EVALUATING SOIL QUALITY ON RECLAIMED COAL MINE SOILS IN INDIANA[1]

C.A. Seybold, R.B. Grossman, H.R. Sinclair, K.M. McWilliams, G.R. Struben, and S.L. Wade[2]

Abstract. On cultivated cropland, soil quality of reclaimed soils after surface mining for coal can be lower than that of the quality before mining. The objectives of the study were to evaluate near surface and profile soil quality on eight soils reclaimed to agricultural land in southwestern Indiana. Several near-surface properties were measured and a soil quality index score calculated from a minimum data set (MDS) of six indicators. The scoring function ranges were based on the soil condition before mining. The near-surface properties of bulk density, soil strength, aggregate stability and particulate organic matter (POM-C) were within the limits observed for cultivated surface horizons. However, surface properties could be improved through best management practices. The profile soil quality was lower on all eight reclaimed sites. The index scores ranged from 68 to 87 on a scale from 0 to 100. The properties that were a major factor in lowering the soil quality of the reclaimed soils were a poor or massive soil structure, lower available water capacity, and increased bulk densities. Organic C, CEC, and soil pH on most sites were generally comparable to the condition before mining. The poor or massive structure, higher bulk densities, and lower AWC of the reclaimed soils could result in water stress and/or lower productivity. Under doughty conditions especially under doughty conditions compared to the reference soil condition before mining.

Additional Key Words: soil quality index, POM, near surface properties.

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[2] Cathy A. Seybold, Robert B. Grossman, and H. Raymond Sinclair, soil scientists, USDA-NRCS, Lincoln, NE 68508. Kendall M. McWilliams, soil scientist, USDA-NRCS, Jasper, IN 47546. Gary R. Struben, soil scientist, USDA-NRCS, Indianapolis, IN. Steve L. Wade, soil scientist and agronomist, Indiana Dept. of Natural Resources-Div. of Reclamation, Jasonville, IN.

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Introduction

Coal mining in west-central and southwestern Indiana has been occurring for more than 150 years (Indiana Geological Survey, 2003). After coal mining, the land must be restored to its pre-mining use or a reasonably likely higher use (Surface Mining Control and Reclamation Act of 1977). Consequently, topsoil removal and handling, and establishment of vegetation become very important. In general, the reclamation operation consists of stock piling and replacing the A and B horizons, and may involve deep subsoiling with a deep-ripper after refilling the original excavations. Reclaimed surface mined soil can have lower soil fertility and organic matter contents, soil compaction problems, massive soil structure, inadequate rooting depths, low water holding capacities, and low soil pH values (Bell et al., 1994; Guebert and Gardner, 2001; Akala and Lal, 2001; Steinhardt et al., 1987; McSweeney and Jansen, 1984). As a result, reclaimed sites often have a lower soil quality for growing crops than the soil before mining.

Soil quality is simply defined as "the capacity of a specific kind of soil to function" (Karlen et al., 1997). In other words, where land use practices diminish, the capacity of the soil to function and soil quality is diminished. Soil function refers to what the soil does such as maintaining productivity, regulating and partitioning water and solute flow, filtering and buffering against pollutants, and storing and cycling nutrients. In a broader sense, soil quality can be used as an indicator of sustainability (Doran et al., 1996). Evaluating soil quality involves measuring soil properties that serve as sensitive indicators of change in soil functions (Karlen et al., 1997). There is no single measurement that will always be useful for evaluating soil quality. Therefore, a minimum data set (MDS) of soil properties or indicators has been proposed as a means to infer the soil's ability to perform basic functions. Many of the soil properties found in these MDSs are those that can limit productivity on reclaimed surface mine soils (Bendfeldt et al., 2001).

When assessing soil quality using a MDS, the indicators can be integrated into an index of overall soil quality (Andrews and Carroll, 2001). Karlen et al. (2003) describes three steps that are involved in developing a soil quality index. The first is selecting appropriate soil quality indicators too efficiently and effectively monitor critical soil functions as determined by specific management goals, such as productivity in this paper. Collectively, the indicators reflect how well critical soil functions associated with each management goal are being performed. Each indicator is scored, often using ranges established by the soil=s inherent capacity or from a reference condition. This step allows for the comparison of the different indicator measurements that have totally different measurement units. The unitless values are then combined into an overall index of soil quality. Surface layer properties are the most sensitive to changes in land use and management. Therefore, soil quality evaluation is focused at, but is not limited to the near soil surface. However, surface mining disturbs the whole soil, and thus, soil quality should be evaluated to include subsoils as well.

The objective of this study was to evaluate soil quality on eight soils reclaimed to agricultural land in Indiana. Specifically, a soil quality index was used to evaluate soil quality of the soil profile. The pre-mining soil condition was used as the reference or standard in the development of the index. Also, soil quality of the near surface will be evaluated using selected soil quality indicators. Discussions will include comparisons of relative soil quality among the eight reclaimed soils and how they compare to agricultural soils in the area before mining.

Materials and Methods

A total of eight reclaimed surface-mine soil sites located in Daviess, Greene, Pike, and Warrick counties in Indiana were studied (Fig. 1). The classification of the soils before mining and years since being reclaimed to agricultural land at each site are listed in Table 1. Sites B, C, D, E, G, and H were in cropland with some combination of a corn-wheat-soybean or corn-wheat-double crop soybean rotation. Site A was in idle cropland (not cropped because of poor productivity) and site F was in grass hay. At each site a pit was opened and the soil profile described. Soil depth, texture, rock fragment content, structure, rupture resistance, color, and root size and density were described for each horizon using standard soil description techniques (Schoeneberger et al., 2002). Soil samples were collected from each horizon and sent to the National Soil Survey Laboratory in Lincoln, Nebraska for analysis. Properties determined were particle size separates (pipette method), bulk density (clod method), water content at 33 and 1500 kPa, cation-exchange capacity (CEC) (buffered ammonium acetate), total C, and pH (1:1 soil:water). All methods are described in Soil Survey Staff (1996). Particulate-organic-matter carbon (POM-C), organic matter associated with the mineral fraction (C-min) and root biomass were determined on the 0-20 cm soil depth, respectively.

POM-C and C-min were determined following the method of Cambardella and Elliot (1992). Root biomass was retained on #30 mesh sieve with 0.084-mm openings (after Brown and Thilenius, 1976).

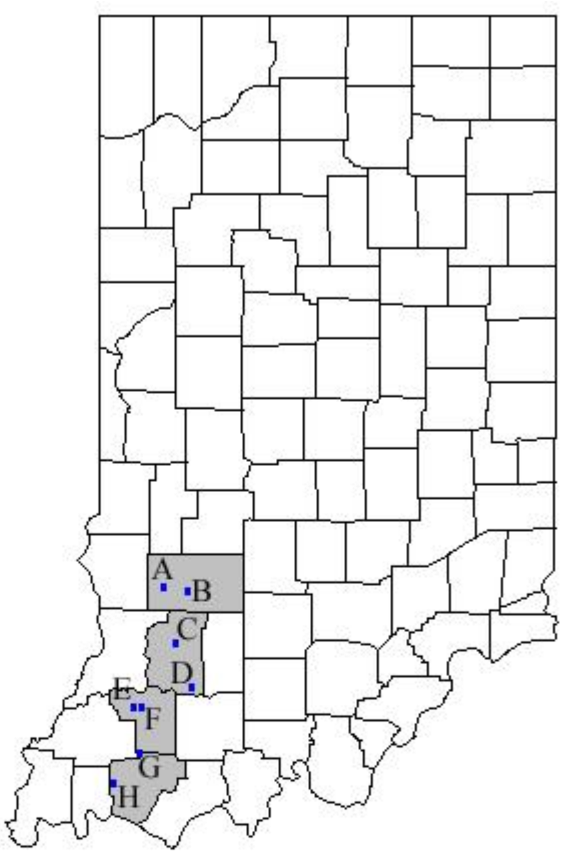

Figure 1. Location of sampling sites in Indiana.

Additional samples were taken from the 0-7.6 cm depth, at three random locations near the pit, for determination of aggregate stability (on-site method of Seybold and Herrick, 2001). Percent of stable aggregates (% of soil > 0.25 mm) was calculated as (weight of sieve plus dry aggregates B weight of sieve plus dry sand)) (weight of sieve plus air-dried soil B weight of sieve plus dry sand) H 100. Bulk density by the ring excavation procedure (Grossman and Reinsch, 2002) was determined on 0-5, 5-10, and 10-20 cm soil depths. Soil surface strength (to 3 cm depth) was measured using a modified singleton blade and pocket penetrometer (Griffiths, 1985). A 15-cm putty knife was used in place of the original singleton blade.

Soil properties and morphological characteristics before mining were obtained from soils of the same series that had been previously characterized as part of an ongoing soil survey. The data are stored in the National Soil Survey characterization database in Lincoln, Nebraska. Soils were selected that had the closest location to the sites in this study and that were cultivated.

Table 1. The soil classification before mining and years reclaimed to agriculture for eight sites in Indiana.

Site	County	Pre-mining soil series	Pre-mining classification	Years reclaimed
A	Greene	Vigo	Fine-silty, mixed, superactive, mesic Aeric Glossaqualfs	16
B	Greene	Shakamak	Fine-silty, mixed, active, mesic Aquic Fragiudalfs	17
C	Daviess	Alford	Fine-silty, mixed, superactive, mesic Ultic Hapludalfs	14
D	Daviess	Hosmer	Fine-silty, mixed, active, mesic Oxyaquic Fragiudalfs	6
E	Pike	Hosmer	Fine-silty, mixed, active, mesic Oxyaquic Fragiudalfs	12
F	Pike	Pike	Fine-silty, mixed, superactive, mesic Ultic Hapludalfs	10
G	Warrick	Hosmer	Fine-silty, mixed, active, mesic Oxyaquic Fragiudalfs	15
H	Warrick	Hosmer	Fine-silty, mixed, active, mesic Oxyaquic Fragiudalfs	13

These soil conditions before mining were used as the standard or reference condition for the reclaimed soils in the calculation of a soil quality index. In addition, properties of an uncultivated (natural) site of the Alford series were also obtained from the National Soil Survey characterization database. This natural uncultivated condition was used to demonstrate soil quality differences between cultivated and noncultivated conditions within the same series.

The near-surface morphological index of Grossman et al. (2001) was modified to provide a morphological index for the whole soil. The modification was extending the depth of observation from 30 cm to a deeper depth in the soil profile. In summary, the index combines information about soil texture, structure, and moist rupture resistance. The index requires a determination of a texture-weighting class, structure class, and rupture-resistance class for each horizon (Grossman et al., 2001). The texture-weighting class is based on the percentage of clay. The structure class is determined by type, grade, and size of structural units in combination that are judged to function similarly. These features are described in the Soil Survey Manual (Soil Survey Division Staff, 1993). The combinations of grade, type, and size of the structural units are grouped into five classes based on a judgement for separating levels of soil permeability and resistance to root growth

(Grossman et al., 2001). The structure class and rupture-resistance classes are then integrated into an index class of structure-rupture resistance (SRI) for each horizon or zone based on a set of rules (Grossman et al., 2001). The SRI score for each horizon is multiplied by the horizon thickness in cm. The horizon SRI scores are summed and divided by the profile thickness (cm) to get an overall index of morphology for the soil. The index score is then put on a 0-100 scale by subtracting one from the profile index score, dividing by 4, and multiplying by 100. A profile morphological index was determined for each reclaimed site and reference soil pair.

A soil quality index was calculated for each site from a MDS consisting of organic C content (OC), CEC, pH, available water capacity (AWC), bulk density (Db), and the morphology index (structure and rupture resistance) of the soil.

$$\text{SQ index} = f(\text{OC, CEC, pH, AWC, Db, morphology}) \qquad \mathbf{(1)}$$

The soil quality index model is based on the additive index of Doran and Parkin (1994) and use of scoring functions described in Karlen et al. (1994) and Andrews and Carol (2001). Each property of the reclaimed soil is compared to a standard, and placed on a standardized scale from 0 to 1 using linear scoring functions. The standard or reference condition is the cultivated soil condition before mining and equates to a score of one. Any score between 0 and 1 is functioning less than the standard or soil condition before mining. The scores for OC, CEC, pH, AWC, and the morphology index were based on a Amore is better@ scoring function. The bulk density scores were based on a Aless is better@ scoring function because of the inhibitory effect that high bulk densities have on root growth and development. The scores are added together and divided by the number of indicators, and multiplied by 100. Dividing by the number of indicators corrects for any missing data. The index range is from 0 to 100. All properties are given equal weight in the index except bulk density, which is given twice the weight (because of its inhibitory effects on root growth and development).

Results and Discussion

Near-surface Properties

The near-surface properties are presented in Table 2. The highest bulk densities of the near surface were found in the 10-20 cm soil depth, which ranged from 1.42 to 1.62 Mg m^{-3}. Bulk density values at the higher end of this range (∃1.60 Mg m^{-3}) may affect root growth and development (Pierce et al., 1983; Grossman et al., 1992). Higher bulk densities at the 10-20 cm soil depth are common in a cultivated or plowed soil with loamy textures, but are not desirable. Compaction from tillage equipment is the most likely cause. Surface soil strength measurements ranged from 20 to 130 N. These soil strength measurements (using the Singleton method) indicate the degree of packing of the soil particles. The values do not indicate any physical limitation for root growth and development (Griffiths, 1985).

Table 2. Near-surface soil properties of eight reclaimed soils after surface coal mining in Indiana. Bulk density of the 10-20 cm soil depth; soil strength and aggregates stability were measured to 5 cm and POM-C, C-min, root biomass, and root C/N ratios were measured to 20 cm.

Site	Bulk density	Soil Strength	Aggregate stability	POM-C	C-min	Root biomass	Roots C/N
	Mg m^{-3}	N	% 2-0.25 mm	g m^{-2}	g m^{-2}	kg ha^{-1}	
A	1.42	60	45 (4.5)H	380	3080	8290	16
B	1.56	130	28 (2.6)	350	3020	4830	18
C	1.61	50	23 (5.6)	330	3500	9950	17
D	1.43	50	32 (2.8)	330	3140	1500	24
E	1.53	20	25 (7.1)	240	2620	8430	17
F	1.62	110	56 (2.5)	230	2440	6170	16
G	1.56	120	33 (6.4)	400	4500	7320	21
H	1.45	30	55 (0.8)	170	3510	4420	15

H Number in parentheses is the standard error.

Soil aggregates and their stability have a strong influence on physical properties such as infiltration (hydraulic characteristics), aeration, soil strength, erosion, and the soil's ability to transmit liquids, solutes, gases, and heat (Topp et al., 1996). Aggregation is a product of interactions of the soil microbial community, mineral and organic components, the composition of the above-ground plant community, and what has happened to the ecosystem in the past (Kemper and Koch, 1966; Tisdall and Oades, 1982; Goldberg et al., 1988). In general, the greater the percentage of stable aggregates, the less erodible the soil will be. Percent of stable aggregates ranged from 23 to 56% (2-0.25 mm in size). A similar aggregate stability range of 27 to 56% (using the same method) has been shown for cultivated silt loam surface horizons (Seybold et al., 2002 and 2003). Aggregate stability can be improved through long-term no-till or conservation tillage practices (Paustain et al., 1997).

Particulate-organic-matter carbon (POM-C) ranged from 170 to 400 g m^{-2} in the 0-20 cm soil depth (Table 2). The POM-C is the amount of organic C found in the particle-size fraction between 0.53 and 2 mm in diameter. It is considered to measure the larger physical fraction of soil organic matter. This larger physical fraction reflects change in the organic matter pool occurring in one to a few years (Franks et al., 2001). The POM-C fraction can be an indicator of the soil organic matter fraction that can move into the active C pool (C. Franks, personal communication, 2003). The active C pool contributes to nutrient cycling and productivity. Cambardella and Elliott (1992) reported POM-C contents in a loam soil under four tillage treatments (bare fallow, stubble mulch, no-till, and native sod) to range from 560 to 1670 g m^{-2}. Bare fallow had the lowest contents and native sod had the largest POM-C contents. The POM-C values of the eight sites in the present study are lower than that obtained under any of the tillage treatments in Cambardella and Elliott (1992). Tillage and soil disturbances such as soil removal by surface coal mining can deplete the POM-C fraction.

The amount of organic matter associated with the mineral fraction (C-min), that < 53 Φm in diameter, ranged from 2440 to 4500 g m^{-2}. The C-min fraction of the eight sites was greater than that obtained by Cambardella and Elliott (1992). This enrichment may have resulted from decomposition of the POM-C that was in the soil before coal mining, and subsequent movement into the mineral associated fraction. The POM-C fraction could be improved through the use of no-till or conservation tillage practices and use of high residue crops such as corn.

Root biomass and C/N ratios are a function of the type of crop grown. At the time of sampling root biomass ranged from 1500 to 9950 kg ha^{-1} (Table 2). Corn and soybeans can have a root biomass of over 2250 and 800 kg ha^{-1}, respectively. The root biomass captures the larger size fraction of organic matter. The decomposing roots provide a source of nutrients that can be made available to plants. However, organic materials can be significantly depleted through decomposition. It is best to continually add organic materials to prevent depletion. Use of high residue crops, cover crops, and manures can help build organic matter (Magdoff and van Es, 2000).

Morphology

The amount of time the sites have been reclaimed to agricultural land ranged from 6 to 17 years, with an average of 13 years (Table 1). The eight sites consisted of five soil series classified before mining as Hosmer, Pike, Vigo, Shakamak, and Alford. Soil profiles that develop under natural soil forming factors and processes have fairly predictable layers. The general horizonation of the reference soils (not mined) have an Ap-E-Bt horizonation (Fig. 2). The AAp@ designation indicates cultivated and dark surface horizons. The ABt@ designation indicates subsoil horizons that have a pedogenic accumulation of clay. In six of the reference soils (sites A, B, D, E, G., and H) a fragipan exists at the lower part of the B horizon. In all but one soil, the fragipan is below the depth of study. The fragipan is indicated by an “x” in “Btx” in site B of Fig. 2. Fragipans are usually characterized as a dense and brittle layer that can restrict the penetration of roots and water (Soil Survey Staff, 1999). They are pedogenic, meaning they form naturally. From an agricultural perspective, fragipans are undesirable because they restrict rooting depth and retard removal of excess water.

The general soil horizonation of the reclaimed soils is an Ap-C profile with dense layers (indicated as “Cd”) in the lower part of the C (Fig. 2). Three of the sites contained dense layers (sties A, B, and G). The AC@ horizon indicates layers that are little affected by soil forming processes. Once a B horizon layer has been removed, and then replaced, it will no longer classify as a B horizon. Evidence for the formation of the B horizon will have been destroyed. For a layer to be classified as a “B” horizon, there has to be evidence that it formed naturally (e.g., clay films for a Bt horizon). If there is no evidence of any soil forming processes, then the layer will be classified as a “C” horizon (little affected by soil forming processes). Even though the fill material contained “B” horizon material, once replaced, it is not automatically a B horizon. The morphology has been altered. Soil forming processes must begin to work on the newly deposited material and reform the B horizon.

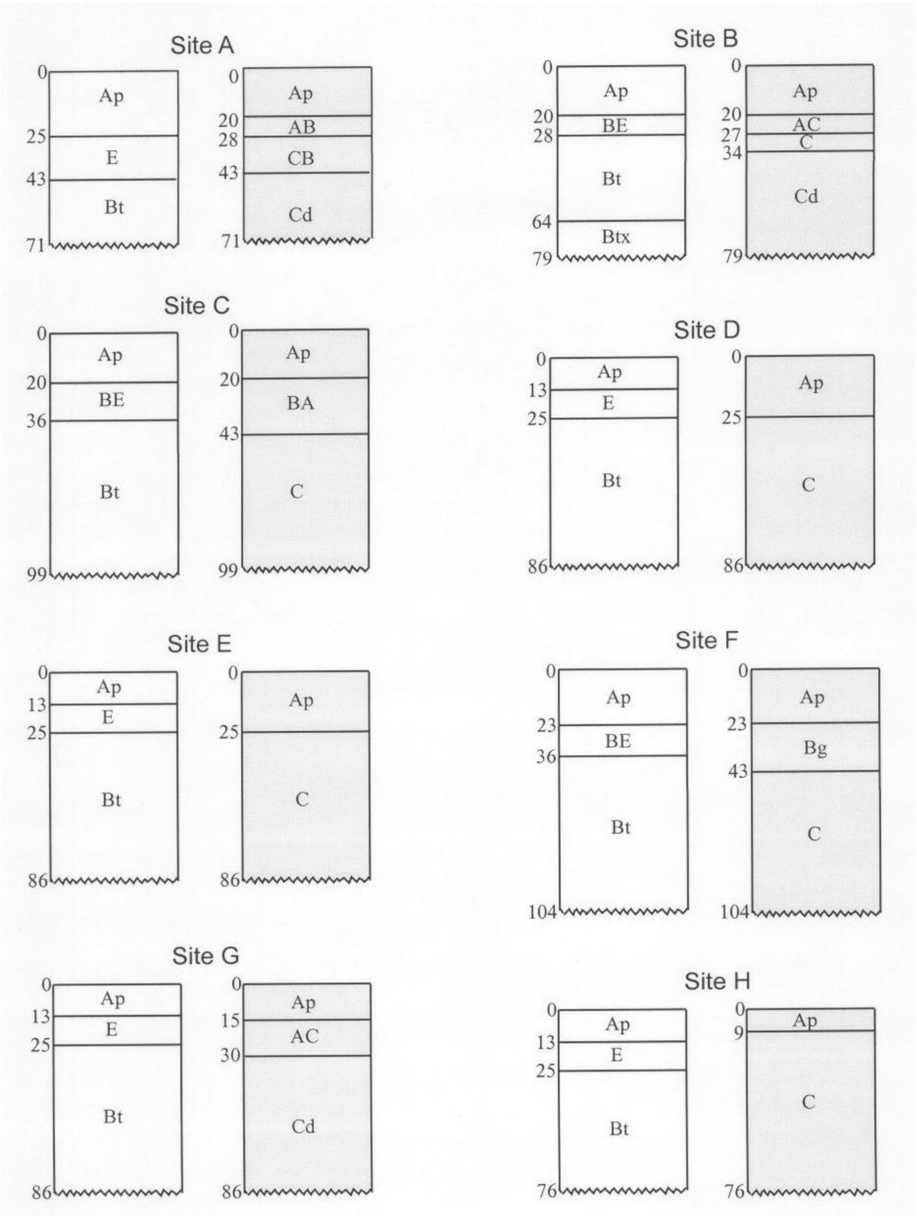

Figure 2. Soil profiles of the eight reclaimed soils (right profile) compare to their respective pre-mining reference condition (left profile). Soil depths are in cm.

<u>Soil Quality Index</u>

The soil quality index for each site is presented in Fig. 3. An index score of 100 indicates the soil has the same general quality as the soil condition before mining. The scores range from 68 to 87 with an average score of 82, indicating that soil quality is lower than the condition before mining at all the sites. These rating are limited to the depth of study. However, the index score does not indicate what properties are not functioning at the condition before mining or where the problem occurs in the profile.

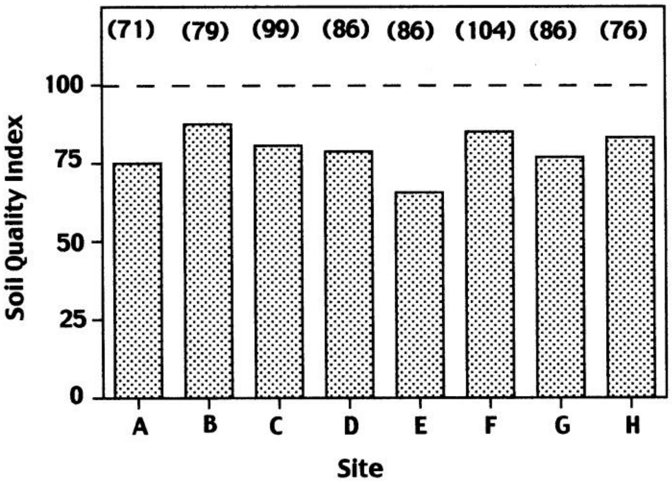

Figure 3. Soil quality index ratings for the eight reclaimed soil sites. The number in parentheses is the soil depth the index was rated too (cm).

To examine how the individual properties scored within the soil quality index, ratings for each property are presented in Figures 4 and 5. Properties that scored lower than the condition before mining would have a score less than one. The organic C contents are generally equal to or better than the condition before mining at five of the sites (Figs. 4 and 5). In some cases, the surface horizon organic C contents were greater for the reclaimed than for the reference soil condition before mining (e.g., Fig. 6a). The reason for the higher amounts of organic C could be due to the replacement of the surface horizon with a mixture of A and Ap horizon material. An AA@ designation indicates an uncultivated surface horizon. Uncultivated surface horizons have generally higher organic C content than cultivated Ap horizons of the same soil type (Paustian et al., 1997). The combination of the two horizons could create a surface layer with greater organic C contents than the cultivated condition before mining. For example, Fig. 6a shows the distribution with depth of organic C for a noncultivated (natural), cultivated, and reclaimed soil of the Alford soil series. The A horizon of the natural condition has over twice the organic C content as the cultivated condition. In Indiana, soils formed under both forest and prairie vegetation, which would contain greater organic matter contents than if they were cultivated.

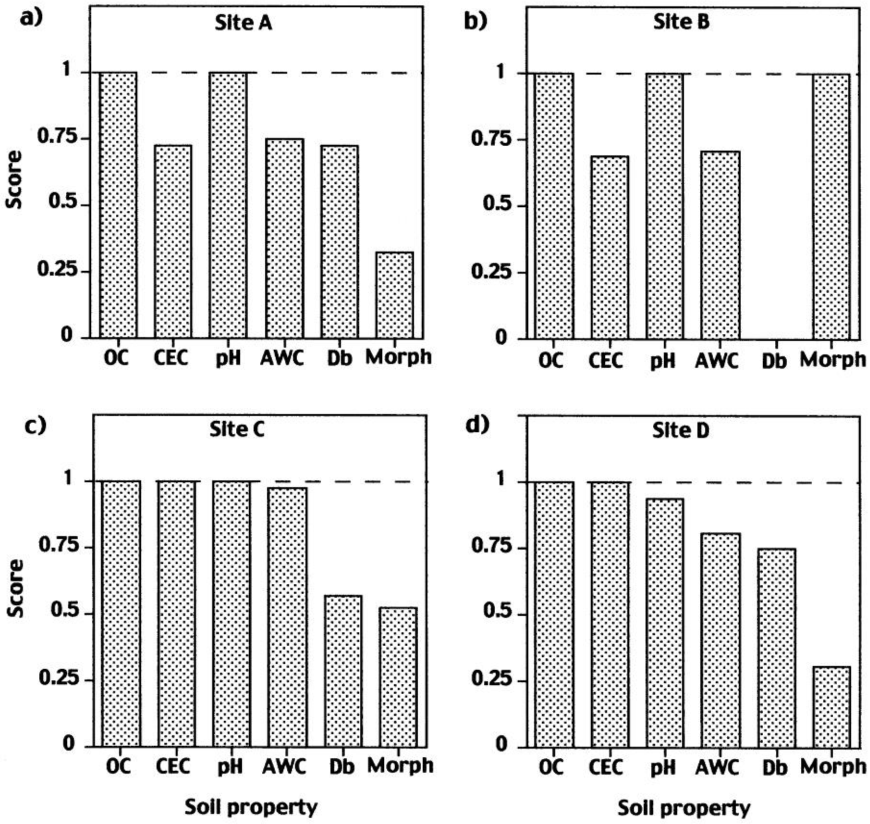

Figure 4. Scores from the linear scoring functions for each of the six indicators for sites A-D. There is no Db score for site B.

At five of the sites, the CEC and soil pH were at or above the condition before mining (Figs. 4 and 5). Soils with a lower CEC would have a lower nutrient holding capacity. Soil pH also affects nutrient availability. The natural pH of the soils at lower depths is generally acidic (e.g., Fig. 6b). Cultivated soils in the area are limed to correct for the acidic conditions. The reclaimed soils generally have a better pH condition for agriculture than the condition before mining (e.g., Fig. 6b).

The available water capacity (AWC) is the amount of water that is available to the growing plant. It is defined here as the amount of water held in the soil between 33 and 1500 kPa. The profile AWC at six of the sites was lower than the condition before mining (Figs. 4 and 5). At five of the sites, the index AWC was about 25% lower than the condition before mining. As a result, during dry years, drought stress may occur sooner on these reclaimed soils than on their undisturbed counterparts (Felton, 1992). The reduction in the AWC tends to increase with depth (e.g., Fig. 6c).

This is probably due to the increase in bulk density and lack of structure at lower depths. It has been shown that crops growing on compacted soils cannot take up enough water to survive and flourish during periods of even moderate drought stress (Jansen, 1987). In general, reclaimed soils show considerably more variability in yields, obtaining near normal yields with good rainfall but more drastic yield reductions if water content is deficient (Steinhardt et al., 1987).

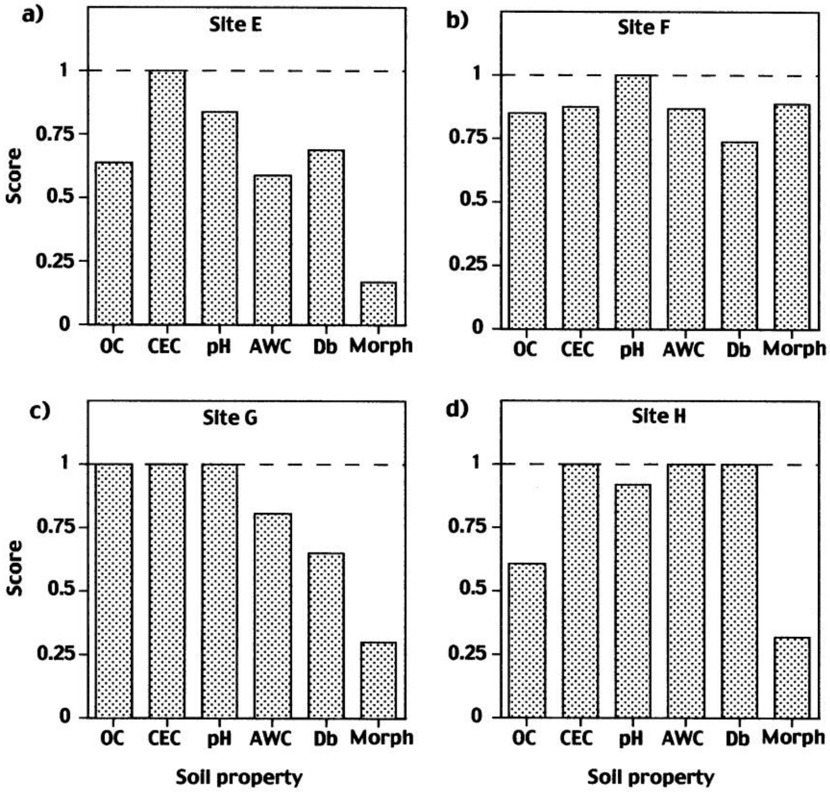

Figure 5. Scores from linear scoring functions for each of the six indicators for sites E-H.

The profile bulk density at six of the sites was greater than the density before mining (Figs. 4 and 5). Only at one site was the profile bulk density at the same density as the soil condition before mining took place. The remaining site (Fig. 4b) did not have a bulk density before mining available for comparison. There was generally a 25% or more increase in the bulk density of the soil profile. The bulk densities tended to increase with depth (e.g., Fig. 6d). Similar bulk density values in reclaimed soils were obtained by Steinhardt et al. (1987) and Becher (1991). Compacted layers limit rooting depth, reduce permeability and increase soil moisture problems. Soil compaction can lead to moisture stress due to reductions in available water (Steinhardt et al., 1987). The bulk densities at lower depths are above 1.7 Mg m^{-3}, which is considered root limiting for these textures (Pierce et al., 1983). In reclaimed soils, the top 15-20 cm is often tilled and a significant measure of the compaction at the surface is ameliorated (Felton and Ali, 1992). The most compacted zone is in the subsoil. In most cases, the compacted soils can be so dense that they do not store enough water to supply crop needs in most years.

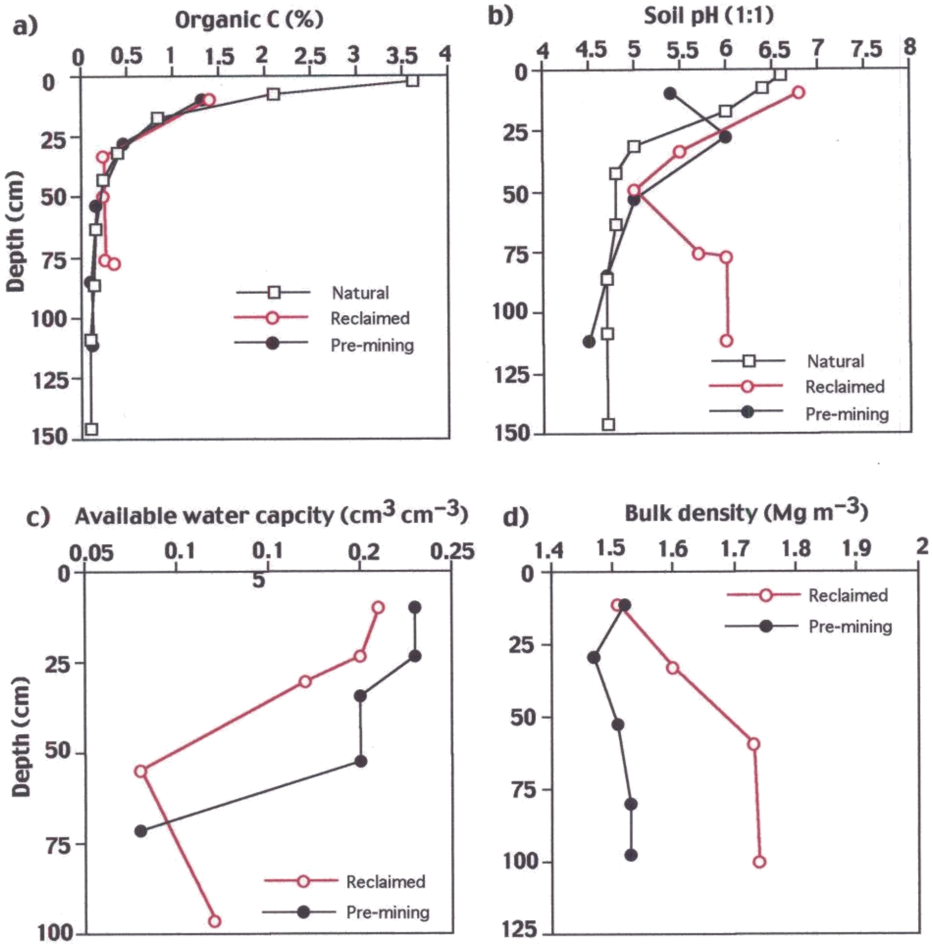

Figure 6. Comparison of (a) organic C, (b) pH, (c) available water capacity, and (d) bulk density between the pre-mining and reclaimed soil conditions. (a) and (b) contain a comparison with a natural site (not cultivated). (a) and (b) are of the Alford series; (c) is the Shakamak series, and (d) is the Pike soil series.

The profile soil-quality-morphology index provides a general quality placement relative to the soil condition before mining. Generally, higher placements indicate a better optimal physical condition for root growth and development, and for free movement of water and air. Seven of the sites had a lower morphology index score than the soil condition before mining (Figs. 4 and 5). Of the seven sites, six had a score between 0.17 and 0.5. The low scores indicate poor structure development in the reclaimed soils compared to the condition before mining. In other words, structure is less developed in the reclaimed soils. Reclaimed soils of the Hosmer soil series had about a 50% or more reduction in the morphology index score (Figs. 4d, 5a, 5c, and 5d). The combination of high bulk densities, poor structure, and moderately-fine texture of reclaimed subsoils can result in compacted and poorly aerated soil (Felton and Ali, 1992). Natural soil forming processes cause structure, pores and rooting zones to develop. Mining and reclamation activities disrupt the soil structure or physical condition of the subsoil. After subsoil replacement, the soil forming processes, pores and channels due to plant root and microbial action begin to redevelop. However, this can be a very slow process.

Summary and Conclusions

The near-surface properties of bulk density, soil strength, aggregate stability and POM-C are within limits observed for cultivated surface horizons. However, in general, cultivated surface horizons generally have poor soil quality compared to their natural or no till managed counterparts. In general, management controls the near surface properties. Therefore, through best management practices (e.g., no-till and use of high residue crops) the near-surface properties can be improved. The morphology of the reclaimed soils lacked pedogenic B horizons. The general horizonation of the reclaimed soils was an Ap-C horizonation. The profile soil quality was lower on all eight reclaimed sites compared to their respective reference condition before mining. The index scores ranged from 68 to 87 on a scale from 0 to 100. These ratings are limited to the depth of study. The properties that were a major factor in lowering the soil quality of the reclaimed soils was poor or massive soil structure, lower available water capacity, and increased bulk density of the subsoils. Organic C, CEC, and soil pH on most sites were generally comparable to the condition before mining. There were a couple of sites that had significantly lower scores, especially for the organic C content. The poor structure, higher bulk densities, and lower AWC of the reclaimed soils could result in water stress and/or lower productivity, especially under doughty conditions.

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