

Emerging technologies for *in situ* measurement of soil carbon

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Abstract Carbon sequestration in the terrestrial biosphere is critical to mitigating the increasing anthropogenic CO₂ content of the atmosphere. However, improved efficiency of methods for soil C measurement is important to better estimate terrestrial C inventories and fluxes at a regional and global scale. Laboratory based measurement of soil C involves intensive, time consuming, and costly methodology that limits applicability for large land areas. Recently, research efforts have focused on measuring soil C *in situ* using a variety of methods. These methods include Laser Induced Breakdown Spectroscopy (LIBS), Inelastic Neutron Scattering (INS), near-infrared spectroscopy (NIRS), and remote sensing. Basic fundamentals of each of these *in situ* methods for soil C determination are presented, and the differences among the methods and their relative advantages and disadvantages are discussed.

Abbreviations

AVIRIS	airborne visible/infrared imaging spectrometer
INS	inelastic neutron scattering
LIBS	laser-induced breakdown spectroscopy
MDL	minimum detection limit
MIR	mid-infrared
NIR	near-infrared
NIRS	near-infrared spectroscopy
SEP	standard error of prediction
SOC	soil organic carbon
SOM	soil organic matter

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Carbon sequestration in the terrestrial biosphere and the subsequent effects on global C flux has recently become the forefront of numerous research efforts. The methods for assessing soil C inventories and fluxes have gained importance, as the ability to measure C stored in soils and aboveground biomass is critical to understanding C cycling in terrestrial ecosystems (Ellert et al. 2001). Additionally, trading of C credits and incentive programs for C sequestration may become reliant on quantification and verification of soil C levels at relatively low cost for large land areas. The efforts to understand and address C management at the regional and global scale have summoned the development of more efficient methods for soil C determination (Greenland 1998; Department of Energy 1999; National Research Council 1999; McCarty and Reeves 2001).

Traditional methods (i.e., Walkley-Black, dry combustion) of quantifying soil organic C by laboratory analysis of soil core samples have widely recognized limitations and can be both time consuming and labor intensive. The Walkley-Black procedure (Walkley 1935) was the standard method used for measuring soil organic matter (SOM) for many years, although the procedure typically involved use of a correction factor (which can vary markedly among surface soils) due to incomplete measurement of all C in the sample (Rosell et al. 2001). Determination of total C by dry combustion (measurement of CO₂ emitted from the oxidation of organic C and thermal decomposition of carbonate materials; Nelson and Sommers 1996) has become the predominant means of laboratory C analysis. However, some laboratories base C measurements on weight change rather than the CO₂ emitted, presenting discrepancies in laboratory results from different areas (Kimble et al. 2001b). The weight loss-on-ignition method tends to overestimate organic matter in soil due to supplementary weight loss of inorganic constituents, primarily hydrated clays, during the heating process and is affected by ignition temperature and sample size (Cambardella et al. 2001).

Soil C estimates using these classical methodologies are further complicated by the spatial and temporal variability inherent in soil horizonation, soil C concentration, and bulk density (Ellert et al. 2001). Wilding et al. (2001) stated that “It is necessary to understand the spatial variability of soil carbon pools in order to make accurate mean estimates of available carbon and integrate variability into predictive models of soil carbon reserves and sequestration potential”. Quantitative measurements of temporal and spatial changes in soil C storage require careful soil sampling and analysis, and caution must be exercised when employing classical statistical methods for interpretation of results. Sampling schemes must be designed and implemented to account for this variability, although as yet there is no universal sampling protocol to assess soil C dynamics (Kimble et al. 2001a). Development of sampling schemes that are repeatable and representative is essential due to the long time spans (possibly several years) needed to detect changes in C sequestration (Ellert et al. 2001). Additionally, quantitative C measurements have relied on bulk density and rock fragment measurements when data are expressed on a volume basis, since methods used to measure C typically give weight percentages. Changes in bulk density with time and land use present similar sampling challenges as for soil C sampling.

Development of methods for soil C analysis that address and minimize the uncertainties associated with conventional methodologies are important for improving estimates of terrestrial C inventories and fluxes. Recently, several advanced analytical methods have been utilized for soil C research. Mid- and near-infrared reflectance spectroscopy have each been assessed as a means to determine soil organic carbon (SOC) content (Dalal and Henry 1986; Ben-Dor and Banin 1995; Janik et al. 1998; Chang and Laird 2001; Reeves et al. 2001; McCarty et al. 2002). Analytical pyrolysis has also been evaluated as a means to determine the composition of SOC (McCarty and Reeves 2001). Carbon isotope techniques have been

Table 1 Comparison of field instrumentation for determination of soil C

Method ^a	Principle	Approximate detection limit	Sampling time	Sampling attributes
LIBS	Intense laser pulse is focused on in-tact sample core, microplasm emission spectrally resolved	300 mg total C kg ⁻¹	<60 s	Invasive
INS	Inelastic scattering of neutrons from C nuclei emits gamma rays that are detected and analyzed for C peak intensity	0.018 g C cm ⁻³ , or 1.2% C for 1.5 g cm ⁻³ bulk density sample	-	Non-invasive
NIRS	Diffuse reflectance properties in the 700 to 2500 nm spectrum are correlated to soil C content	0.6% organic C	200 ms spectrum ⁻¹	Invasive

^aLIBS parameters Reported by Cremers et al. (2001); INS parameters reported by Wielopolski et al. (2003); NIRS parameters Reported by Shonk et al. (1991) and Sudduth and Hummel (1993a).

used to estimate retention time and C turnover rates in soils (Paul et al. 2001), determine net carbon sequestration amounts and rates (Horwath et al. 2001), and evaluate the source and history of C in SOM (Scharpenseel et al. 2001).

Conventional laboratory analysis involves a substantial amount of resources to make relatively few measurements of soil C. *In situ* methods for determination of soil C are important due to the comparatively rapid and potentially cost-effective benefits of these methods, and the reduction in sampling and laboratory errors. The greatest benefit of field analysis of soil C may lie in the potential to minimize soil disturbance while increasing the ability to analyze large areas of soil. Advanced field methods of C analysis should be capable of providing repetitive, sequential measurements for evaluation of spatial and temporal variation at a scale that was previously unfeasible.

The increased interest in assessing C inventories and dynamics has resulted in the advent of several new technologies for soil C measurement in the field. Research attempts to measure soil C *in situ* have included Laser Induced Breakdown Spectroscopy (LIBS, Ebinger et al. 2003), near-infrared spectroscopy (Sudduth and Hummel 1996; Christy et al. 2003), Inelastic Neutron Scattering (INS, Wielopolski et al. 2003) (Table 1), and remote sensing imagery (Chen et al. 2000). This paper presents a review of these relatively recent advances in *in situ* soil C determination.

1 Laser-induced breakdown spectroscopy (LIBS)

Instrumentation using laser-optics, specifically laser-induced breakdown spectroscopy (LIBS), has been used in recent years for determination of a variety of soil constituents including metal ions (Yamamoto et al. 1996; Bublitz et al. 2001; Mosier-Boss et al. 2002), nitrogen (Harris et al. 2004), and total soil C (Cremers et al. 2001; Ebinger et al. 2003). Application of LIBS technology to soil science is appealing due to this method's sensitivity and selectivity and capability for *in situ*, multicomponent soil analysis with minimum

sample preparation. This method is based on atomic emission spectroscopy (Radziemski and Cremers 1989; Moenke-Blanckenburg 1989; Rusak et al. 1997) where an intense laser pulse is focused on a sample, forming a microplasma that emits light characteristic of the compositional elements of the sample. The microplasma emission is recorded in time and spectrally resolved by a time-gated sensor to detect concentrations of elements based on their unique spectral characteristics. Calibration of the LIBS method and determination of soil bulk density allow for quantitative measurements of elements for different soil types.

Although evaluation of LIBS for total soil C measurement is still in its infancy, research results have been promising. Cremers et al. (2001) evaluated the measurement of total soil C using the LIBS method on agricultural soils from Colorado and a woodland soil from New Mexico, USA. The C emission line at 247.8 nm was used for testing and calibration of LIBS with results from conventional dry combustion analysis (Nelson and Sommers 1996). They reported high correlation (adjusted $r^2 = 0.96$) between LIBS and dry combustion C results for the agricultural soils, and the calibration curve developed was effective in predicting total C content of additional agricultural soils as well as woodland soils, despite differences in soil morphology. Results of their study indicated that the LIBS method could be used to rapidly and efficiently measure soil C with detection limits about 300 mg kg^{-1} , precision of 4–5%, and accuracy of 3–14%. Analysis time was less than one minute per sample, providing daily sample throughput much greater than that of traditional C analytical methods.

Further LIBS research by Ebinger et al. (2003) addressed occurrence of spectral interference between C and Fe at the 247.8-nm line and determined that the problem could be diverted by C analysis at 193 nm. Iron present in the soil did not interfere with the 193-nm C, and analysis at 193 nm was as reproducible as the method at 247.8 nm. Calibration of C measured by LIBS with C determined by dry combustion for three Colorado soils indicated that the results of the two methods were highly correlated ($r^2 = 0.99$), and repeated calibration curves indicated that the LIBS method was reproducible (average $r^2 = 0.97$ for 30-d calibrations) for the soils used in their study.

Although still in the developmental phase, field-portable LIBS instrumentation shows potential as a means to rapidly and accurately measure soil C (Cremers et al. 1996; Mosier-Boss et al. 2002). Currently, calibration curves (soil C level versus LIBS peak area) must be developed for each sample set, but development of soil-specific calibration databases may facilitate rapid analysis in the future. Analysis of total soil C *in situ* with LIBS would include soil core sampling and a subsequent spectral scan of the core surface. The frequency of measurements taken along a soil core is variable (as determined by specific research interests) and can represent any length of core greater than the diameter of the laser pulse. With little or no sample preparation, this method has potential limitations with regard to interpretation of the LIBS spectrum. One issue that must be addressed is interpretation of results for samples containing fine roots and other biological substances at varying degrees of decomposition. While the LIBS method could be used to quantify this fraction, no pertinent research has been reported thus far. The effects of inorganic carbonate deposits and soil moisture on the spectral line intensities must also be evaluated. An additional challenge imposed by this method is the spatial variability associated with measurement of a small point sample (sample volume is about 1 to $5 \text{ mm}^3 \text{ pulse}^{-1}$; Cremers et al. 2001). Despite these potential drawbacks, a portable LIBS instrument could allow for efficient measurement of the multitude of soil samples necessary to characterize soil heterogeneity and spatial variation of C distribution and ultimately provide a reliable estimate of soil C inventories.

Table 2 Net number of 4.44 MeV counts (carbon peak) for both NaI(Tl) detectors from initial INS experiment. Adapted from Wielopolski et al. (2000)

Sample	Total	Background	Net	Error ^a
	Counts			
Blank	588757	586952	1805	1200
Sand	725479	718267	7212	1100
Sand + 2% C	699999	687370	12629	1200
Sand + 5% C	762525	745094	17431	1240
Sand + 10% C	744586	719015	25571	1250

^aError in the net number of counts due to counting statistics

2 Inelastic neutron scattering (INS)

Wielopolski et al. (2000) first described the feasibility of using Inelastic Neutron Scattering (INS) and gamma ray spectroscopy to determine soil C. This INS method is based on inelastic scattering of 14 MeV neutrons from C nuclei present in the soil and measurement of the resulting 4.44 MeV gamma ray emission. The 14 MeV neutrons are produced by a Deuterium-Tritium (d,t) neutron generator with the subsequent 4.44 MeV gamma ray emission detected by NaI detectors. The spectrum of gamma rays detected is analyzed for the C peak intensity that is proportional to the C concentration of the soil. A calibration line, with peak areas plotted against soil C concentration, is therefore required for soil C determination. Calibration lines described by Wielopolski et al. (2000) and Wielopolski et al. (2003) were derived using a mixture of sand and pre-determined amounts of C powder (0, 2%, 5%, and 10% by weight).

Initial investigations of this methodology were carried out at a clinical in vivo body composition facility using 32 kg soil samples and two NaI(Tl) detectors (Wielopolski et al. 2000). Promising results from the initial studies (Table 2) prompted development of a field-capable INS instrument that allows for non-invasive measurement of soil C to a depth of about 30 cm (Wielopolski et al. 2003). The INS system consists of a neutron generator and a shielded detector placed on the ground with a shadow shielding of iron, borated-water, and boric acid. The instrument can be used in either static or dynamic modes for scanning large land areas. The processes of neutron penetration, inelastic scattering, and gamma ray emission occur very rapidly, allowing for operation of the INS instrument in a scanning mode.

Validation of the INS methodology was presented by Wielopolski et al. (2003). The INS system was tested, in static mode, at three different field sites (pine stand, oak forest, and sandy patch) to verify the sandpit calibration. Thirty-minute measurements were taken with the INS at each site followed by soil core collection for comparative dry combustion analysis. Results of their study indicated measurements errors of 5–12% and a minimum detection limit (MDL) of 0.018 g C cc⁻¹ (Table 3). The authors suggested improvements of the INS method to reduce errors for improved C analysis, including: increasing the number of detectors, prolonging the counting time, and optimization of the system configuration. Future research should include calibration for a variety of soil types and testing the INS system in a scanning mode for evaluation of large areas.

3 Infrared reflectance spectroscopy

Reflectance spectroscopy provides a rapid and nondestructive method for soil C measurement based on diffusely reflected radiation of illuminated soil. Constituents of organic matter each

Table 3 Comparison of INS and dry combustion results for measurement of soil C. Adapted from Wielopolski et al. (2003)

Site ^a	Analysis method	
	INS	Dry combustion
Pine stand (wl)	0.099 ± 0.005	g C cm ⁻³ –
Pine stand (nl)	0.079 ± 0.005	0.073 ± 0.021
Oak forest (nl)	0.072 ± 0.004	0.085 ± 0.017
Sandy patch	0.026 ± 0.003	0.025 ± 0.002
Sandy soil	0.091 ± 0.007	0.104 ± 0.019
Sand pit (calibration)	0.00	0.0004 ± —

^a(wl), with surface litter; (nl), surface litter removed

have unique absorptive or reflective properties due to stretching and bending vibrations of molecular bonds (e.g., C-H, C-C, CH₂, O-H, N-H) between elements. Spectral signatures related to the various components of soil organic matter generally occur in the mid-infrared (MIR, 2.5–25 μm) range, although the weak overtones and combinations of fundamental vibrations occur in the near-infrared (NIR, 0.7–2.5 μm) region (Shepherd and Walsh 2002). As a consequence, both the NIR and MIR region have been investigated for the determination of soil C (Dalal and Henry 1986; Ben-Dor and Banin 1995; Janik et al. 1998; Chang and Laird 2001; Reeves et al. 2001; McCarty et al. 2002). Analysis in the NIR range has been the predominant means for quantitative determination of soil C, although MIR spectroscopy (primarily used for qualitative C analysis) has recently been reported as a viable quantitative C measurement method (Reeves et al. 2001; McCarty et al. 2002). The recent increase in use of reflectance spectroscopy for soil analysis may be partly attributed to improvements in computer hardware and to improvements in statistical NIRS software (Shenk and Westerhaus 1991).

Laboratory analyses of soils using NIRS have been shown to successfully predict soil C, with r^2 values often reported greater than 0.80 (Morra et al. 1991; Chang and Laird 2001; Chang et al. 2001; McCarty et al. 2002). While several studies have focused on laboratory analysis of soil properties using NIRS, relatively few have been conducted in a field setting (there have been no reports to date regarding *in situ* use of MIRS). The application of NIRS as an *in situ* measurement method constitutes inclusion in this review of emerging technologies. Shonk et al. (1991) reported the development and field-testing of a prototype real-time soil organic matter reflectance sensor. Their prototype used red light emitting diodes (660 nm, peak) and a photodiode to measure the reflected radiant energy from undisturbed soil. Initial field tests of the sensor were successful ($r^2 > 0.83$), with predictable correlation between light reflectance and organic matter content for fine and medium textured soils in the 1–6% organic matter range (Table 4).

Sudduth and Hummel (1993a) designed, fabricated, and tested a portable NIR spectrophotometer. The instrument design included a circular variable filter monochromator, a fiber optic coupling for sensing of remote samples, and a software algorithm to correct the instrument readings to a zero baseline. Initial performance tests indicated a sensing range of 1.65 to 2.65 μm, an optical bandwidth of less than 55 nm, and an optimal data acquisition rate of 200 ms. Laboratory calibrations of soil reflectance data collected with the portable NIR spectrophotometer yielded an r^2 of 0.89 and a standard error of prediction (SEP) of 0.40% soil organic matter for 30 Illinois soils ranging from 1.5 MPa to 0.033 MPa moisture tension levels (Sudduth and Hummel 1993b). Partial least squares regression (PLSR) techniques

Table 4 Field test results of a prototype reflectance sensor, with correlations between sensor output and soil organic matter content determined using the Mebius method (Mebius 1960). Organic matter content of tested soils ranged from 1.7 to 6.1%. Adapted from Shonk et al. (1991)

Test number	Travel speed km h ⁻¹	Soil depth cm	R ²
1	4.8	7.5	0.893
2	4.8	7.5	0.936
3	6.5	7.5	0.837
4	6.5	7.5	0.903
5	4.8	10	0.903
6	6.5	10	0.953

Table 5 Summary of partial least squares regression (PLSR) results for determination of the effect of geographic range of prediction of organic C using NIR data. Adapted from Sudduth and Hummel (1996)

Geographic range (No. of soils)	No. of valid factors ^a	<i>r</i> ²	SEC ^b	SEP ^c	RPD ^d
IL, MO, IN, OH (34)	7	0.90	0.29	0.43	2.2
IL, MO, IN, OH, IA (48)	9	0.90	0.26	0.38	2.3
IL, MO, IN, OH, MN, WI, MI (107)	9	0.82	0.50	0.65	1.8
North-central US (164)	7	0.72	0.63	0.71	1.7

^aMaximum number of valid PLSR factors as determined by cross-validation

^bSEC, standard error of calibration, in percent organic carbon

^cSEP, standard error of prediction, in percent organic carbon

^dIncludes soils from IL, MO, IN, OH, IA, MN, WI, MI, KS, NE, SD, and ND

were used for calibration development and soil property estimation. Optimum laboratory correlations of reflectance with organic C yielded an r^2 of 0.89 and a SEP of 0.23% organic C when data were smoothed to a 40 nm data point spacing and results from 100 scans were averaged. However, field operation of the prototype sensor resulted in much greater errors (SEP = 0.91% soil organic matter) due to movement of soil past the sensor during the scanning process. Further research of the portable NIR sensor indicated that as the geographic range represented by the Illinois soil samples was increased, the predictions of organic C, CEC, and soil moisture became less accurate (Table 5) (Sudduth and Hummel 1996).

More recently, Christy et al. (2003) reported results of an initial field test of a mobile in-situ NIRS device developed by Veris Technologies (Salina, KS). The system they described measured the diffuse reflectance of the soil by emitting incident and reflected light through a sapphire window at the bottom of an implement shank. The durability of window allowed for direct contact with the soil, providing continuous data acquisition under field operating conditions. Measurement depth of the instrument was adjustable, although initial trials were performed at the 7.5-cm depth while traveling at about 6 km h⁻¹. System performance was tested on Iowa loam and clay loam soils at 585, 1056, and 1509 nm absorbance. Field-acquired spectra were similar to spectra determined in the laboratory, although laboratory spectra typically resulted in slightly lower absorbance. Calibration results indicated that better predictions for total C were made at higher wavelengths (900–1700 nm reflectance compared with 350–1050 nm reflectance), with a reported validation r^2 of 0.87. Calibration of field spectra combined with global positioning system (GPS) location logging allowed for creation of a field map of percent total soil C.

Results from the early studies regarding *in situ* NIR analysis of soil C indicate the feasibility of this method. However, continued research of NIR analysis will be essential to broadening the regional and global application of this technology. Various calibration methods have been used to relate NIR spectra with laboratory analyses, including multiple linear regression (MLR), principal component regression (PCR), partial least squares (PLS), and modified PLS. Selection of the calibration equation remains a trial-and-error procedure, as no single mathematical equation gives the best prediction for all applications and validation is the only means by which to assess the effectiveness of the calibration (Ludwig and Khanna 2001). The effects of particle size and soil moisture on spectral absorbance in the NIR region must also be further evaluated, since both have been shown to influence the NIR spectra (Bowers and Hanks 1965; Casler and Shenk 1985). Evaluation of these factors, as well as continued analysis and calibration for soil C beyond the geographic areas previously researched, will be important steps to expanding the use of portable NIR instruments for use in assessing soil C inventories and dynamics.

4 Remote sensing

Remote sensing offers the possibility of spatial and temporal estimates of land cover, land management practices, cropping and tillage practices, net plant productivity, and plant residue – all of which impact soil C dynamics. The capacity for remote sensing to characterize these features is of particular interest due to the relative ease in periodic sampling and potential reduction in cost associated with verification and monitoring soil C sequestration. The breadth of such analyses can extend to the field and watershed scales, allowing for repeatable evaluation of large land areas.

There have been limited studies on the direct measurement of soil C using remote sensing. However, a strong relationship between soil color, or visible reflectance, and SOC has long been recognized, suggesting that this type of analysis may be possible. Research has been conducted on the relationships between soil color and organic matter, although many of these studies were based on Munsell color properties of hue, value, and chroma (Alexander et al. 1969; Fernandez et al. 1988; Steinhardt and Franzmeier 1979). Fernandez et al. (1988) reported a high correlation ($r = 0.94$) between SOC content and soil Munsell value calculated from visible-reflectance data within a landscape. Problems have been encountered in establishing correlations of SOC and soil reflectance because soil color and reflectance properties are a function of many factors in addition to organic matter, including soil moisture, texture, chemical composition, parent material, and surface conditions (Stoner and Baumgardner 1981; Sudduth and Hummel 1993b). These problems are complicated when soils are analyzed from large geographic areas (Pitts et al. 1983, Sudduth and Hummel 1996).

In order to make accurate, direct assessments of SOC using remotely-sensed imagery, it is necessary to understand the influence of soil organic fractions on soil reflectance properties in specific wavebands. Henderson et al. (1992) evaluated the effects of SOC on soil reflectance across the visible, NIR, and MIR spectral regions and the effects of SOM constituents of spectral reflectance of soil. Their results indicated the potential of high dimensional reflectance data to provide information about SOC content, but not SOM composition. On soils formed from similar parent materials, reflectance in the visible bands (425–695 nm) resulted in the highest correlations with SOC. However, MIR bands (1955–2495 nm) resulted in the highest correlation with SOC for soils formed on different parent materials. Further, the influence of SOC on soil reflectance appeared much stronger than any effects of SOM composition, and reflectance response was dominated by soil factors other than SOM content.

Research reporting the direct quantification of SOC or SOM content using remote sensing has been limited. Landsat imagery and ground truth site information were used in part to develop the North American Soil Organic Carbon Digital Database to determine C stocks for North America and variations in existing estimations (Lacelle et al. 2001). Chen et al. (2000) used bare-soil aerial photographs (color slides) to map surface SOC for a 115-ha field in Georgia. Soil organic carbon distribution was predicted using two approaches. The first approach was to apply the statistical relationship between surface SOC and image intensity values in the red, green, and blue bands to individual pixels and then determine the distribution of 8 separate classes. The second approach was to initially classify the image and then apply the statistical relationship to determine means and class boundaries. Predicted and measured surface SOC concentrations were compared using linear regression ($r^2 = 0.97$ and $r^2 = 0.98$ for the two approaches, respectively) and concentrations were correctly classified in 77 and 74% of cases for the two approaches. The area of each class from the two approaches were compared using a paired *t*-test for the area distribution and were found to be very similar ($P > 0.99$). They concluded that high resolution (1063 lines per cm), remotely sensed imagery of bare soil could be quantified to accurately describe spatial variation of surface SOC for a field in Georgia. Limitations of this methodology included effects of noise from other soil properties (e.g., Fe concentration) and consistency in image-intensity values. The use of digital multi-spectral images could minimize these limitations. Palacios-Orueta et al. (1999) used hierarchical foreground and background analysis and AVIRIS (Airborne Visible/Infrared Imaging Spectrometer) data to predict SOM and Fe contents in California. Their results indicated that the ranges of predicted organic matter were consistent with the magnitude and distribution of field samples, although the presence of vegetation and steep terrain adversely affected the ability to resolve soil properties.

Increased adoption of management practices that maximize C sequestration (i.e., conservation tillage or no-till) will limit the potential for direct measurement of soil C by remote sensing, since surface residues will limit the applicability of this method (reduced potential for bare soil imagery). For future success of remotely sensed inventories of soil C, calibration and ground truthing of spectral imagery will be necessary. Assessment of SOM content using sensor data is most likely to be successful if calibration is done on a field by field basis rather than utilizing relationships over a large geographic area (Fernandez et al. 1988). Improvements in calibration procedures may allow for the projection of C sequestration dynamics to various land uses and management practices across a range of spatial scales, although the most applicable use of remotely-sensed data may remain in the collection of data such as plant productivity, residue cover, tillage, etc., that can be used in C models to estimate C sequestration.

5 Summary

Conventional analyses for soil C determination (dry/wet combustion) will likely remain the predominant methods used by researchers in the near future. However, the use of portable, field-applicable, or remote sensing tools for the determination of soil C *in situ* may provide an effective means to estimate soil C constituents that require expensive and time-consuming analytical methods (e.g., litter decomposition rates, microbial biomass, microbial activity, etc.) (Ludwig and Khanna 2001). Research has shown that these new methods are capable, with varying degrees success, of improving our understanding of soil C dynamics at a scale not previously feasible. As yet there are no commercially-available models of most of these methods, with the exception of the various remotes sensing sources. Thus, an assessment

of the relative cost of these procedures with respect to one another or to classical analysis methods is difficult to develop at this point in time. Limitations of each of the described methods may prohibit their widespread adoption, although implementation may yet expand to satisfy the requirements of assessing soil C inventories and dynamics at a large scale.

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