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Environmental Pollution 116 (2002) S209–S219

ENVIRONMENTAL POLLUTION

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Development of a protocol for monitoring status and trends in forest soil carbon at a national level

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"Capsule": *A protocol for monitoring near surface changes in forest soil carbon with bulk density core samplers was evaluated and has been recommended for national implementation.*

Abstract

The national Forest Health Monitoring (FHM) program requires protocols for monitoring soil carbon contents. In a pilot study, 30 FHM plots loblolly/shortleaf (*Pinus taeda* L./*Pinus echinata* Mill.) pine forests across Georgia were sampled by horizon and by depth increments. For total soil carbon, approximately 40% of' the variance was between plots, 40% between subplots and 20% within subplots. Results by depth differed from those obtained by horizon primarily due to the rapid changes in carbon content from the top to the bottom of' the A horizon. Published soil survey information overestimated bulk densities for these forest sites. The measurement of forest floor depths as a substitute to sampling did not provide reliable estimates of forest floor carbon. Precision of replicate samples was approximately 10 30% for field duplicates and 5–10% for laboratory duplicates. Based on national indicator evaluation criteria, sampling by depth using bulk density core samplers has been recommended for national implementation. Additional procedures are needed when sampling organic soils or soils with a high percentage of' large rock fragments.

Keywords: Soil carbon; Soil bulk density; Soil sampling; Forest floors; Forest monitoring

1. Introduction

Soil organic matter (SOM) is an important constituent of forest soils. SOM interacts with other soil components and influences soil chemical, physical and biological properties. Specific soil properties affected by SOM include soil pH, buffer capacity, cation exchange capacity, sorption of pesticides, water infiltration, water retention, aeration, color, and the activity of soil organisms (Sikora and Stott, 1996; Seybold et al., 1997; Povirk ct al., 2001). SOM is a major source of nutrients to plants, particularly N and P (Sanchez, 199X). Forest litter and organic materials are critical to the protection of mineral soil from erosion (Elliot et al., 1999). Soil structural characteristics are also affected by SOM including their form, stability and resiliency (Kay. 1998). The bulk density of a soil is also influenced by the SOM content (Huntington et al., 1989). As a result, SOM content is often considered a critical component of soil quality (Karlen et al., 1997).

Recent interest in the global carbon cycle and the potential of mitigating the build up of atmospheric carbon dioxide through carbon sequestration to forests has brought attention to the importance of measuring organic matter in forest soils (Jain et al., 1997). The carbon content of soil organic matter ranges from 40 to 60% (Huntington et al., 1989). Large amounts of the total carbon reserves in forests arc located in the forest floor and mineral soil. For example, Morrison et al. (1993) determined that 55–68% of carbon in three mature forests of Ontario, Canada was located in the soil. Huntington (1995) documented that the reforestation of former agricultural lands resulted in a significant accumulation of carbon in the soil and suggested this could be an important regional carbon sink. Brown et al. (1992) identified that tropical soils could also serve as a potential carbon storage reservoir. Modeling of the effects of global climate change must therefore take into consideration changes in SOM carbon (Pastor and Post, 1988; Nabuurs and Mohren, 1995). As temperatures rise and season lengths increase in the high latitudes, the rate of decomposition of SOM may also increase, possibly leading to a decrease in soil carbon levels (Kasting and Walker, 1993; Joslin and Johnson, 1998; Makipaa

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PII: S0269-7491(01)00253-6

et al., 1999; Walker et al., 1999). Unexpected carbon declines in SOM on undisturbed sites at Walker Branch Watershed in Tennessee over a 2 1 year period have been attributed to an increase in soil decomposition rates (Trettin et al., 1999). However. Giardina and Ryan (2000) examined forest soil decomposition rates from 82 sites on five continents and concluded that increased temperature alone will not stimulate the decomposition of carbon in forest mineral soils. This conclusion is currently a topic of controversy and will require further study (Davidson et al.. 2000).

Forest management operations such as cultivation. prescribed burning, harvesting, ground preparation, fertilization and drainage can affect SOM content (Johnson. 1992; Jurgensen et al., 1997: Worrell and Hampson, 1997) and thereby cause changes in soil chemical and physical properties (Powers et al., 199X). Management activities such as cultivation, high intensity tires, site preparation or drainage that reduce organic matter inputs or increase soil decomposition rates generally cause a decline in SOM contcnt. Operations that increase organic matter inputs such as reforestation of agricultural lands or fertilization can increase SOM levels. Knoepp and Swank (1997) and Johnson and Todd (1998) evaluated the effects of commercial sawlog harvest and whole tree harvesting on soil carbon concentrations and determined that these harvesting practices did not result in long-term decreases in SOM. Page-Dumroese ct al. (2000) have noted that forest soils with thin litter layers or high rock contents are more sensitive to management disturbances that can change SOM levels.

Increasing the sequestration of carbon in the terrestrial biosphere may be an inexpensive way to help mitigate the increasing concentration of atmospheric carbon while providing ancillary benefits such as improved soil productivity. However, this approach can only be implemented if accounting rules have been determined (Schlamadinger and Marland, 2000). International agreements such as the Kyoto Protocol will require agreed-upon monitoring and verification procedures of carbon sequestration in soil (Rosenberg et al.. 1998). Land managers are also interested in monitoring the effects of land management practices on SOM levels with the goal of improving resource management practices over time (Smith et al., 1999). Given the importance of SOM to forest productivity, the role of SOM in the global carbon cycle, and the potential to affect SOM levels through land management practices, it is not surprising to see a growing interest in the development of national monitoring protocols for the measurement of soil organic carbon.

The Forest Health Monitoring (FHM) program in the United States has been interested in developing national protocols for monitoring the status and trends in forest ecological properties including soil carbon for several years (Riittcrs et al., 1992). The FHM program is composed of three components detection monitoring. evaluation monitoring. and intensive site ecosystem monitoring (Manyold, 1998). The detection monitoring program has been developed to monitor indicators of sustainable forest management on a network of plots distributed across all forest types and land ownerships. This network has recently been incorporated as the third phase of the national Forest Inventory and Analysis program. A 27 km triangular grid providing approximately one plot per 40,000 ha of forest land determines the location of plots.

From 1991 through 1993, the FHM program undertook a research effort to develop ecological indicators in the Southeastern United States (Alexander and Palmer, 1999). A soil scientist was included on each research crew to describe the soils on FHM plots and collect soil samples. Due to the costs incurred by this approach, soil measurements were not incorporated into the FHM program for several years. With the adoption of the Santiago Declaration of criteria and indicators of sustainable forest management by the United States in 1995 (Montreal Process, 1995), the FHM program decided to again encourage the development of a soil monitoring protocol through the implementation of pilot tests at regional and national levels. A soil sampling procedure was proposed for FHM field crews that did not require a soil scientist. The procedure consisted of collecting a litter sample, excavating a hole to 10 cm below the A horizon, and then sampling the A horizon and the 10 cm of soil underlying the A horizon. This procedure took only about one hour of a crew member's time. Regional and national field tests in 1997 and 199X determined that field crews could not reproducibly identify the depth of the A horizon on many soils. Consequently, the procedure for sampling the mineral soil was modified in 1999 to sampling by depth with samples collected from the mineral soil for the 0- 10 cm layer and the 10 20 cm layer. A limitation of this protocol was the lack of bulk density measurements that could be used to convert relative soil contents such as the percentage of carbon in the soil to a mass per unit area such as Mg C/ha. During the summer of 1999, several bulk density procedures were field-tested including soil excavation with volume determination (Page-Dumroese et al., 1999) and soil sampling with small (5 cm) and large (7.5 cm) diameter cylinders. Of these methods, the only procedure deemed as logistically feasible for FHM field crews was sampling with the small diameter cylinder using commercially available equipment. The objective of this paper is to present the results of a special study conducted in the fall of 1999 to assess this monitoring protocol for its potential of being adopted as the FHM national monitoring protocol for long-term soil sampling.

Many approaches have been recommended for assessing nionitoring protocols at a national level in soils (Breckenridge et al., 1995; Burger and Kelting. 1999). Based upon a detailed review of FHM and other national monitoring programs. the National Research Council (2000) developed a list of criteria for evaluating proposed ecological indicators. Their recommendations have been used in this paper as a means for identifying research requirements for evaluating the proposed FHM soil carbon monitoring protocol. Five research questions were identified for specific study in this project:

1. How do results from the proposed sampling by depth method compare to those obtained when sampling by soil horizons?
2. What is the relative variability within sampling sites, between sampling sites on a plot and between plots across ii region?
3. What is the overall measurement error and sources of measurement variability'?
4. Can published soil survey information be used to reduce data collection requirements?
5. Can sampling costs for forest floors be reduced by the collection of a few additional field measurements?

2. Materials and methods

Testing of the proposed method for sampling soil carbon content was conducted at 30 FHM plots across the state of Georgia. These plots were sampled for soil chemistry during pilot studies conducted in 1991 through 1993. Predominant forest types on these plots are loblolly (*Pinus taeda* L.) pine or shortleaf (*Pinus echinata* Mill.) pine.

A FHM plot is 1 ha in size. The FHM plot design consists of four subplots (7.32 m radius, 1 /60-ha) where detailed forest inventory and health measurements are taken. One subplot is located at the center of the plot and the centers of the other three are located at a distance of 36.6 m from plot center on azimuths of 120. 240 and 360

2.1. Sampling by depth increments

The location of these soil sampling sites was 30 m from plot center at azimuths of 144, 254, and 336 (Fig. I). These locations were selected to be adjacent to exterior subplots yet away from planned routine soil monitoring sites. The forest floor was sampled in the following manner. A 30 cm diameter sampling frame wits placed on the forest floor at the sampling site. The depth of the forest floor was then measured to the nearest cm in four directions (N. E, S. and W) at the edge of' the sampling frame. A knife was used to cut down to the mineral soil surface. All coarse wood fragments larger than 5 mm (pencil size) in diameter were removed. The remaining sample was placed in plastic bags and forwarded to the laboratory.

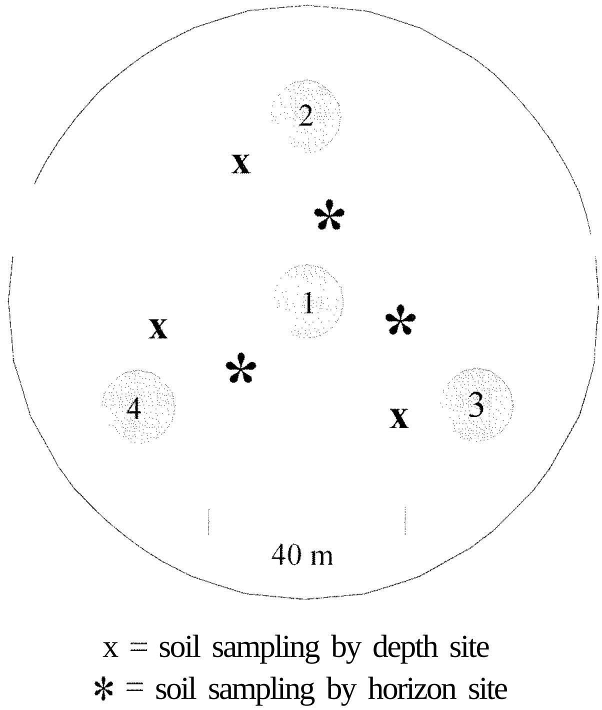

Fig. 1. Location of soil sampling sites on FHM plots. Small circles represent the location of subplots on the plot.

A bulk density sampler (AMS Core Sampler Model #910.00) 5. I cm in diameter and 20.2 cm in length was used to obtain soil cores. The sampler was driven vertically into the ground after the removal of the forest floor with the aid of a slide hammer (AMS Compact Slide hammer #400.92) or a sledgehammer. Brass or plastics liners within the core sampler were used to assist in the extraction of the soil cores from the sampler and the cutting of the soil core into three sections: 0 -5, 5 IO and 10- 20 cm. Soil samples were then sent to the University of Missouri soil characterization laboratory for the measurement of bulk density and total carbon.

2.2. Laboratory analysis

Forest floor and mineral soil samples were stored in a freezer upon arrival at the laboratory until they could be processed. Moisture content was determined by oven drying overnight to 105 C. Bulk density was determined using the National Soil Survey Center (I 996) Method Code 4A3a. After the measurement of bulk densities, total carbon content was determined by dry combustion with a LECO CR- I2 carbon analyzer with the same soil samples.

2.3. Comparison of soil sampling methods

Soils were originally sampled in early FHM pilot studies by horizon at the midpoint between subplot centers. For our study, we relocated the original sampling sites and then resampled these soils at a distance of 3 m from the original sampling site (Fig. 1) to allow for an evaluation of change in soil chemical properties over time. As a consequence, these sampling locations were located approximately 30 m away from the sampling by depth sites. In retrospect, these sampling sites should have been located closer together to minimize the compounding effects of local spatial variability.

Every effort was made to follow the original procedures including using the same methods manuals, data collection programs, trainers and field staff (if still available). The forest floor was sampled with a 30 cm diameter sampling frame by cutting down from the surface of the forest floor to the mineral soil. All large branches above 30 mm in diameter were removed as in the original protocol. It is recognized that, as a result, the forest floor sample included more fine woody debris than the forest floor sampled at the "by depth" sampling sites with a 5 mm cutoff. As a consequence, no comparisons were made between the forest floor samples obtained by the two methods.

The remaining forest floor sample was then placed in sample bags. Soil scientists from the region excavated soil sampling holes to a depth of I m and then described and sampled the soils. A bulk soil sample was collected for soil chemical analysis from each master horizon along with duplicate bulk density cores (5.0 cm diameter x2.5 cm length). Both sets of samples were forwarded to the soil laboratory.

In order to make the comparison between the two methods of soil sampling, the data obtained by the soil scientists when sampling by horizon was converted to the same depth increments used by the foresters when sampling by depths. An example is given in Fig. 2. If a depth increment was found entirely within a horizon, the overall value for the horizon was used to estimate a value for that depth increment. As shown in Fig. 2, the A horizon for this soil had a depth of 12 cm and therefore was used to estimate both the 0–5 cm and 5 10 cm increments. The IO 20 cm increment was estimated by combining the 10 12 cm increment from the A horizon with the 12-20 cm depth of the AB horizon and weighting the amounts according to their relative contributions to the overall depth. Due to the difference in size of coarse woody debris removed from the forest floor samples, a comparison was not made for these results between the two sampling protocols.

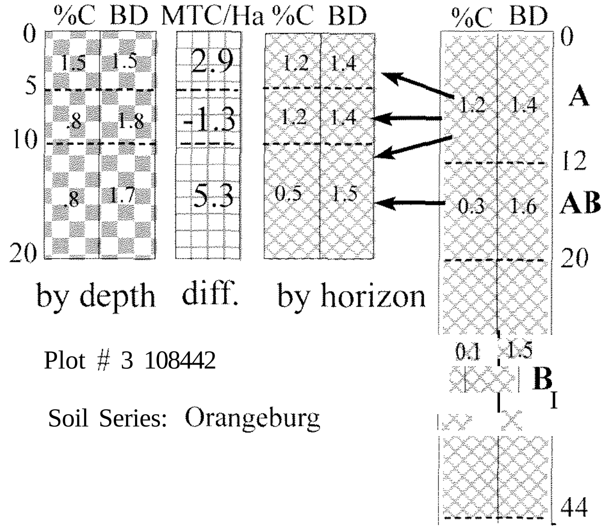

Fig. 2. Comparison of soil carbon estimates using two approaches to soil sampling. %C refers to percentage of carbon by weight in soil sample, BD is the bulk density and Mg C/ha is megagrams (10^6 grams) of carbon per hectare and is represented as the difference calculated from measurement "by depth" to that measured "by horizon". The two figures on the right of the diagram show how the data collected "by horizon" is converted to a "by depth" measurement.

2.4. Soil variability study

In order to detect changes in soil carbon over time, soil measurement protocols must take into account spatial and temporal variability that occur in natural systems. To evaluate variability at different spatial scales, replicate samples were taken by the foresters at sampling sites adjacent to the subplots. By taking duplicate samples at three subplots per plot and at 30 plots across the state of Georgia, it is possible to conduct an analysis of variance to identify the relative magnitudes of the various levels of spatial variability. These were estimated using PROC NESTED (SAS, 1996). Unfortunately, duplicate samples of the forest floor were not taken at each subplot; therefore the soil variability study was limited to an analysis of the mineral soil samples only.

2.5. Measurement system precision

The precision of a measurement system can be evaluated by the analysis of replicate quality assurance samples. These samples include chemical reagents (to determine any analytical limitations), known and blind soil reference samples (to determine any limitations due to extraction procedures), soil batch duplicates (to determine any limitations resulting from soil sample preparation and processing) and field duplicates. For this study, replicate samples from subplot sampling sites were treated as field duplicates. The value of field duplicates is that they represent all sources of variability in the measurement system from field sampling, sample storage, and sample preparation through sample analysis. It must be recognized, however, that field duplicates obtained in this way do include some natural soil variability at the subplot level and therefore tend to overestimate the variability arising from the measurement system to some degree.

2.6. Evaluation of utility of published soil survey information

Soil survey information on bulk densities was obtained from the National Soil Characterization Database (NSCD) based on the soil classification determined by the soil scientists on each plot. Soil series names were entered at the NSCD websitc (http://vmhost.cdp.state.ne.us/~nslsoil/SERIC.HTML) to obtain published information regarding these soil series. Bulk density information was extracted from the results. If more than one pedon was described in the database for a given soil series, results were averaged across pedons.

To compare results between the sampling methods, an average bulk density to a depth of 20 cm was calculated from the NSCD soil series information based upon the relative contribution by depth of each soil horizon. In a similar manner, an average bulk density to 20 cm was calculated for the plot data collected by the two methods (sampling by depths and sampling by horizons).

2.7. Forest floor sampling requirements

The forest floor was sampled at each of the three sampling (by depth) sites on each plot. At each of these sites, the crews also measured the depths of the forest floor. The amount of carbon in the forest Aoor at the second and third sites was estimated by using the value obtained from sampling at the first site and then multiplying by the **ratio** of the average depth at the second oı third site divided by the average depth at the first site. This estimated amount was then compared to the actual amount obtained by sampling these sites and forwarding the samples to the laboratory for analysis.

3. Results

3.1. Comparison of soil sampling methods

Two different approaches are commonly used to sample soils for an evaluation of status and trends in soil carbon. These methods are sampling by soil horizons and sampling by depths. Both of these approaches were used in this study. The objective of this section is to provide a summary of the comparison of results obtained by these two methods.

Due to the annual inputs of carbon into soils from plant residues near the surface, soil carbon tends to be higher at the surface and then decreases with depth. While sampling by soil horizons tends to reflect this trend (e.g. the A horizon has a higher carbon content than the B horizon), it is apparent that within the A horizon of a soil, the soil carbon can change from the top of the horizon to the bottom. As seen in Fig. 2, the A horizon of the soil sampled at Hexagon #3108442 showed a large decrease in soil carbon content below the top 5 cm. The amount of soil carbon estimated from sampling by soil horizon is lower than that obtained by sampling by depth in the top 0–5 cm because the organic content of the soil sampled is higher. This can be explained by the fact that the soil sample obtained for the A horizon is an average of its entire depth (0–12 cm) rather than just the top 5 cm near the surface. It is interesting to note that for this example, the opposite effect occurs for the 5–10 cm increment. in this case, the estimate from sampling by depth is lower than that obtained by sampling by horizon as the carbon content in this depth is less than the average sample from the A horizon. The third depth increment reverses this trend with the estimate again being higher for the soil depth sampling method. The average depth of the A horizon for the soils sampled was 15 cm. The underlying E or B horizons often had much lower average carbon contents. When this lower value was included in the average for 10–20 cm depth increment, a lower estimate for the sampling by horizon method was obtained.

A similar comparison for all soils sampled in this study is presented in Table 1. It is important to note that there was a significant amount of variability in the results due to inherent spatial variability on the plots. It should be remembered that the two sampling methods were not undertaken at the exact same locations on the plot and therefore some inherent soil spatial variability is to be expected. Plot #3108442 was chosen from this list and presented in Fig. 2 as it reflected the overall average and median trends by depth (Table I).

It is interesting to note the effect of A horizon depth when comparing the two sampling methods (Table 1). For the 0–5 cm layer, the difference between the sampling methods was generally negative (more carbon estimated by the horizon method) in shallow soils and positive (more carbon estimated by the depth method) in soils with thick A horizons. In the IO-20 cm layer, the opposite trend is apparent. The depth sampling method in shallow soils where underlying E or B horizons had been encountered found more carbon. In contrast, more carbon was found by the horizon method in the deep soils where the sample is representative of an average value of the A horizon.

It is evident from this comparison that care must be taken when comparing estimates of amounts of soil carbon from two different sampling methods. For purposes of monitoring, it is important to establish one procedure and then follow that same procedure over time. Otherwise, one should expect to see differences even when the soil has not changed in the amount of soil carbon present.

Table 1
Difference in soil carbon content (Mg C/Ha) when sampled by depth as compared to sampling by horizon; difference is "by depth" minus "by horizon"

Plot #	Depth A horizon (cm)	0 5 Diff	5–10 Diff	10–20 Diff
3208362	5	1.72	5.36	6.48
3208487	5	−3.84	3.77	4.81
3108456	6	0.13	8.11	17.10
3308426	7	-7.48	−2.75	4.36
3308352	8	−4.81	−3.10	6.62
3308468	8	−2.09	−0.51	5.19
3308563	8	-5.97	−3.51	6.24
3308481	9	30.63	−26.92	−7.49
3108442	12	2.91	−1.33	5.29
3208365	13	3.42	1.14	−2.11
3308287	13	−3.35	−5.75	−1.40
3308421	14	3.45	−0.28	3.16
3108311	14	10.31	5.07	6.91
3208315	15	3.52	−0.42	−1.59
3208417	15	5.99	3.24	−3.61
3308335	15	6.46	3.58	3.37
3108286	10	3.83	0.19	1.67
3308441	16	-1.15	−1.83	−0.90
3108178	17	10.15	8.23	1.28
3108223	17	4.76	0.83	1.80
3208332	17	1.75	−0.23	−2.59
3208473	17	4.81	−1.93	−4.20
3108342	22	9.65	0.64	−5.53
3308234	26	6.99	−0.56	−2.76
3108256	26	7.18	2.09	−3.75
3108368	28	1.83	0.34	−4.34
Average	14	1.60	−0.25	1.31
Median	15	3.17	−0.02	1.48
S.D.	6.3	x.79	6.41	5.37

3.2. Soil variability study

The results of the analysis of variance are presented in Table 2. For all three parameters (bulk density, percent carbon, and total carbon) an important component of spatial variability occurs between plots and is highly significant. The percentage of the overall variance found at this spatial scale ranged from approximately 18 49% depending on the parameter measured and the depth of sampling. The average value across depths for total carbon content was 41%. This variability reflects the differences in the properties for the variety of soils sampled from across Georgia in this study.

The next source of spatial variability examined was that of differences between subplots at individual plots. This variability ranged from 29 65% of the overall variability for the parameter and sampling depth studied. The average value across depths for total carbon content was 38%. This level of variability was also highly significant suggesting that individual subplots differ from one another in soil properties within FHM plots and these difference can often exceed those found between plots.

The final source of spatial variability examined was that found at individual sampling sites. The distance between replicate sampling locations at a sampling site was generally less than one meter for this study. Therefore, small-scale spatial variability in soils is represented by this component of variance. This variability ranged from 1 5–39% of the overall variability with an average value of 21% for total carbon content. This level of variability was not statistically significant, suggesting that these soils are relatively uniform at small spatial scales.

3.3. Measurement system precision

Another important issue to consider when evaluating variability for a monitoring program is a determination of the amount of variability one can expect from the measurement system that is independent of natural variability. If a measurement system is not very precise and introduces additional variability into the results, any real changes in the natural system may be masked by this lack of precision.

The evaluation of the precision of soil carbon analyses is presented in Fig. 3. Two lines are drawn on this figure. The first line is flat and represents the detection limit for soil carbon determined as being three times the standard deviation of low level soil reference samples or 0.2% carbon. The second line represents the quality control limit used for samples with higher levels of carbon content and has been set at a coefficient of variation of 10% for the evaluation of quality control samples. As shown in Fig. 3, all quality assurance samples can be measured at a level that is less than 10% with the exception of field duplicates. The field duplicates in this study tended to have a coefficient of variation of approximately 20 30% variability at low levels of soil carbon. At higher levels of soil carbon such as for forest floor samples, the standard deviation averaged about 10% of the carbon content in the soil sample. According to Taylor (1987), qualitative decisions require an accuracy of ± 30% while quantitative decisions (such as used for hypothesis testing) should have an accuracy of ± 10%. Based upon this statement, we can conclude that the measurement system for soil carbon is relatively precise and provides for quantitative estimates of soil carbon.

3.4. An evaluation of the utility of published soil survey information

A comparison of the average difference in bulk densities to a depth of 20 cm plots is presented in Fig. 4. In this figure, bulk densities obtained by the field crews when sampling by horizon or sampling by depth is compared to that obtained from the NSCD website for each soil series. An examination of Fig. 4 provides

Table 2
Components of variance for bulk density, percent carbon and total carbon

		Bulk density		Percent carbon		Total carbon	
Depth	Source	% Variance	Pr > F	% Variance	Pr > F	% Variance	Pr > F
0–5 cm	Plots	38.11	< 0.0001	37.89	< 0.0001	49.29	< 0.0001
	Subplots	36.70	< 0.0001	29.41	< 0.0001	3.20	< 0.0001
	Within subplots	25.19		32.70		21.51	
5–10 cm	Plots	32.31	< 0.0001	19.95	< 0.0001	32.23	< 0.0001
	Subplots	45.51	< 0.0001	64.74	< 0.0001	50.38	< 0.0001
	Within subplots	22.18		15.32		17.39	
10–20 cm	Plots	18.47	< 0.0001	35.27	< 0.0001	41.48	< 0.0001
	Subplots	42.98	< 0.0001	47.12	< 0.0001	35.30	< 0.0001
	Within subplots	38.55		17.61		23.22	
Average	Plots	29.63		31.04		41.00	
	Subplots	41.73		47.09		38.29	
	Within subplots	28.64		21.88		20.71	

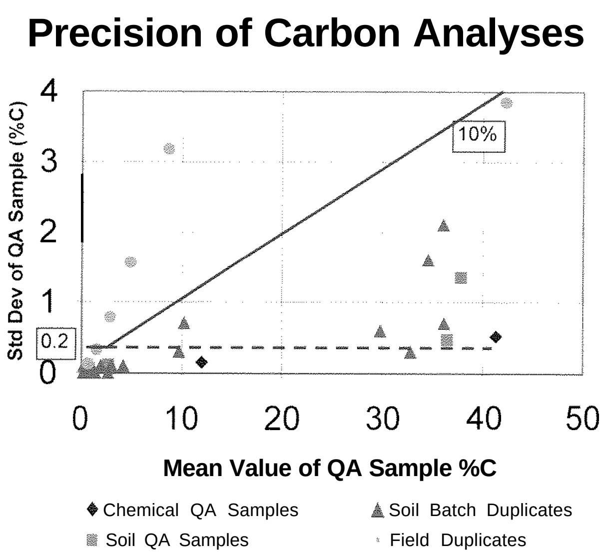

Fig. 3. Precision of replicate quality assurance samples for the measurement on percent total carbon. The two lines depict a detection limit is 0.2% C and a coefficient of variation of 10%.

several important clues as to the utility of published soil survey information for soil monitoring. Soil survey information with bulk density data is not readily available for all soil series. In our evaluation, we were able to obtain data for only 16 of the 30 plots. For these 16 plots, the soil survey information almost always gave an overestimate of the average bulk density of the top 20 cm of soil. This held true for a comparison with both types of soil sampling procedures on our plots (sampling by horizon and by depth).

3.5. Forest floor sampling requirements

A comparison of the actual forest floor carbon measured to the amount predicted using the measurement of forest floor depths is presented in Fig. 5. The predicted amount averaged slightly higher (1 .O Mg C/ha) than the true amount. The variability in results was also high (relative standard deviation of 55%). The conclusion of this comparison is that measuring forest floor depths rather than sampling them does not provide a reliable method for estimating forest floor carbon.

4. Discussion

The National Research Council (2000) has established ten criteria for the evaluation of an ecological indicator proposed for implementation in a national monitoring program. It is possible to divide these 10 criteria into two groups of five those that are conceptual in nature and those requiring data collection during the testing of an indicator (Table 3). We will first discuss the conceptual issues and then review those issues that required data collection and evaluation.

4.1. Concept issues

In their report, the National Research Council (2000) recommended that the measurement of soil organic matter (SOM) be included in national monitoring programs. In terms of general importance. they conclude that SOM content is the best available indicator for evaluating the state of soil quality. From a conceptual basis, SOM is an indicator of ecological condition because it provides information on soil condition as well as erosion potential. SOM content also influences soil productivity and therefore is also an indicator of ecological functioning. Data requirements identified in the report are soil carbon contents and bulk density estimates for the top 20 cm of soil, although they do recommend sampling to a depth of 50 cm if resources arc available. The skills required to sample SOM with a bulk density sampler can be learned in a training session of just a few hours. The method proposed for sampling is comparable to accepted international forest soil monitoring protocols in Europe (United Nations Economic

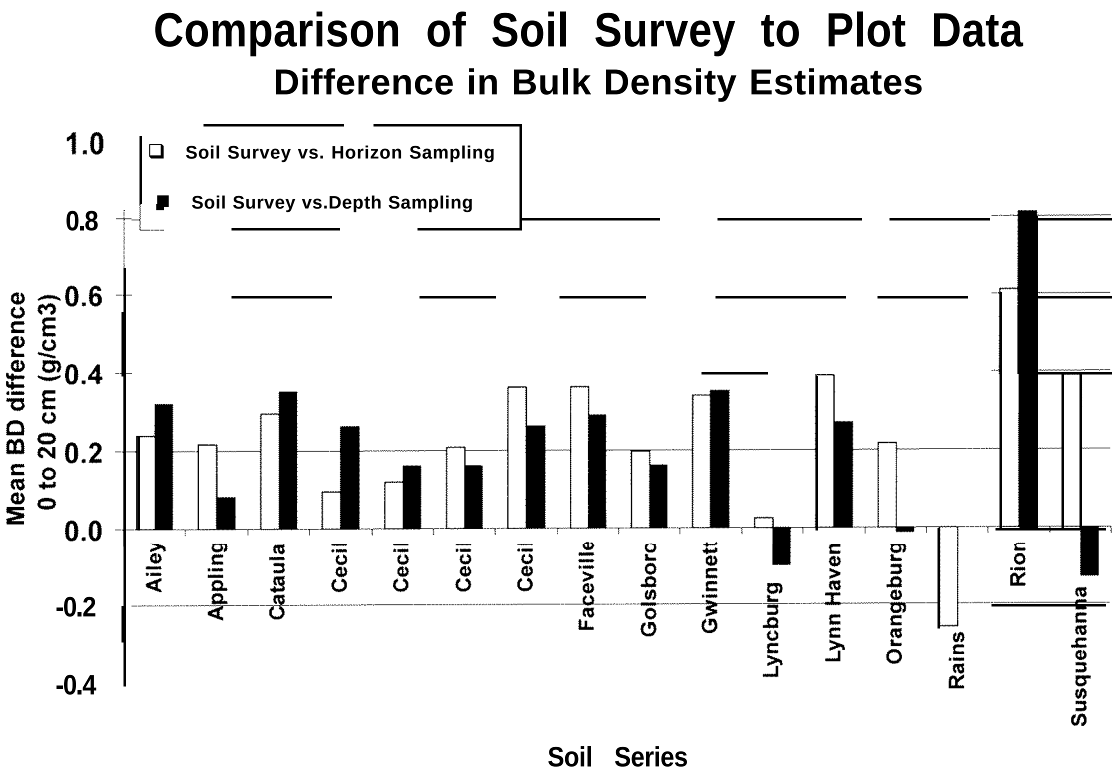

Fig. 4. A comparison the average bulk density of the top 20 cm of mineral soil provided by soil survey information to that measured on the plot by a soil scientist sampling by horizon and a forester core sampling by depths. A positive value indicates that soil survey values were greater than measured values.

Commission for Europe, 199X). However, it does differ from the current monitoring protocols in Canada used in the Acid Rain National Early Warning Network (D'Eon, 1994) where sampling by horizon has been customary. However, the Canadian methods will likely be revised to a sampling by depth procedure in the near future due to difficulties field crews are having in accurately determining the depth of soil horizons (Ian Morrison, Canadian Forest Service, personal communication).

The issue of robustness was not directly addressed in the NRC report or in our study. Subsequent to our field study, a decision was made to test the proposed sampling method at a national level. Sixty crews collected over 7000 soil samples during the 2000 field season. This national test using bulk density core samplers identified the need for additional procedures when sampling organic soils or soils with a high percentage of large rock fragments. Organic soils tended to compact in the samplers and soils with a high percentage of rock fragments could not bc sampled by this method. It should be pointed out that to accurately estimate soil carbon, rock fragment content must also bc measured. Any rock fragments that fit within the 5 cm diameter sampling probe opening can be included with the soil as it is sampled. However, an adequate sample of coarse fragments larger than approximately I cm in diameter would require a much larger volume of sample than that obtained by the core sampler. Soils with a significant amount of larger rock fragments will need to be assessed with additional monitoring protocols.

4.2. Data research issues

Our study to compare the two sampling methods was undertaken to address the reliability of the indicator to monitor status and trends in soil carbon. During the planning of this study, there was a real question as to whether or not the FHM plot network could identify changes in soil properties such as soil carbon over time. It must be remembered that the FHM monitoring design is a statistical sample. The overall monitoring design was not developed to be optimal for soil monitoring. For example, the locations for FHM plots are not selected to be located on uniform soils at uniform landscape positions with uniform land management activities. Areas within plots can span a variety of soil types, landscape positions, vegetation types and treatments.

A second limitation is that soil sampling is destructive. When monitoring tree growth, the same tree can be remeasured to determine changes over time. However, this is not the case with soil sampling as the original sample must be removed in order for it to be analyzed. Subsequent samples should be taken at a distance that is

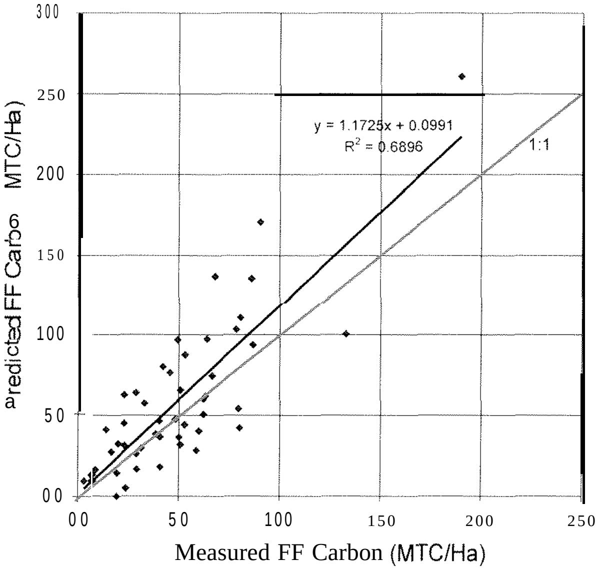

Fig. 5. A comparison of measured forest floor carbon with that predicted by the comparison of forest floor depths. Linear regression trendline and a 1:1 comparison line have been included.

far enough from the first sample so as not to be influenced by the original sampling effort. A consequence of this fact is that spatial variability in soils is an inherent limitation to the detection of trends over time.

As shown in an accompanying paper in this volume (results presented in Conkling et al., 2001), the FHM sampling design does allow for a reliable determination of status and trends in soil carbon on a regional basis. It should be noted that this conclusion is based on the generally accepted reference method of sampling soils by horizon with experienced soil scientists.

As discussed previously, the original FHM soil monitoring design consists of sampling at three predetermined locations on a plot and then returning to resample 3 m away. Based on these results, we expect that the proposed soil sampling protocols will detect real trends. This conclusion is based on the fact that all the factors constraining success with the original sampling protocol (by horizon) are still operable for the new protocol of sampling (by depth). Sampling sites are predetermined from the sampling grid, only three sites are sampled on a plot and remeasurement sites are 3 m away from original sampling sites. It is even possible that the new method may detect more subtle changes than the original protocol because no judgement is required on the port of sampling crews as to a determination of depths for sampling. Where soil horizonation is not very distinct. Iwo different soil scientists might determine to sample soils at different depths. The new proposed method does not require this type of' judgement call.

The analyses of the spatial scales of variability have been helpful in the design of the current soil sampling program for the FHM program. It was initially thought

Table 3
Evaluation criteria for national ecological indicators[a]

Concept issues	Data research issues
General importance	Reliability
Conceptual basis	Temporal and spatial scales of applicability
Necessary skills	Statistical properties
International compatibility	Data requirements
Robustness	Costs. benefits and cost-effectiveness

[a] From National Research Council, 2000.

that there would be a need to take duplicate samples at every subplot sampling site on FHM plots in order to adequately address local sampling site spatial variability (Lister et al., 2000). This study shows that (for forest soils in Georgia) replicate sampling is not needed at subplot sampling sites.

To test this conclusion at a broader scale, a similar analysis of replicate samples collected by the FHM program for quality assessment purposes in 1999 at 12 plots across eight states (C. Palmer, unpublished data) determined 48, 41 and 11% for plot, subplot and within subplot components of variance respectively for % carbon content. The larger between plot variance from these data reflect soil chemical differences for a wider variety of soils sampled (from Idaho to South Carolina). These data also demonstrate the significant level of soil variability between subplots on FHM plots.

Soil surveys have been conducted by the USDA Natural Resources Conservation Service for the majority of soils in the United States. These soils were sampled in the process of soil classification and these results are readily available through the internet. The question can be posed whether or not there are soil properties available through this information that might be useful to a soil monitoring program and thereby reduce some of the need for field data collection?

In evaluating the data available from the soil survey, it is apparent that most of the soil samples were taken from agricultural fields as indicated by a lack of information for a surface organic (forest floor) layer. Agricultural soils are generally lower in organic matter than forest soils. Soils with lower contents of organic matter tend to have higher bulk densities (Huntington et al., 1989; Fcderer et al., 1993). These results suggest that care must be taken when using soil survey information as a replacement for sampling in the field for forest soils.

This study offered an opportunity to evaluate an approach that might reduce the overall costs of a forest soil monitoring program. If this approach were valid, Iwo-thirds of the overall forest floor sampling cost could be saved through simple depth measurements. Unfortunately, this approach did not prove to be valid due to the high variability in results (Fig. 5). It is therefore recommended that forest floor samples be taken at all three sampling sites on FHM plots in the future.

5. Conclusions

A soil sampling procedure using a 5 cm diameter by 20 cm length core was field tested in a soil carbon study across the state of Georgia. A set of national criteria was used to evaluate and test the methodology. Based on this study and subsequent field testing at a national level. wc recommend the implementation of sampling by depth with a bulk density core sampler for the monitoring of near surface changes in forest soil organic matter.

Acknowledgements

This project was funded in part by the USDA Forest Service under Cooperative Agreement number SRS 33-CA-9951 l with the University of Nevada, Las Vegas and Cooperative Agreement number SRS 33-RCRA-99-574 with North Carolina State University. It has not been subjected to USDA Forest Service Agency review. Mention of trade names or commercial products does not constitute endorsement or recommendation for usc.

We wish to thank the following individuals for their assistance and support: Richard Birdsey. Marilyn Buford, William Burkman, James Compton, Paul Dunn, Coeli Hoover, Charles Liff, Robert Mangold, John Simpson, James Steinman, and Bryce Stokes (USDA Forest Service); Edward Ealy, James Lathem and Scott Moore (Natural Resource Conservation Service); David Hammer and Russell Drcsbach (University of Missouri. CO); Terry Price (Georgia State Forest Service); Rick Van Remortel (Lockheed Martin Environmental Services); and Jeff Marler (North Carolina State Forcst Service).

This paper was presented at the USDA Forest Service Southern Global Change Program sponsored Advances in Terrestrial Ecosystem: Carbon Inventory, Measurements, and Monitoring Conference held 3 5 October 2000 in Raleigh, NC.

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