RECLAMATION OF PRIME AGRICULTURAL LANDS AFTER COAL SURFACE MINING: THE MIDWESTERN EXPERIENCE [1]

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Abstract. This paper is a review of the reclamation research conducted in the Midwestern US, primarily at the Universities of Illinois and Kentucky. Chemical problems associated with surface mining, such as acid generating materials, are important and well documented. However, reclamation research has shown that poor soil physical condition is the most limiting factor to successful row crop production on reclaimed mined land in the Midwest. Critical to success are selection of the best available soil materials used in soil construction and a material handling method that minimizes soil compaction. Excellent corn and soybean yields have been achieved on low strength soils both in high weather stress years as well as low stress years. Total crop failures have occurred on high strength soils in years of weather stress. Some deep tillage practices have been successful in improving compacted soils, but it is preferable to avoid compaction in the first place, when the soil materials are handled. Soil strength measurements with a cone penetrometer have proven to be a useful tool in evaluating rooting media and reclamation practices. Research has shown that surface mining can be a short term land use that may be followed by productive farmland, if reclamation is done correctly.

Additional Key Words: strip mining, important farmlands, restoration, soil compaction, deep tillage.

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Introduction

SMCRA (Public Law 95-87), the surface mine control and reclamation act, passed in 1977, had a profound effect on the industry. An industry that once typically walked away from the destruction mining caused was radically transformed by SMCRA. Reclamation became part of the mining process. Initially, there was concern that prime farmland should not be mined because of unproven reclamation techniques. To help allay these fears, a reclamation research program was initiated at the Universities of Illinois and Kentucky to investigate the best reclamation strategies. This paper summarizes that research work on row crop response to various surface mine reclamation practices, particularly in the Midwestern US (Dunker and Barnhisel, 2000). Discussion will focus on reclamation yield responses from the Illinois Coal Basin, including both prime and non-prime farmland. The principles of reclamation for row crops, and to a large degree the potential for success, are quite similar for prime and non-prime farmland, however they are treated differently in the law. Legally, most prime farmland must be reclaimed to row crop capability, but not all row crop reclamation is on prime farmland.

Building Productive Soils

Selection of Materials

Segregation and replacement of horizons from the pre-mine soils is a practice that is required by law under many conditions. Early reclamation research was focused on the evaluation and characterization of soil materials to be used for soil horizon replacement or substitution, if the substituted soil material could be shown to be as productive as the natural soil horizon it replaced. Selection and proper handling of good quality soil materials with desirable physical properties is essential to attaining productivity levels necessary to comply with reclamation laws.

Greenhouse evaluations revealed that replacement or alteration of the claypan subsoils of southern Illinois would increase crop growth by enhancing the chemical and physical properties of mined land (Dancer and Jansen, 1981; McSweeney et al., 1981). Topsoil materials generally produced somewhat greater plant growth than did mixtures of B and C horizons, but the B and C horizon mixtures were commonly equal to or better than the B horizon materials alone. The natural subsoils of this region are quite strongly weathered and acid, or are natric and alkaline (Snarski et al., 1981). The alternative material mixed in or substituted was generally much higher in bases than the acid soils and lower in sodium than the natric soils. A similar situation exists in Texas, where a mixture of materials proved superior for plant growth as compared to the native B horizon used for rooting material (Feagley and Hossner, 2000).

Unlike the situation in Southern Illinois and Texas where the B horizons are infertile, in Western Illinois subsoils are of good quality, and blending of substratum materials with B horizon materials is not particularly beneficial. McSweeney et al., (1981) did get some favorable greenhouse response to blending the high quality subsoils from the Sable soils (fine-silty mixed mesic Typic Endoaquolls) in western Illinois. He also found that lime and fertilizer produced a good yield response and reduced the need for material substitution.

Most of the Illinois research has centered on field experiments to evaluate row crop response to soil replacement and various reclamation practices. Pre-mine soils ranged from the highly productive deep loess soils developed under prairie vegetation (Mollisols) at the western Illinois sites to the lighter colored, more strongly developed Alfisols at the southern Illinois sites. Corn (Zea mays L.) and soybeans (Glycine max (L.) Merr) were grown on these newly constructed soils to evaluate productivity. Following up on the greenhouse studies, most of the early field studies addressed the issue of topsoil and subsoil horizon replacement.

Topsoil Replacement

Topsoil replacement has generally been beneficial for seedbed preparation, stand establishment, and early season growth when compared to graded spoil materials (Jansen and Dancer, 1981). However, yield response to topsoil replacement has ranged from strongly positive to strongly negative. At the Norris mine in western Illinois, an area of highly productive Mollisols, scraper placement of 46 cm of Mollic material over graded wheel spoil resulted in a significant positive corn yield response in three of four years with irrigation and two of four when not irrigated (Table 1). Soybean responded favorably to topsoil in one of the two years studied (Dunker and Jansen, 1987a). Significant negative yield responses to topsoil occurred in years of weather stress. Year to year variation in corn yield was considerably greater on the unirrigated topsoil than the unirrigated wheel spoil. Compaction associated with scrapers to replace topsoil is the reason for low topsoil yields in years of weather stress. The zone directly below the topsoil had a bulk density of 1.7 to 1.9 Mg m^{-3} and very low hydraulic conductivity.

Table 1. Irrigation and topsoiling impacts on corn yields at Norris Mine, western Illinois, 1979-1983.

Treatment	Mean kg/ha
Irrigated Topsoil/Wheel Spoil	11,351 a†
Unirrigated Wheel Spoil	6,396 c
Irrigated Wheel Spoil	8,779 b
Unirrigated Wheel Spoil	5,769 d
Undisturbed Sable Soil	8,215 b

† The same letter in a column indicates no significant differece at 0.05 level.

At the Norris topsoil wedge experiment, A horizon material was replaced over wheel spoil by scrapers in thickness ranging from 0 to 61 cm. There was a significant positive yield response to increasing topsoil thickness for corn, but not for soybeans. Year by year results showed positive relationships to topsoil thickness in years of favorable weather, but negative responses in years of moisture and temperature stress (Jansen et al., 1985).

At Sunspot mine, in western Illinois, topsoil and B horizon replaced over dragline spoil was evaluated over an eight year period. Soil treatments consisted of 38 cm of topsoil over replaced B horizon; 38 cm of topsoil replaced directly over dragline spoil; 91 cm of B horizon replaced directly over dragline spoil; and dragline spoil only. Bulldozers pushed the soil materials onto the plot areas, scrapers were not allowed directly on the plots during construction. An undisturbed tract of Clarksdale soil (Udollic Ochraqualf) was used as an unmined comparison. Topsoil replacement resulted in significantly higher corn yields in four out of eight years when replaced over B horizon materials and six of eight years when topsoil was replaced directly over dragline spoil (Dunker and Jansen, 1987b).

Soybean yields were significantly higher on the topsoil replaced treatments in six of seven years whether or not B horizon materials were replaced. The topsoil/B horizon treatment produced corn yields comparable to the undisturbed Clarksdale soil in five of seven years while the B horizon treatment without topsoil produced corn yields comparable to the undisturbed in only one year. The dragline spoil was unable to equal corn yields in any of the years studied whether topsoil was replaced or not (Table 2).

Table 2. Crop yields (1981-86) in response to topsoil and subsoil replacement at Sunspot Mine in western Illinois.

Treatment	Soybean	Corn
	--------- kg/ha ----------	
Topsoil/B horizon	2,258 b	8,152 a†
Topsoil/dragline spoil	1,944 c	6,898 b
B horizon only	1,693 d	5,393 c
Dragline spoil only	1,066 e	4,076 d
Undisturbed Clarksdale soil	2,508 a	8,466 a

† The same letter within a column indicates no significant difference at the 0.05 level.

Fehrenbacher et al., (1982) found that corn roots penetrated significantly deeper in the B horizon materials than the dragline spoil and that bulk densities were significantly higher in the graded dragline spoil than the replaced B horizon at 56 cm and deeper. Bulk densities between the B horizon material and the undisturbed Clarksdale were similar. It is not possible to determine whether the favorable response to the B horizon treatment was due to the B horizon material, or to the lower soil strength that resulted from the careful handling.

Response to soil horizon replacement in southern Illinois has been less dramatic than has been observed at the western Illinois sites (Table 3). This is understandable considering that local A horizons are more highly weathered and average 20-23 cm in depth compared to 38-46 cm in the highly productive western Illinois soils. At River King, in southern Illinois, topsoil replaced by scrapers over wheel spoil significantly increased corn yields in only one of eight years and soybeans in three of six years. The River King site does have good quality spoil and rather mediocre topsoil.

Table 3. Crop yields in response to topsoil and subsoil replacement at River King Mine in southern Illinois, 1978-85.

Treatment	Soybean	Corn
	---------- kg/ha ----------	
Scraper placed topsoil/wheel spoil	1,129 a†	3,386 a
Wheel spoil only	815 b	3,261 a
Scraper placed topsoil & root media	815 b	2,069 b

† The same letter within a column indicates no significant differece at the 0.05 level.

Replaced Subsoil Thickness

Soil horizon replacement and thickness of soil materials from southern Illinois has been studied at the Captain mine where the natural soils have chemical and physical problems that limit productivity. The Captain wedge experiment was used to evaluate corn and soybean yield response to thickness of scraper placed rooting medium (0 to 122 cm thick) over graded cast overburden, with and without topsoil replaced. Yields of both corn and soybeans increased with increasing thickness of hauled material to about the 61-76 cm depth. Meyer (1983) found very few roots below the 61 cm depth and found that roots in the subsoil were largely confined to desiccation cracks. The subsoil physical condition can best be described as compact and massive with very high bulk density levels and poor water infiltration. Soybean yields on the scraper placed root medium were significantly lower than a nearby undisturbed tract in all seven years of the study, whether topsoil was replaced or not. Corn yields were comparable to the undisturbed site in three of the years, which can be characterized as low stress years (Table 4).

Table 4. Crop yields in response to scraper placed topsoil and root media replacement at Captain Mine in southern Illinois, 1979-86.

Treatment	Soybean	Corn
	---------------- kg/ha	----------------
Scraper topsoil/scraper placed root media	815 b†	2,069 b
Scraper placed root media only	752 b	1,756 b
Undisturbed Cisne/Stoy soil	1,693 a	4,390 a

† The same letter within a column indicates no significant difference (0.05 level).

LIMITING FACTORS

Soil Physical Properties

The results from the topsoil and subsoil replacement studies indicated that material handling was often more important than the materials used. Poor soil physical condition proved to be the most severe and difficult limiting factor in the reclamation of many prime farmland soils. Indorante et al., (1981), in a comparison of mined and unmined land in southern Illinois reported that reconstructed mine soils had higher bulk densities and lacked any notable soil structure. Natural improvement in compacted mine soils is a slow process. Thomas and Jansen (1985) studied soil development in eight mine spoils ranging in age from 5 to 64 years looking at physical, chemical, and micromorphological properties. All eight mine soils showed some evidence of soil development, but depth of structure development ranged from only 14 cm at the 5 yr old site to 36 cm at a 55 yr old site. No evidence of clay translocation attributable to soil development was found. Color and texture pattern changes were determined to be a result of the mixing of materials rather than soil developmental processes.

Illinois has an abundance of high quality soil materials to use for soil construction. Row crop success on reclaimed mine land has been as dependent upon the method by which soil horizons have been replaced as on the quality of soil materials selected. Excellent corn and soybean yields have been achieved on low soil strength soils in high stress as well as low stress years. Soil horizon segregation and replacement in Illinois has generally shown a moderate positive yield response in most cases, however, the soil physical condition that is established during soil construction is clearly a more significant concern than whether or not materials from the natural soil horizons are replaced (Jansen and Dancer, 1981).

McSweeney and Jansen (1984) studied the soil structure patterns and rooting behavior of corn in reclaimed soils. On a site that received extensive grading of the subsoil, the subsoil was severely compacted and massive. Root penetration into these subsoils was extensively horizontal instead of the normal vertical direction. Cross sections of the roots were noticeably flattened and compressed. McSweeney described a "fritted" soil structure in areas where soil materials handled by a mining wheel-conveyor-spreader system where only minimal grading is necessary. Fritted structure was defined as an artificial soil structure consisting of rounded loose aggregates formed by rolling along the soil conveyor. This resulted in a low strength soil with abundant macropores. Although subject to compaction at the upper surface, the extensive void spaces between aggregates allow for excellent root penetration. Corn and soybean yields from soils with well-developed fritted structure were equal to or better than yields obtained on nearby natural soils (McSweeney et al., 1987). By contrast, corn and soybean yields from a nearby set of plots with root media replaced entirely by scrapers were unable to produce comparable yields to the undisturbed soil. The rooting materials for both experiments were similar with the major difference being in the way the soil materials were replaced.

The Captain Mix Plots were with the wheel-conveyor-spreader and were designed to follow up a series of greenhouse experiments that began in 1977. Greenhouse evaluation revealed that alteration of the claypan soils in southern Illinois would increase crop growth by enhancing the chemical and physical properties of the reclaimed land. The Captain Mix Plots consist of several treatments composed of different depth mixes of the original soil profile replaced by the conveyor-spreader. Excellent corn and soybean yields have resulted on these low strength soils in high stress as well as low stress years. Penetrometer data from the Mix Plots reflect the excellent physical condition resulting from placing rooting materials with the wheel-conveyor system (Table 5). Row crop yields comparable to those obtained on nearby undisturbed soils were achieved in all eleven years of this study (Dunker et al., 1992). Topsoil replaced with the soil spreader on these plots only infrequently produced any significant yield response (Table 6).

Table 5. Mean penetrometer resistance values for soil treatments constructed with wheel-conveyor-spreader on the Captain Mix Plots.

Treatment	Depth (cm)			
	23-46	46-69	69-91	91-112
	MPa			
Topsoil/8 cm Mix	1.24 abc†	0.67 d	0.58 b	0.68 b
Topsoil/25 cm Mix	1.26 ab	0.94 bc	0.63 b	0.66 b
Topsoil/38 cm Mix	1.45 a	1.11 ab	0.86 a	0.77 ab
Topsoil/51 cm Mix	1.51 a	1.21 a	0.81 a	0.75 ab
25 cm Mix	0.93 c	0.71 b	0.69 ab	1.17 a
51 cm Mix	0.83 c	0.76 cd	0.70 ab	0.77 ab

† The same letter within a column indicates no significant difference at the 0.05 level.

Table 6. Crop yields on wheel-conveyor-spreader plots at Captain Mine in southern Illinois, 1981-91.

Treatment	Soybean	Corn
	kg/ha	
Topsoil/8 cm Mix	1,819 a†	7,086 a
Topsoil/25 cm Mix	1,693 ab	6,835 a
Topsoil/38 cm Mix	1,693 ab	6,961 a
Topsoil/51 cm Mix	1,693 ab	6,146 b
25 cm Mix	1,505 b	6,271 b
51 cm Mix	1,568 ab	6,396 b
Undisturbed Cisne/Stoy soil	1,693 ab	7,023 a

† The same letter within a column indicates no significant difference at the 0.05 level.

Although the mining wheel-conveyor-spreader system proved successful in constructing productive soils after surface mining, it does not offer a generally applicable solution to the problem of restoring land to agricultural productivity after mining. It is a very inflexible system that can not be used at most mine sites. Evident options are to either develop a method by which excessively compacted soils can be ameliorated to a significant depth or to develop other material handling options which will produce soils with good physical characteristics and will be more cost competitive and applicable than the conveyor system. Natural soil improvement processes are slow, especially at greater depths, as is evident from the 10 year corn and soybean yield trends from the wedge and mix plots. Year to year and across year variation is associated more with weather stress and management factors than from any measurable natural soil improvement.

As an alternative to the wheel-conveyor system, corn and soybean response to mine soil construction with rear-dump trucks and scraper pans were studied from 1985-91 at Denmark Mine in southern Illinois (Hooks et al., 1992). Two truck-hauled treatments, one that limited truck traffic to the spoil base only, and one which allowed truck traffic on the rooting media as it was placed, were evaluated. A third treatment consisting of entirely scraper hauled rooting media was included. The rooting media was comprised primarily of the B horizon of the natural unmined soil and all treatments had 20 cm of topsoil replaced on the rooting media using dozers to prevent wheel traffic compaction. Significant differences in soil strength, a measure of soil compaction, and row crop yields were observed among treatments over the five year period. The lowest soil strength and highest row crop yields occurred on the truck without traffic treatment. Soil strength and yield response were similar for the truck with surface traffic and the scraper treatment (Table 7 and Table 8).

Table 7. Mean penetrometer resistance values for soil treatments on the Denmark Plots.

Treatment	Depth (cm)		
	23-46	46-69	69-91
	------------------ MPa --------------		
Truck placed root media w/o traffic	1.26 b†	1.30 b	1.11 b
Truck placed root media with traffic	1.54 ab	1.57 ab	1.47 ab
Scraper placed root media	1.88 a	1.90 a	1.78 a

† The same letter within a column indicates no significant difference at the 0.05 level.

Table 8. Crop yields in response to rear-dump truck placed and scraper placed root media at Denmark Mine in southern Illinois, 1985-91.

Treatment	Soybean	Corn
	------ kg/ha ------	
Truck placed root media w/o traffic	1,254 b†	6,208 a
Truck placed root media with traffic	1,003 c	4,452 b
Scraper placed root media	1,003 c	3,951 b
Undisturbed Cisne/Stoy soil	1,630 a	6,459 a

† Values followed by the same letter within a column are not significantly different at the 0.05 level

Soil Compaction Evaluation

Severe compaction and compacted interfaces between soil layers have proven to be major problems that limit productivity of most reclaimed soils. A truck handling system, which handles both topsoil and subsoil in one operation, was evaluated at Cedar Creek Mine in western Illinois from 1992-94. During plot construction, each rear-dump truck was loaded with the equivalent of 91 cm of subsoil and 30 cm of topsoil on top of the load. Subsoil and topsoil was dumped in one operation eliminated the need for topsoil replacement by scrapers. Some mixing of the topsoil and subsoil occurred but the majority of topsoil remained at the soil surface. Thin lenses of topsoil extended into the subsoil material, encouraging root exploration into the subsoil. Two other treatments, one being rear-dump truck placed subsoil with scraper placed topsoil and the other rear-dump truck placed subsoil without topsoil were included in the evaluation. Penetrometer resistance data collected in 1994 indicated that wheel traffic from the use of scrapers to replace topsoil had a negative impact on the underlying placed subsoil. Soil strength values increased due to scraper traffic by 82% over that of the rear-dump system. 1992-94 mean yields indicate the system using rear-dump trucks to simultaneously replace both rooting media and topsoil is superior to using scrapers to replace topsoil over hauled rooting media. Results also show a significant response to topsoil replacement using this system (Table 9).

Table 9. Corn yields in response to rear-dump truck and scraper placed soils at Cedar Creek Mine in western Illinois, 1992-94.

Treatment	Corn kg/ha
Truck placed root media with topsoil	9,971 a†
Scraper placed topsoil over truck placed root media	8,215 b
Truck placed root media w/o topsoil	8,152 b

† Values followed by the same letter within a column are not significantly different at the 0.05 level

Thompson et al., (1987) used root length and root length densities to evaluate bulk density and soil strength as predictors of root system performance. Because root restriction is generally the factor most important in limiting crop performance in mine soils, determining the suitability of soils for root system development could be a useful method of evaluating reclaimed soils. Soil strength was evaluated with the use of a constant rate recording cone penetrometer developed by Hooks and Jansen (1986). Results indicated that both penetrometer resistance and bulk density are useful predictors of root system performance in soils. They are especially useful in predicting root extension into deeper regions of the root zone. Penetrometer resistance and bulk density were highly correlated in the lower root zone, but poorly correlated nearer the soil surface.

Penetrometer data has proven useful for evaluating the soil strength effects of several reconstruction methods, of high traffic lanes on reclaimed areas, and of tillage methods for alleviating compaction (Vance et al., 1987). Soil strength values decreased with decreasing traffic. Scraper soil material handling systems produced the highest soil strengths, soils from truck-haul systems were intermediate, and soils built by a wheel-conveyor-spreader system had the lowest soil strength.

The relationships between soil strength levels measured with a recording cone penetrometer and five-year corn and soybean yields of four reclamation methods were studied at two mine sites in southern Illinois (Vance et al., 1992). Reclamation treatments included the wheel-conveyor system, truck-hauled root media with and without surface traffic, and a scraper-hauled rooting media system. Penetrometer measurements indicated variable soil compaction levels among reclamation treatments with corresponding wide-ranging crop yields. Correlation of penetrometer resistance with crop yield has been significant within most years for both corn and soybeans. Reclamation treatments with the highest soil strength had the lowest yields; those with the lowest soil strength had the highest yields. Average soil strength over the 23-112 cm profile depth was highly correlated with five-year mean yields across reclamation treatments.

Soil Compaction Mitigation

Various tillage tools have been designed to remove the deep-seated compaction associated with soil placement procedures that compact soil (Dunker et al., 1995). In general, there is a good relationship between depth of tillage and reclamation success (Fig.1). Although it is preferable to avoid compaction in the first place, deep tillage, properly done, can largely mitigate compaction. Deep tillage is expensive and is best applied when the soil is dried to the depth of tillage. Therefore, tillage is usually restricted to the late summer to fall after a deep-rooted crop has grown on the site for several seasons.

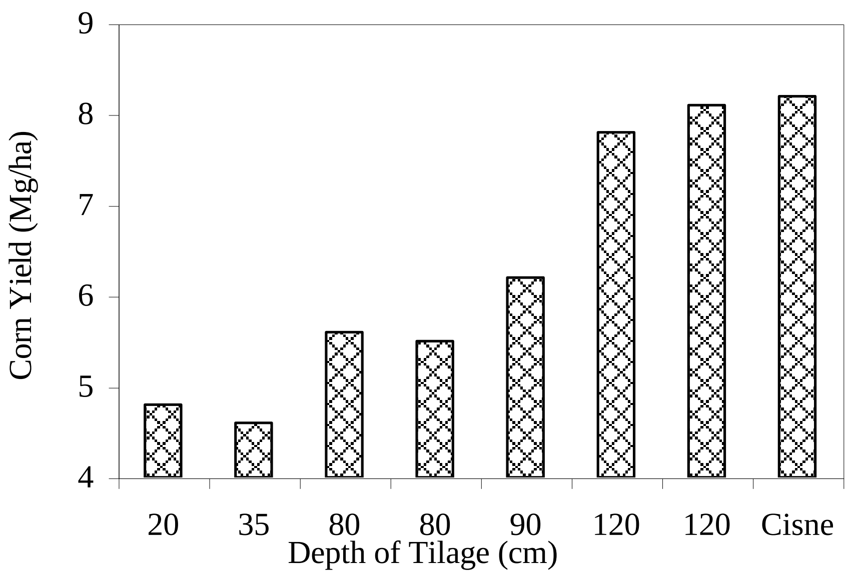

Figure 1. Corn yield on Southern Illinois reclaimed mine soil research plots (1989-93) as influenced by depth of tillage. Cisne soil serves as an undisturbed reference.

SUMMARY

In summary, the lesson learned from reclamation research is that mined lands can return to higher agricultural uses. This requires proper planning and execution of a well-designed reclamation plan. Results from the Illinois work show that achieving mine land productivity is possible if reclamation plans are designed to minimize compaction, if good quality soil materials are used, and if high management levels (herbicides, fertility, adapted crop varieties) and practices are followed. The Midwestern US has an abundance of high quality materials to use for soil construction and row crop success on mined land has been dependent upon the method by which soil horizons have been replaced and the quality of the materials selected. Excellent corn and soybean yields have been achieved on low strength soils in high stress as well as low stress years. However crop failures have occurred when reclamation methods result in mine soils with high soil strength. Truck handling of rooting media, where there is limited surface traffic, has resulted in a more productive and less compacted soil as compared to a high traffic scraper haul system for replacing root media. Tillage to 120 cm depth has proven effective in removing most of the yield limitation associated with compaction. However we feel that avoiding compaction in the first place will more easily lead to highly productive reclaimed mine soils, particularly where good quality soil materials are available and properly handled.

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