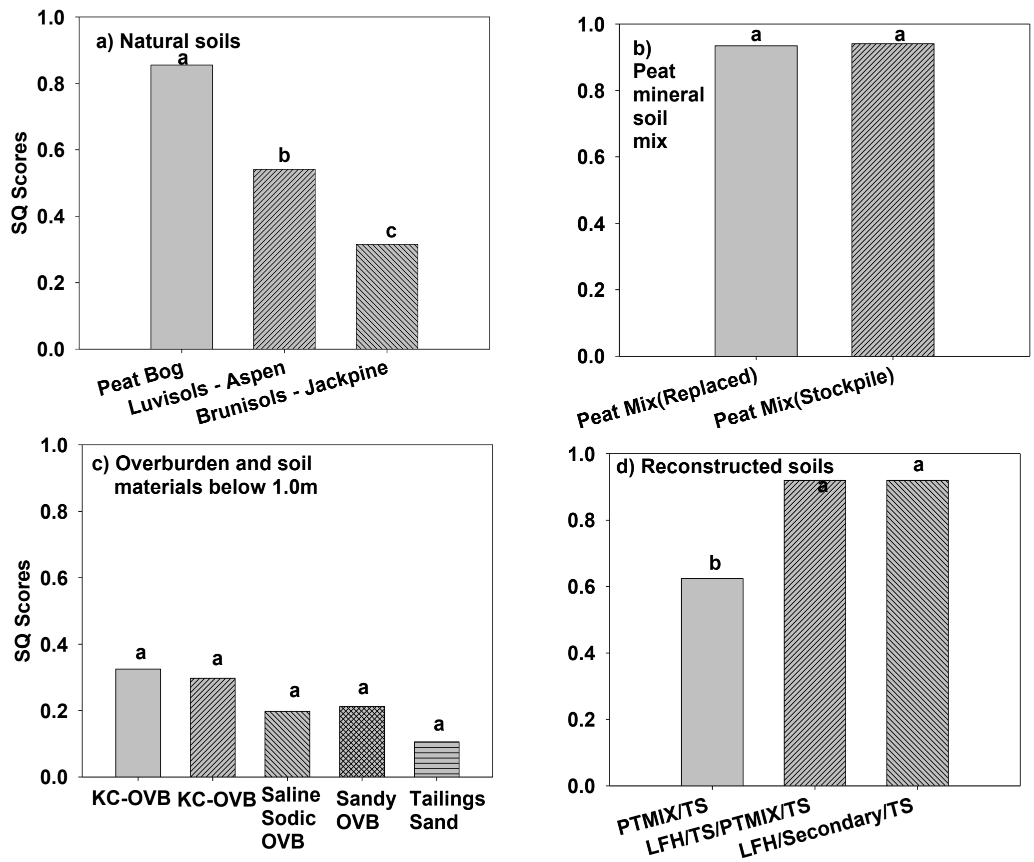

Figure 3.7. Soil quality ratings of a) natural soils, b) peat- mineral soil mix, c) overburden materials collected at depths below 1.0m, and d) reconstructed soils, based on capacity to supply nitrogen. Reconstructed soils includes PTMIX which is peat mineral mix, LFH is litter, fibric and humic, secondary is B and C horizon, and TS is tailing sands.

Chapter 4 Variation of Soil Organic Carbon in Alberta's Oil Sands Region: Applications of Soil Quality Function to Improve the Design and Quality of Land Reclamation Covers.

1. Introduction

Soil quality indicators (SQI) are physical, chemical and biological properties of soils that are sensitive to changes in management practises such as shift in soil nutrient supply and capability to support plant productivity (Doran and Parkin, 1994; Carter, 2002). Quantitative soil quality assessment calibrates predictive SQI with indicators of management goals or a measure of performance to generate soil quality-scoring functions (SQF) (Harris et al., 1994; Karlen et. al., 1997; Janzen et al., 1997). The SQF are further validated using SQI data from independent sites, with similarity in soil biogeochemical properties and processes (Larson and Pierce, 1991, Doran and Parkin, 1994, Andrews et al., 2004). The numerical functions are further applied in rating in quality of soils (Stott et al., 2009; Kaufmann et al., 2009). An implication of this approach to soil quality assessment (SQA) is the need to properly characterize baseline variation in predictive SQI and identify distinct soil management units before developing SQF, especially when SQA is conducted at regional scale. This will ensure that SQF properly account for possible or characteristics variation of SQI in its application (Arshad and Martin, 2002).

To minimize error in soil quality scoring or to prevent generating meaningless soil quality scores without any correlations to the soil physical, chemical and biological systems it was meant to model, SQF needs to be constrained in its application to distinct soil management units. This is done by analysing the statistical measure of central tendency and dispersion of the chosen predictive SQI that characterise the soil system of interest. These measures of variability quantitatively define the valid predictive range of SQF (Stott et al., 2009).

These soil quality- scoring functions or SQF are expected to generate soil quality scores that can reproduce similar significant or non-significant treatment effects of changes in soil management on SQI or vice versa (Andrews et al., 2004). Reproducing such treatment effects is only possible when soil quality scores are generated using properly constrained range of SQI input into SQF. The boundary conditions applied to SQI must account for the baseline variation in SQI as influenced by changes in land use, soil types, ecosites, landscape or other relevant soil management units. Output from SQF derived from constrained range of SQI will also improve the reliability of soil quality ratings generated for single soil management objectives or integrated soil quality ratings for multiple soil management objectives.

Characterizing variation in SQI as influenced by relevant landscape or soil factors allows for quantitative definition of boundary conditions of soil management units, which is required for the definition of boundary conditions of SQF. The boundary conditions are the lower and upper limits of SQI beyond which the SQF is no more applicable. The definition of soil management units in spatial or temporal dimensions also provides a robust option for handling regional scale variation in SQI. Therefore, SQF developed for assessing the quality of soils for each management units defined based on characteristic range of predictive SQI for each unit will provide better option for addressing uncertainty in outputs of SQF due to spatial variation in input SQI. Properly constrained SQF will significantly improve reliability of any metrics derived from the numerical function especially when the focus is to design reclamation covers and assess their quality with respect to ecosystem restoration.

Applications of SQF during SQA process in land reclamation present a unique opportunity to design reclamation covers that meet specific objectives or performance goals using a quantitative framework. Analysis of SQF will provide SQI's thresholds within which desired performance goals are achievable. SQF also allows for quantitative definition of equivalent land capability or functionalities, the basis for which soil quality improvement or degradation is judged in soil reconstruction operation. SQF provides the numeric framework for such analysis while conducting SQA during land reclamation operation. Therefore, a properly constrained SQF that accounts for the variation in its input SQI will further increase the reliability of decision made in land reclamation when SQF are applied.

This is the case with the Alberta oil sands reclamation within the Athabasca Oil Sands Region (AOSR) where preliminary analysis indicates that soil organic carbon (SOC) is a critical SQI capable of defining soil management units, based on existing land classification system (Beckingham et al., 1996) and also acts as a suitable predictive indicator in SQF designed for assessing and monitoring changes in soil management goals (Ojekanmi et al., 2014). Typical example of such management goal in land reclamation is the need to assess nutrient supply potentials, especially soil nitrogen (N) which is a major limiting factor for vegetation establishment in this boreal forest ecosystem (Yan et al., 2012). Previous studies within the region also confirmed that mineralization rates is a critical or functional process driving the availability of N in these natural and reclaimed soils (McMillan et al., 2007; Kwak et al., 2016; Howell et al., 2017). Also, regulations guiding the development of reclaimed sites demands self-sustainability of such critical functionalities such as carbon and nitrogen mineralization in reclaimed soils (Naeth, 2012). These are the rationale for focusing on SOC – N relationship as the basis for designing SQF and applications during SQA for this region. This forest ecosystem is also actively undergoing land reclamation and soil reconstruction operation due to mining activities, with the need for a rigorous and quantitative approach to SQA to support the operations (Ojekanmi et al., 2014).

The objective of this research is therefore to demonstrate the development, analysis and applications of SQF which are constrained to specific soil management units within the AOSR. SQF will be developed for each soil management units which are existing group of soil and landscape factors with distinct and significantly different SOC content. The SQF will be further subjected to threshold analysis to derive suitable soil quality metrics for applications in the design of reclamation covers based on the need to ensure the optimum N supply potentials from the reclaimed profile. Finally, the SQF will be validated and applied with emphasis on 3 possible scenario of defining ecosystem performance target, equivalent capability and functionalities for land reclamation covers.

2. Materials and Methods

2.1 Site description

Athabasca Oil Sands Region (AOSR) is located northeast of the Province of Alberta, Canada within the boreal forest region. The southern limit of AOSR is around (416513.99 m E, 5996830.83 m N, UTM 12) and northern limit extend up to (476902.52 mE, 6650497.17 mN, UTM 12). The climate is continental where winters are typically long and cold, with short and cool summers. Mean daily temperatures range from −18.8°C in January to 16.8°C in July. Annual precipitation is 455 mm, which falls predominantly as rain (342 mm) during the summer months. The soils within the region are dominantly Luvisols developed from lacustrine deposits and Brunisols from glacio-fluvial outwash. The dominant vegetation within the boreal forest includes white spruce (*Picea glauca)*, black spruce (*Picea mariana*), trembling aspen (*Populus* *tremuloides*), balsam poplar (*Populus balsamifera*), white birch (*Betula papyfrifera*), and jack pine (*Pinus banksiana*) (McMillan et al., 2007).

According to Alberta Energy Regulatory, the AOSR has 4,800 km^2 of surface oil sands mineable areas with 767 km^2 of the area already disturbed as at 2012 to support the development of the bitumen deposit. The disturbance within the surface mineable oil sands lease include tree clearing, soil removal and conservation, changes in landscape and site hydrology. This identifies the need for land reclamation activities such as soil conservation, landscape reconstruction, cover soil designs, revegetation and final development of healthy ecosystem. This ecosystem reconstruction operation also manages large volume of soils, justifying the need for a rigorous SQA framework to make decisions in regard to; what soils should be conserved?, what type of reclamation covers should be replaced in disturbed soil? what are the critical soil functionalities or capability in such reclaimed soil and how to monitor such over a space of 2 to 3 decade with minimal cost to support closure operations? These questions, among others indicate the need for a quantitative soil quality assessment framework to support land reclamation within AOSR.

2.2 Experimental designs

The data used for this study was collected between years 2000 and 2010 by the consortium of industries actively reconstructing landscape, soil and vegetation in the AOSR (CEMA, 2011). This involves the establishment of about 116 permanent sampling plots within the AOSR which includes 50 natural and 66 reclaimed plots. The dimensions of each of the plots are 10 by 40 m. The spatial distribution of the plots was designed to capture representative's ecosites and reclamation designs within the AOSR using complete randomized designs. The purpose of these long-term soil and vegetation monitoring plots were to collect reclamation performance data including the need to demonstrate improvement in SQ of reclaimed soils using natural soils as the basis for SQA. Natural plot locations were selected based on the 10 natural ecosites and used as targets for land reclamation (Beckingham et al., 1996), while reclaimed plots were selected based on type of cover design or series.

2.3 Soil sampling and chemical analysis

Records of landscape data including soil profile description, vegetation type, horizons, ecosites, parent materials, drainage, slope position and others were compiled. These data were used to determine the soil series, taxonomic groups, subgroup, moisture and nutrient regime (Beckingham et al., 1996). Data were collected from the field plots and entered into a database developed using the Canadian land classification system (Day, 1982). Soil sampling performed over 10 years included 94 plots, which were sampled once around September between the year 2000 and 2004, and 74 plots which were sampled up to three times annually in September between 2005 and 2010. The sampling design for natural plots included composite samples taken at depths corresponding to Ae, B_m, B_t, BC and C horizons of the natural soils. The reclaimed soils were sampled by material types and at depths ranging from 0 to 0.2 m for topsoil (TS), 0.2 to 0.5 m for upper subsoil (US) and 0.5 to 1 m for lower subsoils (LS). Within these depth ranges, composite soil samples were collected per natural or reclaimed soil profile.

The soils were analysed for various physical, chemical, biological properties and the data generated from the analyses were organised into a relational database for further analysis. Soil organic carbon was analysed using LECO CN-2000 analyser (Wright and Bailey, 2011) and total soil nitrogen (N) was determined using Kjeldahl digestion technique (Bremner, 1996; Mckeague, 1978). Soil bulk density was determined using soil core method using a cylinder with dimensions of 0.68m in height and 0.73m in diameter (Blake and Hartage, 1986). Soil textural content was determined using hydrometer method (Gee and Bauder, 1986). Soil chemical analyses performed included pH in water (Thomas, 1996), cation exchange capacity and exchange acidity (CEC – NH_4OAC at pH 7), sodium adsorption ratio and electrical conductivity measured in soluble extracts as outlined by Mckeague, (1978) analytical manuals. The data were stored in a reclamation database over 10 to 12 years' period.

In this study, we designed and ran a database query to retrieve a subset of the soil and landscape parameters including slope, parent material, soil horizon, drainage and other soil parameters. Soil parameters queried includes horizon depth, bulk density, SOC and N. Measures of SOC and N which were reported in mass unit of mg/kg were converted to volumetric units of Mg/ha using the reported bulk density and horizon depth. This mass to volumetric unit conversion has a significant implication for reclaimed profiles, generally reporting high amount of SOC considering that the reconstructed horizon thicknesses were fixed at 0.2mfor topsoil (TS), 0.3mfor upper subsoil (US) and 0.5m for lower subsoil (LS), in comparison to natural soils with highly variable horizon thickness ranging up to 0.3m.

2.4 Development of soil quality functions

Using the SQA framework for reconstructed ecosystem proposed by Ojekanmi et al. (2014) in Figure 4.1, the objective of SQA was to assess soil capacity to supply N for plant's use while using the changes in SOC as a predictive indicator of a shift in N supply capacity. The choice of SOC – N relationship is directly influenced by the fact that previous work has shown that N supply is a primary limiting factor in this boreal forest (Yan et al., 2012) and mineralization of organic matter is widely recognized as a critical fundamental process to affirm self-sustainability in nutrient supply potential of the reclaimed soils. Therefore, SOC (Mg/ha) was selected as the predictive indicator of SQ and corresponding N (Mg/ha) as the measure of performance or soil management goal.

The soil management units considered in this study included classes of ecosites ranging from a, b, d to e, which represent unique soil and vegetation stands characterized for the AOSR (Beckingham et al., 1996). Others management units with distinct SOC content in this region includes soil texture classes of sandy (coarse textured), clayey (fine textured) and loamy (medium textured) soils; soil moisture regime classes that includes subclasses of xeric to subxeric, mesic to submesic and hygric to sub-hygric; soil nutrient regime classes of poor, medium and rich; drainage classes of moderately well to well, very rapid to rapid and imperfect to poor subgroups. These classes have been previously identified in the Canadian soil classification systems and also represent statistically significant different ($p < 0.05$) range of SOC content for AOSR.

The characteristic range of SOC and N (Mg/ha) reported for all the soil and landscape factors of consideration and their respective subclasses were determined using Fisher`s protected LSD or mean comparison test. In other to analyse and compare the SOC - N dynamics of natural and reclaimed soils based on the effects of various soil and landscape factors defining respective soil management units, SQF were developed for each significant ($p < 0.05$) factors of SOC variation using methods proposed by Andrews et al. (2004). The following equations were solved:

$$Normalized\ (Y) = Yi/\max(Y) = y = soil\ quality\ score\ [\,0, 1]$$ [1]

$$SQF\ [y = f(x)], \qquad Rate\ of\ change\ in\ SQ = \delta(y)/\delta(x)$$ [2]

$$Threshold\ value\ x,\ \ when\ \delta(y)/\delta(x) = maximum(optimum\ rate\ of\ change\ in\ SQ)$$ [3]

$$where\ Y = Nitrogen\ (Mg/ha) and\ x = SOC\ (Mg/ha)$$

Nitrogen (Mg/ha), reported in the database were normalized and regressed with SOC to derive SQF for the significant ($p < 0.05$) factors of SOC variation. Nitrogen concentrations (Mg/ha) were normalized between 0 and 1 by diving with the maximum reported N concentration for each of the factors of SOC variations and regressed with SOC to derive the SQF (Equation 1). The best fit for each regression was determined using Curve Expert Software which contains a database of about 200 built in and custom regression functions (Weinhold et al., 2009). of the SQF based on δ(N)∕δ(SOC) with units in Mg/ha of N – Mg/ha of SOC, were completed for both natural and reclaimed soils (Equation 2), to define broad SQ thresholds producing the best or optimum range of N concentrations. Emphasis was on subclasses of soil and landscape factor showing significant differences in SOC content for natural and reclaimed soils for this region. The SOC – N relationship was characterised as a “more is better” relations in which increasing SOC leads to increased N input due to SOM mineralization, resulting in other nutrient elements including N, being released into the soil.

Changes in SQ in this study was defined quantitatively as the rate of change in N (Mg/ha) with respect to the changes in SOC (Mg/ha), i.e. δ (N)∕δ (SOC). Differential analysis of the SQF based on δ(N)∕δ(SOC) were completed for each set of factors and their respective sub-classes(Equation 3). The δ(N)∕δ(SOC) distribution function for natural soils was defined as the natural, baseline or pre-disturbance SQF which also forms the basis for defining equivalent or representative SQ capability for reclaimed soils, while the SQF for reclaimed soils were used to independently compare reclaimed soils as an independent class of anthropogenic or reconstructed soils.

Even though this study emphasizes the use of SOC as a central and principal SQI (Ojekanmi et al., 2014), there is also the need to further demonstrate typical examples of threshold analysis for multiple SQI. Therefore, similar numerical functions for predictive indicators such as percent clay, pH (water), electrical conductivity and sodium adsorption ratio, and normalized N as the measure of performance were developed and analysed for range of SQI that captures the optimum N supply capacity by ecosite management units, using equations 1 to 3.

2.5 Validation and application of soil quality functions

To test the performance of the developed SQF in assessing N supply of different types of soils used in land reclamation within AOSR, we choose an independent dataset from Yan et al. (2012). This study focussed on the effect of forest productivity on soil N or vice-versa within the AOSR and thereby reported all the characteristics soil variables including SOC (Mg/ha) (Yan et al., 2012). This makes the data very useful in assessing the capability of our designed SQF to produce SQ indices that can demonstrate similar effect of forest stands on soil N status reported in this study.

The SOC (Mg/ha) reported for each treatment was inserted into the developed SQF for each class of the factors that cause SOC variation, and the SQ scores or index of N supply potential were generated between 0 and 1. The SQ scores were analysed for effect of forest stand types including white spruce (*picea glauca*), trembling aspen (*populous tremuloides*) and jackpines species (*pinus banksiana*). Similarly, the effect of these tree species on actual N (Mg/ha) content was also analysed. These analyses were completed for both mineral soil and forest floor materials as reported in Yan et al. (2012). Mean comparisons using Tukey test between means of N (Mg/ha) and respective SQ score for mineral soil (MS) or forest floor (FF) materials were compared. The mean differences or comparison for the SQ scores were assessed based on the extent to which the indices or SQ scores represent the actual effect of forest stands on N supply potentials of the soils.

To further demonstrate the application of these numerical functions, we chose another independent dataset from the same study region as reported by Macyk et al. (2005). This study summarized the effect of SOC content on soil respiration and reported SOC (Mg/ha) for various natural and reclaimed soils in AOSR. We chose this dataset and tested the ability of SQF to rate the SQ of natural soils as an independent validation for this dataset. This was done considering that natural and reclaimed soils have distinct differences in SOC content and designs, in which the reclaimed soils are best described as anthropogenic soils (Naeth et al., 2012). Further assessment of the SQ of reclaimed soils using natural soils as the projected ecosystem or expected ecosystem target of the reconstructed soils over the long term was completed. Also, considering that reclaimed soils are anthropogenic and distinct from natural soils, this study assesses the quality of reclaimed soil in comparison to other reclaimed profiles within the same region. Finally, this study carefully demonstrated how the designed SQF could be applied in the design of reclamation covers when there is a clear and quantifiable set of ecosystem targets for soil reconstruction operations. Additional advantages of such a quantitative approach to reclamation cover designs were also examined.

2.6 Statistical and numerical analysis

The regression analysis of SOC (Mg/ha) and normalized N concentrations was completed in Curve Expert Pro. (Daniel Hyams, 2012) using database of about 200 built in and customized numerical functions. Considering the general sigmoid relationship between SOC and N irrespective of the effect of factors of variations, we chose the function 0.5*(1.0+erf ((SOC - Δ)/(β* sqrt (2))))) or it's variant to consistently model the SOC - N relationship. The sigmoid functions and its variants have been previously demonstrated as the best set of mathematical functions to explain the SOC – N relations (Stott et al., 2012; Andrews et al., 2004; Weinhold et al., 2009; Ojekanmi et al., 2014). Further analysis of the rate of changes (δ(N) ⁄ δ(SOC)) was completed to assess SQ thresholds corresponding to range of SOC where the optimum N supply was observed for each class of factor representing unique SOC range, with defined boundary condition.

In the SQF validation process, we used generalized linear model (GLM) to test the effect of forest species on both N (Mg/ha) reported in Yan et al., (2012) and the corresponding SQ scores generated by each SQF for the factors of SOC variation. Mean comparison was completed using Tukey and Bonferroni test at the probability of 95%.

3. Results

3.1 Soil quality thresholds in natural soils

The SOC – N relations for distinct classes of factors of SOC variation or management units are presented in Figure 4.2a-f. The corresponding SQF designed by using natural soils data are presented in Figure 4.2g-l. The graphs of the rates of N cycling with respect to changes in

SOC content for each management units are presented in Figure 4.2m-r, respectively. Table 4.1 presents the algorithms representing the developed SQF for each of the management units, while reporting respective boundary condition and equation constants. Table 4.2 summarize the optimum or threshold of SOC content data to ensure the N supply capability in the natural soils. These SQF represent SOC and N relations in pre-disturbance or baseline condition, showing the characteristics SOC to N range or variation as impacted by significantly different ($p < 0.05$) groups of soil and landscape factors. These factors include classes of ecosites, soil texture, soil moisture regime, nutrient regime and drainage for natural soils. The use of the SOC to N relations in pre-disturbance soils as the basis for SQA meet the needs to define a quantitative, equivalent land or soil capability function which forms the basis for assessing reconstructed soils with a well-defined ecosystem boundary, such as the soils of AOSR. These pre-disturbance SQF are expected to represent all the necessary baseline variations in soil processes related to N supply in the natural system, thereby providing a better and more representative basis for SQA. This is unlike the arbitrary selection of baseline parameters based on proximity to site and the assumption that such undisturbed environment has a representative baseline quality suitable for assessing disturbed soil of interest in land reclamation (Arshad et al., 2002, Harris et al., 1994).

Ecosites a, b, d, and e were observed within the AOSR, representing a unique combination of dominant forest stand and soil type. The mean SOC content ranges up to 20 Mg/ha in ecosite a, to 120 Mg/ha in ecosites b, d, and e (Figure. 4.2a). The relevant SQF for the 4 ecosite classes were represented in the equations 1 to 4 (Table 4.1), with regression coefficients (R^2) ranging from 0.57 to 0.80 (Figure 4.2g and Table 4.1). The highest rate of SOC – N transformation, $\delta(N)/\delta(SOC)$, was observed in ecosite a with about 61 gN/kg of SOC between the range of 4 to 8 Mg/ha of SOC (Figure 4.2m and Table 4.2). The minimum rate was observed in ecosites e with 9 gN/kg of SOC within the range of 30 to 50 Mg/ha of SOC. The optimum mineralization rates of OM to supply N increases in the order of ecosites e, d, b and a with reducing range of SOC content. There are significant ($p < 0.05$) differences in mineralization rates of N among the ecosites classes.

Grouping soil textural classes into three subgroups of clayey, sandy and loamy soils based on the significant differences ($p < 0.05$) observed in SOC content (Figure 4.2b). The characteristic range of SOC in sandy soils is up to about 30 Mg/ha, up to 80 Mg/ha in clayey soils and up to about 120 Mg/ha in loamy soils. The SQF that represents the effect of soil textures on SOC to N relations are represented in equations 5 to 7 (Table 4.1). The R^2 was 0.16 in sandy soils and 0.93 in clayey soils (Figure 4.2d and Table 4.1). The highest rate of N supply was observed in sandy soils around 15 Mg/ha of SOC corresponding to 17.6 gN/Kg of SOC, while the lowest rate of N supply was noted for loamy soils around 40 Mg/ha of SOC representing 10.36 gN/kg SOC (Figure 4.2n and Table 4.2). From a regional perspective, the optimum rates of N supply increases in the order of loamy, clayey and sandy soils.

Further characteristics range of SOC in natural soils as impacted by other significantly different factors that cause variations in SOC or management units including soil moisture regime, nutrient regime, soil types and drainage were presented in Figure 4.2c-f. The R^2 for SQF accounting for the effect of soil moisture regime ranges from 0.46 to 0.69, 0.15 to 0.68 for nutrient regime, 0.40 to 0.70 for soil drainage and 0.46 to 0.73 for soil types or order (Figure 4.2i-l and Table 4.1). These SQF are numbered equations 8 to 19 in Table 4.1, while respective thresholds of SOC at which the optimum N supply rates was observed were also reported in Table 4.2 and Figure 2o-r. As an example, the optimum rates of N supply as impacted by the soil moisture regime increases from 11.56 gN/kg SOC in the hygric-subhygric group (H–SH) to 20 gN/kg SOC in the xeric – subxeric groups (X-SX). Increasing or decreasing trends in rates of N supply were also observed for classes of soil nutrient regime, drainage and soil types (Table 4.2, Figure 4.2p-r). To further demonstrate the multi-indicator requirements of SQA or in the design of reclamation covers, a summary of the SQI thresholds that corresponds to optimum N supply capacity were presented in Table 4.3.

3.2 Soil quality thresholds in reclaimed soils

The SOC – N relations, designed SQF and rate of N cycling analysis for reclaimed soils are presented in Figure 4.3a-e, f-j and k-o respectively, with respective algorithms and boundary conditions provided in Table 4.4, while summary of threshold analysis of SOC with optimum rates of N supply potentials in reclaimed soils are presented in Table 4.5. Soil and landscape factors of SOC variation representing proposed management units which were considered for reclaimed soils includes reclamation horizons, nutrient regime, drainage, cover design and moisture regime. These soils are reconstructed with specific natural system or ecosite target in minds but recent examinations have also classified them as anthropogenic soils (Naeth, 2012).

This is justifiable in terms of the ranges of SOC content in various reclamation designs (Table 4.4) which are sometimes 3 - 4 times more than the quantity of SOC found in the natural system (Table 4.1), thereby influencing the characteristics N supply potentials.

Horizons in reclaimed soils shows increasing SOC content from a maximum of 350 Mg/ha in the upper subsoil (20 - 50 cm) and lower subsoil (50 – 100 cm) to about 400 Mg/ha in the topsoil (0 – 20 cm), directly reflecting the effect of soil reconstruction operations (Figure 4.3a). The SOC to N relations as represented by the SOF with equation number 20 to 22 reported positive R^2 values from 0.48 to 0.57 (Figure 4.3f and Table 4.4). The highest mineralization or optimum rates supporting N supply are exceptionally high in the lower subsoils at 15.18 gN/kg SOC around 8.5 Mg/ha of SOC in comparison to both topsoil and upper subsoils with rates of 1.89 to 2.25 gN/kg SOC, around 260 to 300 Mg/ha of SOC (Table 4.5).

The range of SOC reflecting the effect of soil nutrient regime, drainage, reclamation design and soil moisture regime for these reclaimed soils were presented in Figure 4.3b-e, respectively. Corresponding SQF numbered equation 23 to 33 shows strong, positive regression (R^2) between SOC and normalized N (Table 4.4, Figure 4.3g-j). Optimum rates of N supply with corresponding range of SOC at which the best N supply rate was observed for all the significant ($p < 0.05$) factors of SOC variation or management units reported for reclaimed soils were also presented in Table 4.5 and Figure 4.3l-o. The relevant thresholds of SOC where the optimum N supply potentials for these reclaimed soils were observed are reported in Table 4.5.

3.3 Validation of soil quality functions in pre-disturbance soils

The results of the SQF validation test were presented in Table 4.6 and 4.7, using the independent dataset published by Yan et al. (2012). The SQ scores were generated by using the SOC reported in this study as the predictive parameter and were used as input into the designed SQF for natural soils. The SQ scores successfully captures the effect of forest stands or species on soil N supply, based on the results of the mean comparison tests.

White spruce stands have soils which are significantly different ($p < 0.05$) in N content with mean of 1.309 Mg/ha in comparison to soils from jackpine stands with mean of 0.311 Mg/ha for forest floor materials. The same trend was observed in mineral soils (A horizon) with increasing N content from jack pine stands with means of 0.226 Mg/ha to 0.987 Mg/ha in white spruce stands (Table 4.6).

Analysis of the SQ scores generated using SOC as input variables also demonstrates that the SQF captures the effects of the classes of ecosites, soil nutrient regime, drainage and soil moisture regime. The SQF ratings repeated similar trends of SOC–N relations observed in the original dataset for forest floor materials as noted earlier; with significant differences ($p < 0.05$) in SQ index or scores reported between the white spruce and jack pine stands (Table 4.6). The forest stands accounted for 35% of the variation observed in N, while the SQ scores generated using the designed SQF for each factors also represents 33% to 39% of the same effect (Table 4.7).

With regards to the mineral N from A horizons, the SQ scores representing the effect of soil drainage, moisture regime and soil types or order based on Canadian soil classification systems generally have similar mean difference trends reported in the original datasets. This includes the differences in N content between the white spruce and jack pine stands (Table 4.6). Forest stands accounted for 41% of N variations in mineral soils while the SQ score generated by the SQF reflecting the effect of soil drainage, moisture regime and soil types also accounted for 29% to 39% of the same effects (Table 4.7). The SQF validation tests confirms that the SQ scores reliably account for the N supply potential reported in the original study and are therefore suitable for independent SQA within the same region, especially when testing the effect of forest stands on N supply potential.

3.4 Applications of soil quality functions

To further demonstrate the application of the designed SQF within the AOSR, we further validated and applied the SQF using a third and independent dataset reported by Macyk et al. (2005). To test the applicability of pre-disturbance SQF in this study, we examined the SQ score generated for 3 different natural soils with mature forest stands aging between 50 and 70 years based on the assumption that the soils in such mature system are expected to have the best SQ and serve as a suitable targets or reference systems for reclaimed soils. We used the SOC reported for each of the soils as the SQ predictive indicator. The overall SQ scores in terms of capacity to supply N in natural peat bog site is 0.87, 0.70 for Luvisols and 0.81 for Brunisols on a scale of 0 to 1 (Table 4.8).

Assessment of the reclaimed soils using the pre-disturbance SQF indicates that these reclaimed soils are generally designed for optimum performance to self-sufficiently supply N with overall SQ scores ranging from 0.95 to 0.98, when natural soils are treated as the projected or final target ecosystem (Table 4.9). If reclaimed soils are treated as an independent class of anthropogenic soils rather than expecting the reclaimed soils to emerge as a natural system, we can further justify the use of the SQF designed using reclaimed soil data within AOSR as the basis to assess other reclaimed soils (Table 4.10). In this case, the SQ scores ranged between 0.2 to 0.4, indicating that the reclaimed soils have between 20% to 43% of their capacity to supply N in comparison to other anthropogenic soils within AOSR (Table 4.10).

4. Discussion

This study demonstrated the design and use of SQF or soil quality models in a quantitative SQA process and the reliability of such numerical functions when a functional, process based approach to SQA is adopted and supported by a clearly defined SQA framework as demonstrated in this study (Figure 4.1). Generally, the designed SQF are only applicable and robust to model SQ within the AOSR and the application of these SQF beyond its regional boundary may not be justifiable. The transferability from one site to another and applicability of validated SQF within this region is further justified considering similarities in SOC to N trends and dynamics irrespective of the factors causing the shift in the rate of mineralization. It is important to re-emphasize that the SOC to N transformation process is a critical process that infers the self-sustainability of the boreal forest ecosystems to supply N without nutrient amendment (Chan et al., 2002). Self-sustainability is highly desired in reclaimed soils as an indicator for the development of healthy nutrient cycling in reconstructed soils within this region.

The characteristic range of SOC reported in reclaimed soils in comparison to natural soils confirmed that the current cover soil designs within the AOSR were designed for optimum performance in terms of N supply and further justified the need to classify such soils as anthropogenic soils, since natural soils generally reported less SOC (Mg/ha). The trends of optimum rates of N supply observed in ecosites classes is best explained by the reason that ecosites a and b which have the highest rates of N supply are systems with a more balanced combination of air and moisture encouraging microbial dynamics, though with limitations in source and quantity of litter available for decomposition from conifers such as jack pine, thereby causing a faster rate of SOC transformation (Wang et al., 2014). In comparison, ecosites d and e potentially could have more or excessive moisture and less air in combination with abundance of litter from deciduous species, thereby creating a system with slower rates of N supply at level potentially more suitable for long term development of reconstructed soils (Table 4.2, Figure 4.2m).

Soil textures, drainage, moisture regime and nutrient regime's effect on N mineralization rates also shows that sandy (coarse) textured soils with xeric to subxeric moisture regime, poor nutrient regime, very rapid to rapid drainage as seen in Brunisols generally demonstrate the highest rates of N pool supply to the soil. This is attributed to the factors identified above in terms of the balance of soil moisture, air, quantity and quality of litter supply. Soils with clayey (fine) textures, hygric to subhygric moisture regime, rich nutrient regime, moderately well to poor soil drainage as represented by Luvisols and Regosols demonstrated lower to medium rates of N supply potentials (Table 4.2, Figure 4.2) as previously reported by Tan et al., (2007) and Teklay et al., 2008. These will have direct implication in terms of long term nutrient availability while preventing N loss.

Similar trends of N supply potential based on the dynamics of SOC in soils of boreal forest have been previously reported by Tan et al. (2007), Teklay et al. (2008) and Arevalo et al. (2010). Arevalo et al. (2010) noted the combined effect of substrate quality, biomass and nutrient availability including differences in soil texture on ecosystem carbon storage (addition) and respiration (loss) under different land use systems. Tan et al. (2007) reported the significant effect that soil porosity has on SOC and N dynamics and the differences in rate of transformation process due to forest litter effects. These further affirm the effects of soil moisture and aeration balance, in relation to the effect of litter source as the major factors influencing the SOC to N dynamics. These factors also influence the characteristics SOC and N balance in the soils of AOSR.

Younger reclaimed soils also show the same trends in N supply rates in which soils with poor nutrient regime, rapid drainage, having coarse textured substrates as in the A-B-E-H-N groups of reclamation designs and subxeric moisture regime generally demonstrate the highest rates of N supply in contrast to reclaimed soils with medium to rich nutrient regime, moderately well to well drained soils, having fine textured substrates as in the F-I-J-M-N-O groups of reclamation designs and mesic to submesic moisture regimes (Table 4.4). Similar to the trend in coarse textured soils, the reclamation horizons in which SOM was incorporated at 0.5 m – 1 m depth (lower subsoils) during soil reconstruction operations, seems to be transforming and releasing N faster, possibly due to the additional effect of higher and stable subsoil temperature in the fall season (Arevalo et al., 2010).

It is worth noting that high or low soil N supply rates in this study might not directly translate into the best nutrient uptake and plant productivity, considering that this process is influenced by plant physiology. Therefore, our next study will account for this relation in SQA. This will require the building of a multi-factor SQA framework with multiple objectives, factors, and predictive indicators for modelling SQ as briefly demonstrated in Table 4.3. N supply or mineralization of organic matter as defined in this study implies the potential to create and retain a suitable pool of N for plant's use. The mobility of N is indirectly accounted for by the drainage and soil texture factors, thereby making these SQF suitable for other environmental management goals like monitoring the potentials for nitrate leaching of reclaimed soils using the SQF that account for both soil texture and drainage effects.

This study treated the effect the multiple soil and landscape factors of SOC variation grouped into management units on N supply as independent set of factors, but at the process level these factors work together and are not necessarily independent (Hawkes et al., 1997; Yang et al., 2005; Choi et al., 2007; Teklay et al., 2008; Lilles et al., 2010; Yan et al., 2012; Song et al., 2012; Jung et al., 2013; Hu et al., 2013; Wills et al., 2013; Wang et al., 2014; Jung et al., 2014). We choose not to test the statistical interaction of these factors considering the limitations of our experimental design. Such study will be best completed with additional field experimental designs.

Generally, the SOC based SQF performed very well in assessing soil N supply potentials in the boreal forest soils of AOSR and the pre-disturbance SQF further provides a non-bias (proper representation of indicators variation), quantitative, baseline or pre-disturbance numerical functions useful for defining ecosystem targets for reclaimed soils. The shift in SOC to N relations is also well calibrated using the long-term dataset and allows us to account for the effect of specific soil and landscape factors while conducting SQA. This systematically addresses a major issue of bias or representativeness of baseline soils in SQA when defining SQ targets or reference systems for judging reclaimed soils.

We also noted that constrained and validated SQF can be directly used at regional scale for AOSR, in deciding the amount of SOC to be incorporated into reclamation covers to ensure the availability of adequate nutrient pool for the plants use, while analysing for the effect of other factors of SOC variation in soil. Threshold analysis of SQF provide optimum amount of SOC content to ensure a level of N supply, a critical variable in the design of reclamation covers. This will be a valuable tool for land reclamation practitioners in making informed decision while reclaiming land back to the pre-disturbance condition. The SQF developed using reclaimed soils also provide the opportunity to assess and compare the soil N supply potentials of anthropogenic soils based on differences in reclamation design or test the impact of reclamation best management practises related to soil reconstruction. Furthermore, the thresholds of other predictive SQI as demonstrated in Table 4.3 provided suitable site specific or regional metric for design and monitoring of SQ in post-soil constructions phases of land reclamation.

5. Conclusion

Using SOC to N transformations as a baseline functional process, we successfully calibrated, validated and accounted for the effect of multiple soil and landscape factors on SOC to N dynamics or mineralization of organic matter during SQA. These allow for the development of SQF for each soil management units as delineated by the soil and landscape factors. The designed SQF performed very well in assessing soil N supply potentials and delineating the effect of forest stands on soil N supply potentials. Statistical analysis of the SQ index or scores proved to be reliable when trends in mean differences of the factors of SOC variation are compared. The means differences in the N supply data served as a reliable basis for validating the trends reported the SQ scores.

The design and use of SQF in SQA especially for land reclamation operation provides the opportunity to define, i) a quantitative, non-biased, representative reference for judging reclaimed soils, ii) a numerical framework of SQA that avoids bias in selecting the right performance target, and iii) proved to be a reliable tool in the design of reclamation covers while optimizing its functionalities.

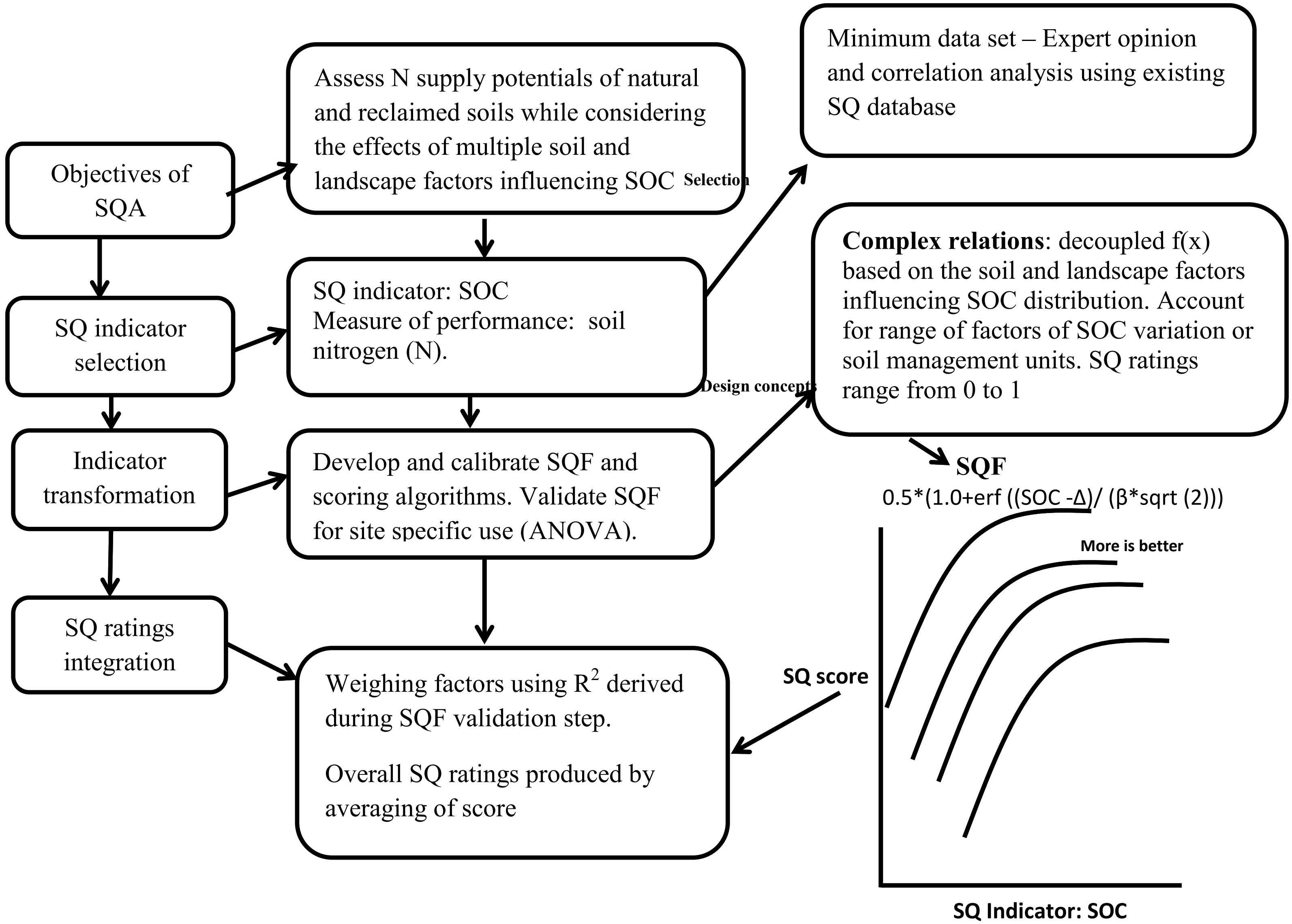

Figure 4.1.Soil quality assessment framework adopted in this study.

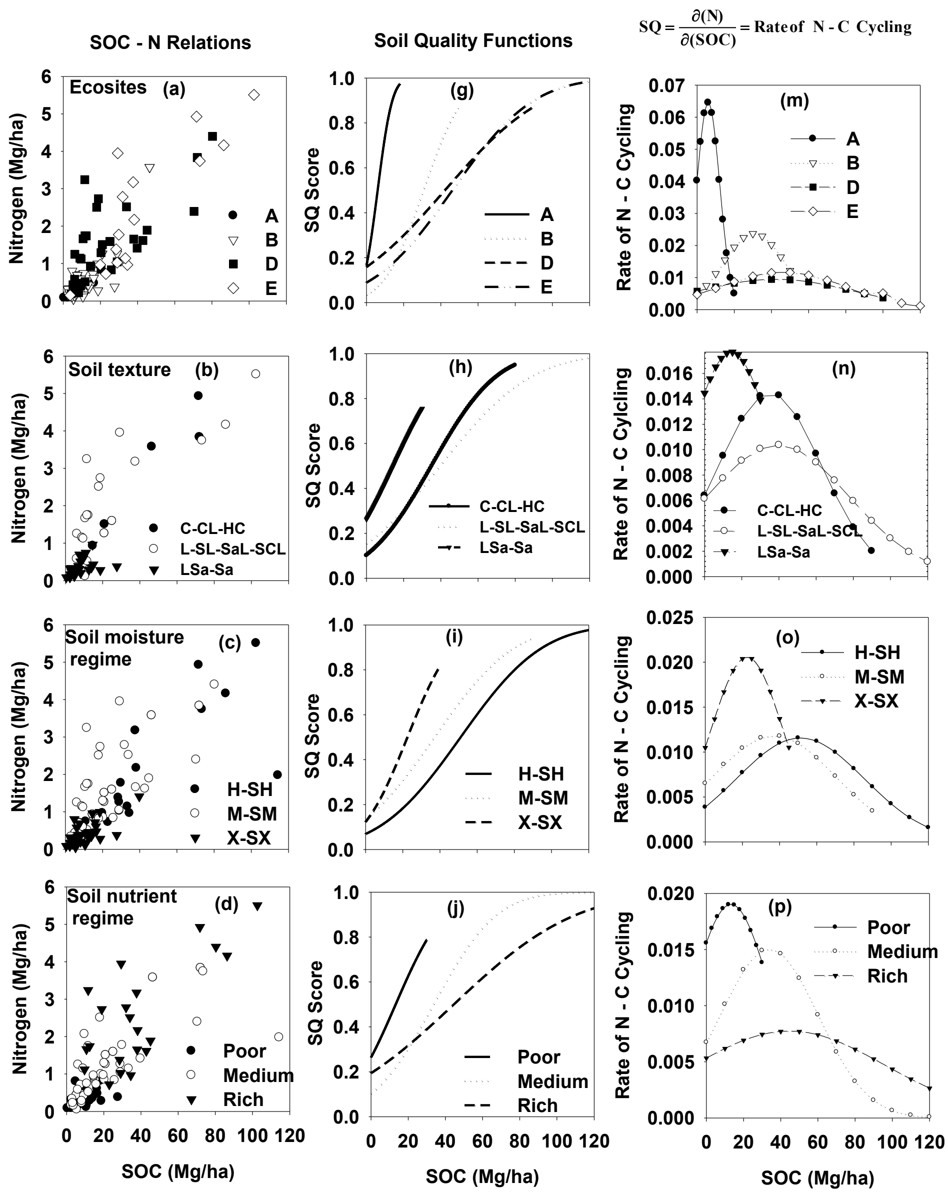

Figure 4.2. Soil organic carbon – nitrogen relations, soil quality functions and rate of N - SOC cycling in natural soils as influenced by ecosites, soil texture, moisture, drainage, soil types and nutrient regimes within the Athabasca oil sands region.

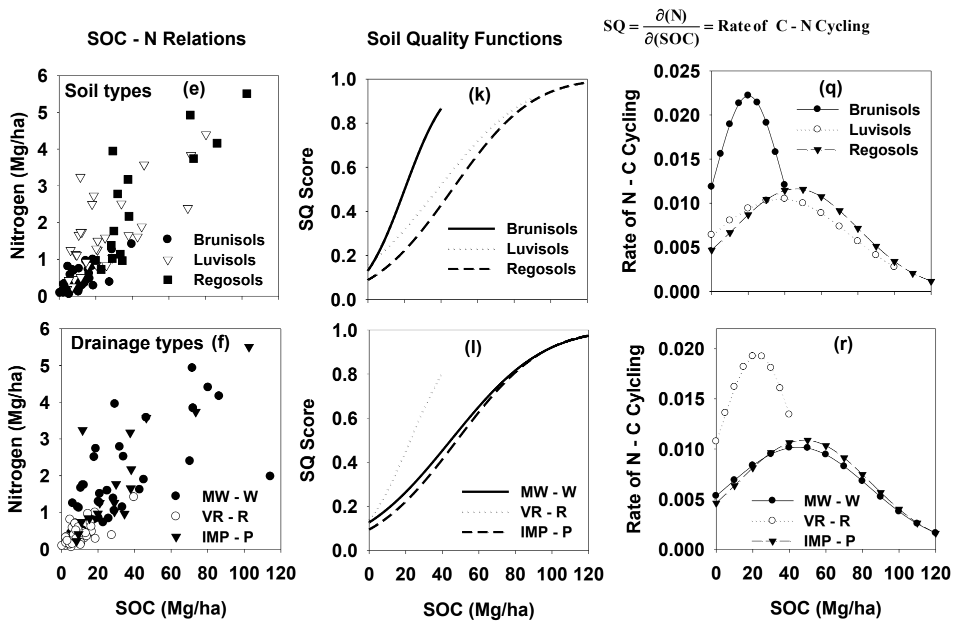

Figure 4.2.(cont.) Soil organic carbon – nitrogen relations, soil quality functions and rate of N - SOC cycling in natural soils as influenced by ecosites, soil texture, moisture, drainage, soil types and nutrient regimes within the Athabasca oil sands region.

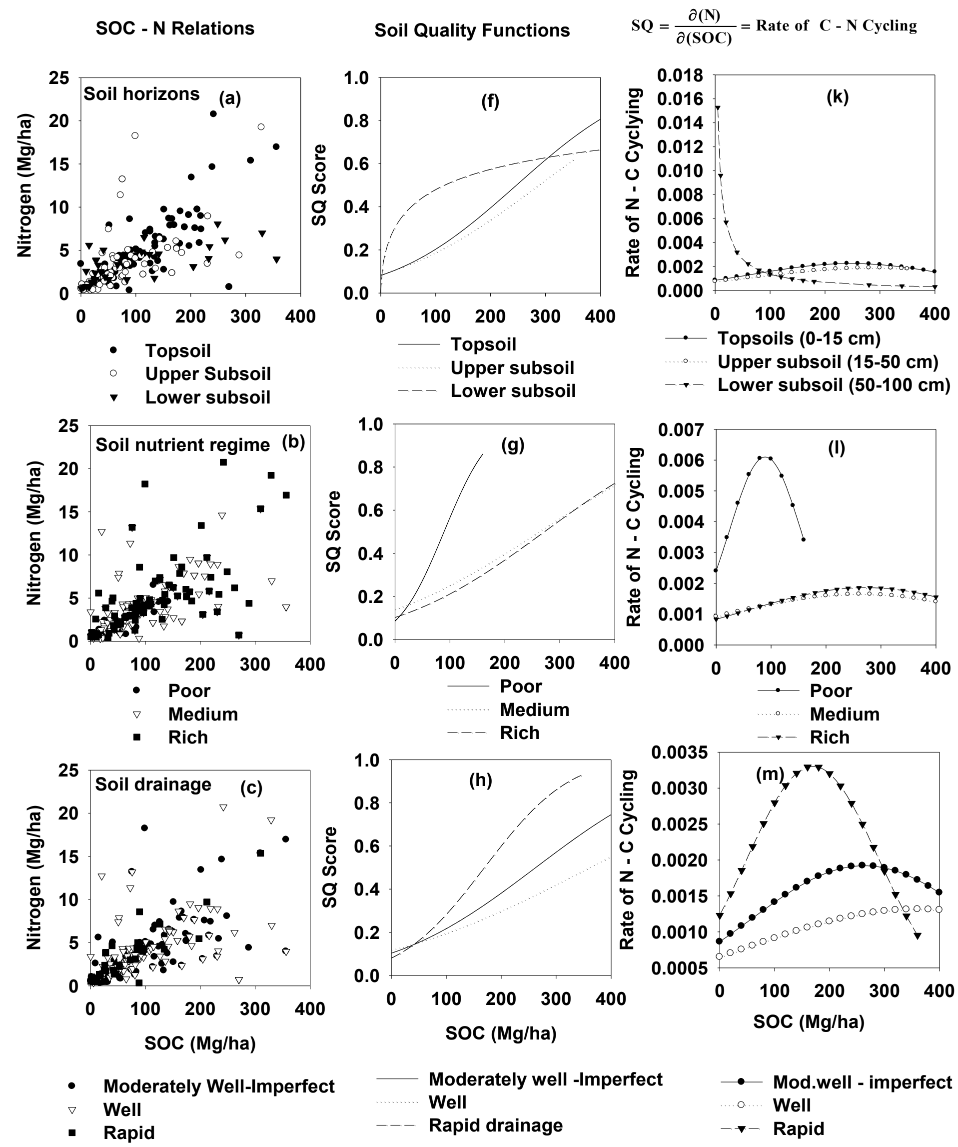

Figure 4.3. Soil organic carbon – nitrogen relations, soil quality functions and rate of N - SOC cycling in reclaimed soils as influenced by soil horizon, reclamation series, moisture regime, nutrient regime and drainage within the Athabasca oil sands region.

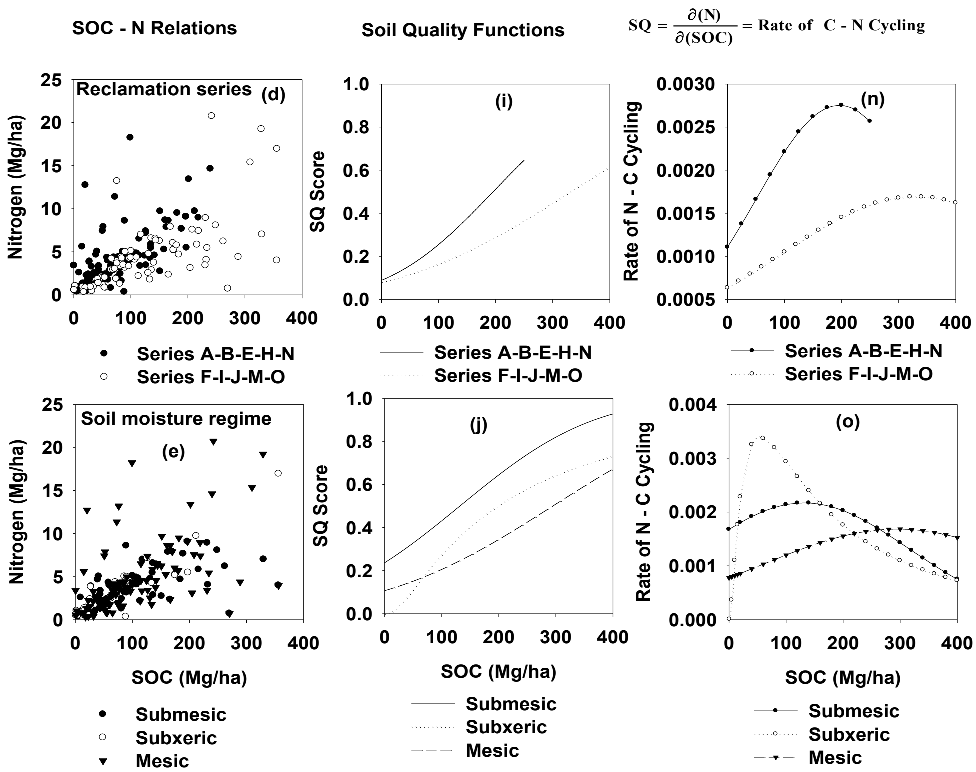

Figure 4.3. (cont.). Soil organic carbon – nitrogen relations, soil quality functions and rate of N - SOC cycling in reclaimed soils as influenced by soil horizon, reclamation series, moisture regime, nutrient regime and drainage within the Athabasca oil sands region.

Table 4.1. Baseline or predisturbance soil quality functions to assess nitrogen supply potential of soils in the Athabasca oil sands regions as impacted by soil and landscape factors influencing SOC distribution.

Natural soil and landscape properties	Subclass based on SOC content (Mg/ha)	Scoring Algorithms, Thresholds and Constants[†]					
		SQS = F = 0.5*(1.0+erf((SOC-Δ)/(β*sqrt(2)))	Δ	β	R^2	R	#[‡]
Ecosites	a	IF SOC< 18 Mg/ha, SQS = F, IF SOC > 18 Mg/ha, SQS = 1	6.02	6.19	0.75	0.87	1
	b	IF SOC< 50 Mg/ha, SQS = F, IF SOC > 50 Mg/ha, SQS = 1	30.57	16.83	0.80	0.89	2
	d	IF SOC< 90 Mg/ha, SQS = F, IF SOC > 90 Mg/ha, SQS = 1	42.18	42.15	0.57	0.76	3
	e	IF SOC< 120 Mg/ha, SQS = F, IF SOC > 120 Mg/ha, SQS = 1	46.19	34.26	0.73	0.85	4
Soil Textures	Clayey	IF SOC< 80 Mg/ha, SQS = F, IF SOC > 80 Mg/ha, SQS = 1	35.27	27.55	0.93	0.96	5
	Loamy	IF SOC< 120 Mg/ha, SQS = F, IF SOC > 120 Mg/ha, SQS = 1	39.46	38.49	0.67	0.82	6
	Sandy	IF SOC< 30 Mg/ha, SQS = F, IF SOC > 30 Mg/ha, SQS = 1	14.36	22.54	0.16	0.40	7
Moisture Regime	Hygric-Subhygric	IF SOC< 120 Mg/ha, SQS = F, IF SOC > 120 Mg/ha, SQS = 1	51.14	34.48	0.69	0.83	8
	Mesic-Submesic	IF SOC< 90 Mg/ha, SQS = F, IF SOC > 90 Mg/ha, SQS = 1	36.90	33.78	0.59	0.77	9
	Xeric-Subxeric	IF SOC< 40 Mg/ha, SQS = F, IF SOC > 40 Mg/ha, SQS = 1	22.53	19.40	0.46	0.68	10
Nutrient Regime	Poor	IF SOC< 30 Mg/ha, SQS = F, IF SOC > 30 Mg/ha, SQS = 1	13.26	20.97	0.15	0.39	11
	Medium	IF SOC< 120 Mg/ha, SQS = F, IF SOC > 120 Mg/ha, SQS = 1	33.62	26.51	0.68	0.82	12
	Rich	IF SOC< 120 Mg/ha, SQS = F, IF SOC > 120 Mg/ha, SQS = 1	44.54	51.55	0.53	0.73	13
Soil Drainage	Mod. well - well	IF SOC< 120 Mg/ha, SQS = F, IF SOC > 120 Mg/ha, SQS = 1	44.69	39.17	0.60	0.77	14
	V. Rapid - Rapid	IF SOC< 40 Mg/ha, SQS = F, IF SOC > 40 Mg/ha, SQS = 1	22.36	20.59	0.40	0.63	15
	Imperfect- Poor	IF SOC< 120 Mg/ha, SQS = F, IF SOC > 120 Mg/ha, SQS = 1	48.10	36.64	0.70	0.84	16
Soil types	Brunisols	IF SOC< 40 Mg/ha, SQS = F, IF SOC > 40 Mg/ha, SQS = 1	20.14	17.97	0.46	0.68	17
	Luvisols	IF SOC< 90 Mg/ha, SQS = F, IF SOC > 90 Mg/ha, SQS = 1	37.88	37.95	0.60	0.77	18
	Regosols	IF SOC< 120 Mg/ha, SQS = F, IF SOC > 120 Mg/ha, SQS = 1	46.19	34.26	0.73	0.85	19

[†] SQS is the soil quality score/index ranging from 0 to 1, computed using function, F. Δ and β are constants in F, R^2 and R are regression coefficients and Pearson correlation coefficients between SOC – normalized N concentrations. [‡] # is the assigned equation number for each of the functions, F.

Table 4.2. Soil quality threshold representing the optimum range of SOC content and corresponding rates of N supply as influenced by soil and landscape factors affecting SOC variation in natural soils.

Soil and Landscape Properties	Classes based on SOC Content (Mg/ha)	Optimum Range SOC (Mg/ha)	Average Rate (g N/Kg SOC)	Optimum SOC (Mg/ha)	Maximum Rate (g N/Kg SOC)
Natural Soils					
Ecosites	a	4 - 8	61	6	64.5
	b	25 - 35	22.5	30	24
	d	40 - 60	11	50	12
	e	30 - 50	9	40	9
Soil Textures	Clayey	20 - 50	12.45	35	14.2
	Loamy	30 - 50	10.01	40	10.36
	Sandy	12 - 18	17.5	15	17.6
Moisture Regime	Hygric-Subhygric	40 - 60	11.09	50	11.56
	Mesic-Submesic	30 - 50	11.23	40	11.80
	Xeric-Subxeric	15 - 30	19.1	22.5	20.5
Nutrient Regime	Poor	9 - 15	18.75	12	18.98
	Medium	20 - 40	13.86	30	14.91
	Rich	30 - 50	7.55	40	7.71
Soil Drainage	Very Rapid - Rapid	15 - 30	18.13	22.5	19.24
	Moderately well - well	30 - 50	9.80	40	10.11
	Imperfect- Poor	40 - 60	10.47	50	10.87
Soil types	Brunisols	15 - 25	21.2	20	22.2
	Luvisols	30 - 50	10.09	40	10.11
	Regosols	30 - 60	10.55	45	11.60

Table 4.3. Analysis of soil quality function to derive multi-indicator criteria for ecosite units based on optimum nitrogen supply capacity.

	Critical thresholds - soil quality indicators			
Ecosites[†]	Clay (%)	pH(Water)	EC(*d*S/m)	SAR
a	3-5	6-7	< 0.25	< 0.5
b	30-40	5-7	< 0.65	<2.0
d	60-80	4.5-7	<2.0	<7.0
e	25-30	4.5-7	<2.0	<7.0

[†] Ecosites are management units with unique soil and vegetation stands: “a” and “b” have sandy, coarse textured soils with lichen and blueberry as the dominant understory species respectively and jackpines as the dominant overstory species. Ecosites “d” and “e” have clayey, fine textured soils with low-bush cranberry and dogwood as the dominant understory species and white spruce as the dominant overstory species

Table 4.4. Soil quality functions to assess and compare nitrogen supply potential of reclaimed soils in the Athabasca oil sands regions as impacted by soil and landscape factors influencing SOC distribution.

Reclaimed soil and landscape properties	Classes based on SOC Content (Mg/ha)	Scoring Algorithms, Thresholds and Constants[†]					
		SQS = F1 = 0.5*(1.0+*erf*((SOC -Δ)/(β*sqrt(2))))) or SQS = F2 = 0.5*$erfc$(-(ln(SOC)-Δ)/(β*sqrt(2))	Δ	β	R^2	R	#
Horizons	Topsoil	IF SOC< 400 Mg/ha, SQS = F1, IF SOC > 400 Mg/ha, SQS = 1	247.08	176.99	0.57	0.75	20
	Upper subsoil	IF SOC< 350 Mg/ha, SQS = F1, IF SOC > 350 Mg/ha, SQS = 1	286.62	211.15	0.28	0.52	21
	Lower subsoil	IF SOC< 400 Mg/ha, SQS = F2, IF SOC > 400 Mg/ha, SQS = 1	4.76	2.92	0.48	0.69	22
Nutrient Regime	Poor	IF SOC< 160 Mg/ha, SQS = F1, IF SOC > 160 Mg/ha, SQS = 1	89.31	65.28	0.66	0.81	23
	Medium	IF SOC< 400 Mg/ha, SQS = F1, IF SOC > 400 Mg/ha, SQS = 1	261.53	241.99	0.30	0.55	24
	Rich	IF SOC< 400 Mg/ha, SQS = F1, IF SOC > 400 Mg/ha, SQS = 1	272.09	214.58	0.40	0.63	25
Drainage	Mod. Well	IF SOC< 400 Mg/ha, SQS = F1, IF SOC > 400 Mg/ha, SQS = 1	262.86	207.76	0.39	0.62	26
	Well	IF SOC< 400 Mg/ha, SQS = F1, IF SOC > 400 Mg/ha, SQS = 1	359.96	303.43	0.23	0.48	27
	Rapid	IF SOC< 350 Mg/ha, SQS = F1, IF SOC > 350 Mg/ha, SQS = 1	169.68	120.72	0.79	0.89	28
Reclamation Design	A-B-E-H-N	IF SOC< 250 Mg/ha, SQS = F1, IF SOC > 250 Mg/ha, SQS = 1	195.81	144.95	0.47	0.69	29
	F-I-J-M-N-O	IF SOC< 400 Mg/ha, SQS = F1, IF SOC > 400 Mg/ha, SQS = 1	330.58	235.99	0.39	0.63	30
Moisture Regime	Submesic	IF SOC< 400 Mg/ha, SQS = F1, IF SOC > 400 Mg/ha, SQS = 1	131.97	183.95	0.34	0.59	31
	Subxeric	IF SOC< 400 Mg/ha, SQS = F2, IF SOC > 400 Mg/ha, SQS = 1	5.29	1.13	0.75	0.87	32
	Mesic	IF SOC< 400 Mg/ha, SQS = F1, IF SOC > 400 Mg/ha, SQS = 1	294.87	237.00	0.30	0.53	33

[†] SQS is the soil quality score/index ranging from 0 to 1, computed using function, F. Δ and β are constants in F, R^2 and R are regression coefficients and pearson correlation coefficients between SOC – normalized N concentrations. # is the assigned equation number for each of the function F.

Table 4.5. Soil quality threshold representing the optimum range of SOC content and corresponding rates of N supply as influenced by classes of soil and landscape factors affecting SOC variation in reclaimed soils.

Soil and Landscape Properties	Classes based on SOC Content (Mg/ha)	Optimum Range SOC (Mg/ha)	Average Rate (g N/Kg SOC)	Optimum SOC (Mg/ha)	Maximum Rate (g N/Kg SOC)
Reclaimed Soils					
Horizons	Topsoil	220 – 260	2.23	240	2.25
	Upper subsoil	260 – 300	1.88	280	1.89
	Lower subsoil	5 – 80	8.57	6.5	15.18
Nutrient Regime	Poor	60 – 120	5.50	90	6.09
	Medium	220 – 300	1.63	260	1.65
	Rich	240 – 320	1.83	280	1.86
Drainage	Moderately Well	220 – 300	1.88	260	1.92
	Well	320 – 400	1.30	360	1.32
	Rapid	140 – 200	3.21	170	3.30
Reclamation	A-B-E-H-N	150 – 225	2.68	200	2.75
Design or Series†	F-I-J-M-N-O	300 – 380	1.66	340	1.69
Moisture Regime	Submesic	100 – 180	2.17	140	2.17
	Subxeric	20 – 80	2.74	50	3.40
	Mesic	260 – 340	1.66	300	1.68

† Reclamation designs A-B-E-H-N group represents reconstructed soils with coarse textured, sandy substrates such as natural and tailings sands while the F-I-J-M-N-O groups represents reconstructed soils with fine textured, clayey substrates.

Table 4.6. Validation of predisturbance SQF, by testing its ability to model N supply potential of forest floor and mineral soils.

Treatments/ Tree Species †	Horizons/ Soil Material Types	Number of Replicates	Mean Nitrogen (Mg/ha) †	Soil quality ratings (0 -1) for soil N supply potentials as impacted by factors of SOC variation					
				Ecosite	Nutrient Regime	Drainage	Moisture Regime	Soil Type	Soil texture
White Spruce	Forest Floor	5	1.309 a	0.528 a	0.646 a	0.530 a	0.499 a	0.571 a	0.484 a
Trem. Aspen	Forest Floor	8	0.815 ab	0.240 ab	0.423 ab	0.302 ab	0.314 ab	0.338 ab	0.407 a
Jackpine	Forest Floor	8	0.311 b	0.317 b	0.336 b	0.280 b	0.258 b	0.293 b	0.427 a
White Spruce	A horizon	5	0.987 a	0.206 a	0.334 a	0.254 a	0.265 a	0.290 a	0.260 a
Trem. Aspen	A horizon	8	0.703 ab	0.176 a	0.323 a	0.224 ab	0.224 ab	0.250 ab	0.306 a
Jackpine	A horizon	8	0.226 b	0.123 a	0.234 a	0.165 b	0.150 b	0.161 b	0.296 a

† Effect of forest stands on N supply potentials of AOSR soils by Yan et al. (2012). Means with different alphabets are significantly different ($p < 0.05$).

Table 4.7. Analysis of the effect of forest stands on soil nitrogen supply potentials in relation to SQ scores generated by the pre-disturbance SQF.

	DF	F	$P < 0.05$	R^2 (%)
		Forest Floor		
Soil Nitrogen	**2**	**4.94**	**0.02**	**35.42**
		SQ Scores – Forest Floor		
Ecosite	2	2.43	0.117	21.23
Nutrient Regime	2	5.77	**0.012**	39.08
Drainage	2	4.180	**0.032**	31.690
Moisture Regime	2	4.630	**0.024**	33.950
Soil Types	2	4.570	**0.025**	33.660
Soil Texture	2	0.62	0.547	6.49
		A horizon		
Soil Nitrogen	**2**	**6.41**	**0.008**	**41.61**
		SQ Scores – A horizon		
Ecosite	2	0.98	0.394	9.84
Nutrient Regime	2	1.8	0.194	16.65
Drainage	2	4.52	**0.026**	33.41
Moisture Regime	2	3.73	**0.044**	29.29
Soil Types	2	5.99	**0.01**	39.97
Soil Texture	2	0.78	0.475	7.94

Table 4.8. Quality assessment of natural soils to validate pre-disturbance SQF using another independent natural soil as the target ecosystem.

Natural Soil Description[†]	SOC (Mg/ha)	Natural Site Description	Selected SQF[‡]	SQ ratings (0 -1) for soil N supply potentials as impacted by factors of SOC variation							
				Ecosite	Soil texture	Moisture Regime	Nutrient Regime	Soil Drainage	Soil types	Integrated SQ Score[‡]	SQ Class[§]
Natural peat bog site - Black spruce, Labrador tea, mosses, lichens	92	Ecosite e, hygric-subhygric, rich, imperfect to poor, organic soil	4,8, 13,16	0.909		0.882	0.821	0.885		**0.874**	**1**
Luvisol- Fine textured site - Aspen (> 50 yrs)	56	Ecosite d, clayey, mesic - submesic, medium, moderately well-well, luvisols	3,5,9, 12,14,18	0.628	0.774	0.714	0.801	0.614	0.683	**0.702**	**2**
Brunisol- Coarse textured site - Jackpine (> 70 yrs)	34	Ecosite a or b, sandy, xeric-subxeric, poor, very rapid to rapid, Brunisols	1,2,7,10, 11,15,17	1.000	0.808	0.723	0.839	0.714	0.780	**0.811**	**1**

[†] Natural soil description and related SOC content (n = 3 to 5) as presented in Macyk et al. 2005
[‡] Reference to equation numbers in Table 4-1 and 4-2.
[§] SQ score from 0 – 0.2 represents class 5; 0. 2 – 0.4 represents class 4, 0.4 – 0.6 represents class 3, 0.6 – 0.8 represents class 4 and 0.8 – 1.0 represents class 1. Integrated score represents average of the SQ scores for the factors of SOC variation.

Table 4.9. Quality assessment of reclaimed soils using natural soil as the projected ecosystem

Reclaimed Soil Description†	SOC (Mg/ha) (n > 3)	Projected Ecosystem ††	Selected SQF‡	SQ ratings (0 -1) for soil N supply potentials as impacted by factors of SOC variation							
				Ecosite	Soil texture	Moisture Regime	Nutrient Regime	Soil Drainage	Soil types	Integrated SQ Score§	SQ Class¶
50cm PTMIX/TS - Jackpine, Blueberry, Strawberry	64	Ecosite b, sandy, xeric-subxeric, poor, very rapid to rapid, Brunisols.	2,7,10,11 , 15,17	0.977	0.986	0.984	0.992	0.978	0.993	**0.987**	**1**
2cm Organic Litter/30cm PTMIX/TS - Jackpine 18 yrs, dogwood, grasses	105	Ecosite b, sandy, xeric-subxeric, medium, very rapid to rapid, Brunisols.	2,7,10,12 ,15,17	1.000	1.000	1.000	0.996	1.000	1.000	**0.999**	**1**
20 cm LFH/ Secondary/TS- Wildrose, blueberry, bluebell, grasses	105	Ecosite a, Loamy, Mesic-Submesic, rich, Mw-well, Luvisol.	1,6,9,13, 14,17	1.000	0.956	0.978	0.880	0.938	1.000	**0.950**	**1**

† Reclaimed soil description and related SOC content (n = 3 to 5) as presented in Macyk et al. 2005.
‡ Reference to equation numbers in Table 4-1 and 4-2. [3] Average of SQ ratings.
¶ Soil quality score from 0 – 0.2 represents class 5; 0. 2 – 0.4 represents class 4, 0.4 – 0.6 represents class 3, 0.6 – 0.8 represents class 4 and 0.8 – 1.0 represents class 1. Integrated score represents average of the SQ scores for the factors of SOC variation.
†† Projected ecosystem in order of ecosites, soil texture, nutrient regime, drainage, soil type according to Canadian soil classification system.

Table 4.10. Quality assessment of reclaimed soils using anthropogenic soils as the projected ecosystem

Reclaimed Soil Description[†]	SOC (Mg/ha) (n > 3)	Projected Ecosystem[††]	Selected SQF[‡]	SQ ratings (0 -1) for soil N supply potentials as impacted by factors of SOC variation						
				Horizons	Design	Moisture Regime	Nutrient Regime	Drainage	Integrated SQ Score[§]	SQ Class[¶]
50cm PTMIX/TS - Jackpine, Blueberry, Strawberry	64	Anthroposols - Topsoil, Poor, Rapid, ABEHN, Subxeric	20,23,28, 29,32	0.150	0.182	1.000	0.349	0.191	**0.430**	**4**
2cm Organic Litter/30cm PTMIX/TS - Jackpine 18 yrs, dogwood, grasses	105	Anthroposols - Topsoil, Medium, Moderately well - well, ABEHN, Submeric	20,24,26, 29,31	0.211	0.265	0.442	0.259	0.224	**0.297**	**4**
20cm LFH/Secondary/TS- Wildrose, blueberry, bluebell, grasses	105	Anthroposols - Topsoil, Rich, Well, ABEHN, Mesic	20,25,27, 29,33	0.211	0.265	0.212	0.218	0.200	**0.224**	**4**

[†] Reclaimed soil description and related SOC content (n = 3 to 5) as presented in Macyk et al. 2005.
[‡] Reference to equation numbers in Table 4-1 and 4-2. [§] Average of SQ ratings.
[¶] SQ score from 0 – 0.2 represents class 5; 0. 2 – 0.4 represents class 4, 0.4 – 0.6 represents class 3, 0.6 – 0.8 represents class 4 and 0.8 – 1.0 represents class 1. Integrated score represents average of the SQ scores for the factors of SOC variation.
[††] Projected ecosystem based on reclamation horizon, nutrient regime, drainage, reclamation cover group and moisture regime.

Chapter 5 Calibration and Application of Soil and Stand Quality Functions using Soil-Forest Productivity Relationships in Land Reclamation

1. Introduction

Soil quality effects on productivity of forest stands have been studied over the last few decades to determine how soil properties influence plant growth, biomass yield, plant nutrition and ecosystem health (Knoepp et al., 2000; Ponge and Chevalier, 2006). Recent advances in functional and quantitative soil quality assessment (SQA) frameworks are yet to quantitatively incorporate soil-forest productivity relationships. Focus has been on soil effects on annual crops to increase yield, protect environmental and human health (Stott et al., 2009).

The lack of soil – forest productivity relationships in existing SQA framework may be due to the need to account for multiple indicators with bi-directional relationships between soil factors and forest productivity indicators. At the initial phase of stand development, plants require inputs of soil nutrients, water and energy from sunlight to produce biomass (Grant, 2014). Later phases require effective nutrient and water cycling systems with plants contributing to the soil organic matter pool through litter deposition and decomposition, influencing soil nutrient and water dynamics (Teklay and Chang, 2008). At the latter stages of forest development, plant demands for soil resources for biomass development become more stable. Quantifying this relationship can be further complicated by the need to assess the effects of plant physiology, climate and forest management practices on biomass productivity and stand growth over time.

A potential conceptual model of the soil-forest productivity relationship includes three system partitions: soils, soil-plant rhizosphere and plants. Soil systems focus on quality indicators and measures of performance for soil based processes such as nutrient cycling, exchange, retention and availability over time, including soil water transmission and retention as influenced by soil hydraulic conductivity and texture (Ojekanmi and Chang, 2014). Soil-plant rhizosphere systems include functions such as plant nutrient and water uptake, and effects of rooting on soil quality, including release of enzymes and exudates to enhance soil respiration (Jamro et al., 2015). Plant systems support functions such as phloem transport or translocation and stomata exchange of gas and nutrients, especially O_2 and CO_2 to support photosynthesis and biomass production (Nave et al., 2009). These partitions are not independent and interact over time to support productive forest stand development, capturing the processes supporting above and below ground net primary productivity.

There is no known effort to quantitatively calibrate specific soil quality indicator and forest stand productivity relationships into SQA frameworks, especially when soils are managed or reconstructed with long term objectives to develop forest stands, such as in land reclamation. This relationship can be incorporated into quantitative SQA using soil quality models or numerical functions with soil quality indicators to predict forest stand productivity through time. The numerical or soil quality-scoring functions (SQF) can be analytical or regression functions for calibrating soil quality indicators with specific measures of forest productivity (Stott et al., 2009). These relationships can also be calibrated by relating outputs from process models, which were properly validated for specific site and climate conditions (Arshad et al., 2002; Wander et al., 2002). Both options are potentially capable of capturing the conceptual partitions discussed earlier and ensure critical processes are integrated into the SQA framework within the relevant time frame (Burger and Kelting, 1999).

Advances in SQA involve the integration of multiple soil processes and functions by using calibrated SQF to score soil quality indicators (Stott et al., 2009), accompanied by a clear framework of assessment for consistency and comparison of results (Harris et al., 1996; Karlen et al., 1997; Burger and Kelting, 1999; Andrews et al., 2004). SQF produces normalized quality scores allowing statistical integration into overall soil quality (SQ), without deviating from known treatment effects (Andrews et al., 2004). Identification of relevant soil relationships for specific ecosystems which have been studied extensively and validated over time is required for design, calibration, validation and application of SQF (Karlen et al., 1997).

The SQF are applicable to soil management efforts in land based industries such as surface mining, construction and watershed conservation, where restoration of healthy forest communities is a primary objective during land reclamation (Ojekanmi and Chang, 2014). Land reclamation requires conversion of disturbed land to its former or other productive uses, including forest ecosystems. This involves soil reconstruction, revegetation and development of related ecosystem processes such as those associated with hydrology and the food web. A critical land reclamation objective is redevelopment of soil processes, functionality and inherent capability to sustain biogeochemical processes associated with plant productivity while maintaining environmental and human health (Naeth, 2012; Powter et al., 2012).

Soil quality assessment therefore plays an important role in land reclamation, soil reconstruction or design of soil covers and underlying substrates to support plant productivity by providing adequate nutrients, hydrologic capacity and a supporting environment. SQF can be applied to generate metrics of cover design such as depth and volumes of soil materials required to supply adequate plant nutrients, support plant rooting structure, retain or transmit water, and build a landscape with capacity to regenerate a productive forest community similar to pre-disturbance productivity. The quality of soil replaced during land reclamation directly affects overall land capability, vegetation productivity and post reclamation ecosystem performance.

Extensive research into fundamental processes required to support functional soil-forest productivity systems has been conducted. Research shows land use affects distribution, sequestration of soil organic carbon (SOC) and forest productivity (Sheng at al., 2014); atmospheric deposition and soil acidification also affect plant productivity (Jung and Chang, 2013). Hu et al. (2013) found soil nitrification influenced plant nitrogen (N) intake as measured by foliar N analysis, showing declining nitrification with increasing stand age as the main N-limiting mechanism in forest soils. Tan et al. (2006) found soil compaction and forest floor removal changed understory community structure with no significant effect of water availability on tree productivity, although soil N dynamics or uptake by aspen were affected. Previous research effort also demonstrated significant effect of forest management on soil quality indicators, with strong correlations between tree growth indicators and soil quality indicators (Tan et al. 2008; Teklay and Chang, 2008; Boussougou et al., 2010). Watt et al. (2005) identified CN ratio, total soil nitrogen and phosphorus, among others as the best predictors of forest productivity. Ponge and Chevalier, (2006) demonstrated a clear relationship between forest soil humus index and stand development parameters. Research shows that site specific determinants of forest growth are influenced by the soil system (Zellweger et al., 2015) with some forest soil quality indicators such as biological indicators (Muscolo et al., 2016) more sensitive than others (Duval et al., 2016),

To consolidate the extensive knowledge base around soil-forest productivity relationships in forming the basis for SQA, Burger and Kelting, (1999) proposed a qualitative SQA framework using soil based indicators to assess forest productivity. The proposed framework includes steps that establish the proper inference space, identify soil attributes, functions and SQ indicators, combine indicator responses in a soil quality model, establish baseline conditions for comparing soil change, validate relationships between indicators and soil productivity, and implement a sampling scheme to measure indicators, analyze trends and interpret change due to changes in forest stands. The objective of our study was to calibrate soil-forest productivity relationships as the basis for determining soil quality functions for quantitative SQA using the Athabasca oil sands region (AOSR) as a case study. This involved identifying relevant SQ indicators that best correlate with critical soil functions or plant productivity; demonstrating options for calibrating SQ indicators with measures of forest stand performance while transforming the numerical relations into SQF. Application of the SQF was assessed with land reclamation examples using a consistent framework for SQA.

2. Materials and Methods

2.1 Analysis of soil-forest productivity relations with AOSR

A forest soil and plant properties database compiled by Chang et al. (2011) was used to analyse soil and forest productivity relations within the AOSR. The database includes all the data generated while determining soil nitrogen indicators that correlates with forest productivity from mature stands of trembling aspen (*populous tremuloides*), jack pine (*pinus banksiana*) and white spruce (*picea glauca*). Soil parameters per plot for each plant species included soil organic carbon (SOC), total nitrogen (N), soil texture, cation exchange capacity (CEC), pH, in situ nitrogen mineralization rates, inorganic N concentrations and available N supply.

These parameters were reported for both forest floor (FF) and mineral soils (MS) when possible. Plant productivity and nutrition data included stand age, density, tree height, foliar N concentration, intrinsic water use efficiency, above ground net primary productivity, annual biomass increment and tree ring width. Details of analytical techniques for these parameters were compiled and discussed in Chang et al. (2011) and published in Yan et al. (2012).

The relationships between soil and plant productivity parameters were examined using correlation analysis. Soil quality indicators that best correlated ($p < 0.05$) and explained the trends in plant productivity were identified using regression analysis. Correlation analysis was completed for 5 groups of indicators of soil and plant productivity, including indicators of biomass productivity, annual tree growth, intrinsic water use, foliar nitrogen concentrations and the group of soil quality indicators such as SOC, N, soil texture, CEC and pH. Based on the framework presented in Figure 5.1, SQF were developed by regressing soil and normalized plant productivity parameters. These analytical functions are suitable for assessing soil cation exchange capacity, soil water and nutrient cycling, soil nitrogen supply capacity, plant nutrition status, forest stand characteristics and biomass productivity using soil parameters as predictive indicators (Weinhold et al. 1997; Andrews et al., 2004; Ojekanmi and Chang, 2014).

2.2 Development of analytical SQF for assessing age-stand productivity relations

To analyze productivity by stand age, which is highly desirable in comparing productivity of forest stands on reclaimed and natural soils, various indicators of forest productivity must be calibrated by age of stands. The GYPSY analytical models developed and validated within the AOSR by the Alberta government were used for modelling age-stand productivity relations (Huang et al., 1994, Huang, 2006). Input data from Chang et al. (2011) are summarized in Table 5.7. GYPSY's calibrated age (years) to height (m) curves for natural sites growing each of the three tree species were averaged as representative curves for natural sites and compared with age-height data from reclaimed soils within AOSR. Tree growth data from reclaimed soils were compiled by age of stands from the long term soil and vegetation plot database compiled by the consortium of industries involved in land reclamation and monitoring of tree growth indicators of relevant species within the AOSR (Cumulative Environment Management Association, (CEMA), 2011). Slopes of age (years) to height (m) curves for natural and reclaimed sites were compared for each of the 3 species to assess the rates of growth per year. The calibrated age to height curves for each species were subsampled into 10 years and transformed into SQF using the framework in Figure 5.1, for further application in assessing the quality of stands growing on reclaimed soil within the first 10 years of revegetation.

2.3 Development and application of SQF using outputs from process based models.

To calibrate the effect of soil water retention capacity on productivity of jack pine stands growing in water limiting conditions such as Brunisols within the AOSR, existing process models that solved equations for available water holding capacity (AWHC) and other metrics of jack pine productivity such as leaf area index (LAI, m^2m^{-2}) and net primary productivity (NPP, $gCm^{-2}yr^{-1}$) were identified. Brunisols have a thin layer of organic horizons (0 - 10 cm) overlaying heterogeneous, coarse textured, sandy soil with a total depth of at least 1 m. Land cover designs within the AOSR to reproduce soil profiles similar to Brunisols involves use of 10 - 30 cm of peat mineral soil mix or organic litter overlaying coarse textured, sandy soils or sandy extracts from tailing waste (Figure 5.2).

Details of the validated process based models (RMSE = 1.33) selected for analysis of AWHC relations to stand productivity of conifer species including jack pine in water limiting sites within the AOSR was published by Huang et al. (2013). BIOME-BGC was used to model indicators of forest productivity such as NPP and LAI. Available water holding capacity was determined from soil texture distribution using HYDRUS - 1D for the same sites. The models output were AWHC (mm per m), NPP ($gCm^{-2}yr^{-1}$) and LAI (m^2m^{-2}). The outputs were used to produce non-linear regression functions calibrating AWHC (mm per m) to LAI ($m^2 m^{-2}$) and NPP ($gCm^{-2}yr^{-1}$). Following the SQA framework in Figure 5.1, the relationships (regression functions) were transformed into SQF to analyze stand productivity using AWHC as input parameters or predictive indicators. To validate and test applicability of the SQF, the database generated by House (2015) while assessing water availability effects on tree growth in reclaimed soil within AOSR, was used to demonstrate typical applications of the SQF. House (2015) reported various reclamation design parameters with corresponding AWHC in relation to LAI and NPP of jack pine species. The SQF were used to test the effect of various reclamation cover design parameters on jack pine productivity while comparing treatment effects such as years after planting on reclaimed soils, slope of reclamation cover, depth and bulk density of topsoil on LAI and NPP. AWHC (mm m^{-1}) reported in this study were used to score each of the 4 treatment factors; the scores were further summarized to account for the effect of each factor. Treatment differences for jack pine productivity indicators in the original dataset were compared to treatment differences of the quality scores to assess SQF performance and applicability.

2.4 Statistical analysis and design of SQF

Correlation analyses between soil properties and five classes of forest productivity indicators were completed in MINITAB statistical software (Alin, 2010). To analyse the age to height trajectory of plants species on natural and reclaimed stands, linear fits of the data were determined while comparing the slopes (rates of increase in height per year). Curve Expert Pro. software was used to regress the age to normalized height data and the AWHC to normalized NPP or LAI, while selecting the best regression model and defining appropriate boundary conditions for each SQF. Stand or soil quality scores were normalized between 0 and 1 to facilitate statistical integration of scores, where 0 is the lowest possible score and 1 is the highest. A GLM model was used to test the effect of reclamation cover design parameters such as years after revegetation (16, 20, 21 years), slope of the reclaimed profile (< 25, 25-35, > 35 %), depth of topsoil or organic cover (< 20, 20-30, > 30 cm) and bulk density of topsoil (< 1 gcm^{-3}, > gcm^{-3}), on NPP, scores-NPP, LAI and score-LAI, with Tukey comparison test at $p < 0.05$ to delineate treatment effects. The score-NPP and score-LAI are the corresponding soil quality scores derived from inputting AWHC into the SQF.

3.0 Results

3.1 Soil-forest productivity relations within AOSR

Soil quality indicators such as soil organic carbon (SOC), forest floor's nitrogen content (FF - N) and mineral soil's nitrogen content (MS - N), % clay, sand and silt and cation exchange capacity (CEC), significantly ($p < 0.05$) correlated to other soil properties, irrespective of forest stand type. Sand fractions were strongly but negatively correlated with other variables. Soil pH was significantly ($p < 0.05$) correlated with % clay and CEC. FF - bulk density was not significantly correlated with other soil variables, although mineral soil bulk density was significantly correlated with SOC and N (Figure 5.3).

With trembling aspen, FF - SOC, MS - SOC, % silt and pH were significantly and strongly correlated ($p < 0.05$) with biomass productivity. MS - SOC, FF - bulk density and MS - bulk density correlated best with jack pine biomass productivity. MS - SOC, % silt, FF – bulk density, and MS - bulk density were significantly correlated with biomass productivity for white spruce (Figure 5.4).

Stand growth parameters such as age, density, height and diameter at breast height (DBH) were significantly correlated with soil quality indicators. For aspen, soil pH and CEC were significantly ($p < 0.05$) correlated with growth parameters. FF – bulk density, MS - bulk density, FF - N and FF - SOC were strongly correlated with growth parameters for jack pine. FF – SOC, FF - bulk density and MS - bulk density are promising predictive indicator of soil quality in white spruce stands (Figure 5.5). Using measures of intrinsic water use efficiency (Chang et al., 2011), significant ($p < 0.05$) correlations were observed with % sand, silt and clay for all species (Figure 5.6). Foliar N concentrations were also strongly correlated with selected soil quality indicators (Figure 5.7).

3.2 Soil quality assessment using analytical functions

Using indicators of forest soil productivity as management goal parameters or measures of performance, correlating soil quality indicators were used as predictive indicators to develop SQF (Tables 5.1 to 5.3). The SQF developed to assess soil's CEC, a critical process influencing nutrient availability, use % clay, % sand, % silt, soil pH, FF - SOC and MS - SOC as predictive indicators (Table 5.1). The SQF calibrated to assess natural and reclaimed soil's nutrient cycling and organic carbon mineralization potentials use FF - SOC status (amount of organic litter released by forest stand) and MS - SOC (amount of organic carbon in soil matrix) as the main predictors of N and SOC mineralization potentials (Table 5.2). Soil textural composition representing available water holding capacity are also suitable indicators of N mineralization potentials, considering the effect of soil water retention on N mineralization (Table 5.3). The R^2 for the SQF ranged from 0.10 to 0.99, with each SQF having defined boundary conditions for each forest species.

The SQF accounting for soil-forest productivity relationships in which measures of performance are directly related to plant productivity or nutrition and predictive indicators are mainly soil quality indicators are presented in Tables 5.4 - 5.6. The SQF for assessing soil potentials to support plant nutrition as represented by leaf N uptake have varying soil quality indicators such as % clay, soil pH, MS - N and MS - SOC as predictive indicators (Table 5.4). The SQF for assessing soil potentials to support stand development as represented by height, density and DBH are FF – SOC, MS - SOC, FF - N and pH (Table 5.5). The SQF designed for assessment of biomass productivity have soil pH, FF – SOC, MS - SOC and % silt as the predictive indicators (Table 5.6). Since previous work had demonstrated the approach to site specific or regional validation, and applications of these analytical SQF (Ojekanmi and Chang, 2014), this study focuses on validation and application of SQF to assess forest productivity in temporal dimensions, while producing stand quality scores that can be integrated into scores generated by other SQF, in a multi-indicator, multi-functional and multi-process based SQA (Figure 5.1)

3.3 Stand quality assessment using GYPSY model output, transformations and applications

Input data into GYPSY model included stand age, density, height, DBH and stand basal areas (Table 5.7). The model outputs and projections for up to 250 years included basal area, height, % stocking, DBH, stand density, total merchantable volume, merchantable density and mean annual increment of biomass (Figure 5.8a to h). Most parameters increased with increasing time except percentage stocking and stand density, which peaked and remained constant.
The modelled and subsampled stand height data up to 50 years were compared to actual height measurements for each tree species on reclaimed plots (Figure 5.9a to c). GYPSY Jackpine's height increased by average of 0.19 m $year^{-1}$, white spruce by average of 0.16 m $year^{-1}$ and trembling aspen by average of 0.23 m $year^{-1}$ in natural soils. In reclaimed plots jackpine grew 0.28 m $year^{-1}$, white spruce 0.31 m $year^{-1}$ and trembling aspen 0.75 m $year^{-1}$, clearly confirming that reclaimed soils in the AOSR are generally designed with functional capabilities greater than natural soils to support forest productivity. Forest stand heights and rate of increase in height are generally higher on reclaimed sites in comparison to natural sites.

Stand quality functions were designed to rate productivity of forest stands over time (Figure 5.10a and b). Subsampled projections of age-height relationships were made over 10 years for the three forest species (Figure 5.10a). Trembling aspen had almost double rate of increase in height than white spruce and jack pine within the first 10 years for natural soils. Using the framework presented in Figure 5.1, the stand quality functions presented in Figure 5.10b are useful for scoring plant productivity over time, thereby addressing the time dimension of forest plant productivity, especially at the initial stages of revegetation in land reclamation.

3.4 Soil-forest productivity calibration using BIOMES BGC output, transformations and applications

The relationships between AWHC (mm m^{-1}), jack pine's maximum leaf area index (Figure 5.11a), and NPP for water limiting soils (Figure 5.11b) were modelled for the AOSR. Profile AWHC up to 1m depth was modelled using HYDRUS - 1D to account for subtle heterogeneity of the coarse textured substrate in Brunisols (Simunek et al., 2016, Huang et al., 2013) while the NPP was modelled for the same sites using BIOME-BGC (Thornton et al., 2002, Huang et al., 2013).

These relationships confirmed increasing leaf area index (LAI) and NPP with increased profile AWHC for the year 2013 when the measurement and models were completed. For the purpose of this study, this relationship is best expressed using Weibull functions, a version of sigmoid functions, which rise to maximum and peak at critical thresholds (Figure 5.11a and 5.11b). The derived SQF from the soil – forest productivity relationship shown in Figure 5.11 are presented using a normalized index to represent quality scores (Figure 5.12). Threshold analysis of these non-linear functions using differential analysis indicates that any soil profile configuration with capacity to support a minimum of 100 mm m^{-1} of AWHC has the capability to efficiently support soil water dynamics required for the best stand productivity. This corresponds to the AWHC where SQF peaked with a maximum value of 1 (Figure 5.12). The design of reclamation covers must therefore provide at least 100 mm m^{-1} of water holding capacity to ensure the best response for jack pine productivity in terms of LAI and NPP.

To further demonstrate the application and validation of these SQF in assessing the quality of reclaimed soil to support jack pine productivity, the proposed framework (Figure 5.1) was adopted using data provided by House (2015) from four reclamation designs (Table 5.8). The non-significant ($p < 0.05$) effect of years after planting or revegetation of reclaimed soils with jack pine seedlings on the mean LAI and NPP were repeated by the scores of LAI and NPP reported for this site specific situation. The range of slope, depth of topsoil and bulk density reported for this site specific study did not indicate any significant effect of these factors on the mean LAI or NPP. Similar non-significant effects were captured by the scores generated using AWHC as input into the SQF. This directly confirms that the SQF are suitable for assessing jack pine productivity for this site and is suitable for further integration into multi-functional SQA framework.

4.0 Discussion

Analysis of the soil-forest productivity relationships within the AOSR confirms that there are suitable soil quality indicators with robust metrics to adequately predict forest productivity within the AOSR. To ensure appropriate calibration and application of this relationship, multiple soil quality indicators with multiple mechanistic linkages to ecosystem processes and functions must be used. This will ensure that soil-forest productivity calibration curves adopted for SQA reflect all the necessary functions and processes supporting stand productivity.

The implication of this for the proposed SQA framework (Figure 5.1) is the need to identify all relevant processes supporting the objectives of SQA and the best soil quality indicator to represent such functionality. This is best done using a decision support system that accounts for predictive soil quality indicators, measures of performance such as metrics of forest productivity and the process linkages between the two indicators (Andrews et al., 2004, Stott et al. 2009). Use of only statistical methods for selecting these indicators such as principal component analysis might not effectively delineate the importance of these two groups of indicators (Brejda et al., 2000a; Brejda et al., 2000b).

Soil quality indicators such as SOC and N best represent nutrient cycling and transformation processes within forest soils systems. Soil chemical parameters such as pH and CEC adequately reflect biomass productivity and plant nutrition based on their capability to regulate nutrient availability and influence the rhizosphere to control nutrient uptake. Soil physical indicators such as textural composition and bulk density also control water retention, transmission and indirect flow of resources between the soil and plant systems. To effectively integrate these indicators while considering the time consequence of forest productivity, analytical SQF and stand quality functions will be selected and validated for site specific use before application in soil quality rating. This will be a data intensive and costly process, suggesting the preference for validated, site specific process models to calibrate such relationships.

The advantage of analytical functions in calibrating soil-forest productivity relationships occurs when the focus of quality assessment is constrained in application, such as assessing age to stand productivity relationships over time. Analysis of the slopes of stand quality functions in this study clearly identifies a success for the land reclamation industry in the AOSR; the existing cover design seems to have more than adequate capability to support forest productivity relative to forest stands growing on natural soils. Tree species on reclaimed soils are growing faster than those on natural soils. A similar trend was also reported by Farden et al., (2013). The reclaimed soils in this region are designed with adequate nutrient and water buffer capacity such as the use of 20 to 30 cm of organic cover rather than the average of 10 cm found in natural, water limiting sites with Brunisolic soils (House, 2015). The stand quality functions could be subsampled based on the number of years after revegetation of reconstructed soils while producing quality metrics that can be integrated into the overall SQA scores produced by existing SQF (Figure 5.1).

A more direct approach to soil quality indicator's calibration with forest productivity parameters involves the use of forest growth and other process based models. These models account for critical fundamental processes while solving related algorithms, thereby providing better alternative in calibrating soil-forest productivity relationships, than the use of analytical models (Tables 5.1 to 5.6). The advantage of using pre - calibrated and validated process models such as BIOME BGC and others in quantifying soil-forest productivity relationships is that the issues of fundamental process linkages are addressed pre-calibration of SQF, and provide a better opportunity for site specific calibrations of predictive soil quality indicators. SQF produced using this approach can be analyzed like analytical functions to assess a threshold of indicators and form a quantitative basis for design of reclamation covers, when optimum plant productivity is the main objective of designing such covers. Soil quality functions designed to assess jack pine productivity using AWHC demonstrated outstanding performance in predicting such productivity in the site specific application presented earlier in the study.

This study demonstrated application of SQF or stand quality functions by comparing the rate of change in plant height between stands growing on natural and reclaimed soils. Validated SQF also generated meaningful scores statistically, with potential for integration into a multi-functional SQA framework. SQF also provides the basis for quantitative SQA to test the effect of various cover design factors on stand productivity. Other potential application of validated SQF includes derivation of soil cover design metrics based on optimum measure of performance (in this case, the optimum value of forest productivity indicator).

5. Conclusions

This research demonstrates two broad options to calibrate soil-forest productivity relationships while developing SQF for application in quantitative SQA process: *analytical and process models*. Multiple soils based predictive indicators and measures of stand productivity will be required to calibrate the relationship, considering the soil and forest relationships in the AOSR are site specific, tree species dependent and need to account for the effect of time and other factors influencing stand productivity. The best set of soil quality indicators that represent forest stand productivity for the AOSR includes biological, chemical and physical indicators of soil quality and functions.

The soil quality functions derived from outputs of analytical models will require more effort at the validation stage, considering the need for adequate amount of data to validate multiple regression functions. To address the challenges posed by availability of validation datasets, SQA objectives can be streamlined as presented in this study, to assess the trajectory of vegetation performance using stand quality functions. SQF derived from outputs of process based models have the advantage of account for critical mechanistic processes before calibration of SQF, thereby producing representative numerical relations for calibrating soil quality indicators.

Application examples include assessment of stand performance over time using analytical functions to confirm that reclaimed soils in the AOSR are supporting the growth of three species of trees faster than that in natural soils. Analysis of SQF derived from process models using AWHC as input suggest that reclaimed covers must have at least 100 mm m^{-1} of water to support best stand productivity. The SQF effectively reproduce non-significant ($p < 0.05$) effects of four reclamation design covers on jack pine productivity. Future study will include the need to recalibrate such process models for fine textured soils growing other plant species in the AOSR. Further field validation and applications of the analytical and time series SQF will be interesting, especially for young reclaimed sites with active growing vegetation stands.

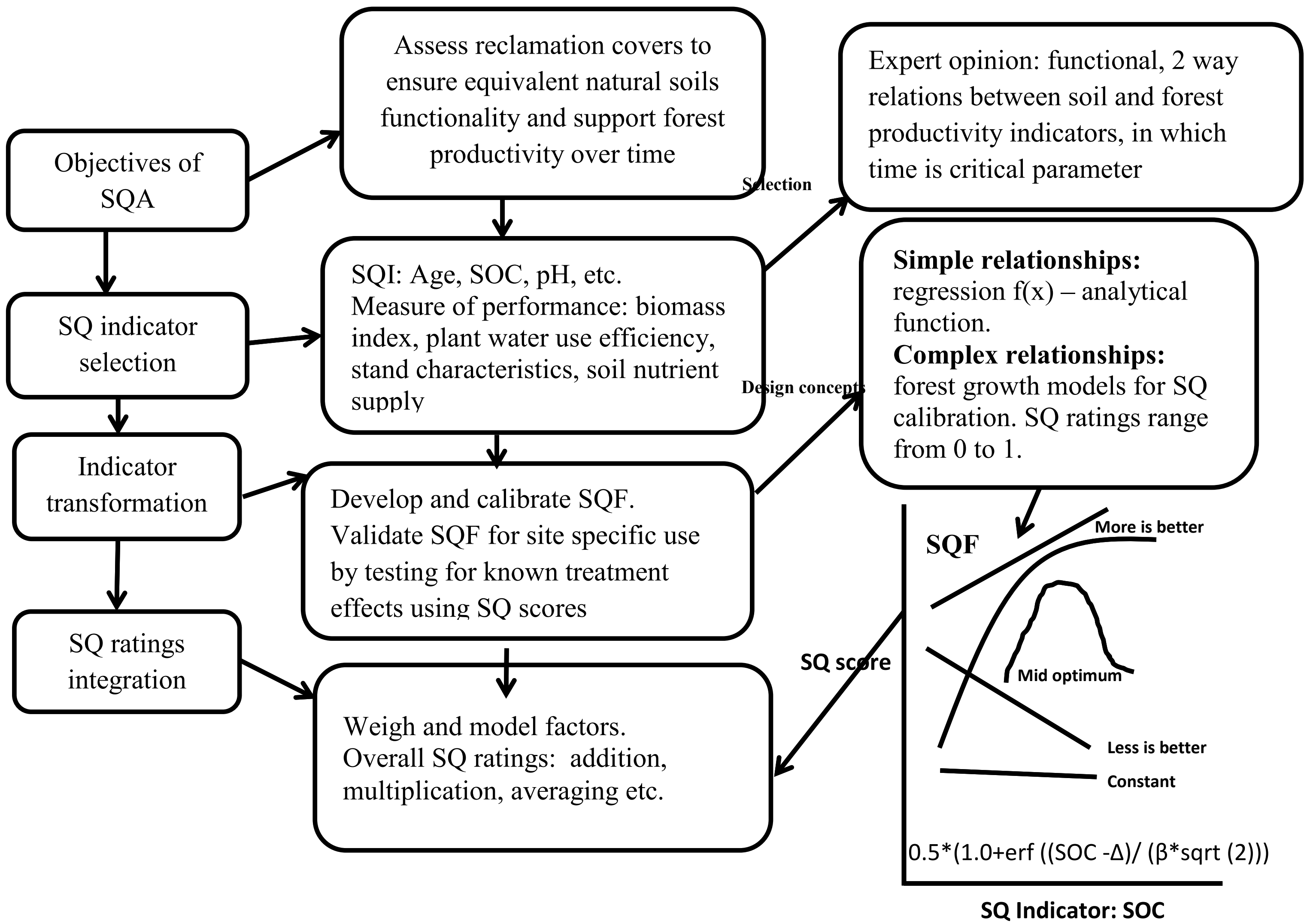

Figure 5.1. Soil quality assessment (SQA) framework adopted in this study.

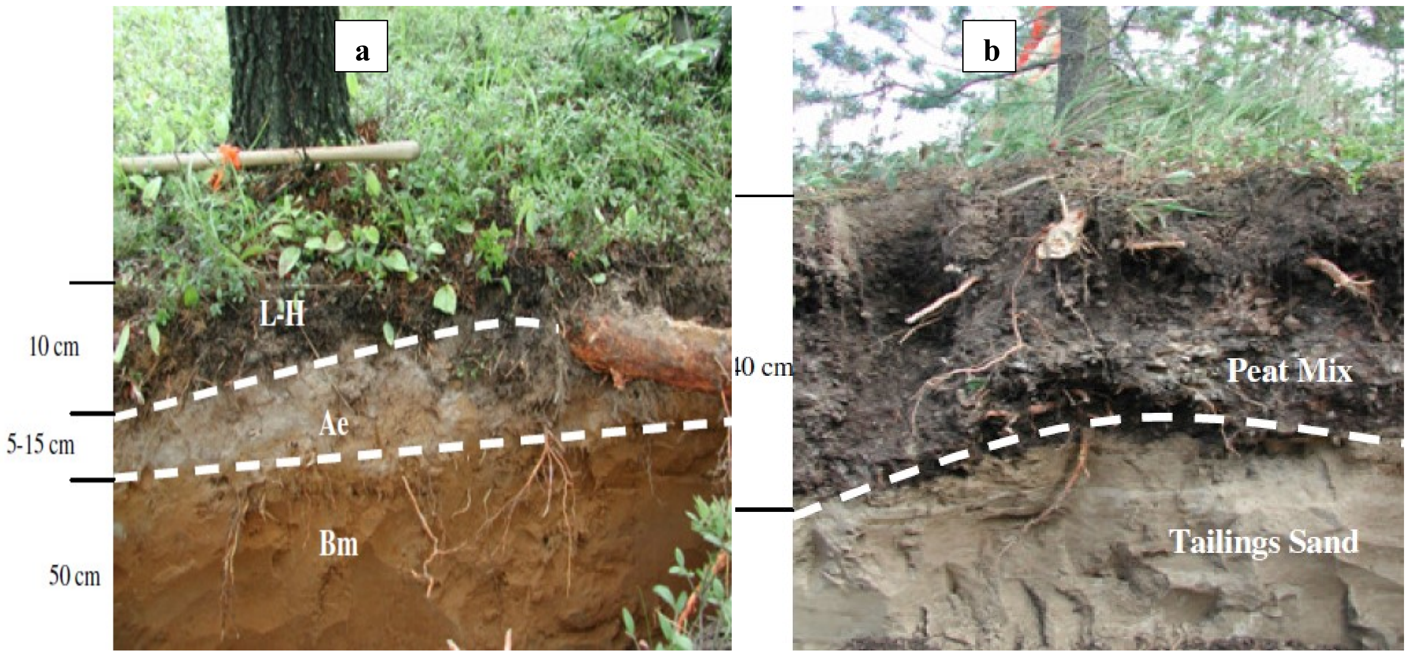

Figure 5.2. Comparison of a) Brunisols with b) peat-mineral mix designs overlay tailing sands while both support the growth of jack pine species.

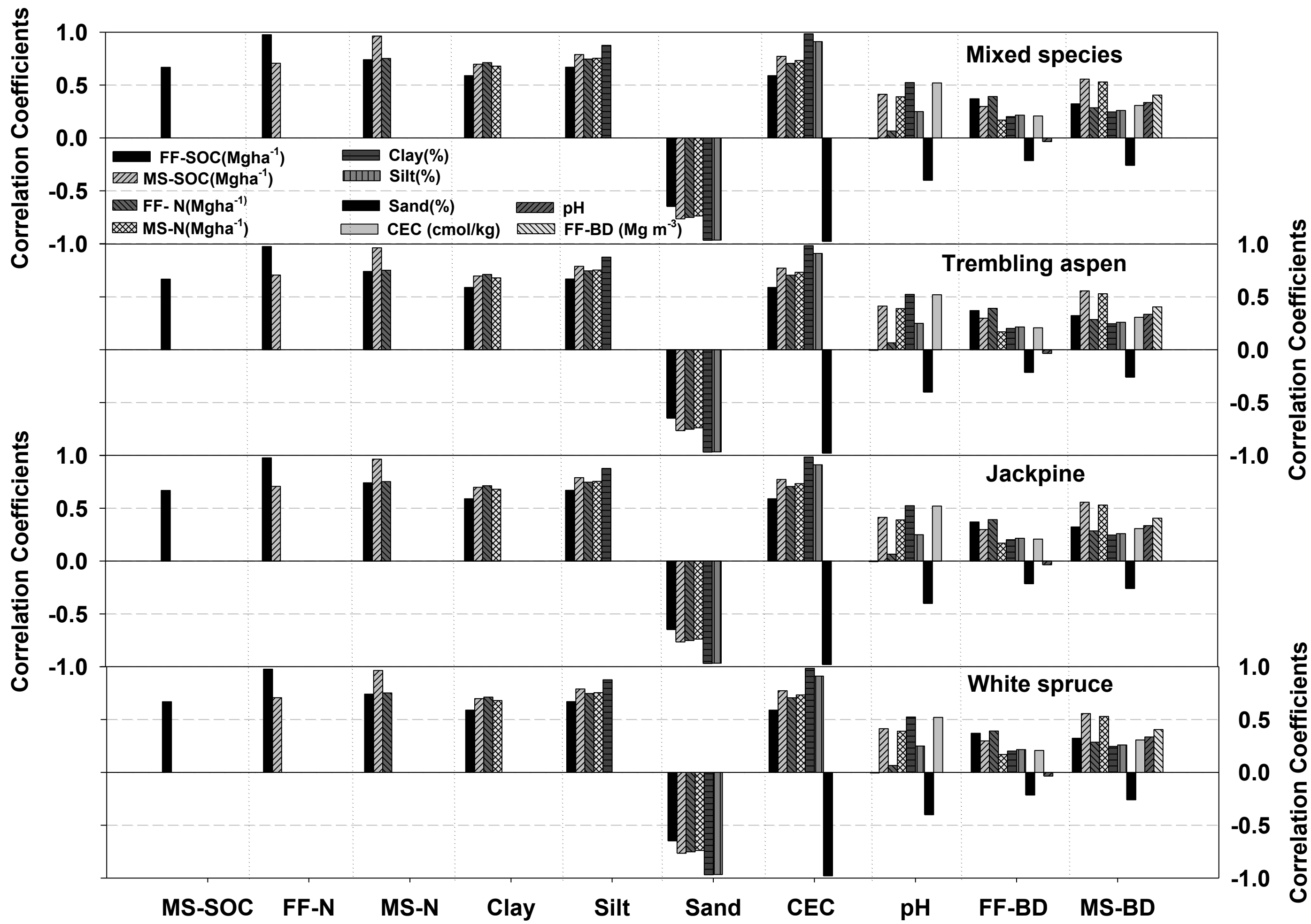

Figure 5.3. Correlations among indicators of soil quality by stand types in the Athabasca oil sands region. Indicators include MS – SOC = soil organic carbon in mineral soils, FF–N = nitrogen in forest floor, CEC = cation exchange capacity, FF-BD = bulk density of forest floor and MS-BD = bulk density of mineral soils.

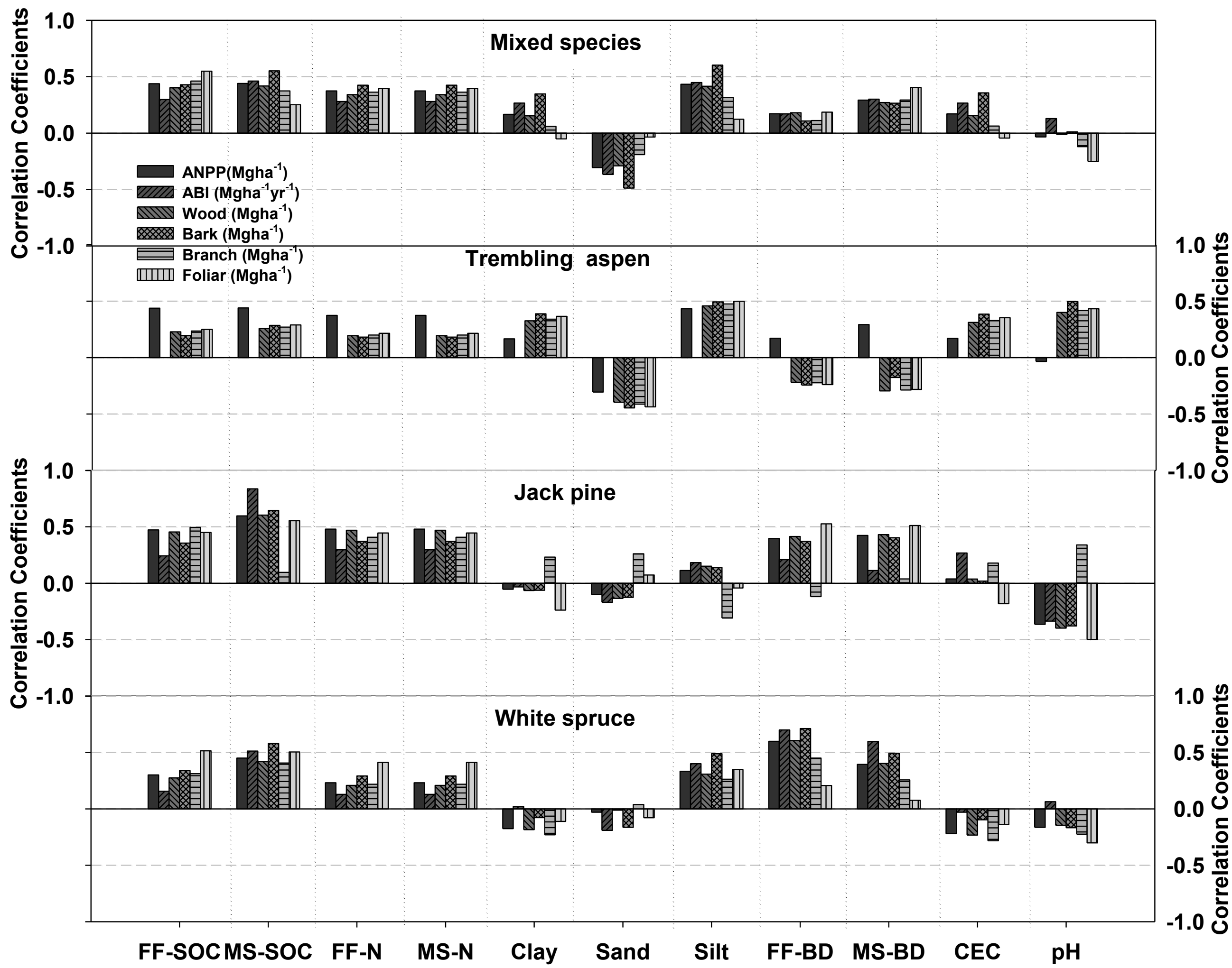

Figure 5.4. Correlations between soil quality indicators and biomass productivity of forest species in the Athabasca oil sands region. Indicators include MS – SOC = soil organic carbon in mineral soils, FF –N = nitrogen in forest floor, CEC = cation exchange capacity, FF-BD = bulk density of forest floor and MS-BD = bulk density of mineral soils.

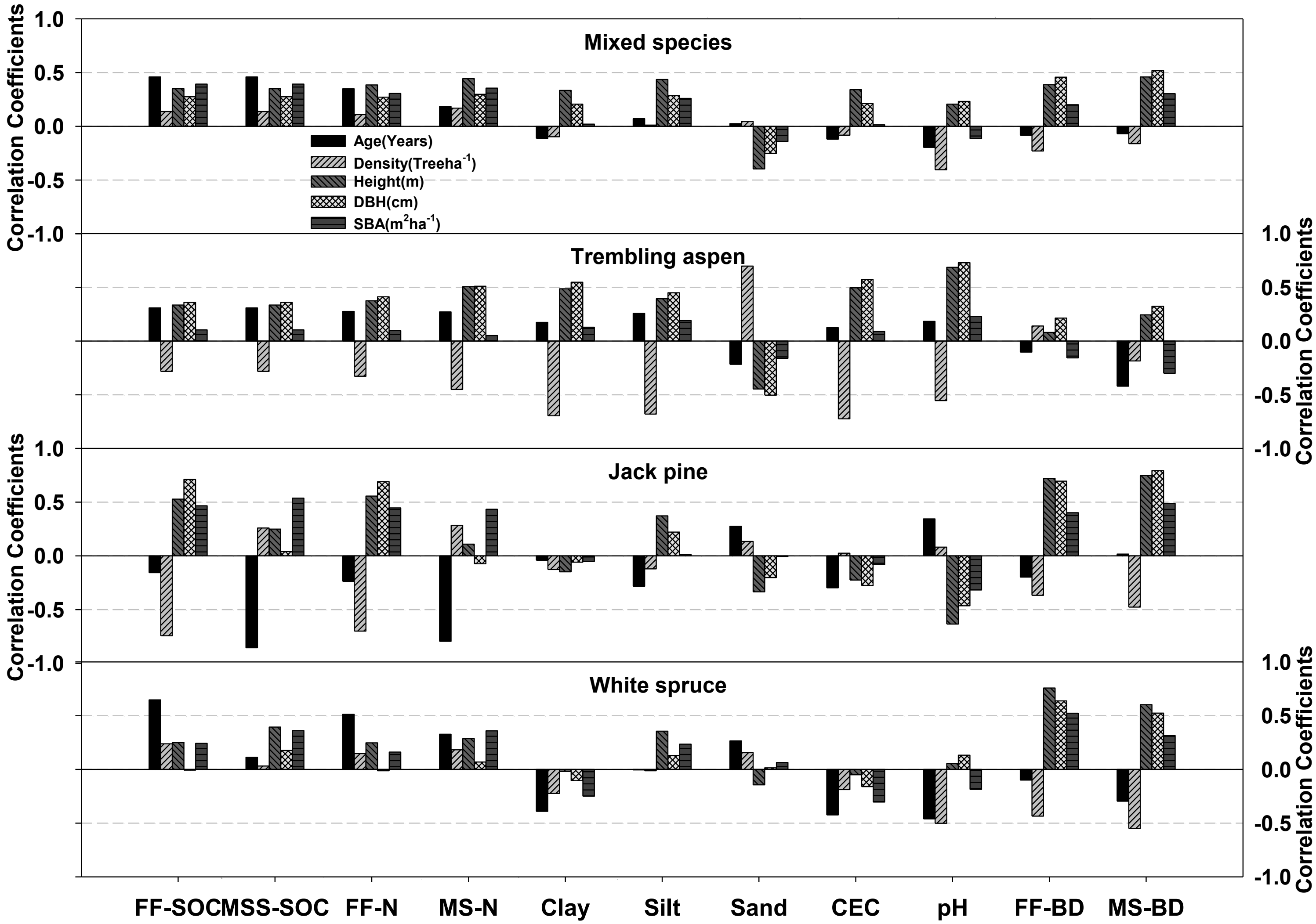

Figure 5.5. Correlations between soil quality indicators and stand growth parameters within the Athabasca oil sands region. Indicators include MSS – SOC = soil organic carbon in mineral soils, FF –N = Nitrogen in forest floor, CEC = cation exchange capacity, FF-BD = bulk density of forest floor and MS-BD = bulk density of mineral soils.

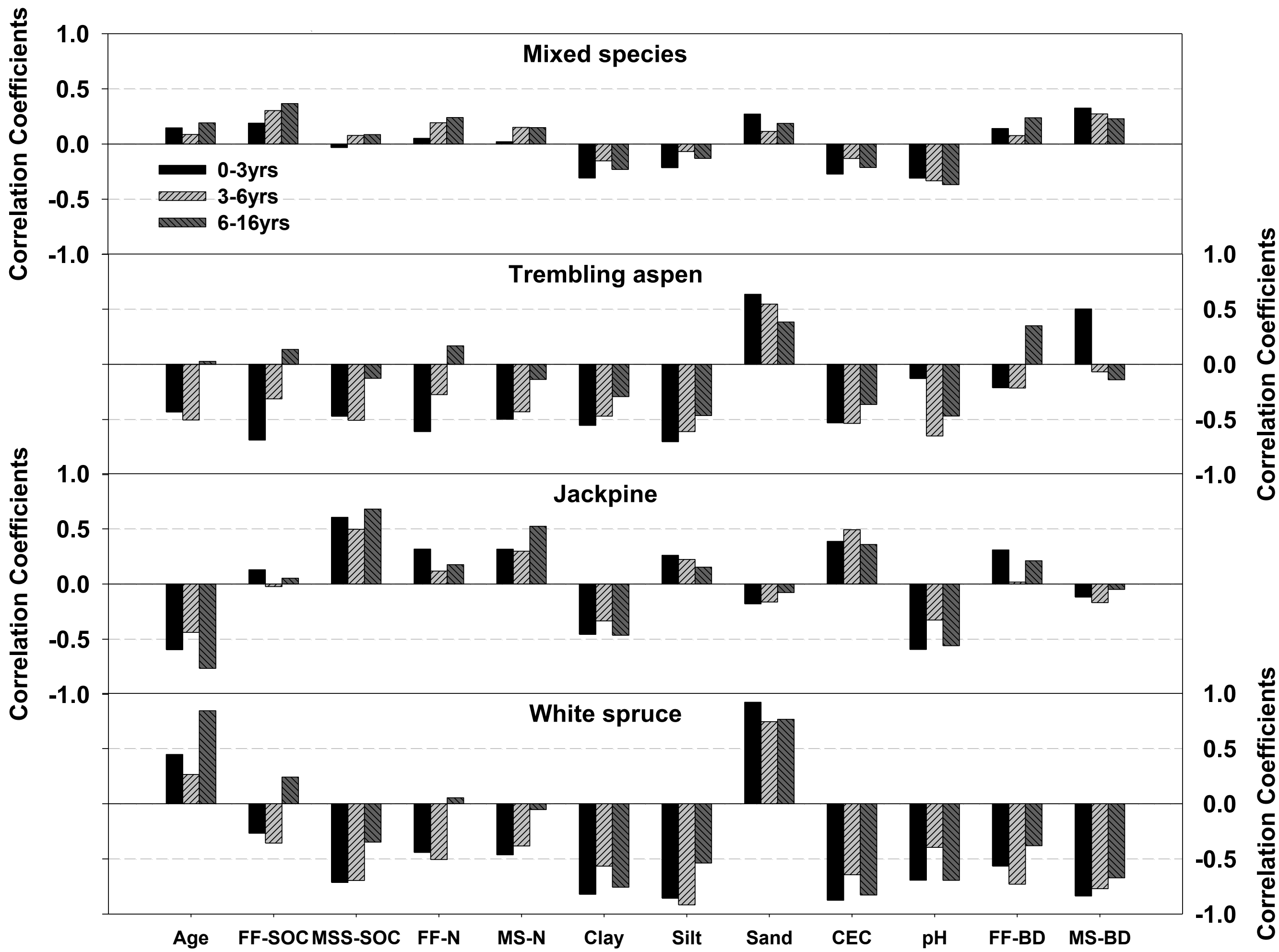

Figure 5.6. Correlations between soil quality indicators and intrinsic water use efficiency of forest species within the Athabasca oil sands region. Indicators include MSS – SOC = soil organic carbon in mineral soils, FF –N = nitrogen in forest floor, CEC = cation exchange capacity, FF-BD = bulk density of forest floor and MS-BD = bulk density of mineral soils.

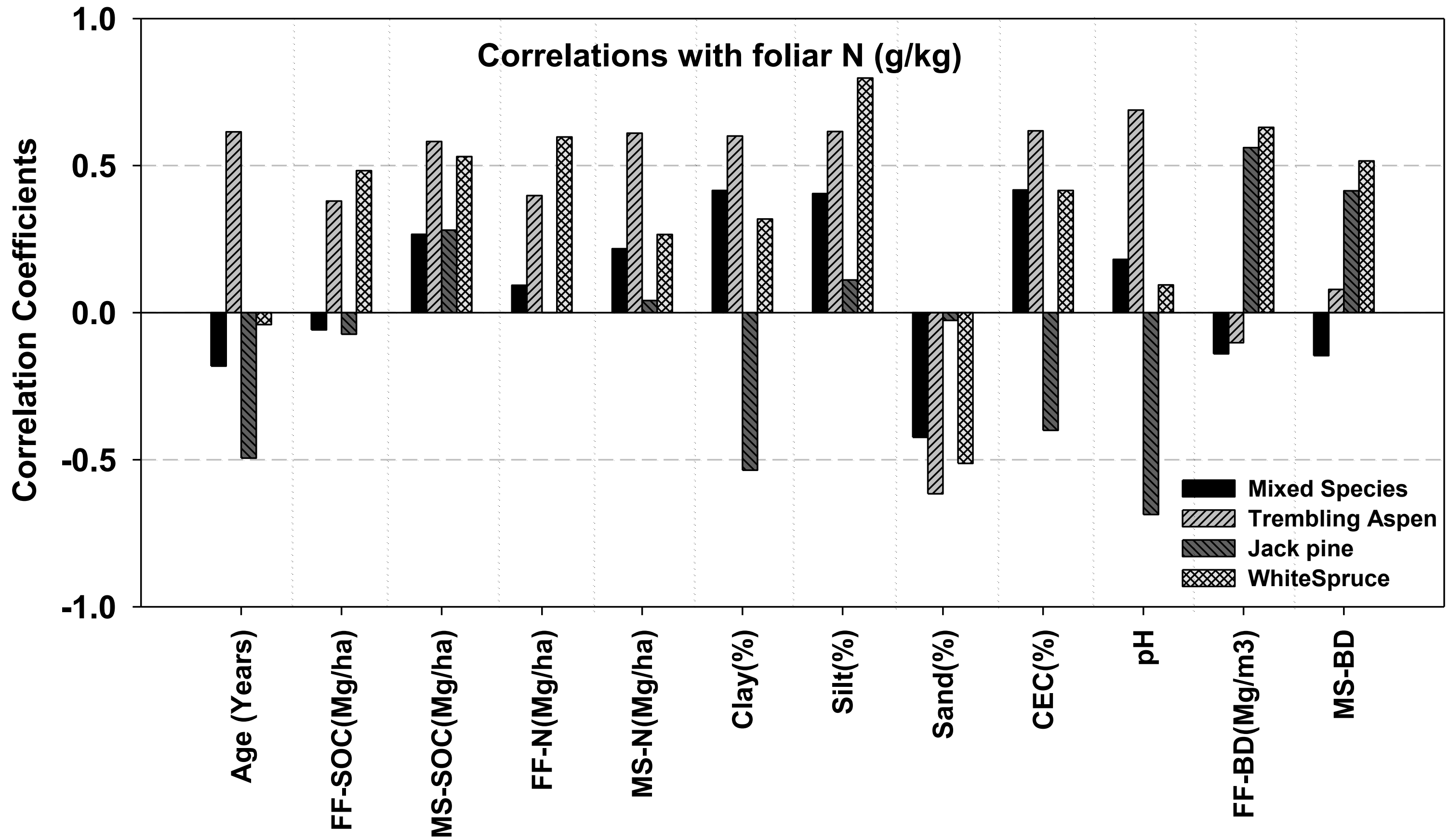

Figure 5.7. Correlations between soil quality indicators and foliar nitrogen (gkg^{-1}) concentration of forest species within the Athabasca oil sands region. Indicators include MS – SOC = soil organic carbon in mineral soils, FF – N = Nitrogen in forest floor, CEC = cation exchange capacity, FF-BD = bulk density of forest floor and MS - BD = bulk density of mineral soils.

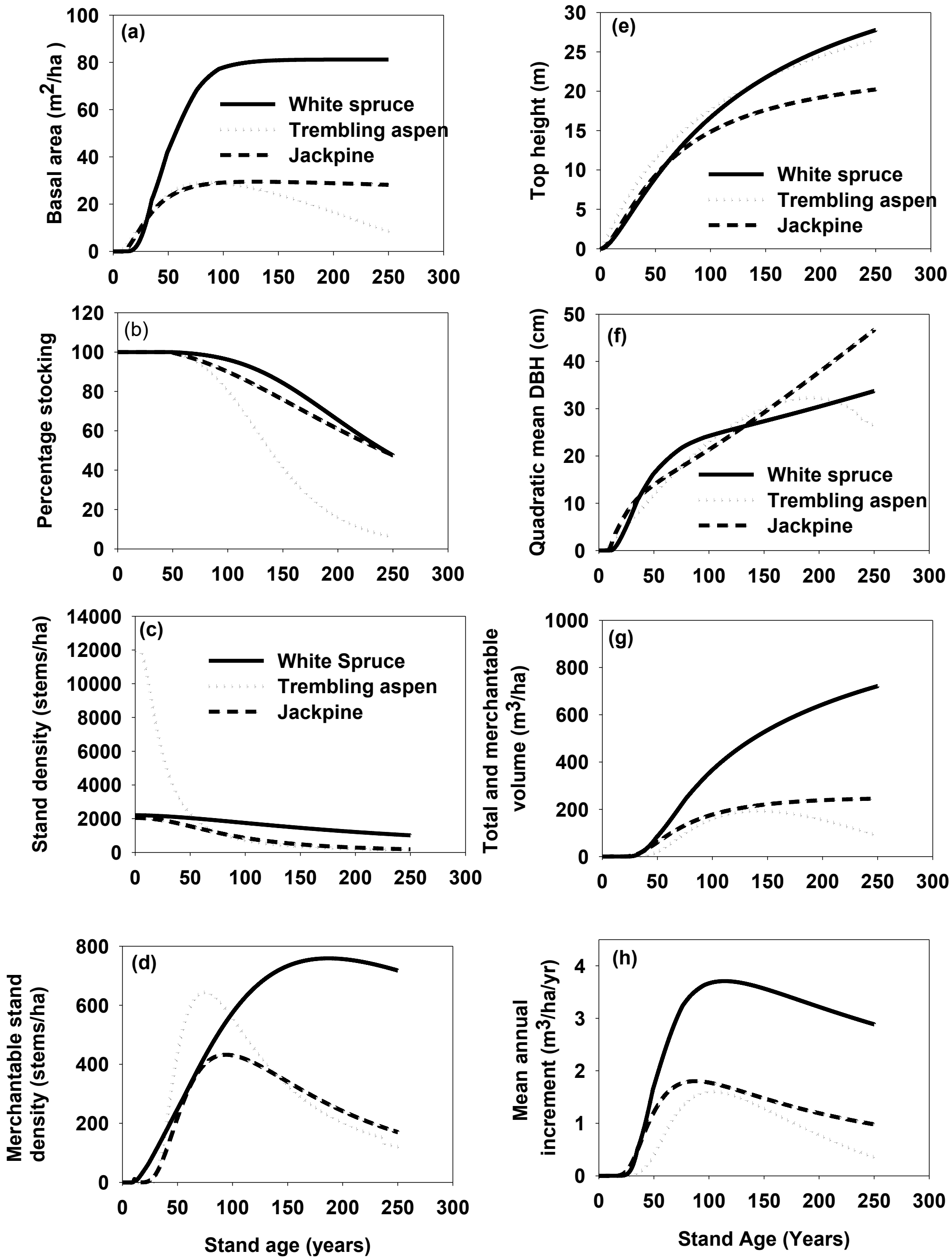

Figure 5.8. Forest growth projection using GYPSY model, (DBH = diameter at breast height).

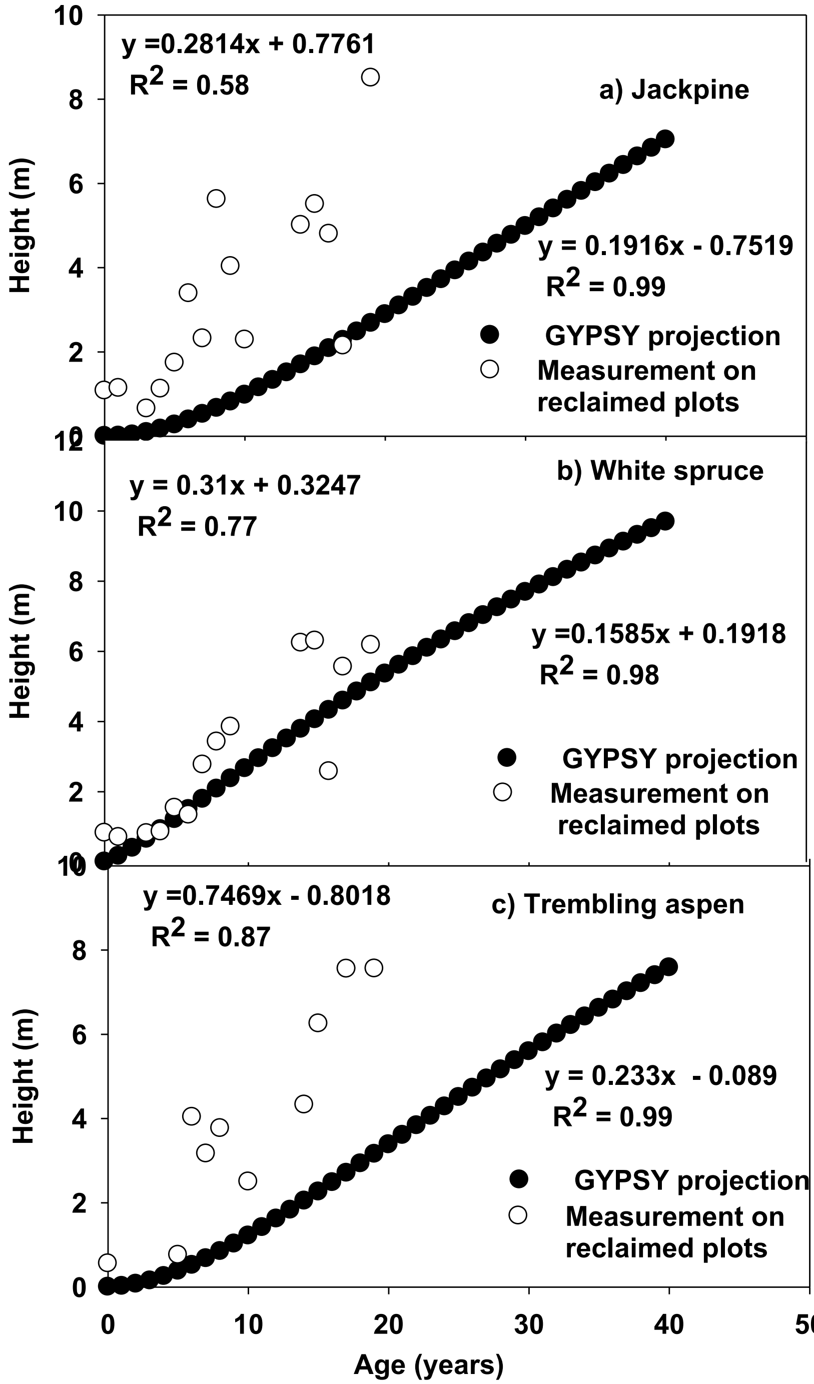

Figure 5.9. Comparison of height of forest species growing on reclaimed soils to projected heights of similar species growing on natural soils between 15 to 20 years of growth.

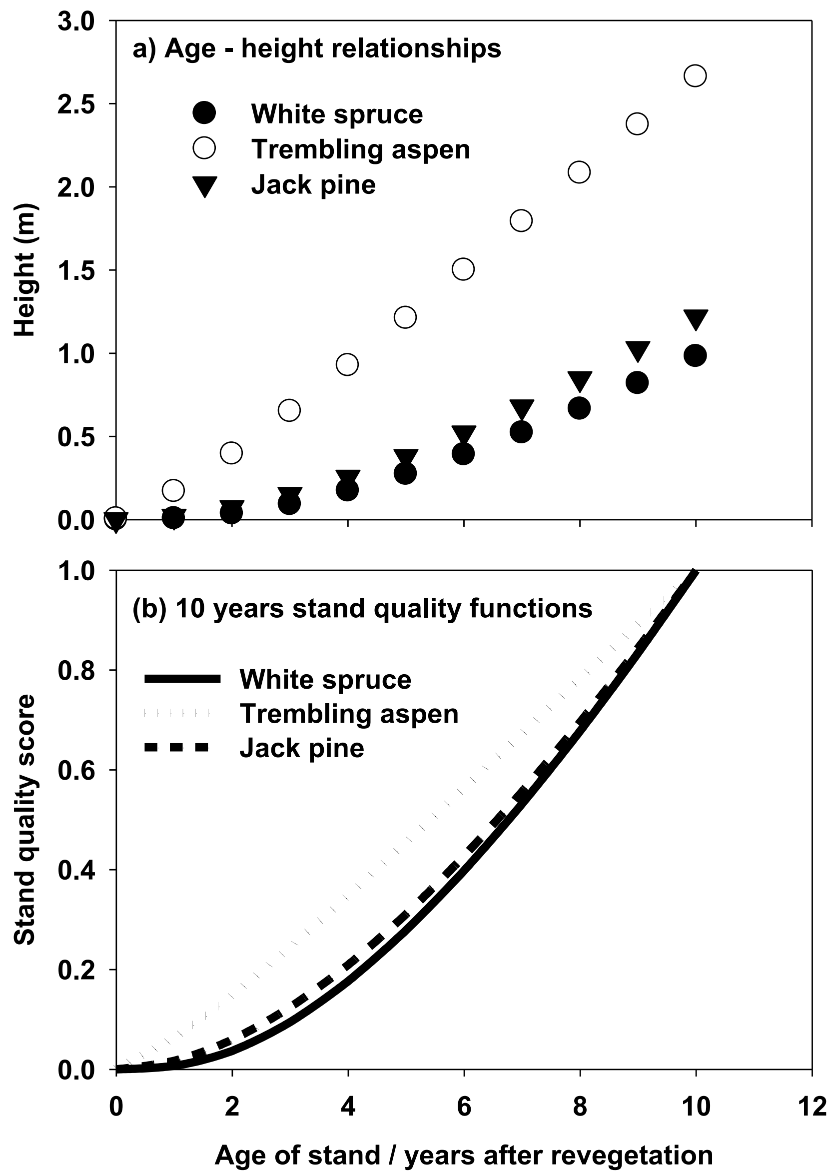

Figure 5.10. Transformation of, a) 10 years age – height relationships into, b) stand quality functions to produce normalized scores that can be integrated with other quality scores in multi-indicator soil quality assessment or test specific treatment effects on tree height.

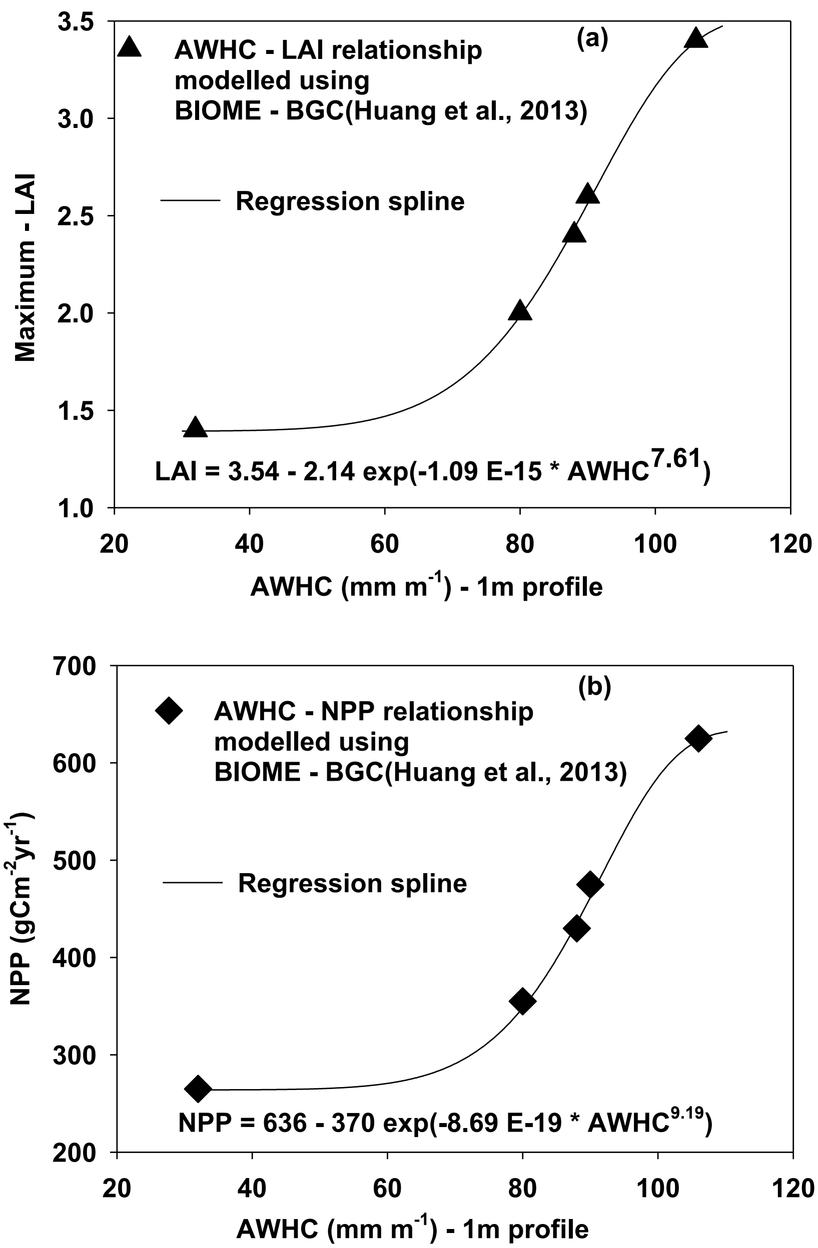

Figure 5.11. Effect of profile available water holding capacity (AWHC) on indicators of jack pine productivity growing in Brunisolic soils such as, a) maximum leaf area index (LAI) and, b) net primary productivity (NPP).

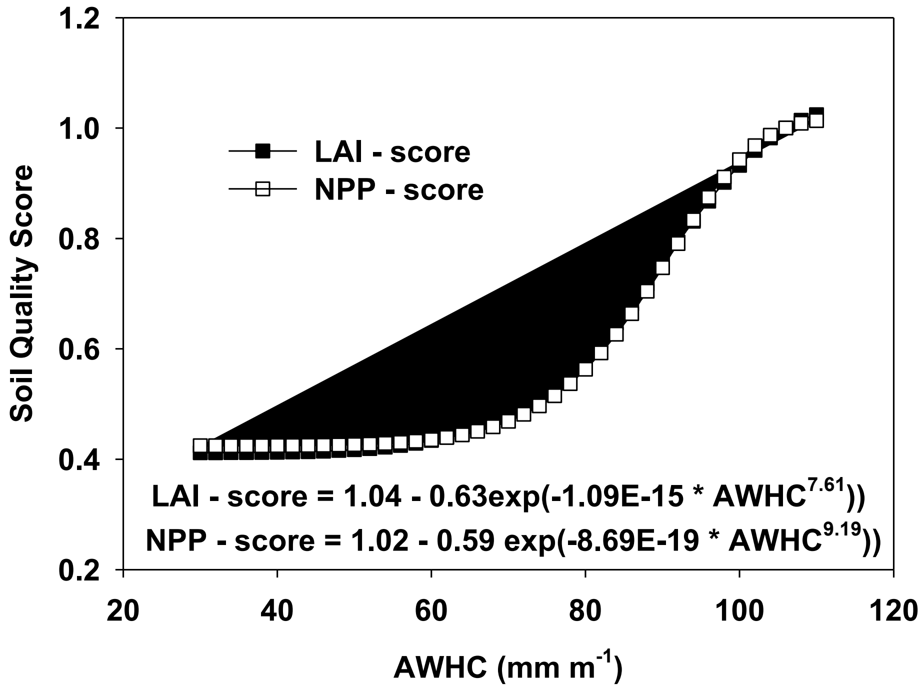

Figure 5.12. Soil quality functions relating available water holding capacity (AWHC) to normalized measures of jack pine productivity (LAI – score = ratings for leaf area index, and NPP – score = ratings for net primary productivity).

Table 5.1. Soil quality functions for assessing cation exchange capacity (CEC) of forest soils using multiple predictive indicators.

Tree species [a]	SQ indicator (x) [b]	Soil quality functions (Quality score = normalized (y) = f(x))	R^2
Aspen	Clay (%)	IF $x < 0.8$, $y = 0$, $x > 0.8$, $y = 0.0675\ x^{0.71}$, $x > 48$, $y = 1$	0.98
Spruce	Clay (%)	IF $x < 2.0$, $y = 0$, $x > 2.0$, $y = 0.0926\ x^{0.63}$, $x > 44$, $y = 1$	0.98
All	Clay (%)	IF $x < 0.8$, $y = 0$, $x > 0.8$, $y = 3.75 / (1 +(x / 164.993) – 0.805)$, $x > 48$, $y = 1$	0.98
All	Sand (%)	IF $x < 10$, $y = 1$, $x > 10$, $y = 1.01 – 1.41 \exp^{(-193.10x-1.34)}$, $x > 98$, $y = 0$	0.97
Aspen	Sand (%)	IF $x < 10$, $y = 1$, $x > 10$, $y = 1.125 – 0.011\ x$, $x > 98$, $y = 0$	0.96
All	Silt (%)	IF $x < 1.3$, $y = 0$, $x > 1.3$, $y = 1.13 / (1 + 14.50 \exp^{(-0.09x)})$, $x > 42$, $y = 1$	0.84
All	MS-SOC ($Mgha^{-1}$)	IF $x < 0.2$, $y = 0$, $x > 0.2$, $y = (5.136 + 1.678\ x^{1.246})/(69.674 + x^{1.246})$, $x > 34$, $y = 1$	0.60
All	pH	IF $x < 3$, $y = 0$, $7 < x >3.0$, $y = 1/(12.09 – 1.84\ x)$	0.38
All	FF-SOC ($Mgha^{-1}$)	IF $x < 3$, $y = 0$, $x > 3$, $y = 0.5 (1.0+erf((x – 32.357) / (28.402*sqrt(2))))$, $x > 58$, $y = 1$	0.35

[a] Tree species : All = includes jackpine, spruce and aspen. [b] SQ indicators includes MS = mineral soil, FF = forest floor, CEC = cation exchange capacity, SOC = soil organic carbon.

Table 5.2. Soil quality functions for assessing the transformation of organic carbon in relation to nutrient cycling in forest soils.

Tree species	Soil quality indicator (x) [a]	Measure of performance (x)[b]	Soil quality functions (Quality score = normalized (y) = f(x))	R^2
Aspen	FF-SOC	FF-N	IF $x < 4$, $y = 0$, $x > 4$, $y = 0.024\ x – 0.0376$, $x > 41$, $y = 1$	0.99
Spruce	FF-SOC	FF-N	IF $x < 5$, $y = 0$, $x > 5$, $y = 0.0173\ x – 0.0035$, $x > 57$, $y=1$	0.96
Aspen	MS-SOC	MS-N	IF $x < 0.3$, $y = 0$, $x > 0.3$, $y = 0.124 + (1 – 0.124)*(1+erf((0.137\ x – 2.110) /sqrt(2))) / 2$, $x > 34$, $y = 1$	0.96
Spruce	MS-SOC	MS-N	IF $x < 7.3$, $y = 0$, $x > 7.3$, $y = 0.592\ (x – 7.374)\ 0.163$, $x > 20$, $y = 1$	0.95
Jack pine	FF-SOC	FF-N	IF $x < 3$, $y = 0$, $x > 4$, $y = 0.0597\ x – 0.0087$, $x > 18$, $y = 1$	0.92
Jack pine	MS-SOC	MS-N	IF $x < 0.2$, $y = 0$, $x > 0.2$, $y = 0.268 \exp^{(x/0.445)}$, $x > 6$, $y = 1$	0.80
Aspen	FF-SOC	MS-SOC	IF $x < 4$, $y = 0$, $x > 4$, $y = 0.60 / (1 + \exp^{(3.88-0.30x)})$, $x > 41$, $y = 1$	0.58
Spruce	FF-SOC	MS-SOC	IF $x < 5$, $y = 0$, $x > 4$, $y = 0.86 / (1 – \exp^{(-0.12x)})$, $x > 57$, $y = 1$	0.49

[a] SQ indicators: MS = mineral soil, FF = forest floor, SOC = soil organic carbon ($Mgha^{-1}$). [b] Measure of performance: N = nitrogen

Table 5.3. Soil quality functions for assessing nitrogen supply potential in mineral soils (MS –N) using covariates of available water holding capacity or water retentions as predictive indicators.

Tree species [a]	Soil quality indicator (x)	Soil quality functions (Quality score = normalized (y) = f(x))	R^2
All	Silt(%)	IF x < 1.3, y = 0, x > 1.3, y = 1 / (8.559 – 0.458 x + 0.0072 x^2), x > 42, y = 1	0.69
Spruce	Clay(%)	IF x < 2.5, y = 0, x > 2.5, y = 0.559 $\exp^{(0.014x)}$, x > 44, y = 1	0.61
All	Clay(%)	IF x < 0.8, y = 0, x > 0.8, y = 1 / (5.678 – 0.251 x + 0.0035 x^2), x > 48, y = 1	0.58
All	Sand(%)	IF x < 10, y = 1, x > 10, y = 0.845 – 0.0071 x, x > 98, y = 0	0.55
Aspen	Clay(%)	IF x < 0.8, y = 0, x > 0.8, y = 0.637 / (1 + 2.923 $e^{(-0.114x)}$), x > 48, y = 1	0.46
Jack pine	Clay(%)	IF x < 1.8, y = 0, x > 1.8, y = 1 / (5.131 – 1.247 x), x > 2.9, y = 1	0.10

[a] Tree species : All = included jackpine, spruce and aspen.

Table 5.4. Soil quality functions for assessing plant nutrition as measured by leaf nitrogen concentrations.

Tree Species	Soil quality indicators (x) [a]	Soil quality functions (Quality score = normalized (y) = f(x))	R^2
Aspen	MS-SOC ($Mgha^{-1}$)	IF x < 0.4, y = 0.82, x > 0.4 , y = 0.826 + 0.0055x, x > 34, y = 1	0.34
Aspen	MS-N ($Mgha^{-1}$)	IF x < 0.07, y = 0.75 , x > 0.07 , y = 0.299 (3.597 – $\exp^{-0.756x}$), x > 2, y = 1	0.39
Aspen	Clay(%)	IF x < 0.8, y = 0.80 , x > 0.8 , y = 0.183 (5.427 – $\exp^{-0.0392x}$), x > 48, y = 1	0.40
Aspen	Soil pH	IF x < 4, y = 0.75, x > 4, y = 1 – exp (-1.297 $x^{4.967}$), x > 6.5, y = 1	0.64
Jack pine	Soil pH	IF x < 4, y = 1, x > 4, y = 2.116 $\exp^{(-x/5.622)}$, x > 6, y=0	0.47
Jack pine	Clay(%)	IF x < 1.8, y = 1, x > 1.8, y = 1.124 $\exp^{(-x/12.023)}$, x > 3.5, y=0	0.29
White spruce	Clay(%)	IF x < 0.25, y = 0.88, x > 0.25, y = 0.956 / (1 + 0.127 $\exp^{(-0.166x)}$), x > 3.5, y = 0	0.47

[a] SQ indicators: MS = mineral soil, SOC = soil organic carbon ($Mgha^{-1}$), N = nitrogen.

Table 5.5. Soil quality functions for assessing forest stand characteristics using multiple soil quality indicators.

Tree species	Soil quality indicators (x)[a]	Measures of performance (y) [b]	Soil quality functions (Quality score = normalized (y) = f(x))	R^2
Trembling Aspen	Soil pH	Height (m)	IF x < 4.14, y = 0, 6.02 < x > 4.14, y = 0.872 $(x – 4.086)^{0.19}$, 7 < x > 6.02, y = 1	0.58
Trembling Aspen	Soil pH	DBH (cm)	IF x < 4.14, y = 0, 6.02 < x > 4.14, y = 0.8537 $(x – 4.02)^{0.20}$, 7 < x > 6.02, y = 1	0.59
Jack pine	FF-SOC	Density (Tree ha^{-1})	IF x < 3 , y = 1, x > 3 , y = 0.532 $\exp^{(2.035/x)}$, x > 18, y = 0	0.69
Jack pine	FF-SOC	Height (m)	IF x < 3 , y = 0, x > 3 , y = 0.902 $\exp^{(-0.264x)}$, x > 18, y = 1	0.55
Jack pine	FF-N	Density (Tree ha^{-1})	IF x < 0.09, y = 0, x > 0.09 , y = 0.54 $\exp^{(0.057/x)}$, x > 0.55, y = 1	0.67
Jack pine	FF-N	Height (m)	IF x < 0.09, y = 0, x > 0.09 , y = 0.89 $(1 – \exp^{(-9.20x)})$, x > 0.55, y = 1	0.54
All	MS-SOC	Height (m)	IF x < 0.2, y = 0, x > 0.2 , y = 0.543 $\exp^{(0.0165x)}$) , x > 34, y = 1	0.24
All	FF-N	Height (m)	IF x < 0.09, y = 0, x > 0.2 , y = 0.545 + 0.117 x , x > 2.3, y = 1	0.15

[a] Soil quality indicators : FF = forest soil, MS = mineral soil, SOC = soil organic carbon ($Mgha^{-1}$), N = nitrogen ($Mgha^{-1}$). [b] Measure of performance : DBH = diameter at breast height

Table 5.6. Soil quality functions for assessing forest biomass productivity using multiple soil quality indicators.

Tree species [a]	Soil quality indicators (x) [b]	Measures of performance (y) [c]	Soil quality functions (Quality score = normalized (y))	R^2
All	FF-N ($Mgha^{-1}$)	ANPP	IF x < 0.09, y = 0, x > 0.09 , y = 0.771 $\exp^{(-0.106/x)}$, x > 2.225, y = 1	0.31
All	MS-N ($Mgha^{-1}$)	ANPP	IF x < 0.04, y =0, x > 0.04 , y = 0.452 + 0.223x, x > 2.225, y = 1	0.20
All	FF-SOC ($Mgha^{-1}$)	Foliar	IF x < 3, y = 0, x > 3 , y = 0.228 + 0.008x, x > 58, y = 1	0.30
All	MS-SOC ($Mgha^{-1}$)	Bark	IF x < 0.2, y = 0, x > 0.2 , y = 0.209 + 0.015x, x > 34, y = 1	0.31
All	Silt (%)	Bark	IF x < 1.3, y = 0, x > 1.3 , y = 0.209 + 0.015x, x > 42, y = 1	0.36
Aspen	Soil pH	ANPP	IF x < 4, y = 0.1, 6.5 < x > 4 , y = $(0.0423x – 0.163)/(1 – 0.425x + 0.047x^2)$, x > 6.5, y = 0.2	0.75
Aspen	Soil pH	ABI	IF x < 4, y = 0.2, 6.5 < x > 4 , y = $5.91x – 0.56x^2 – 14.50$, x > 6.5, y = 0.2	0.81

[a] Tree species : All = includes jackpine, spruce and aspen. [a] Soil quality indicators : FF = forest soil, MS = mineral soil, SOC = soil organic carbon ($Mgha^{-1}$), N = nitrogen ($Mgha^{-1}$).[c] Measures of performance : ANPP = annual net primary productivity ($Mgha^{-1}$), foliar = biomass component in foliage ($Mgha^{-1}$), bark = biomass component in bark ($Mgha^{-1}$), ABI = annual biomass increment ($Mgha^{-1}yr^{-1}$).

Table 5.7. Input data into GYPSY for modelling growth pattern of forest stands in the Athabasca oil sands region.

Forest stand	Stand code	Latitude (N)	Longitude (W)	Stand age (Years)	Density (Tree ha^{-1})	Height (m)	DBH (cm)[a]	SBA ($m^2 ha^{-1}$)[b]	Percent of SBA
Aspen	SV81A	56.15°	110.88°	35	2050	5.2	7.3	9.9	94
Aspen	SV8	57.26°	111.48°	52	1550	13.9	15.3	23.1	93
Aspen	SV83	56.46°	111.08°	53	1825	13.4	12.7	23.3	100
Aspen	SV61	56.44°	111.19°	55	1575	17.1	18.2	24.9	100
Aspen	SV18	56.45°	111.19°	59	1400	13.6	14.9	32.6	97
Aspen	SV77	56.46°	111.09°	60	2025	10.2	11.8	24.3	78
Aspen	SV59	57.47°	111.48°	62	2200	13.7	14.7	37	81
Aspen	SV4	56.95°	111.72°	70	2000	11.7	11.7	32.4	97
Jack pine	SV10	57.07°	111.59°	43	1675	10.6	12.7	28.2	90
Jack pine	SV29	57.10°	111.64°	45	1650	10.9	13	25.5	92
Jack pine	SV49	57.10°	111.64°	49	1325	12.6	14.9	24.4	95
Jack pine	SV62	57.50°	111.52°	60	1100	10	14.6	25.1	98
Jack pine	SV63	57.50°	111.52°	64	1150	13.4	19.1	33.8	100
Jack pine	SV26	57.51°	111.43°	68	2075	5	6.9	15.1	100
Jack pine	SV58	57.47°	111.47°	69	1375	12	15.5	25.8	100
Jack pine	SV27	57.51°	111.44°	78	1075	7.8	12.6	21.6	100
White spruce	SV81B	56.15°	110.88°	35	6.9	1900	10.4	16.4	65
White spruce	SV6	56.99°	111.73°	49	9.9	1675	12.7	25.6	76
White spruce	SV50A	56.64°	111.09°	76	18	1775	21.8	66.7	59
White spruce	SV50B	56.64°	111.09°	76	16.4	1400	18	36.6	61
White spruce	SV21	57.29°	111.27°	83	11.2	2100	12.1	35.5	45
White spruce	SV2	57.01°	111.45°	96	6.8	2750	8.5	32.6	94

[a] DBH = diameter at breast height, [b] SBA = stem basal area.

Table 5.8. Application of soil quality functions calibrated from outputs of BIOMES-BGC to assess effects of multiple reclamation design factors on productivity of jack pine growing on reclaimed soils.

Reclamation design factors	LAI [a]		Score-LAI		ANPP ($gCm^{-2}yr^{-1}$) [b]		Scores-ANPP	
	Mean [d]	SEM [c]	Mean	SEM	Mean	SEM	Mean	SEM
Years after planting on reclaimed soils								
16 years	1.40a	0.58	0.31a	0.08	321a	38.12	0.32a	0.07
20 years	2.42a	0.71	0.36a	0.09	86.8b	46.69	0.37a	0.09
21 years	2.17a	0.50	0.35a	0.07	222ab	33.02	0.36a	0.06
Slope percentage of reclaimed soils								
< 25	1.58a	0.52	0.34a	0.07	265a	42.37	0.35a	0.06
25-35	2.17a	0.60	0.33a	0.08	263a	48.92	0.35a	0.07
>25	2.42a	0.74	0.36a	0.10	86.8a	59.92	0.37a	0.09
Depth of topsoil/organic cover								
< 20 cm	1.77a	0.46	0.25a	0.03	259a	51.35	0.27a	0.02
20-30 cm	2.69a	0.72	0.42a	0.04	171a	81.19	0.43a	0.04
> 30 cm	1.75a	0.72	0.48a	0.04	196a	81.19	0.48a	0.04
Bulk density of topsoil cover								
< 1 gcm^{-3}	2.35a	0.48	0.40a	0.06	223a	57.41	0.40a	0.05
> 1 gcm^{-3}	1.66a	0.43	0.30a	0.05	227a	51.35	0.31a	0.05

[a] LAI = leaf area index. [b] ANPP = annual net primary productivity. [c] SEM = standard error of mean. [d] Means with similar alphabets are not significantly different at $p < 0.05$.

Chapter 6 Research Synopsis

Soil quality assessment (SQA) of disturbed lands needing reclamation due to mining and various engineering operations require analysis of physical, chemical and biological indicators of critical soil functions to make optimum land management decisions and recommendations for appropriate changes. Those decisions should include guidelines regarding the depth of suitable soil material for salvage and conservation before disturbance as well as design recommendations addressing depth, material type, and composition of reclamation covers. They should also provide a mechanism for assessing performance of reconstructed soils using measurements such as the growth trajectory of plants to determine the extent to which reclaimed sites meet the equivalent capability or functionality of natural systems.

The SQA framework developed through this project shows consistency and clarity in approach for calibration of predictive soil quality indicators such as soil organic carbon (SOC) and pH. It thus fulfills recommendations by Wander et al. (2002) who stated that soil quality-scoring functions (SQF) should be sensitive to management goals such as plant yield, biomass production and soil nutrient supply potentials. The importance of calibration at site specific or regional scales to properly assess local soil quality issues was demonstrated, thus confirming conclusions by Andrews et al. (2004) that generalized assumptions about soil quality have very limited applications.

Soil quality-scoring functions are used to quantitatively transform multiple indicators into integrated soil quality ratings without deviating from known treatment effects between the predictive indicators and measure of performance (Weinhold et al., 2009). The SQF are also expected to properly account for baseline variations in predictive indicators, while ensuring proper definition of soil quality thresholds, baseline functionalities and capabilities (Arshad et al., 2002).

This research work was completed using case studies relevant to the AOSR (Figure 1). Chapter 1 provides a detailed review of advances in SQA and discusses its application to Alberta land reclamation operations. Chapter 2 demonstrates development, calibration, validation and application of SQF for the peat mineral-soil mix (PMM) covers using SOC as the predictive indicator. Chapter 3 addresses variation in predictive indicators of soil quality (SOC in this case) as impacted by various soil and landscape factors affecting functional soil quality and management at the regional scale.

Chapter 4 further demonstrated how to account for functional soil management units in the design and application of SQF. Chapter 5 focused on the calibration of soil quality indicators to measures of plant or forest productivity to further demonstrate how SQF can be applied. A summary of linkages among soil indicators, their usefulness as predictive indicators, calibration requirements and techniques, and relevant applications within the land reclamation industry are summarized in Table 1.

The SQF discussed in Chapter 2 uses SOC as a predictive indicator to demonstrate the capability for rating the quality of peat-mineral mix (PMM) covers. Important measures include managing nutrient and moisture supply potentials that are critical to long-term success of reconstructed soils. The SQF were able to independently repeat expected treatment effects between changes in SOC content and indicators of moisture and nutrient supply, and confirm SQF' transferability to other similar sites. Approximately 50 – 75 % of existing land reclamation covers within the Athabasca oil sands region is PMM considering the operational constraint of salvaging thin layered organic layers in natural soils. This research provided the template for the design of SQF by reclamation operators to assess and monitor the quality of such reclamation covers.

Using indicators such as SOC as predictive indicators, analysis in Chapter 3 confirmed significant baseline variation in predictive indicators with the opportunity to define distinct, functional, soil management units. In other words, the variability of predictive soil quality indicators should not be viewed as a weakness in quantitative SQA, but strength in allowing proper demarcation of functional management units especially for SQA at regional scale. This research defined the range and boundary content of SOC for functional soil management groups. Existing land management classes as defined in the Canadian land classification systems are not necessarily distinct functionally and needed to be further refined or re-grouped to quantitatively capture the need for functional management units during SQA.

In Chapter 4, analysis of SQF developed using SOC as predictive indicator and soil nitrogen (N) as indicator of nutrient supply potential were related using non-linear regression models for each soil management units. This further improved the reliability and ability of SQF to integrate soil quality ratings. The SQF were useful in critical thresholds analysis, providing critical limits of SOC content for the design of reclamation covers based on projected or optimum N supply potentials. The SQF also provided 3 possible options in defining baseline equivalent capabilities using natural – natural soils, natural-reclaimed soils and reclaimed-reclaimed soils options. This research allowed for quantitative definition of baseline or pre-disturbance functionality and capabilities, which formed the basis for assessing the extent to which reconstructed soils demonstrate self-sufficiency in performing nutrient supply functions.

Finally in Chapter 5, correlations of soil quality indicators and forest productivity parameters confirmed that soil factors only, significantly ($p < 0.05$) accounted for a range of 15 – 90% of forest productivity depending on the plant species. This suggested that genetic, climatic and other factors also significantly influenced forest productivity over time. The approach to soil-forest productivity calibration required the use of more numerically complex approach to predictive indicator calibration using both analytical (GYPSY) and process based (BIOME-BGC) models. Both options provided opportunity to effectively calibrate indicators of moisture and nutrient availability with plant productivity, which were translated into normalized functions for site, stand and soil quality assessment while demonstrating further applications in reclamation, following similar SQA framework proposed earlier in Chapter 1.

A major contribution to knowledge in this research involves the application of recent concepts in quantitative SQA to soil and vegetation management issues in land reclamation. The proposed framework will allow operators of the Alberta oil sands industry and various other land use operations to define a more robust, quantitative, scientific and justifiable measure of success in land reclamation. This has implications in regards to the need for emerging techniques to assess the success of land reclamation operation and support compliance assessment procedures defined in the Environmental Protection and Enhancement Act (EPEA), in Alberta, Canada. Application of quantitative SQA concept in land reclamation will support the vision of sustainable resource development in other land use industries beyond agriculture into mining, road construction, parks and watershed management, linear feature engineering, contaminated site assessment and general land use planning.

Soil quality scores are meant to integrate multiple functionalities. This research demonstrated consistency or clarity in the use of indicator's transformation technique adopted within a properly defined SQA frameworks, thereby facilitating comparison of soil quality scores or ability to follow similar procedure by soil quality experts. Introduction of SQF validation test before application increased reliability of quality scores. Also, properly constrained SQF within boundary condition of functional soil management units generally demonstrated the capability to repeat expected treatment effects thereby justifying the soil quality rating framework, apart from similarities in the mechanistic process linkages between predictive indicators and measures of performance.

Application of critical thresholds of SQF includes defining the limits for soil quality indicators required to identify the best soil materials for conservation during soil disturbance operation. The critical limits is also applicable in the design of the depth, volume, composition and other properties of reclamation covers based on pre-defined end objectives for reclamation covers. Other potential applications of SQF include assessing the performance of soil remediation technologies and managing risks to performance of reclamation covers.

Future research includes testing the proposed SQA framework using other integrative and predictive indicators such as soil pH and soil texture among others, validate and apply SQF using field scale studies, perform quantitative SQA for other land reclamation scenario, assess impact of mine wastes incorporated into reclamation covers on specific soil functionalities, calibrate soil – forest productivity relationship for species growing on fine textured natural or reclaimed soils and transfer of concepts into best management practice document for application in land reclamation industry.

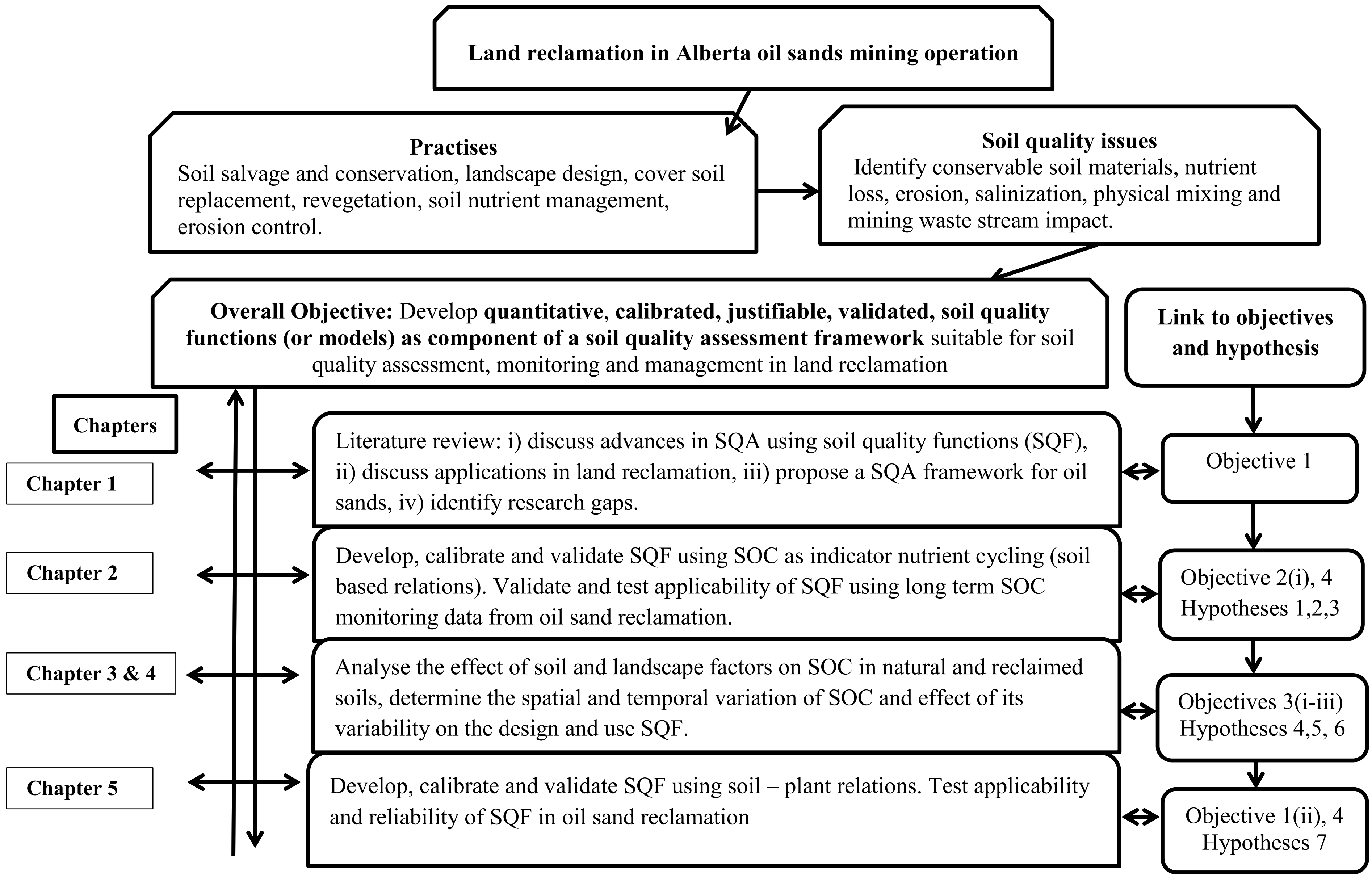

Figure.1. Linkages between the research objective and thesis structure.

Table 1. Synopsis of thesis structure and linkages between research objectives.

	Chapter 2	Chapter 3 and 4	Chapter 5
Scale of SOA	Local (within AOSR)	Regional (AOSR)	Local – regional
Soil functionalities	Moisture supply and retention, nutrient supply and retention, soil fertility	Nitrogen retention and supply potentials	Plant nutrient uptake, litter decomposition, support for tree growth etc.
Soil processes	Mineralization of organic matter releasing carbon and soil nutrient. Interaction among H_2O molecules, clay lattice and organic molecules.	Organic matter mineralization releasing carbon and nitrogen	Characteristic nutrient and moisture cycling by ecosite on forest growth
Predictive indicators	Soil organic carbon	Soil organic carbon	Multiple – SOC, pH, CEC etc
Measure of performance	Multiple – nutrient and moisture retention parameters	Single – soil nitrogen (N)	Multiple
Soil quality relation	Simple direct relation : SOC – indicators of moisture and nutrient retention	Simple direct relation : SOC – indicators of nutrient retention/supply	Complex relations : soil – plant effect, plant – soil effect, effect of time etc.
SQF calibration technique	Normalization and regression	Normalization and regression per soil management units	Use validated , analytical, growth models (GYPSY) and process models (BIOME-BGC)
Focus of study	Design, validate and apply SQF to rate soil quality of reclamation covers	Variation of predictive indicator of soil quality, definition of soil quality management units, designs SQF to account for each management units, threshold and critical limit analysis of predictive indicators.	Address complex, time sensitive, multiple direction relations between soil and forest plant productivity in calibrating SQF. Soil variables treated as categorical to account for ecosite effects.
Applications in land reclamation	Analysing the effect changes in SOC content due to rates of peat-mineral soil mixing on nutrient and moisture supply, or retention potentials of reclamation covers. Time series analysis of SOC data to make inferences on nutrient and moisture supply potentials of reclamation covers	Assessing effect of soil material types on N supply potentials of reclamation covers. Testing effect of cover designs on N supply potential of reclamation covers. Providing metrics for the design of reclamation covers based on projected ecosystem targets	Analysing forest stand performance by age as influenced by ecosite. Testing effect of soil moisture retention capability on biomass productivity for moisture limiting sites and reclamation designs.

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