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Presented at the Second Annual Conference on Carbon Sequestration
Alexandria, VA
May 05, 2003 – May 08, 2003

November 2005

Environmental Science Department
Environmental Research and Technology Division

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Non-Destructive *In situ* Soil Carbon Analysis: Principle and Results

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Abstract

Global warming is promoted by anthropogenic CO₂ emissions into the atmosphere, while at the same time it is partially mitigated by carbon sequestration by terrestrial ecosystems. However, improvement in the understanding and monitoring of belowground carbon processes is essential for evaluating strategies for carbon sequestration including quantification of carbon stores for credits. A system for non-destructive *in situ* carbon monitoring in soil, based on inelastic neutron scattering (INS), is described. The system can be operated in stationary or scanning mode and measures soil to depth of approximately 30 cm. There is a good agreement between results obtained from INS and standard chemical analysis of soil cores collected from the same study site.

Key Words: carbon sequestration, neutron scattering, gamma spectroscopy, and carbon belowground.

Introduction

Terrestrial ecosystems, including vegetation and soils containing microbial and invertebrate communities are huge natural biological scrubbers of CO₂. These systems currently sequester, directly from the atmosphere, about 25% (~2 GtC/y) of the 7.4 GtC emitted annually by human activities. For example, in 1995 coal burning alone contributed about 0.5 Gt of carbon to the atmosphere [Marland 1998]. Soil carbon dynamics are governed by factors such as variations in photosynthates, carbon content of plant roots, and plant litter on the soil surface.

The terrestrial biosphere is considered the largest natural sink for atmospheric CO₂ which is capable of sequestering carbon in the form of Soil Organic Carbon (SOC). Sequestering massive amounts of carbon using proper soil management practices has been suggested as a means to mitigate the atmospheric buildup of CO₂. Quantifying changes in soil carbon stocks is essential for evaluating mitigating schemes and documenting their performance. Current methods of quantifying carbon in soils by core sampling are slow, invasive, labor intensive, and by their nature limited in scope. The need for new and better technology for *in situ* carbon monitoring that is non-invasive, quantitative, and can operate in either static or dynamic modes for scanning large land areas, is being recognized and is cardinal to further our understanding of belowground carbon processes. The new technology should reduce the costs, speed up the rate of analysis, enable repetitive sequential measurements at the same field site, and allow continual monitoring of large areas for carbon credits.

Two attempts were recently made to measure soil *in situ*; one uses Laser Induced Breakdown Spectroscopy (LIBS) [Cramers et al., 2001] and the second uses infrared spectroscopy [McCarty et al., 2002]. However, these *in situ* approaches are invasive. In the first case, small volumes of about 50 microliters are vaporized and the second case it is a basic surface analysis. A third method that uses Inelastic Neutron Scattering (INS) and gamma ray spectroscopy to analyze carbon in soil is briefly introduced here. The feasibility of the INS method, demonstrated by Wielopolski et al. [2000], is truly non-invasive, is capable of analyzing large aggregates of soil and can be used in either static or dynamic modes for scanning large fields. Based on present results with INS, it is possible to measure yearly changes of 100 gC/m^2 , which assuming 1% homogenous carbon distribution down to a depth of 30 cm, corresponds to about a 2.6% annual change in carbon content at soil bulk densities around 1.3 g/cm^3 .

Method

The INS method is based on fast, 14 MeV, neutrons scattering inelastically from carbon nuclei encountered in soil, and monitoring the resulting 4.44 MeV gamma ray emission from the excited carbon nuclei. The source of fast neutrons is a (d,t) neutron generator [Csikai, 1998] that is considered to be a point source emitting neutrons almost isotropically. Upon impinging the soil, they penetrate and undergo inelastic scattering with carbon nuclei inducing emission of 4.44 MeV gamma rays, which are detected by NaI detectors. The three step process of neutron penetration, inelastic scattering, and gamma ray detection are very fast; neutrons move at speeds of about 5 cm/ns, inelastic scattering and subsequent emission of a gamma ray occurs in few pico-seconds, and the gamma ray travels at the speed of light. At these time intervals a movement of the INS system at 5 to 10 mph, or faster, can be considered stationary for practical purposes, thus allowing operation of the INS in a scanning mode. The measured gamma spectra are subsequently analyzed for the intensity of the carbon peak that is proportional to the carbon concentration in the soil [Nargowalla SS. et al., 1973]. The conversion from peak intensity to carbon concentration is done using a calibration line in which peak areas are plotted versus soil carbon concentration. Such a calibration line was derived by mixing sand with known amounts of carbon and measuring for 30 min using one large, 5" by 6" high NaI detector; the calibration line is shown in Fig. 1.

The INS system consists of a neutron generator and a shielded detector that are placed on the ground with a shadow shielding between them. At present, the shadow shielding includes iron, borated-water, and boric acid for neutron absorption. Fig. 2 shows the system placed in an oak forest.

Results

Following the feasibility studies by Wielopolski [Wielopolski et al., 2000], the INS system was calibrated in a 4'x5'x1.5' sandpit filled with a mix of sand and known amounts of carbon (0, 2%, 5%, and 10% by weight). The resulting calibration line is shown in Fig. 1. Following calibration, double blind studies with the measurement system were performed at three different field sites to verify the validity of the calibration performed in the sandpit. First, at each site 30 min measurements were taken with the INS system, then five soil core samples (5 cm in diameter and 40 cm long) were taken from each corner of an one foot square and from the center of the square where the INS measurement took place. The core samples were partitioned into 0-5, 5-10, 10-20, 20-30, and 30-40 cm increments. These soil increments were measured for soil water content and soil bulk density using standard analysis techniques (Dane and Topp, 2002). The subsamples of soil were dried (55°C), ground to pass a 0.15 mm sieve, and analyzed for total carbon and total nitrogen on a LECO CN 2000 (LECO Corp., Saint Joseph, MI). A typical inelastic gamma spectrum acquired during the neutron pulse in an oak forest is shown in Fig. 3. The results of the comparison between INS and chemical analysis are summarized in Table 1.

Table I. Summary of the INS and chemical analysis results, where (w,l) stands for litter and (n,l) the litter from the top of the soil has been removed.

Site	INS (gC/cc)	Chemical Analysis (gC/cc)
Pine Stand (w,l)	0.099 ± 0.005	---
Pine Stand (n,l)	0.079 ± 0.005	0.073 ± 0.021
Oak Forest (n,l)	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 (Cal.)	0.00	0.0004 ± ---

Summary

The utility of the INS system to measure non-invasively carbon in soil has been demonstrated. Normal levels in a pine stand and an oak forest were measured with an error of about 5%; the low level of carbon in a sandy patch had an error of about 12%. Increasing the number of detectors, prolonging the counting time and further optimization of the system configuration can further reduce these errors. It should be pointed out that scanning a large area would inherently increase the counting time. Similarly, incorporation of these improvements will improve the sensitivity of the system and reduce the minimum detection limit (MDL) of the system that at present stands at about 0.018 gC/cc, (or assuming a soil bulk density of 1.5 g/cc the MDL is 1.2% C by weight). Although the litter on top of the soil in the pine stand was not included in the chemical analysis, the carbon content in the INS measurements with and without the litter is significantly different indicating the sensitivity of the method to the carbon encountered in the litter.

The high zero intercept in the calibration line is due to similar gamma transition of 4.44 MeV in the silicon nucleus that cascades from the 6.27 MeV level through the 1.78 MeV level to the ground state. Since these two peaks are measured simultaneously and they are correlated, it is possible to use the intensity of the 1.78 MeV peak to correct the intercept in the calibration line. This procedure has been applied successfully for adjusting the carbon concentration in the sandy patch in Table 1.

The gamma ray spectrum shown in Fig. 3 demonstrates the capability to measure additional elements in the soil. Prompt gamma ray spectra collected after the neutron pulse (not shown here) show that nitrogen also can be measured in soil, which is an element of great interest in agricultural systems.

It is planned to further validate the universality of the calibration line for various soil types as well as to deploy an INS system in a scanning mode. Such a system will be useful in scanning large fields for evaluating land management practices (e.g., conventional tillage versus no-tillage agriculture) as well as monitoring sites used for trading carbon credits.

Acknowledgement

Work supported by the U.S. Department of Energy under contract No. DE-AC02-98CH10886.

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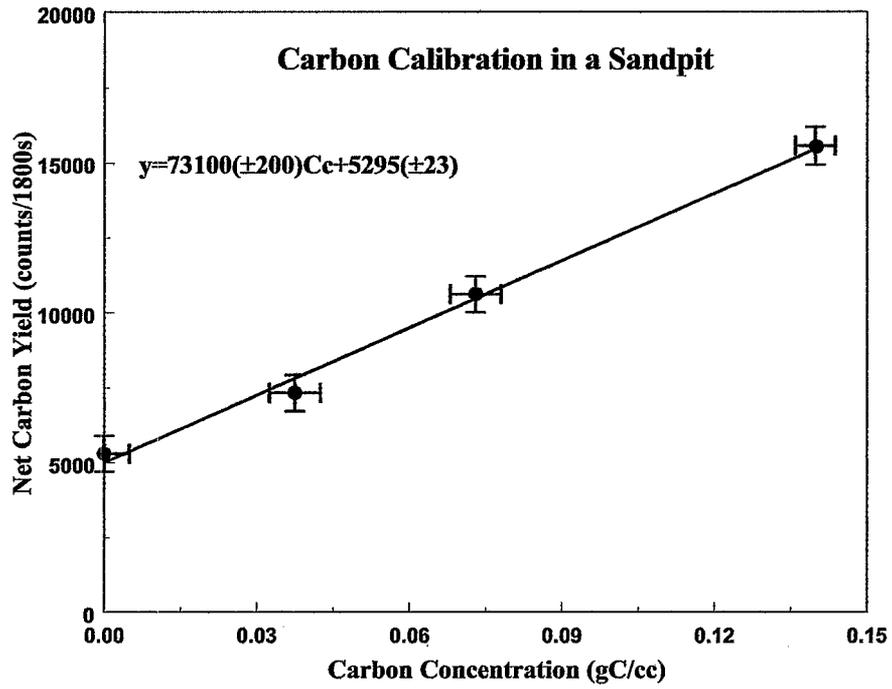


Figure 1. Carbon yield calibration versus concentration in a sandpit.



Figure 2. Oak Forest with the INS system in place.

"Inelastic" Gamma Ray Spectrum From An Oak Forest

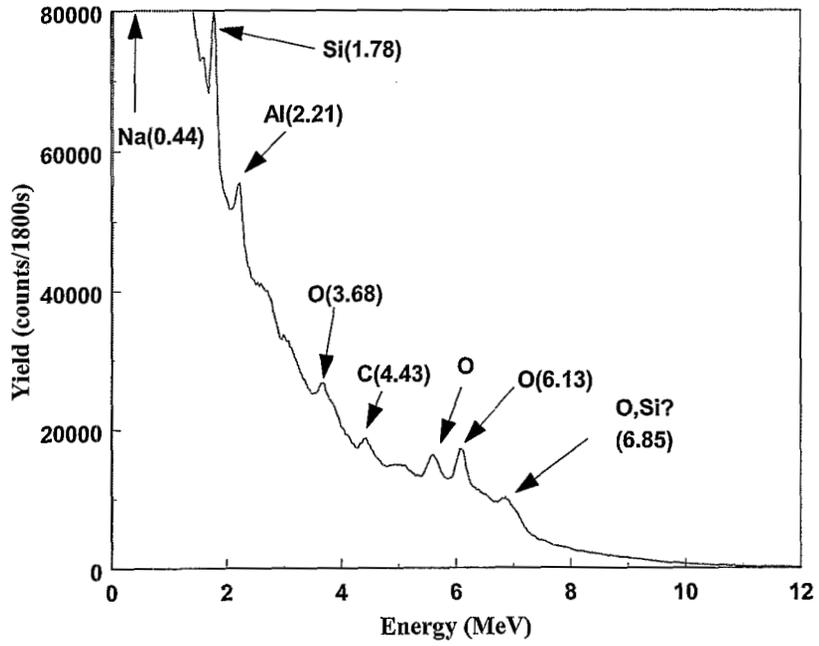


Figure 3, Typical inelastic gamma spectrum measured in the Oak Forest.