RECLAMATION FOR ROW CROP PRODUCTION AFTER SURFACE MINING, STATE OF THE ART[1]

I. J. Jansen and R. E. Dunker[2]

Abstract. — The literature reveals both successes and failures in reclamation of surface mined land for row crop production. Some newly constructed soils have produced yields comparable to pre-mine natural soils. Others are toxic to plants or much more subject to drought stress than natural soils.

Good reclamation begins with a thorough mapping, sampling, and analysis of available overburden materials. The next step is to develop and implement a design for the soils to be constructed. Critical to success are selection of the best available soil materials for each layer of the new soil and selection of a material handling method that will establish a desirable soil physical condition as the soil material is placed. Several deep tillage methods are at least partially effective in subsequent improvement of soil physical condition, where that accomplished during soil construction is inadequate.

INTRODUCTION

The following is written from a Midwestern perspective. The authors' experience is there, but it is also appropriate in that the Midwest is the region where the greatest competition between row crop agriculture and mining is centered. Literature from other regions and only indirectly related to row crop production is included where pertinent.

There will be little attempt to distinguish between prime and non-prime farmland, even though prime farmland is addressed separately in federal legislation. The principles of reclamation for row crops, and to a large degree, the potential for success are quite similar for prime and much of the non-prime farmland. Most prime farmland must by law be reclaimed to row crop capability, but not all row crop reclamation is on prime farmland.

The public pressure for restrictive legislation which climaxed in the 70's followed years of neglect as a highly competitive surface mining industry operated with few legal requirements concerning reclamation. Some surprisingly good reclamation was done voluntarily, but periodic overcapacity in the industry and the associated economic stress forced even the most responsible operators to minimize their investment in reclamation, in order to survive in the market place.

Early regulation of surface mine reclamation was done at the state level (6). Reclamation requirements varied greatly from state to state. The industry was at a disadvantage in those states which began passing relatively stringent reclamation requirements, relative to in states which required very little. That served to discourage costly state reclamation requirements, for fear of losing economic activity.

Public concern arose as the number of aesthetic and environmental disasters increased, and as surface mining operations begin to move increasingly into prime land areas, after strippable reserves under marginal land were largely exhausted. Individual states started passing legislation to require more effective reclamation and the federal government took the regulatory initiative in 1977.

The federal law, Public law 95-87 (41), requires that prime farmland be reclaimed and restored to productivity for row crops equivalent to that present before mining, within a reasonable time after surface mining. Illinois law (19), requires that success in revegetation of crop land be determined on the basis of crop production from the mined land area as compared to an approved reference area or other technical guidance procedures. Production shall not be considered equal if it is less than 90% of the production of the approved standard with 90

---

[1] Contribution from Department of Agronomy, University of Illinois, Urbana, IL 61801.

[2] Professor of Pedology, and Agronomist, Department of Agronomy, University of Illinois, Urbana, IL 61801, respectively.

Proceedings America Society of Mining and Reclamation, 1987 pp 19-26
DOI: 10.21000/JASMR87010019

https://doi.org/10.21000/JASMR87010019

percent statistical confidence when planted to crops commonly grown, such as corn, soybeans, hay, sorghum, wheat, oats, barley, or other crops found on surrounding prime farmland.

FEASIBILITY OF RECLAMATION FOR ROW CROP PRODUCTION

Significant efforts to reclaim surface mined land for row crop production were underway in Illinois twenty five years before such was required by law (14). Ten-year average corn yields of 5,488 kg/ha were achieved on graded cast overburden, with no soil horizon replacement, between 1953 and 1963. Grandt (14) applied about 38cm of topsoil from near-by Ipava[3] silt loam (Aquic Argiudolls) to part of an area of old spoils which had been graded for hay production shortly after mining in the mid 50's, and put the area into corn production for three years. Average corn yields were 7,580 kg/ha on the portion having replaced topsoil, and 4,760 kg/ha on graded spoil without topsoil. Adjacent areas of undisturbed Ipava silt loam produced an average yield of 7,900 kg/ha under the same management. This mine spoil had been in alfalfa and bromegrass for about twenty years before topsoil was added and the plots established in 1974. Although these soil treatments do not meet the federal requirements for B horizon replacement nor the coarse fragment content criteria of the Illinois legislation, 60 to 96% of the undisturbed land productivity was obtained.

Corn yields for reclaimed land reported to Nielsen and Miller (33) in a 1980 national survey were highly variable depending on original soil, fertility, initial planting of legumes and grasses, soil replacement, weather variability, and age of spoil. Nineteen measured corn yields from Illinois, Ohio, and Pennsylvania ranged from 10 percent to 96 percent of those on adjacent undisturbed soils. Henning and Colvin (16) reported that corn grown on an Iowa coal project demonstration mine the first year after reclamation yielded 67 to 31% less than corn on similar soils which were undisturbed. Powell et al., (39) reported that target yields were achieved on prime farmland in Kentucky for grain crops such as corn, soybeans, and wheat as well as for forage crops such as alfalfa, timothy, and tall fescue.

The surface mining industry in Germany has a long history of regulation and serious reclamation efforts. Successful reclamation with crop yields approximating those on natural soils has been accomplished by innovative equipment and several different soil construction methods (17,53). A cooperative spirit among the various interests; industry, public, and government; is evident and likely contributes to their success.

GENERAL PROPERTIES OF MINESOILS

Depending upon the properties of their parent materials, mine soils may have objectionably high or low pH, a very low cation exchange capacity (CEC) requiring extensive fertilization, or a high coarse fragment content (35). Other mine soils have nearly ideal chemical properties. Bulk densities are commonly high, while infiltration rates and hydraulic conductivities are commonly low (35,24). Soil structure is typically absent or very weakly expressed (20), a factor which certainly contributes to the high density and poor water movement.

MATERIAL SELECTION

Segregation and replacement of horizons from the premine soils has been widely advocated and is a practice that is required by law under many conditions. Numerous greenhouse and field studies have evaluated that practice. The results have ranged from a strong positive productivity response to soil horizon replacement, to a negative response. The advisability of soil horizon replacement as a reclamation practice depends on the quality of the available soil horizon material relative to that of the available substitute material.

Greenhouse evaluation has revealed that replacement or alteration of the claypan subsoils of southern Illinois would increase crop growth by enhancing the chemical and physical properties of reclaimed land (9,28). Topsoil materials generally produced somewhat better plant growth than did materials from soil B or C horizons, but mixtures of B and C horizons were commonly equal to or better than B horizon materials alone (9,46). The natural subsoils of the region are quite strongly weathered and acid, or are natric and alkaline (45,32). The alternative material mixed in or substituted was generally much richer in bases than the acid soils and lower in sodium than the natric soils. Liming and fertilizing of the soil horizon material produced a good yield response and reduced the need for material substitution or admixing. McSweeney et al. (28) also got a favorable response to blending of some substratum materials with B horizon materials when working with soil horizon materials from the high quality Sable (Typic Haplaquolls) soils of Western Illinois. This response to blending was much less pronounced than that observed with materials from southern Illinois soils.

Advance mapping, sampling, and analysis of overburden materials is essential to development of an effective mining and reclamation plan (43, 49). Chemical analysis of spoil, in association with greenhouse plant growth studies, can estab-

---

[3] These soils were classified as Muscatine silt loam at the time of Grandt's publication (13). They have since been reclassified as Ipava silt loam in a newer soil survey.

lish the presence of toxic elements and enable selection of amendments for effective planning of field revegetation (2). The properties of cast-overburden materials vary widely with character of the geologic column and with mining methods (5,7,8,25,26,36,37,38,51,54).

Barnhisel (3) observed that P and water were more commonly the limiting factors in obtaining adequate vegetative cover in western Kentucky than the acidic nature of the spoils. Acidic spoils did tend to restrict root development and produce more drought-susceptible plants. His study involved cast-overburden properties and forage yields on four types of existing surface mine coal spoils, from neutral to very acid. McFee et al., (27) used a greenhouse study to evaluate several soil and geologic materials from coal overburden in southwest Indiana. The best plant growth was observed on lacustrine sediments and on soil A horizon materials. Regression analysis of plant growth against chemical and physical properties of the overburden materials did not reveal properties that could be consistently used in a formula approach to predicting plant growth potential. Materials having distinctly unfavorable chemical or physical properties could be readily eliminated, however. Electrical conductivity of the material extract and water storage capacity were most frequently significantly related to growth, and toxic levels of B, Fe, Mn, and Al decreased growth on some materials.

Soil horizon replacement has generally produced a sizable yield or plant cover response in field studies where the spoil was chemically or physically unfavorable. Power et al., (40) observed a favorable response to both topsoil and subsoil replacement in North Dakota. Plots that had topsoil replaced separately over subsoil produced higher yields than where a mixture of topsoil and subsoil was used. Alfalfa, crested wheatgrass, native grasses, and spring wheat were used as test crops on the sodic mine spoil. Barth and Martin (4) placed a mixture of A, B, and C horizon materials in a wedge design over mine spoil at fifteen sites in the Northern Great Plains. Perennial grass yield response to replaced soil material varied with the characteristics of the underlying spoil. Soil material thickness required for maximum perennial grass yields was about 100 cm where the underlying spoil was acidic and about 70 cm where the underlying spoil was sodic. Fifty cm of soil was adequate for maximum yields where underlying spoil was neither acidic nor sodic. Halvorson, et al. (15) observed a favorable grain yield response to up to 70cm of topsoil plus subsoil over non-acid, non-sodic spoil in North Dakota.

Sites in Illinois with replaced topsoil (A horizon material) generally had better tilth, which led to easier seedbed preparation and stand establishment than those without topsoil (21,23). Beyond that, the several Illinois field experiments which evaluate soil horizon replacement practices need to be separated into two categories, one being the western Illinois studies where the natural soils are of excellent quality, and the other being the southern Illinois studies where the natural soils have undesirable chemical and physical properties which limit productivity.

The Norris topsoil wedge experiment was in western Illinois in an area having excellent quality natural soils. Thickness of replaced A horizon material ranged from 0 to 60 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 resulted in years of moisture and temperature stress (22). Dunker et al., (10,11) has shown that irrigation can be used to reduce or eliminate this stress factor and promote satisfactory corn and soybeans yield response on surface-mined land.

Another western Illinois site had post-mine soils constructed according to four different designs (12). One had 55 cm of A horizon material over 77 cm of replaced B horizon material, one had 55 cm of A horizon replaced over dragline spoil, the third had only B horizon material replaced, and the fourth was just graded dragline spoil with no soil horizon material replaced. An undisturbed tract of Clarksdale soil was used as a control. No scraper traffic was allowed directly on the plots during construction resulting in a better physical condition in the replaced B horizon material than could be achieved generally in reclamation practice using scrapers. Topsoil replacement resulted in higher yields in all four years for both corn and soybeans. Corn yields in the A/B treatment were higher than the A/spoil in 3 of 4 years while soybean yields on the A/B and A/spoil were not different. The B horizon only material produced higher soybean yields all 4 years and corn yields higher 3 of 4 years compared to the dragline spoil plots. It was not possible to determine to what degree the observed yield responses to B horizon replacement were due to superior physical conditions resulting from the unusually careful material handling, as opposed to superior materials. Mined land produced yields comparable to the Clarksdale soil in 2 of 3 years for corn and all three years for soybeans.

Soil horizon replacement and thickness of soil materials was also studied in southern Illinois where the natural soils have chemical and physical problems which limit productivity (22). A wedge design was used to evaluate corn and soybean yield response to thickness of scraper placed rooting medium material (0 to 120 cm thick) over graded cast overburden, with and without topsoil replaced. There were crop failures in 2 of the 5 years studied due to shallow rooting of corn and weather stress.

Yields of both corn and soybeans increased with increasing thickness of hauled material to about the 60-80 cm depth. No response to increasing thickness beyond 80 cm was observed. That should not be surprising since corn roots were not exploiting depths deeper than 80 cm. There was no basis for determining whether or not the yield response to thickness of selected rooting material would have continued beyond 80 cm thickness had it been possible to avoid compaction in the hauled material so that roots could penetrate to greater depths.

Most, but not all of the Illinois work has indicated a modest, positive, row crop yield response to soil horizon segregation and replacement. Excellent quality alternative materials are available at most Illinois sites, however, and 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 (21). Soil horizon replacement appears to be an essential practice for achieving maximum productivity at some sites, but might do more harm than good at some other sites, particularly if excessive compaction is induced by the horizon replacement process.

ESTABLISHING A SUITABLE SOIL PHYSICAL CONDITION

Reclamation and construction of soils on surface-mined land commonly involves extensive traffic by large earth moving equipment, severely compacting the soil material, creating excessively high soil strength and an inadequate network of soil pores. Albrecht et al. (1), measured the pre-mining and post-mining bulk densities and found values ranging from 1.2-1.4 g/cm^3 for the premine soils while the postmine soils were 1.7-1.8 g/cm^3. The use of scrapers was identified as the cause of the increased bulk densities. Root proliferation and plant performance are commonly inhibited in high-density or high-strength soil materials (42,47,55).

McSweeney and Jansen (29) studied the soil structure patterns and rooting behavior of corn in constructed soils. On a site that received extensive grading of the subsoil, the subsoil was severely compacted and massive. Root penetration into these subsoils was extensive horizontally instead of in 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 and where only minimal subsequent grading had been practiced. Fritted structure was defined as an artificial soil structure characterized by features which are imparted by soil handling operations rather than by natural processes; the structural arrangement consists of rounded aggregates loosely compressed together. Subsoils with a fritted physical condition favor good rooting. Although subject to compaction at the upper surface, the extensive void spaces between aggregates allow for adequate root penetration of the medium and subsequent proliferation below the compaction zone. Four year average corn and soybean yields on these plots with well developed fritted structure were equal or better than yields obtained on nearby natural soils (30).

Meyer (31) observed similarly restricted and flattened roots in a variety of massive minesoils. The flattened roots penetrated primarily along the planar vertical fissures, conforming tightly to the crack faces. There was generally little lateral branching and little proliferation into the massive, dense soil matrix. In western Illinois, Fehrenbacher et al. (13), has shown that corn root penetration was significantly deeper in the undisturbed soil than any of the four mine soils studied. Root penetration and root length densities were evaluated on two rooting mediums with and without topsoil. The rooting medium treatments consisted of topsoil replaced over graded dragline spoil for one and over 77 cm of the B horizon replaced from the premine soil for the other treatment. Bulk densities in the graded cast overburden (dragline spoil) were significantly higher than the replaced B horizon. Corn root penetration and root length densities were significantly greater in the topsoil/B horizon than the topsoil/dragline spoil.

Stucky and Lindsey (46) artificially compacted soil materials to three different bulk densities, 1.2, 1.4, and 1.6 $g\ cm^{-3}$. Soybeans were used as the test crop in a greenhouse experiment to evaluate plant performance on each of the above. Generally, yields decreased with increased compaction. In all instances, plants grown in soil compacted to 1.4 $g\ cm^{-3}$ outyielded plants grown in soils compacted to approximately 1.6 $g\ cm^{-3}$. Their soils ranged from silt loam to clay in texture. The above is consistent with earlier work by Voorhees, et al. (52) in which they observed that barley roots penetrated artificial aggregates compacted to a dry bulk density of 1.4 $g\ cm^{-3}$, but were restricted to the periphery of those compacted to 1.8 $g\ cm^{-3}$. Many disturbed soils have bulk densities well in excess of 1.6 $g\ cm^{-3}$.

Veihmeyer and Hendrickson (54) observed that the critical bulk density for root exclusion versus root penetration varies with the particle size distribution of the soil material. They observed no root penetration in any of their soil materials at bulk densities of 1.9 $g\ cm^{-3}$ or above, whereas clay soils had total root exclusion above bulk densities of 1.6 or 1.7 $g\ cm^{-3}$. They suggested critical bulk densities of 1.46 to 1.6 $g\ cm^{-3}$ for clays and of 1.75 $g\ cm^{-3}$ for sands.

Thompson (48) used root length and root length densities to evaluate how effective bulk densities and soil strength values are 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 a constant rate recording cone penetrometer (18). Results indicate 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 in the soil surface.

Penetrometer data has also proven useful for evaluating the soil strength effects of several soil reconstruction methods, of high-traffic lanes on reclaimed areas, and of tillage methods for alleviating compaction (deep soil loosening) (50). 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 strength. Deep tillage of severely compacted soils by the Kaelble-Gmeinder (TLG-12) machine was found to be effective in reducing soil strength values in the top 62 cm to less than 3.0 MPa. The effect of the TLG-12 was less noticeable when used in soils with fairly low soil strengths prior to treatment.

Powell et al.(39) observed a positive crop response to depth of soil replacement, ripping treatments, and soil handling methods that affect the physical properties such as bulk density. Subsoiling with a conventional farm type subsoiler increased yields of agronomic crops, especially corn and soybeans, but only for 2 or 3 years. Ripping with a large "Cat" ripper produced significantly greater yields and the effect lasted for at least 4 years. They reported that yields were also influenced by past soil management such as crop rotation, organic amendments, and crop cultivars.

In summary, good reclamation begins before the coal is out, even before the mining plan is complete and the equipment acquired. Begin with a thorough overburden analysis to enable determination of potential reclamation options and selection of the best available materials. Design mining and reclamation plans which complement each other in working toward the best finished product. Subsequent amelioration, such as chemical amendments or deep soil loosening, is a promising option to be exercised where needed, but preferably as part of an overall reclamation plan, rather than as an attempt to fix a reclamation failure.

LITERATURE CITED

1. Albrecht, S. C., and E. R. Thompson. 1982. Impact of surface mining on soil compaction in the midwestern U.S.A., Bureau of Mines Open File Report 174-82.

2. Armiger, W. H., J. N. Jones, and O. L. Bennett. 1976. Revegetation of land disturbed by strip mining of coal in Appalachia. U. S. Dep. of Agric. Res. Serv., ARS-NE-71.

3. Barnhisel, R. I. 1977., Reclamation of surface mined coal spoils., USDA/EPA Interagency Energy-Environment Research and Development Program Report. CSRS-1, EPA-600/7-77-093.

4. Barth, Richard C., and Brooks K. Martin. 1984. Soil depth requirements for revegetation of surface-mined areas in Wyoming, Montana, and North Dakota. J. Environ. Qual., 13:399-404.
https://doi.org/10.2134/jeq1984.00472425001300030016x

5. Berg, W. A., and W. G. Vogel. 1968. Manganese toxicity of legumes seeded in Kentucky strip-mine spoils. U. S. Dep. of Agric., Northeast Forest Exp. Sta. Res. Paper NE-119.

6. Bowling, Kenes C. 1978. History of legislation for different states. Chapter 6 in Reclamation of Drastically Disturbed Lands. American Society of Agronomy, Madison, Wisconsin. pp.95-116.

7. Cummins, D. G., W. T. Plass, and C. E. Gentry. 1965. Chemical and physical properties of spoil banks in the eastern Kentucky coal fields. U. S. Dep. of Agric., Forest Serv. Res. Paper CS-17.

8. Czapowskyj, M. M. 1973. Establishing forest on surface-mined land as related to fertility and fertilization. U. S. Dep. of Agric., Forest Serv. Grn. Tech. Rep. NE-3.

9. Dancer, W. S., and I. J. Jansen. 1981. Greenhouse evaluation of solum and substratum materials in the southern Illinois coal field. I. Forage crops. Journal of Environmental Quality. 10:396-400.
http://dx.doi.org/10.2134/jeq1981.00472425001000030031x

10. Dunker, R. E., and I. J. Jansen. 1986. Rowcrop response to topsoil replacement and irrigation on surface-mined land in western Illinois. J. Soil and Water Cons. (In Press).

11. Dunker, R. E., I. J. Jansen, and M. D. Thorne. 1982. Corn response to irrigation on surface-mined land in western Illinois. Agron. J. 74:411-414.
http://dx.doi.org/10.2134/agronj1982.00021962007400030003x

12. Dunker, R. E., I. J. Jansen, C. W. Boast, and C. L. Hooks. 1984. Corn and soybean yield response to topsoil and B horizon replacement on surface-mined land in western Illinois. Agron. Abstr. p. 247.

13. Fehrenbacher, D. J., I. J. Jansen, and J. B. Fehrenbacher. 1982. Corn root development in constructed soils on surface mined land in western Illinois. Soil Sci. Soc. Am. J. 46:353-359.
http://dx.doi.org/10.2136/sssaj1982.03615995004600020028x

14. Grandt, A. F. 1978. Reclaiming mined land in Illinois for row crop production. J. Soil Water Conserv. Vol. 33(5):242-244.

15. Halvorson, G. A., S. W. Melsted, S. A. Schroeder, C. M. Smith, and M. W. Pole. 1986. Topsoil and subsoil thickness requirements for reclamation of nonsodic mined-land. Soil Sci. Soc. Am. J. 50:419-422.
http://dx.doi.org/10.2136/sssaj1986.03615995005000020033x

16. Henning, S. J., and T. S. Colvin. 1977. Management of reclaimed surface-mined lands for row crop production. Fifth Symposium on Surface Mining and Reclamation. NCA/BCR Coal Conference and Expo IV. Louisville, Ky.

17. Heusler, Helmut. In Press. Equipment concepts for soil reclamation and recultivation. Innovative Approaches to Mined Land Reclamation. C. L. Carlson, and J. H. Swisher (eds). Carbondale: Southern Illinois University Press. pp. 143-171.

18. Hooks, C. L. and I. J. Jansen. 1986. Recording penetrometer developed in reclamation research. Soil Sci. Soc. Am. J. 50:10-12.
http://dx.doi.org/10.2136/sssaj1986.03615995005000010002x

19. Illinois Public Act 81-1015. 1981 Surface Coal Mining Land Conservation Act.

20. Indorante, S. J., I. J. Jansen, and C. W. Boast. 1981. Surface mining and reclamation: initial changes in soil character. J. Soil Water Conserv. Vol. 36(6):347-351.

21. Jansen, I. J., and W. S. Dancer. 1981. Row crop response to soil horizon replacement after surface mining. Symposium on Surface Mining Hydrology, Sedimentology and Reclamation. University of Kentucky, Lexington, Kentucky. Dec. 7-11, 1981.

22. Jansen, I. J., R. E. Dunker, C. W. Boast, and C. L. Hooks. 1985a. Rowcrop yield response to soil horizon replacement. Symposium on Reclamation of Lands Disturbed by Surface Mining: A Cornerstone for Communication and Understanding. Science Reviews Limited, Middlesex, England. pp 410-430.

23. Jansen, I. J., R. E. Dunker, and W. S. Dancer. 1985b. Row crop response to topsoil replacement after strip mining. Abstracts, Soil Conservation Society of America, 40th Annual Meeting, St. Louis, Missouri.

24. Lah, R. 1980. Saturated hydraulic conductivity of reclaimed surface-mined soils. Unpubl. M.S. Thesis, Univ of Ill., Urbana, Illinois.

25. Massey, H. F. 1972. pH and soluble Cu, Ni and Zn in eastern Kentucky coal mine spoil materials. Soil Sci. 114:317-321.
http://dx.doi.org/10.1097/00010694-197209000-00009

26. Massey, H. F., and R. I. Barnhisel. 1972. Copper, nickel, and zinc released from acid coal mine spoil materials of eastern Kentucky. Soil Sci. 113:207-212.
http://dx.doi.org/10.1097/00010694-197203000-00011

27. McFee, W. W., W. R. Byrnes, and J. G. Stockton. 1981. Characteristics of coal mine overburden important to plant growth. J. Environ. Qual. 10:300-308.
https://doi.org/10.2134/jeq1981.00472425001000030009x

28. McSweeney, K, I. J. Jansen, and W. S. Dancer. 1981. Subsurface horizon blending: An alternative strategy to B horizon replacement for the construction of post-minesoils. Soil Sci. Soc. Am. J. 45:795-799.
http://dx.doi.org/10.2134/jeq1981.00472425001000030009x

29. McSweeney, K. and I. J. Jansen. 1984. Soil structure and associated rooting behavior in minesoils. Soil Sci. Soc. Am. J. 48:607-612.
http://dx.doi.org/10.2136/sssaj1984.03615995004800030028x

30. McSweeney, K., I. J. Jansen, C. W. Boast, and R. E. Dunker. 1986. Row crop productivity of eight constructed minesoils. Reclamation and Revegetation Research. (In press)

31. Meyer, J. J. 1983. Corn root behavior in soils constructed after surface mining for coal in southern Illinois. Unpubl. M.S. Thesis, Univ. of Ill., Urbana, Illinois.

32. Miles, C. C., B. W. Ray, and W. R. Oschwald. 1970. Soil associations of Perry County, Illinois. Circ. no. 1018, Coop. Ext. Serv., Univ. of Illinois-Urbana.

33. Neilson, G. A., and E. V. Miller. 1980. Crop yields on native soils and strip mine soils: a comparison. J. Soil Water Conserv. Vol. 35(1):44-46.

34. Pedersen, T. A., A. S. Rowgowski, and R. Pennock, Jr. 1978. Comparison of morphological and chemical characteristics of some soils and minesoils. Reclam. Rev. 1:143-156.

35. Pedersen, T. A., A. S. Rowgowski, and R. Pennock, Jr. 1980. Physical characteristics of some minesoils. Soil Sci. Am. J. 44:321-328.
http://dx.doi.org/10.2136/sssaj1980.03615995004400020024x

36. Plass, W. T. 1969. Pine seedlings respond to liming of acid strip-mine soil. U. S. Dep. of Agric., Forest Serv. Res. Not. no. NE-103.

37. Plass, W. T. and J. P. Capp. 1974. Physical and chemical characteristics of surface mine spoil treated with fly ash. J. Soil Water Cons. 29(3):119-121.

38. Plass, W. T., and W. G. Vogel. 1973. Chemical properties and particle-size distribution of 39 surface-mine spoils in southern West Virginia. U. S. Dep. of Agric., Forest Serv. Res. Paper no. NE-276.

39. Powell, J. L., R. I. Barnhisel, W. O. Thom, M. L. Ellis, J. R. Armstrong, and F. A. Craig. 1985. Reclamation of prime farmland in Kentucky. 1985 National Meeting of the American Society for Surface Mining and Reclamation; Denver, Colorado. Oct. 8-10, 1985.

40. Power, J. F., F. M. Sandoval, R. E. Ries, and S. D. Merrill. 1981. Effects of topsoil and subsoil thickness on soil water content and crop production on a disturbed soil. Soil Sci. Soc. Am. J. 45:124-129.
http://dx.doi.org/10.2136/sssaj1981.03615995004500010027x

41. Public Law 95-87. 1977. Surface Mining Control and Reclamation Act. U. S. Code Vol. 30, Sec 1265.

42. Rimmer, D. L. 1979. Effects of increasing compaction on grass growth in colliery spoil. Journal of the Sports Turf Research. 55:153-162.

43. Smith, Richard Meriwether, and Andrew A. Sobek. 1978. Physical and chemical properties of overburdens, spoils, wastes, and new soils. Chapter 9 in Reclamation of Drastically Disturbed Lands, F. W. Schaller and Paul Sutton, editors. American Society of Agronomy, Madison, Wisconsin. pp.149-172.

44. Smith, W. H., and J. B. Stall. 1975. Coal and water resources for coal conversion in Illinois. Cooperative Resources Report 4. Illinois State Geological Survey and Illinois State Water Survey.

45. Snarski, R. R., J. B. Fehrenbacher, and I. J. Jansen. 1981. Physical and chemical characteristics of pre-mine soils and post-mine soil mixtures in Illinois. Soil Sci. Soc. Am. J. 45:806-812.
http://dx.doi.org/10.2136/sssaj1981.03615995004500040027x

46. Stucky, D. J. and T. C. Lindsey. 1982. Effect of soil compaction on growth and yield of soybeans grown in a greenhouse on several reconstructed soil profiles from prime farmland in southern Illinois. Reclamation and Revegetation Research, 1:297-309.

47. Taylor, H. M., G. M. Robertson, and J. J. Parker. 1966. Soil strength-root penetration relations for medium to coarse textured soil materials. Soil Science. 102:18-22.
http://dx.doi.org/10.1097/00010694-196607000-00002

48. Thompson, P. J. 1985. Use of recording penetrometer for predicting root system performance in mine soils. M.S. Thesis, Univ. of Illinois-Urbana.

49. Thurman, N. C., and J. C. Sencindiver. 1986. Properties, classification, and interpretations of minesoils at two sites in West Virginia. Soil Sci. Soc. Am. J. 50:181-185.
http://dx.doi.org/10.2136/sssaj1986.03615995005000010034x

50. Vance, S. L., C. L. Hooks and I. J. Jansen. 1986. Use of a cone penetrometer to evaluate soil reconstructive methods after surface mining for coal. Agron. Abst. p. 255.

51. VanLear, D. H. 1971. Effects of spoil texture on growth of K-31 tall fescue. U. S. Dep. of Agric., Forest Serv. Res. Note no. NE-141.

52. Voorhees, W. B., Min Amemiya, R. R. Allmaras, and W. E. Larson. 1971. Some effects of aggregate structure heterogeneity on root growth. Soil Sci. Soc. Amer. Proc. 35:638-643.
http://dx.doi.org/10.2136/sssaj1971.03615995003500040043x

53. Wuertz, Wolfgang. In press. Methods and successes in agricultural and forest reclamation in German Lignite Mines. Innovative Approaches to Mined Land Reclamation. C. L. Carlson, and J. H. Swisher (eds). Carbondale: Southern Illinois University Press. pp.173-186.

54. Yammamoto, T. 1975. Coal mine spoil as a growing media. p. 49-61. In Third Symp. on Surface Mining and Reclamation. Vol. 1. NCA/BCR Coal Conf. and Expo. II. National Coal Assoc., Washington, D.C.

55. Veihmeyer, F. J. and A. H. Hendrickson. 1948. Soil density and root penetration. Soil Science. 65:487-493.
http://dx.doi.org/10.1097/00010694-194806000-00006