Can a Labile Carbon Test be Used to Predict Crop Responses to Improved Soil Organic Matter Management?

S. T. Lucas* and R. R. Weil

ABSTRACT

Permanganate ($KMnO_4$) oxidizable C (POXC), an estimate of labile soil C, was evaluated for use as a soil test to identify soils that may respond positively to soil organic matter (SOM) management. We hypothesized that soils lower in POXC would be more likely than soils higher in POXC to show increased crop productivity in response to practices that increase SOM. At four sites, paired fields of the same soil but contrasting management history (cropping vs. sod) were studied. Fields with sod history tested higher in total organic C (TOC) and POXC than fields with cropped history. Permanganate-oxidizable C was strongly related to TOC ($r = 0.94$). We examined crop stover, grain, and biomass responses to two cover crop treatments within each field: winter rye (*Secale cereale* L.) or no rye. After at least 1 yr of treatment, there was a significant negative correlation between relative stover response to rye and POXC ($r = -0.60$) at sites with finer textured soils. After at least 2 yr of treatment, crop responses to rye showed a significant negative correlation with POXC and TOC. The strongest relationships to POXC occurred in the stover response at two sites with finer textured soils (Keedysville: $r = -0.74$; Holtwood: $r = -0.84$). Permanganate-oxidizable C was comparable to TOC at predicting crop responses to rye. These results suggest that POXC may be a useful test for identifying soils where improved SOM management is likely to improve productivity. The rapid, simple POXC methodology enables on-site or laboratory soil testing.

Modern soil quality (SQ) assessment tools, particularly ones that can be used on-site, are needed to facilitate sustainable soil management (Wander and Drinkwater, 2000; Karlen et al., 2008) and identify high-risk or priority soils (Bone et al., 2010). Soil organic matter is a key determinant of SQ because it influences nutrient holding and exchange, soil structure, erosion resistance, and soil biological processes such as N mineralization (Weil and Magdoff, 2004). Measurements of SOM are often estimated by measuring TOC. Because the bulk of TOC is comprised of highly recalcitrant substances, the effects of contrasting soil management practices may take many years to become apparent in TOC measurements (Weil et al., 2003).

Labile soil organic C (LOC) is a relatively small fraction of TOC that responds quickly to changes in soil management (Weil and Magdoff, 2004). This fraction is important to SQ because it influences soil aggregate stabilization (Tisdall and Oades, 1982), and it is directly related to mineralization of soil C, N (Gunapala and Scow, 1998), S (Banerjee and Chapman, 1996), and P (Jenkinson and Ladd, 1981). Soil parameters related to LOC, including microbial biomass C (Islam and Weil, 2000), microbial biomass N (Jenkinson, 1988), mineralizable C, mineralizable N (Carter and Rennie, 1982), particulate organic matter (Cambardella and Elliot, 1992), and light fraction organic matter (Wander et al., 1994), are sensitive to soil management practices.

Because of their importance to SQ, an estimate of SOM or LOC would be useful in on-site SQ assessment. On-site SQ assessment kits, such as the 12-parameter kit developed by the USDA-NRCS (2001), generally do not include tests for SOM or LOC because most methods for estimating these parameters require specialized laboratory processing or equipment. A simplified SOM or LOC test would be a useful addition to on-site SQ assessment kits.

Measuring the POXC in a soil is a simple method for estimating LOC. It involves reacting soil with $KMnO_4$ and measuring the concentration change in $KMnO_4$ due to reaction with LOC (Blair et al., 1995; Weil et al., 2003). Weil et al. (2003) modified an earlier method developed by Blair et al. (1995) to make it more sensitive to LOC and suitable for both laboratory and on-site use. The 0.33 mol L^{-1} $KMnO_4$ solution used by Blair et al. (1995) oxidizes LOC but also reacts with some recalcitrant C (Lefroy et al., 1993; Weil et al., 2003). Weil et al. (2003) found that 0.02 mol L^{-1} $KMnO_4$ generally oxidized only labile forms of soil C and was closely correlated with SQ indicators such as microbial biomass, microbial biomass C, basal respiration, and aggregate stability. Work by Mirsky et al. (2008) supported these findings. They found POXC estimated by the Weil et al. (2003) method to be strongly related to particulate organic matter C, a widely accepted, but cumbersome to determine, estimate of LOC. Weil et al. (2003) prepared the $KMnO_4$ solution in 0.10 mol L^{-1} $CaCl_2$, which promotes soil flocculation and settling

S.T. Lucas and R.R. Weil, Dep. of Environmental Science & Technology, Univ. of Maryland, College Park, MD 20742; S.T. Lucas, current address: Dep. of Plant and Soil Sciences, Univ. of Kentucky, N122F Ag. Sciences North Building, 1100 South Limestone St., Lexington, KY 40546-0091. Received 20 Dec. 2011. *Corresponding author (Shawn.Lucas@uky.edu).

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Abbreviations: LOC, labile soil organic carbon; MH, management history; POXC, permanganate-oxidizable carbon; SOM, soil organic matter; SQ, soil quality; TOC, total soil organic carbon.

after the oxidation reaction. This modification eliminates the need for centrifugation and, in conjunction with a hand-held spectrophotometer, makes the Weil et al. (2003) method practical for on-site use.

The Weil et al. (2003) POXC method is sensitive to soil management practices that alter SOM content. Weil et al. (2003) found their POXC method to be more sensitive than TOC to tillage-induced SOM changes. Melero et al. (2009) measured SQ indicators including POXC, TOC, water-soluble soil C, microbial biomass C, and soil enzyme activity in two soils. They found POXC to be the most sensitive and consistent of these indicators to differing tillage regimes. Others using the Weil et al. (2003) method have found POXC to be sensitive to changes in SOM induced by manure additions (Mirsky et al., 2008; Miles and Brown, 2011), cover crop treatments (Jokela et al., 2009), and high-residue cropping systems (Miles and Brown, 2011). Culman et al. (2012), in a meta-analysis of data across 12 studies, compared the sensitivity of POXC, particulate organic matter C, microbial biomass C, and TOC to a range of different management or environmental factors. They found POXC to be comparable to or better than the other methods for detecting soil differences due to these factors. Another meta-analysis, conducted by Stiles et al. (2011), examined data sets from across the United States that used the Weil et al. (2003) POXC method for on-site SQ assessment. They found it to be reliable and consistent across a wide range of soils and suggested that POXC has the potential to improve SQ interpretations for producers. These findings support earlier, similar suggestions by Weil et al. (2003).

For producers, soil management decisions are based on maintaining or improving crop productivity. Demonstrating direct effects of SOM on crop productivity is difficult because SOM levels are strongly related to variable environmental factors, such as climate, topography, and soil texture. These factors can confound the results in studies conducted across differing soils and regions (Dick and Gregorich, 2004). The effects of SOM on crop yields can also be obscured when researchers impose SOM-altering treatments, such as crop rotations, tillage systems, or manure applications. These treatments often affect crop yields through other mechanisms, such as N inputs from legume residues or manure applications, or physical alteration of soil structure by tillage.

Some studies have related SOM and SOM-associated parameters to crop productivity. Positive correlations between SOM content and crop yields have been observed (Kravchenko and Bullock, 2000; Majchrzak et al., 2001; Alvarez et al., 2002). Stine and Weil (2002) found SOM, POXC, macroaggregate stability, and soil porosity to be related to crop productivity under different tillage regimes. Alvarez et al. (2002) observed light fraction organic matter and mineralizable N to be related to wheat (*Triticum aestivum* L.) yield variability. Other studies found that gains in SOM coincided with crop yield gains (Bauer and Black, 1994) and that losses in SOM coincided with crop yield losses (Díaz-Zorita et al., 1999). When crop residues were returned to the surface of degraded soils, Bruce et al. (1995) found the restoration of soil productivity to coincide with an increase in SOM. Lal (2006) found that increasing TOC by 1 Mg ha^{-1} translated to yield increases of 20 to 70 kg ha^{-1} for wheat, 10 to 50 kg ha^{-1} for rice (*Oryza sativa* L.), and 30 to 300 kg ha^{-1} for corn (*Zea mays* L.). Strickling (1975), as cited in Weil and Magdoff (2004), successfully isolated SOM effects on crop yields when crop rotations were imposed to alter SOM for 20 yr, and then all plots were treated alike for 2 yr. He found SOM levels to account for 82 to 84% of the variation in corn yields during these 2 yr. Strickling (1975) suggested that SOM influences on soil aggregation enhanced water infiltration and, consequently, crop yields.

These studies suggest that managing soils to improve SOM levels should maintain or improve crop productivity. Winter rye (*Secale cereale* L.) is a high-biomass cover crop that provides an organic input to the soil when it is killed and its residues decay. Increases in TOC have been reported after multiple years of winter rye (Kuo et al., 1997a; Wagger et al., 1998). Winter rye has also been related to increases in SQ indicators including microbial biomass C (Hu et al., 1997; Mendes et al., 1999; Ndiaye et al., 2000), mineralizable C and mineralizable N (Mendes et al., 1999), particulate organic matter (Hu et al., 1997), soil enzymes (Ndiaye et al., 2000), and aggregate stability (Hermawan and Bomke, 1997).

Permanganate-oxidizable C may be useful for identifying soils where productivity could be enhanced with improved SOM management practices. The objective of this study was to determine if the Weil et al. (2003) procedure for POXC can be used as a soil test to predict crop responses to improved SOM management practices. We investigated crop responses to winter rye. We hypothesized that when all else is equal, fields that initially test lower in POXC, relative to a similar field that tests higher in POXC, would be more likely to show an increase in crop productivity from treatment with a rye cover crop.

MATERIALS AND METHODS

Establishment of the Experiment

This experiment was initiated in fall 2001 at four sites, located at the University of Maryland Research and Education Centers at Beltsville, Upper Marlboro, and Keedysville, MD, and at Cedar Meadow Farm, Holtwood, PA. At each site, two fields consisting of similar soils but contrasting management history (MH) were identified (Table 1). One field had a history of long-term crop production with conventional tillage and the other field had a history of long-term sod. Soil similarity between fields (Table 1) was evaluated using soil surveys (Matthews, 1962; Kirby et al., 1967; Custer, 1985) and confirmed by auger profile descriptions along a transect in each field. Before establishing experimental plots, the A horizon in each field was characterized for pH using a 1:1 soil/water slurry, particle size distribution, and TOC (Table 1) using the methods referenced below.

In October 2001, the sod at Keedysville and Upper Marlboro was sprayed with paraquat (1,1′-dimethyl-4,4′-bipyridinium) at a rate of 1.05 kg a.i. ha^{-1}. This treatment was not necessary at Beltsville and Holtwood because the sod fields at these sites had already been converted to crop production when this study was initiated. The sod field at Beltsville was chisel tilled in spring 2000 and converted to no-till production. At Holtwood, the sod field was a grazed pasture from 1967 to 1990, which was converted to no-till production in spring 1991.

Implementation of Soil Organic Matter Management: Cover Crops

During this study, no-till management was used in all fields. At Beltsville, Keedysville, and Upper Marlboro, each field

Table 1. Management history, soil series, taxonomic classification, initial pH, preliminary total organic C (TOC), P index, K index, and A horizon particle size analysis of soils found in contrastingly managed fields at four research sites.

Site	MH†	Time under MH	Soil series	A horizon texture	Taxonomic class	pH‡	TOC‡	P‡	K‡	Sand	Silt	Clay
		yr					g kg^{-1}	kg ha^{-1}		g kg^{-1}		
Beltsville	cropped	32	Evesboro/Galestown	sand/loamy sand	mesic, coated Typic Quartzipsamment/siliceous, mesic Psammentic Hapludult	6.3	20.0	149.3	101.3	726	111	163
	sod	40	Evesboro/Galestown	sand/loamy sand	mesic, coated Typic Quartzipsamment/siliceous, mesic Psammentic Hapludult	6.0	32.4	127.7	108.6	714	90	196
Upper Marlboro	cropped	34	Adelphia/Donlonton	fine sandy loam	fine-loamy, mixed, active, mesic Aquic Hapludult/fine-loamy, glauconitic, mesic Aquic Hapludult	5.9	23.0	31.1	124.8	481	195	324
	sod	18	Adelphia/Donlonton	fine sandy loam	fine-loamy, mixed, active, mesic Aquic Hapludult/fine-loamy, glauconitic, mesic Aquic Hapludult	5.2	51.0	34.6	136.0	485	182	333
Keedysville	cropped	19	Hagerstown	silt loam	fine, mixed, semiactive, mesic Typic Hapludalf	6.5	36.0	140.9	267.3	148	597	255
	sod	51	Hagerstown	silt loam	fine, mixed, semiactive, mesic Typic Hapludalf	6.2	62.3	23.7	252.5	176	570	254
Holtwood	cropped	34	Glenelg/Chester	channery loam/silt loam	fine-loamy, mixed, semiactive, mesic Typic Hapludult	6.7	38.0	420.8	208.7	204	477	319
	sod	24	Glenelg/Chester	channery loam/silt loam	fine-loamy, mixed, semiactive, mesic Typic Hapludult	6.8	58.0	193.0	117.2	82	556	362

† Management history determined through farmer interviews and research of farm records.

‡ Values were measured in the A horizon (0–15cm depth) before any experimental treatments were applied.

was divided into four blocks, each containing two subplots. Subplots within each block were randomly assigned one of two possible winter cover crop treatments: rye cover crop or no cover crop (bare). At Holtwood, blocks and subplots had been established in 1998. To simplify operations for the commercial farmer at Holtwood, subplots were adjacent strips alternating systematically between rye and bare treatments. Adjacent rye and bare plots were considered one block. Because of this arrangement, all dependent variables at this site were examined for systematic spatial variability by plotting them along the spatial gradient. No systematic variance was observed.

Winter rye was planted in the rye treatment subplots in fall 2001 and fall 2002 after the summer crops were harvested (Table 2). Based on soil test results (Northeast Coordinating Committee on Soil Testing,1995) conducted by the University of Maryland Soil Testing Laboratory, all fields were limed and fertilized with P and K in late March 2002. Winter rye was killed each spring by applying glyphosate [*N*-(phosphonomethyl) glycine] at 1.2 to 1.5 kg a.i. ha^{-1} (Table 2).

Before killing the winter rye, cover crop shoot and root biomass were measured. Cutting as close to the soil surface as possible, all shoot biomass was harvested within two random, 0.25-m^2 areas within each rye subplot. These samples were weighed fresh (±0.5 g), dried for 4 d at 60°C, and reweighed (±0.5 g). The resulting moisture contents were used to calculate the dry matter biomass for each rye subplot. Rye biomass estimates were not obtainable at Upper Marlboro in spring 2003 because of the excessive wetness described below.

In rye subplots, winter rye root biomass was estimated by collecting a 1900-cm^3 core of soil to a 7.5-cm depth in areas where the shoot biomass was removed. Roots were washed by gently spraying soil off with a stream of water and catching roots in a nest of sieves (2-mm sieve nested above a 1-mm sieve). Coarse mineral fragments were hand separated from the roots. The washed roots were dried for 4 d at 60°C and weighed (±0.01 g).

Except where noted below, we measured weed shoot and root biomass on the bare subplots using the method described for rye. Weed biomass on bare subplots was not measured at Beltsville and Upper Marlboro in spring 2002 because these subplots were treated with 1.2 kg a.i. ha^{-1} glyphosate in March, resulting in negligible weed growth. Upper Marlboro weed growth was negligible, and not measured, in spring 2003 because of the excessive wetness described below.

The fields at the Upper Marlboro site were located in a low-lying area on the research farm. The wet conditions at Upper Marlboro in fall 2002 and spring 2003 (Fig. 1) caused prolonged periods of ponding on these fields shortly after the cover crops were sown in fall and again through much of the spring. Cover crop germination was negligible, essentially preventing implementation of a cover crop treatment, thus this site was not analyzed for effects and crop responses for 2003.

Main Crops

Corn or soybean [*Glycine max* (L.) Merr.] crops were planted subsequent to killing winter rye (Table 2). Soybean seeds were inoculated with *Rhizobium* before planting. In 2002, corn (Pioneer 34M94) was grown at Beltsville, Keedysville, and Upper Marlboro, while Holtwood produced soybean (Asgrow 4403). In 2003, Beltsville and Keedysville grew soybean

Table 2. Fertilizer applications and crop production schedules at four research sites for rye winter cover crops and subsequent summer crops.

Site	Winter rye planting date	Winter rye kill date	Main crop planting date	Main crop fertilization dates, fertilizer rate, fertilizer compound	Main crop harvest date
			Winter 2001–summer 2002		
Beltsville	24 Oct. 2001	1 May 2002	corn, 27 Apr. 2002	27 Apr.: 33.6 kg ha^{-1} N, NH_4NO_3† 6 June: 106.4 kg ha^{-1} N, NH_4NO_3	18 Sept. 2002
Upper Marlboro	26 Nov. 2001	15 May 2002	corn, 31 May 2002	15 May: 33.6 kg ha^{-1} N, urea–NH_4NO_3 3 June: 33.6 kg ha^{-1} N, urea–NH_4NO_3 19 June: 33.6 kg ha^{-1} N, urea–NH_4NO_3 2 July: 56.0 kg ha^{-1} N, urea–NH_4NO_3	29 Sept. 2002
Keedysville	20 Nov. 2001	16 May 2002	corn, 30 May 2002	11 Apr.: 56.0 kg ha^{-1} N, urea 30 May: 56.0 kg ha^{-1} P, triple super phosphate‡ 30 May: 112.1 kg ha^{-1} N, urea	5 Oct. 2002
Holtwood	29 Oct. 2001	22 Apr. 2002	soybean, 29 Apr. 2002	none applied	8 Oct. 2002
			Winter 2002–summer 2003		
Beltsville	18 Oct. 2002	12 May 2003	soybean, 25 June 2003	none applied	7 Oct. 2003
Keedysville	28 Oct. 2002	20 May 2003	soybean, 30 May 2003	44.8 kg ha^{-1} P, 56.9 kg ha^{-1} K, potassium metaphosphate‡§	17 Oct. 2003
Holtwood	29 Oct. 2002	2 May 2003	corn, 15 May 2003	15 May: 84.1 kg ha^{-1} N, NH_4NO_3 17 June: 84.1 kg ha^{-1} N NH_4NO_3	11 Oct. 2003

† At Beltsville, 16.8 kg ha^{-1} of N resulting from 2001 soybean stubble was taken into account when 2002 fertilizers were applied.

‡ Per University of Maryland Soil Testing Laboratory recommendations, P was applied to Keedysville sod history plot only.

§ Potassium metaphosphate was the only P-supplying fertilizer available at the time at the Keedysville site. Plant response to K applied should have been negligible because all plots at Keedysville tested excessive for K content.

(Pioneer 93B68), while corn (Garst 848Bt) was planted at Holtwood. Corn received N fertilizer as indicated in Table 2. Based on the results of soil fertility testing (Northeast Coordinating Committee on Soil Testing, 1995) conducted by the University of Maryland Soil Testing Laboratory, the sod field at Keedysville received P and K fertilizer in 2002 and 2003 (Table 2). During the summer drought in 2002 (Fig. 1), irrigation was applied at Upper Marlboro and Holtwood but was not available at Beltsville or Keedysville. Monthly precipitation data for 2001, 2002, and 2003 were collected from weather stations located within 16 km of the sites (Fig. 1).

Corn yields were estimated by harvesting two adjacent rows 6.1 m in length near the center of each subplot. Cobs and stalks were weighed (±0.01 kg) in the field. Randomly selected subsamples of cobs and stalks were weighed (±1 g) fresh and again after drying for 5 d at 60°C. Dry grain was then removed from the cobs and weighed (±1 g). We used these weights to calculate grain, stover (all aboveground non-grain material), and plant biomass (the sum of stover and grain) yields for each subplot.

Soybean yields were estimated by harvesting and weighing (±0.01 kg) all plants within two adjacent 3.0-m rows near the center of each subplot. A subsample of 10 plants was randomly collected, weighed (±1 g), dried for 5 d at 60°C, and weighed again (±1 g). Soybean seeds in these subsamples were removed from their pods and weighed (±1 g). Stover, grain (soybean seeds), and plant biomass yield estimates for each subplot were then calculated using these weights.

Grain, Stover, and Biomass Response to Cover Crop Treatment

Crop response to winter rye cover crop treatment was calculated for grain, stover, and plant biomass. Crop responses were calculated by subtracting the dry grain, stover, or biomass yield (kg ha^{-1}) in a bare subplot within a block from the dry grain, stover, or biomass yield (kg ha^{-1}) in the rye subplot within that block. For analyses of relationships across all sites, responses within blocks within a MH at each site were transformed to relative responses. Relative responses (kg ha^{-1}) for grain, stover, and biomass were calculated as

$$\text{Relative response} = \left(\frac{\text{yield in rye subplot} - \text{yield in bare subplot}}{\text{yield in bare subplot}}\right)\times 100 \quad [1]$$

Relative response is the percentage change between yields in rye subplots and bare subplots within a block. The use of relative responses allowed the examination of relationships between soil C parameters and crop response without the confounding effects of crop species and site.

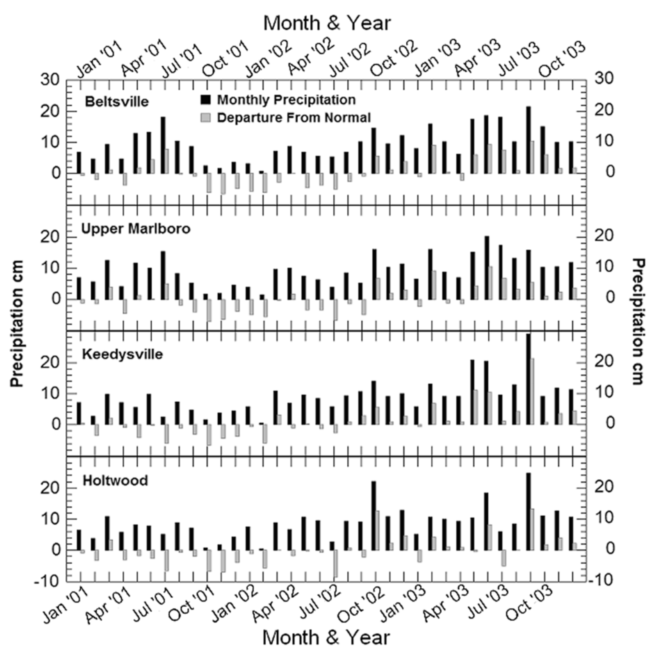

Fig. 1. Monthly precipitation and departure from normal for 2001, 2002, and 2003 at four research sites.

Soil Sample Collection and Processing

Before establishment of the experiment, soil testing was conducted on samples randomly collected from the 0- to 15-cm layer of soil in each field. Laboratory testing was conducted according to the methods described by the Northeast Coordinating Committee on Soil Testing (1995). Elemental fertility estimates were measured by Mehlich 3 extraction followed by inductively coupled plasma spectrophotometry. After the experiment was established, soil sampling for soil C parameters was conducted on 15 Oct. 2001 and 16, 22, and 24 Jan. 2002 for Holtwood, Keedysville, Beltsville, and Upper Marlboro, respectively. Composite soil samples were collected by taking 14 randomly located cores to a depth of 7.5 cm within each subplot. The 7.5-cm depth was chosen because most observable changes in no-till farming systems initially occur within the upper 5 to 10 cm of soil (Blevins et al., 1985; Dick et al., 1991). Samples were stored at 4°C until they were processed and analyzed. Soil samples were also taken in spring 2002 and spring 2003 for fertility analysis. These samples were also taken to a depth of 15 cm.

Soil Analyses

Field-moist soil was pushed through a 4-mm sieve to remove coarse debris and then passed through a 2-mm sieve and air dried. Particle size analysis was performed using the micropipette method described in Miller and Miller (1987). Analysis of TOC was performed with a LECO combustion analyzer (Tabatabai and Bremner, 1991). Soil POXC was estimated using the Weil et al. (2003) method, modified by reacting 2.5 g instead of 5.0 g of soil (<2 mm) with 20 mL of 0.02 mol L^{-1} $KMnO_4$ in 0.10 mol L^{-1} $CaCl_2$. The use of 2.5 g of soil was necessary because 5 g of a soil with very high POXC prevented accurate colorimetry by consuming all of the $KMnO_4$ in the reaction. Using 2.5 g of soil was also recommended by Stiles et al. (2011) for soils having high POXC.

Briefly, 2.5 g of soil was placed into a 50-mL plastic, screw-top centrifuge tube. The soil was reacted with 20 mL of a 0.02 mol L^{-1} $KMnO_4$ solution in 0.1 mol L^{-1} CaCl by shaking for 2 min on a reciprocating shaker at 180 rpm. After the samples settled for 10 min, a 0.5-mL aliquot of the supernatant was placed into 49.5 mL of distilled water and mixed by hand shaking. The solution absorbance at 550 nm was measured using a single-wavelength, hand-held colorimeter (Hach Co.). To determine the sample $KMnO_4$ concentration, the sample absorbance was compared with a standard curve that ranged from 0.005 to 0.02 mol L^{-1} $KMnO_4$. Sample POXC was calculated as in Weil et al. (2003) and Blair et al. (1995) as follows:

$$\mathrm{POXC}\left(\mathrm{mg\ kg}^{-1}\right)=\left[0.02\ \mathrm{mol\ L}^{-1}-\left(a+bz\right)\right]\times \left(9000\ \mathrm{mg\ C\ mol}^{-1}\right)\times\left(\frac{0.02\ \mathrm{L\ solution}}{0.0025\ \mathrm{kg\ soil}}\right) \quad [2]$$

where 0.02 mol L^{-1} is the initial concentration of the $KMnO_4$ reactant, a and b are the intercept and slope of the standard curve, respectively, z is the sample absorbance, 9000 mg C mol^{-1} is the amount of C (0.75 mol) oxidized by 1 mol of MnO_4, changing Mn^{7+} to Mn^{4+}, and 0.0025 kg soil is the amount of soil reacted with $KMnO_4$.

Statistical Analyses

Statistical analyses were conducted using Systat version 10 (Systat Software, Inc., Point Richmond, CA). Pearson's correlation was used to examine the relationships between crop parameters and soil C parameters. Stover, grain, and biomass ANOVA was performed using a split-plot model, where whole plots consisted of fields of contrasting MH and subplots consisted of cover crop treatment. For an ANOVA of crop measurements within one site, the error and degrees of freedom associated with blocks within MH were used to test whole-plot effects. Effects in subplots (cover crop treatment and cover crop × MH interactions) were tested using the error and degrees of freedom associated with the interaction between cover crop and blocks within MH. The interaction between cover crop and MH is relevant to testing our stated hypothesis. Significant interaction could indicate different crop responses to a cover crop in fields differing in MH. It should be noted that inferences on effects seen via ANOVA of single-site-level data should not be made beyond that site because replication occurs as blocks within a MH. Each block within a MH represents a pair of observations (one rye and one bare) within the same experimental unit (a field consisting of a specific MH). Because these blocks within a MH all lie within the same experimental unit, they are not statistically independent, true replicates.

In ANOVAs performed across multiple sites, each site represents a true, independent replication. When data were analyzed across multiple sites, the error term and degrees of freedom associated with blocks within MH within site were used to test whole-plot effects. Subplot effects were tested using the error and degrees of freedom associated with the cover crop × block interaction within MH within site. In the ANOVA models used, the random effects were site and block, while MH and cover crop were fixed effects. The cover crop × MH interaction within site and the residual error of cover crop × block within MH within site were also random effects. Means comparisons were conducted using Tukey's honestly significant difference test.

RESULTS AND DISCUSSION

Cover Crop and Weed Dry Matter and Organic Carbon Input Estimates

Cover crop shoot biomass and root biomass means for rye plots are given in Table 3. With the exception of rye grown at Keedysville in 2002, rye shoot inputs were not significantly different between fields of contrasting MH at each site. At Keedysville in 2002 there was significantly more rye aboveground biomass in the cropped field. This was probably due to a P deficiency noted in the sod field at this site in 2002 (Table 1). Despite P application on 30 Apr. 2002 at Keedysville, the fertilizer did not facilitate enough growth by 16 May 2002 for the rye biomass in the sod field to be similar to that in the cropped field.

Significant differences in rye root biomass inputs were seen at Upper Marlboro in 2002 and at Keedysville in 2003. The difference at Upper Marlboro in 2002 may have been an artifact due to the nature of the vegetation in the sod field

Table 3. Oven-dry root and shoot biomass for rye and weed cover at each site for fields with contrasting management history in 2002 and 2003.

Site	Cover plant	Plant part†	Biomass 2002 Cropped	Biomass 2002 Sod	Biomass 2003 Cropped	Biomass 2003 Sod
			kg ha^{-1}			
Beltsville	rye	roots	923.3	1642.1	2125.3	2340.0
		shoots	2845.0	3602.5	1830.0	2362.5
	weeds	roots	–	–	55.0	26.8
		shoots	–	–	47.3	111.8
Upper Marlboro	rye	roots	1387.6 a‡	7729.6 b§	–	–
		shoots	4212.5	3117.5	–	–
	weeds	roots	–	–	–	–
		shoots	–	–	–	–
Keedysville	rye	roots	2847.9	3988.9¶	630.5 a	1957.2 b¶
		shoots	7537.5 a	2702.5 b¶	2365.0	2340.0¶
	weeds	roots	–	–	2.7	–
		shoots	25.5	78.6	3.9	7.3
Holtwood	rye	roots	1578.4	1175.1	760.6	650.0
		shoots	3802.5	2345.5	637.5	630.0
	weeds	roots	–	–	23.9	1.2
		shoots	23.5 a	95.1 b	7.6	14.2

† Shoots were estimated by collecting all shoots in a 0.25-m^2 area. Roots were collected (to a depth of 7.5 cm) and washed from a 1900-cm^3 volume of soil sampled from areas where shoots were previously cut. Samples were dried at 60°C.

‡ Means followed by different letters in the same row and year indicate that ANOVA showed significant differences (α = 0.05) due to management history between these means.

§ This root value is probably confounded by the presence of roots from previous vegetation in the history field that had not fully decomposed when rye samples were taken.

¶ Rye in these plots was subject to grazing by deer.

before conversion to crop production in 2002. This vegetation consisted primarily of a mixture of fescue (*Festuca* spp.) cultivars, but there was also significant growth of small woody weeds whose roots had not completely decomposed by the time cover crop root samples were taken. During washing, these roots were difficult to separate from the rye roots and probably confounded the rye root weights.

The significant rye root difference seen at Keedysville in 2003 may have been due to sampling errors caused by the wet conditions at this site that spring. The soil was wet at the time of rye sampling and obtaining root cores in the cropped field was difficult compared with the sod field because the soil structure in the cropped field had been compromised by years of tillage. Significant differences in water-stable aggregates between the Keedysville sod and cropped fields (data not shown) provided evidence for these observed soil structure differences. Any significant interactions and crop responses to the cover crop at these sites should therefore be considered in light of these unintended rye biomass differences.

Carbon inputs due to weeds on bare plots were negligible (Table 3). The greatest weed biomass occurred in the sod field at Holtwood in 2002, where the weed biomass in the bare plots was approximately 4% of the rye biomass in rye plots. The weed biomass at Holtwood in spring 2002 was significantly different between contrasting MHs at this site, but this difference is negligible when compared with the total spring plant biomass difference between rye and bare treatments.

Crop Stover, Grain, and Total Biomass Yields

No significant cover crop × MH interactions were seen in stover yield at any individual site in 2002 (Table 4). The significant difference in corn stover yields between differing MHs at Beltsville in 2002 (Table 4) was probably due to the soils at this site being very sandy and drought sensitive. The higher SOM levels in the sod field may have provided enough additional water-holding capacity to promote greater stover yields during the severe drought conditions of 2002 (Fig. 1).

Soybean stover was significantly greater in the cropped field at Holtwood in 2002 (Table 4), possibly due to a difference in K availability. Soil test K in the cropped field was optimum to excessive, while in the sod field soil test K was in the moderate to optimum index range (Table 1). No K fertilizer was applied at this site. Soybean has a high K demand (Cox and Uribe, 1992), and most K taken up moves to the roots by a diffusion gradient, a process that can be impeded by dry soil conditions (Haby et al., 1990). The drought conditions in 2002 may have exacerbated any soil K differences in these fields (soybean tissue was not analyzed for K).

In 2002, the corn grain yield was significantly greater in the cropped fields at Keedysville and Upper Marlboro (Table 4). The sod fields at these sites were brought directly from sod into no-till management. Sod had been killed in place, with residues left in and on the soil, possibly causing N immobilization that limited grain production. Scharf et al. (2000) reported this phenomenon in corn that was grown immediately following sod on land that had been enrolled in the Conservation Reserve Program. No significant cover crop × MH interactions were observed (Table 4).

At Beltsville in 2003, soybean stover and grain yields were significantly greater in the sod field than in the cropped field (Table 4). Despite the relatively wet conditions in 2003 (Fig. 1), SOM may again have played a role in improved water-holding capacity in the sod field at this sandy site. At Keedysville, soybean stover and grain yields were significantly greater in the cropped field (Table 4), possibly because of the proximity of the sod field to a forested area that promoted crop damage by deer. On 30 July 2003, crop injury due to deer grazing was observed to be more severe in the sod field than in the cropped field, which was farther from the tree line. While electric deer fencing was installed by the farm manager at this site in mid-July, the damage before that time may have been enough to cause the difference seen in crop yield parameters.

Whole-plant biomass was significantly higher (29%) in the cropped fields at Holtwood in 2002 and at Keedysville (56%) and Holtwood (8%) in 2003 (Table 4). Biomass was significantly higher (44%) in the sod field at Beltsville in 2003. No cover crop × MH interactions were seen at individual sites in 2002, but in 2003 there was significant cover crop × MH interaction at Keedysville. Biomass was 27% higher in rye plots in the cropped field at Keedysville compared with 10% higher in rye plots in the sod field.

There were significant cover crop × MH interactions in 2003 crop stover yields at Keedysville and Holtwood (Table 4). At Keedysville, soybean stover yield was 28% higher in rye plots in the cropped field, while in the sod field the increase was only 11%. At Holtwood, a similar trend was observed, with rye plots in the cropped field yielding 23% more corn stover, while rye plots in the sod field yielded 9% less corn stover than bare plots. A similar but nonsignificant trend was also seen at Beltsville. The

Table 4. Mean dry stover, grain, and biomass yields of crops grown in 2002 and 2003 with (rye) and without (bare) a cover crop.

Plant part	Site	Crop	Field management history		Cover crop within management history			
					Cropped		Sod	
			Cropped	Sod	Rye	Bare	Rye	Bare
			Mg ha^{-1}					
			2002					
Stover	Beltsville	corn	4.85 a†	6.13 b	5.11	4.59	5.74	6.53
	Upper Marlboro	corn	6.33	6.02	6.76*	5.89*	7.34*	4.70*
	Keedysville	corn	6.65	7.15	8.42*	4.88*	8.04*	6.26*
	Holtwood	soybean	9.53 a	7.57 b	10.19	8.88	7.87	7.27
Grain	Beltsville	corn	6.44	6.26	6.71*	6.18*	7.51*	5.01*
	Upper Marlboro	corn	5.48 a	4.24 b	5.44	5.53	4.03	4.45
	Keedysville	corn	8.74 a	7.41 b	8.85	8.63	7.66	7.15
	Holtwood	soybean	4.30	3.19	4.68	3.92	3.72	3.11
Biomass	Beltsville	corn	11.29	12.39	11.81	10.76	13.25	11.54
	Upper Marlboro	corn	11.81	10.27	12.20*	11.41*	11.37*	9.16*
	Keedysville	corn	15.39	14.56	17.28*	13.51*	15.71*	13.41*
	Holtwood	soybean	13.83 a	10.76 b	14.86	12.80	11.14	10.38
			2003					
Stover	Beltsville	soybean	3.43 a	4.86 b	3.90	2.96	4.79	4.92
	Keedysville	soybean	5.14 a	3.28 b	5.77‡	4.51‡	3.45‡	3.11‡
	Holtwood	corn	5.69	5.18	6.28‡	5.09‡	4.96‡	5.41‡
Grain	Beltsville	soybean	1.85 a	2.72 b	2.08	1.61	2.64	2.81
	Keedysville	soybean	3.18 a	2.04 b	3.56‡	2.80‡	2.11‡	1.97‡
	Holtwood	corn	10.02	9.37	10.32*	9.31*	9.61*	9.13*
Biomass	Beltsville	soybean	5.28 a	7.58 b	5.98	4.58	7.43	7.73
	Keedysville	soybean	8.32 a	5.32 b	9.33‡	7.32‡	5.56‡	5.08‡
	Holtwood	corn	15.70 a	14.55 b	17.00	14.41	14.56	14.54

* Rye cover crop treatment had a significant effect on yields in the same row at $P < 0.05$.

† Means followed by different letters in the same row are significantly different ($\alpha = 0.05$) due to management history.

‡ Significant interaction between cover crop and management history in the same row at $P < 0.05$.

Keedysville results could possibly be confounded by deer activity, but the general trend is consistent with that seen at other sites.

Grain yields at Keedysville also showed significant cover crop × MH interaction in 2003, with the rye plots yielding 27% more in the cropped field but only 7% more in the sod field than the bare plots (Table 4). If the significant interactions seen in 2003 at Keedysville and Holtwood are related to soil C changes occurring with the rye treatment, it is interesting to note that these two sites are Piedmont province sites that have much finer soils than the sandy soils found at the two Coastal Plain sites of Upper Marlboro and Beltsville (Table 1). According to Six et al. (2002), greater silt and clay contents, as seen in the two Piedmont soils, impart a higher C saturation threshold to a soil. Thus the Piedmont soils should be capable of accumulating a greater amount of soil organic C than the sandier Coastal Plain soils.

The overall effect of MH within site on stover was significant in 2002 ($P = 0.018$) and 2003 ($P < 0.001$); however, this effect is difficult to interpret because of the nested nature of the variables and because the general trend was not the same at each site where a significant effect was observed. Beltsville had significantly higher stover production in the sod field in both 2002 and 2003, while Holtwood and Keedysville had significantly higher stover production in their cropped fields in 2002 and 2003, respectively (Table 4).

The overall effect of MH within site on grain yield was significant in 2003 ($P < 0.001$) but not in 2002. In 2003, similar to the situation described for stover, the results are difficult to interpret. No uniform trend was seen across all sites. Beltsville had a significantly higher grain yield in the sod field, while Keedysville had significantly higher grain production in the cropped field in 2003 (Table 4).

Overall, the effect of MH within site on the total biomass was significant in both 2002 ($P = 0.049$) and 2003 ($P < 0.001$). Again, this result is difficult to interpret for the same reasons discussed regarding grain and stover.

No significant cover crop × MH within site interaction was seen in grain, stover, or total biomass yields analyzed across all sites in 2002. In 2003, significant cover crop × MH interaction within site was present for the stover ($P = 0.022$) and total biomass ($P = 0.032$) yields, but not grain yields, across all sites. In the cropped fields, stover production was generally higher in rye plots than in bare plots (Table 4). In sod fields, this difference averaged only 2.8%. A similar trend can be seen in total biomass in Table 4.

The significant interactions observed in 2003 indicate that when responses occurred, crops, particularly crop stover production, responded more positively to the cover crop in cropped fields than in sod fields. The data from 2002, while not statistically significant, suggest that the trend was beginning to appear in crop parameters measured that year. This may indicate that the effects of cover crops were cumulative in nature. This trend was similar in all three sites that received 2 yr of cover crop treatment.

The interaction between cover crop and MH was of primary interest in this research; however, we also observed instances where this interaction was not present and the rye treatment had a significant, positive impact on crop productivity (Table

4). In 2002, crop stover and total biomass production was significantly greater on rye subplots at Upper Marlboro and Keedysville. Corn grain yields were significantly greater in rye subplots at Beltsville in 2002 and at Holtwood in 2003. The effects seen in 2002, when crops were subjected to drought (Fig. 1), were probably due to improved soil moisture retention under the mulch-like layer of rye residues in the rye subplots. The rye effect at Holtwood in 2003 may have been due to improved N availability to corn in the rye subplots. Rye cover crops scavenge residual soil N (Ranells and Wagger, 1997) and improve soil organic N levels (Kuo et al., 1997b). At Holtwood, rye may have assimilated residual mineral N from the 2002 soybean crop and, as the rye residues decayed, returned it to the soil as organic N, improving the N mineralization potential in the rye subplots.

Total Carbon and Labile Soil Carbon

The effect of MH on TOC was highly significant at each site (Table 5). The sod fields had 87, 112, 114, and 80% greater TOC levels than the cropped fields at Beltsville, Upper Marlboro, Keedysville, and Holtwood, respectively. The effect of MH was also significant on POXC at each site (Table 5), following the same trend seen in TOC. The sod fields had 39, 78, 79, and 36% greater POXC than the cropped fields at Beltsville, Upper Marlboro, Keedysville, and Holtwood, respectively. There was a close relationship between POXC and TOC (Fig. 2). Based on the initial SOM analysis (Table 1), these results were expected and essential to testing the hypothesis of greater crop response in fields that test lower for POXC. This relationship is similar to that found across a wide range of surface soils by Culman et al. (2012) and suggests that POXC can also serve as a rapid and field-adaptable method to estimate TOC.

Relationships between Crop Response and Soil Carbon Parameters

In general when crop responses to the rye cover crop treatment were significantly related to soil C parameters, lower levels of soil C parameters coincided with greater crop response (Table 6). The only significant relationships seen in 2002 were observed in the stover response to the rye treatment. In 2002, the relative response of stover to the rye treatment across all sites was not significantly correlated with TOC or POXC. Within the Piedmont (Keedysville and Holtwood), however, the relative response of stover was significantly correlated to POXC ($r = -0.60$). In the Piedmont, greater stover responses coincided with lower levels of POXC, supporting our initial hypothesis that low POXC may be predictive of a crop response to improved SOM management. The comparable relationships were not significant at Coastal Plain sites (Beltsville and Upper Marlboro). The relationships seen in the Piedmont soils may have been due to the finer texture of these soils, which could have a lower level of C saturation leading to greater potential accumulation of soil organic C relative to the coarser Coastal Plain soils (Six et al., 2002). When the results at each site were examined, it was observed that the stover response was significantly correlated to TOC at Upper Marlboro ($r = 0.72$) but not at the other sites. At Upper Marlboro, a greater stover response to rye coincided with higher TOC levels. This was the only instance in which a greater crop response coincided with higher soil C levels. The results seen in this instance may have been confounded by the fact that

Table 5. Mean values for total soil organic C (TOC) and permanganate-oxidizable C (POXC) in fields with contrasting management history at each research site.

Site	TOC		POXC	
	Cropped	Sod	Cropped	Sod
	g kg^{-1}		mg kg^{-1}	
Beltsville	9.4 a†	17.6 b	374.2 a	520.6 b
Upper Marlboro	11.7 a	24.8 b	413.7 a	738.1 b
Keedysville	13.3 a	28.4 b	413.4 a	740.8 b
Holtwood	16.8 a	30.2 b	572.6 a	777.6 b

† For paired fields of differing management history at each site, different letters following the means beneath each soil C parameter indicate that these means are significantly different ($P < 0.001$).

corn at this site was regularly irrigated. Elevated SOM combined with rye cover crop mulch may have held more of the irrigation water, providing more available water to the corn crop during the 2002 drought (Table 1).

We observed multiple significant relationships between crop responses to the rye treatment and soil C parameters in 2003, after the sites had received at least 2 yr of cover crop treatment (Table 6). Due to the wet conditions described above at Upper Marlboro in 2003, and consequentially the lack of a cover crop treatment in 2003, this site was not included in the across-site analyses of relative responses for the second year of the experiment. When analyzed across the other three sites in 2003, the relative response of stover was significantly correlated to both POXC ($r = -0.48$) and TOC ($r = -0.57$). The relative response of grain was significantly correlated with TOC ($r = -0.43$). A significant negative correlation was also seen between the relative response of biomass and both POXC ($r = -0.42$) and TOC ($r = -0.50$). When analyzed within the finer soils of the Piedmont sites, these relationships were stronger (Table 6), and the relative response of grain was also significantly correlated with POXC ($r = -0.54$). The relationship between the relative response of biomass and POXC in the Piedmont is shown in Fig. 3. In 2003, all crop parameters showed a

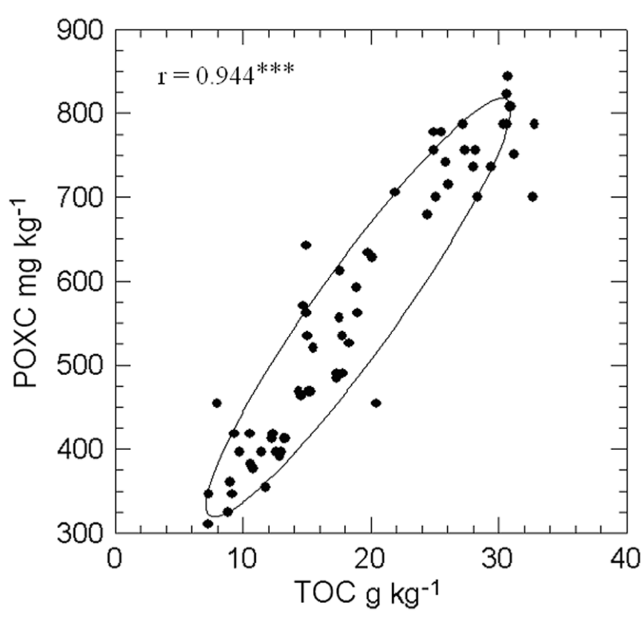

Fig. 2. Relationship between total soil organic C (TOC) and permanganate-oxidizable C (POXC) in soils from four research sites. The Gaussian bivariate confidence ellipse has $P = 0.6278$. ***Significant correlation at $P < 0.001$.

greater response to the rye treatment at lower levels of soil C parameters. The strength of the relationships of crop parameters to both POXC and TOC was similar.

In 2003, stover response, grain response, and biomass response were significantly related to TOC but not POXC at Beltsville (Table 6). There were greater crop responses at lower levels of TOC at this site. At Keedysville, significantly greater stover response coincided with lower levels of both POXC ($r = -0.74$) and TOC ($r = -0.79$). The biomass response at Keedysville in 2003 was also negatively correlated with POXC ($r = -0.72$) and TOC ($r = -0.76$). There was also a similar significant negative correlation between grain response and TOC ($r = -0.72$) but not grain response and POXC. At Holtwood, stover response and biomass response were significantly greater at lower levels of POXC, and greater stover response also coincided with lower levels of TOC. No significant relationships between grain response and soil C parameters were seen in 2003 at Holtwood.

In general, when the relationships between soil C parameters and crop responses to the rye cover crop treatment were significant, POXC and TOC were comparable to one another in terms of their ability to predict the crop response. When significant, relationships between crop responses and POXC were slightly less strong than those with TOC when analyzed across all sites (Table 6). This slight disparity is probably due to the nonsignificant relationships between POXC and crop response seen at the Beltsville site in 2003. In the finer textured soils of the Piedmont locations, POXC was a slightly better predictor of crop response in grain and biomass, while TOC was slightly better when stover response was analyzed. At Holtwood, where cover crop treatments had been in place for 3 yr before the initiation of this study, crop response relationships with POXC were stronger than those with TOC (Table 6).

The Beltsville site provided an exception to the general similarity of soil C parameters in crop response predictability. At this location in 2003, strong, significant crop response relationships were seen with TOC but no relationships with POXC were statistically significant. Hudson (1994) documented the strong positive correlation between plant-available water content and TOC in sandy soils. It is likely that plant-available water content was influenced by TOC in the sandy soils at Beltsville, possibly driving the relationship between crop responses and TOC at this site. Specifically, in rye subplots in the cropped field at Beltsville, the decomposing cover crop residues probably acted as a mulch, holding more water than the bare subplots and allowing greater crop yields. The importance of this mulch effect may have been less in the sod field where more SOM was present in general.

That SOM should be an important factor in crop productivity in sandy soils should not be surprising. It is the main source of the cation exchange capacity (CEC) and nutrient holding in sandy soils (Yuan et al., 1967). Soil organic matter, in conjunction with microbial activity, is the primary driving force behind the development of good soil structure in sandy soils (Oades, 1993), and as shown in Hudson (1994), it is a major factor in the soil water-holding capacity. In soils where SOM contents were severely degraded, Kimetu et al. (2008) saw more improvement in crop yields in sandy soils, relative to finer textured soils, when SOM management practices such as green manures and animal manures were applied. It is curious that TOC showed strong relationships with crop responses, while POXC did not, at the Beltsville site. The majority of

Table 6. Correlations between crop responses [= (yield in rye plot) – (yield in bare plot) for rye and bare plots in the same block] to a winter rye cover crop and the soil C parameters of permanganate-oxidizable C (POXC) and total soil organic C (TOC). Relative responses [= (crop response in a block)/(yield in bare plot in that block)] were used when relationships were evaluated across more than one site.

Soil C parameter	Pearson's correlation coefficient (*r*)					
	2002			2003		
	Stover	Grain	Biomass	Stover	Grain	Biomass
Relative response across all sites						
POXC	0.02	–0.16	0.00	–0.48*	–0.35	–0.42*
TOC	0.05	–0.14	0.04	–0.57**	–0.43*	–0.50*
Relative response across Coastal Plains sites (coarser textured soils)						
POXC	0.46	–0.25	0.19	–	–	–
TOC	0.48	–0.18	0.28	–	–	–
Relative response across Piedmont sites (finer textured soils)						
POXC	–0.60*	0.11	–0.26	–0.66**	–0.54*	–0.64**
TOC	–0.48	0.03	–0.23	–0.68**	–0.51*	–0.62**
Beltsville, MD						
POXC	–0.43	0.30	–0.13	–0.38	–0.39	–0.38
TOC	–0.20	0.46	0.15	–0.73*	–0.77*	–0.75*
Upper Marlboro, MD						
POXC	0.70	–0.12	0.54	–	–	–
TOC	0.72*	–0.02	0.60	–	–	–
Keedysville, MD						
POXC	–0.55	0.16	–0.28	–0.74*	–0.67	–0.72*
TOC	–0.55	0.09	–0.33	–0.79*	–0.72*	–0.76*
Holtwood, PA						
POXC	–0.20	–0.33	–0.28	–0.84**	–0.52	–0.74*
TOC	–0.13	–0.27	–0.21	–0.77*	–0.44	–0.66

* Correlation is significant at $P < 0.05$.
** Correlation is significant at $P < 0.01$.

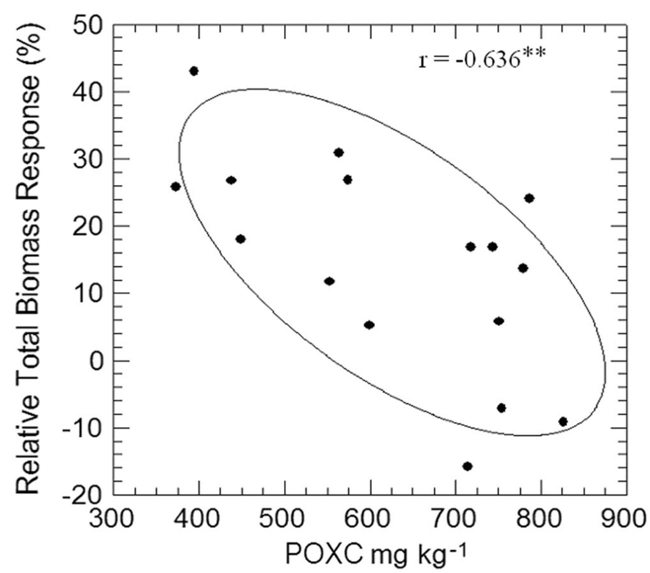

Fig. 3. Relationship observed in crops grown in 2003 between relative total biomass response to a rye cover crop and permanganate-oxidizable C (POXC) content in soils at two sites in the Piedmont physiographic region of the Mid-Atlantic United States. The Gaussian bivariate confidence ellipse has *P* = 0.6278. **Significant correlation at *P* < 0.01.

TOC consists of humified substances that provide significant water-holding capacity and CEC to soils (Stevenson, 1994), while Weil et al. (2003) stated that POXC measured by their method estimates a C pool more closely associated with soil biological functions. In the drought-prone sandy soils at Beltsville, water is probably the most important, potentially limiting factor in determining crop growth, particularly when fertility is bolstered through use of soluble fertilizers. Speculatively, perhaps the benefits of humic SOM are more important than those of biologically active SOM in sandy soils when adequate fertilizers are applied. It should also be noted that the correlation between POXC levels and TOC levels, while strong, was lowest at Beltsville ($r = 0.78$) compared with Upper Marlboro ($r = 0.98$), Keedysville ($r = 0.98$), and Holtwood ($r = 0.91$), suggesting that there may be a somewhat different relationship between POXC and TOC in coarser textured soils. Tirol-Padre and Ladha (2004) previously noted that different labile organic compounds were not oxidized uniformly by $KMnO_4$ in different-textured soils.

CONCLUSIONS

This research has shown that at three sites in the Mid-Atlantic region of the eastern United States, crops grown following at least 2 yr of winter rye cover crops generally gave a greater positive response to cover crops in fields that initially tested lower in TOC and POXC when compared with crop responses in fields that initially tested higher in TOC and POXC. Greater responses were seen in fields where TOC tested between 9.4 and 16.8 g kg^{-1} and POXC tested between 374 and 573 mg kg^{-1} compared with fields where TOC tested between 17.5 and 30.0 g kg^{-1} and POXC tested between 521 and 778 mg kg^{-1}. This positive response was more consistent in stover and total biomass than in grain. During 2 yr of observation, the responses were stronger in finer textured soils. The less consistent grain response may have been due in part to fluctuations in weather conditions, such as the unusually dry midseason in 2002, which may have affected pollination.

The POXC ranges where we observed responses should not be taken as threshold values where larger or smaller crop responses to SOM management will or won't occur. The same environmental factors (climate, topography, soil texture, etc.) that make it difficult to directly link crop yields to SOM levels are also likely to make it difficult to establish a standard POXC index that rates POXC levels as poor, moderate, or optimal. Such an index may be possible at regional levels or within soil types; however, these values have yet to be established. This is an area where more research is required.

Our results suggest that POXC and TOC are generally comparable in predicting a crop response to SOM management with winter rye. In the sandy soil we studied, only TOC was predictive of crop responses. This was possibly due to the water-holding properties of the humified materials that comprise the largest proportion of TOC. The relationship between POXC and TOC in coarse-textured soils may also require further study. While POXC by the Weil et al. (2003) method was closely correlated with TOC, the POXC methodology is simpler and more rapid than the TOC methodology. The Weil et al. (2003) POXC method may be attractive for laboratories wishing to conduct rapid assessments of SOM and, unlike current methods for estimating TOC, it is also practical for use in on-site field testing. Assessing POXC using 0.02 mol L^{-1} $KMnO_4$ as described in Weil et al. (2003) is a promising tool for SOM-based evaluation of SQ and identification of situations where improved SOM management may lead to higher soil and crop productivity. As suggested by Weil et al. (2003) and Stiles et al. (2011), this test may be a beneficial addition to the current NRCS SQ test kit and other field evaluation protocols (Card, 2004; Franks et al., 2004) that do not include any test for SOM.

Further study of POXC as a potential tool for predicting crop productivity responses to SOM management should attempt to evaluate the crop response predictive potential of the test across a broader range of soils, crops, SOM management practices, and regions. In light of the fact that the strongest relationships between crop responses and soil C parameters seen in this study were at the site that had more years of winter rye cover crop treatments (Holtwood), studies that span a longer time period may be useful in evaluation of the cumulative effects of improved SOM management. It would also be useful to develop a POXC index that establishes guidelines for what constitutes good, fair, and poor amounts of POXC in specific soil types.

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