SOIL DEVELOPMENT IN TWO OHIO MINESOILS UNDER CONTINUOUS GRASS COVER FOR TWENTY-FIVE YEARS FOLLOWING RECLAMATION[1]

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Abstract. During 2001, two Ohio surface mined sites were re-examined to assess soil development in Bethesda and Fairpoint minesoils that have been in continuous, tall cool-season grass cover, principally tall fescue (*Festuca arundinacea Shreb.*), since reclamation in 1975-76.11581158 Topgrowth was cut and removed from 1979-94 while being utilized for forage research. Bethesda (loamy-skeletal, mixed, acid, mesic, Typic Udorthent) and Fairpoint (loamy-skeletal, mixed, nonacid, mesic, Typic Udorthent) have each been mapped on more than 60,000 hectares of minespoils in Ohio and neighboring states. Five years after reclamation (1981), morphological descriptions and physical and chemical characterization of samples collected from pits showed negligible evidence of pedogenesis. Twenty-five years after reclamation, morphological descriptions and physical and chemical analyses of samples were again obtained at these sites. During the 20 year interval from 1981 to 2001, organic carbon content has increased ≥2.6-fold in the surface 9 to 11 cm, soil structure now extends 23 to 27 cm below the Ap horizon into the spoil, soil consistence has become more friable, rooting depths have increased, the release and oxidation of Fe has yielded higher chroma colors in the uppermost portion of the spoil, significant quantities of extractable Na and K have been released by mineral weathering, and calcite has been removed from the Fairpoint minesoil by dissolution. These changes indicate that significant soil development has occurred during this 20 year period. Whereas the minesoils were described in 1981 with only A and C horizons, the uppermost portion of the spoil in 2001 was described as a Bw horizon in Bethesda and as a CB horizon in Fairpoint. Because both the Bw and CB horizons qualify as cambic horizons, both the Bethesda and Fairpoint minesoils now classify as Dystric Eutrudept and Typic Eutrudept, respectively.

Additional Key Words: pedogenesis, soil formation, soil morphology, soil classification

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Introduction

Modern coal surface mine reclamation procedures were first adopted in the 1970's to provide minesoils with higher immediate potential for successful plant growth, long-term productivity, and protection from erosion. Key provisions of the 1972 Revision of the Ohio Stripmine Law (Anonymous, 1972) included (a) grading of land to the approximate original contour, (b) placement of 15 cm or more of topsoil, or equivalent, over the spoil, and (3) prompt establishment of vegetative cover to limit soil erosion and improve runoff water quality. The Federal Surface Mining Control and Reclamation Act of 1977(PL95-87) closely followed provisions of the Ohio law, but it also included stringent regulations concerning prime farmland, a land class which is limited in Ohio's coal-producing region.

Studies in the mid to upper Eastern Appalachian coal-producing region have focused on soil development following modern surface mine reclamation at sites that provide a range of climatic and edaphic regimes. In steep mountainous terrain, reclamation is often hampered by a lack of sufficient topsoil, consequently amendments and suitable materials from deeper strata are often used as a replacement for topsoil. At such sites in southwestern Virginia, Haering et al. (1993) documented that rapid soil-forming processes occurred in sandstone overburden used as a substitute for topsoil. Distinct organic matter enrichment at the surface was evident after two growing seasons and discernible horizon development after four years; both were much more distinct after eight years. At a north central West Virginia location, Gorman and Sencindiver (1999) compared soil development at sites with substitute topsoil to sites with conventional minesoil dominated by lithic overburden and found reduced bulk densities, increases in aggregation and total porosity, and changes in particle size distribution after nine years where a fly ash/wood waste mixture was used as a topsoil substitute. Soil profile development at a mountaintop removal minesite in southern West Virginia was investigated using sites representing 2, 7, 11, and 23 years after reclamation, two slope classes, and comparisons to nearby native soils (Thomas et al., 2000 and 2001). Whereas two minesoils exhibited Bw horizons, only one Bw (in 23 year old minesoil) was thick enough to qualify as a cambic horizon for classification of the minesoil as an Inceptisol. Compared to native soils, minesoils had thinner sola, except for 2-year-old minesoils which had thicker A horizons than native soils. These findings suggest that these minesoils will have potentially equal or better future productivity than native soils and similar land use capabilities. Studies at sites where prime farmland was mined and reclaimed in western Kentucky showed a few morphological changes in Ap horizons after 5 years, but after 10 and 21 years, major changes had occurred in the upper part of the B horizons (Barnhisel and Gray, 2000). They concluded that the time required for significant minesoil formation is much shorter than previously thought. Studies of 70 to 130 year-old iron mine sites in northern West Virginia disclosed that minesoils have developed deeper zones of root growth, have higher bulk densities, and weaker grades of soil structure than nearby native soils (Smith et al., 1971).

The studies in Virginia and West Virginia cited above examined soil development in more mountainous terrain than present in Ohio. Surface mine coal production in Ohio largely occurs within the unglaciated Allegheny plateau with gently rolling to steep topography. Although hardwood forest is the native vegetation in Ohio coalfields, Akala and Lal (1999) indicate that the greatest long-term potential for organic carbon sequestration is provided by graded minespoils seeded with grass forages rather than trees because of greater biomass production and the ability of grasses to incorporate more organic matter into the minesoils. Agricultural use of reclaimed stripmine land is common, especially with farms having forage-based beef, sheep and/or dairy enterprises. Many thousands of hectares of reclaimed stripmine land are now being used for forage production in Ohio. Frequently farmers harvest the spring growth from reclaimed land as hay, and utilize the regrowth through grazing. In order to assess agricultural potential for hay and pasture use of minesoils in Ohio, forage fertility plots were established on representative minesoils in Ohio's coal-producing region to (a) determine the relative suitability of minesoils for use in agriculture, and (b) to identify best management practices for success with forages and grains on adapted minesoils (Underwood and Sutton, 1992, 1993, and 1994). The plot areas were seeded to a mixture of clovers (*Trifolium spp.*) and cool-season grass species in 1975, but by 1977 stands were primarily tall fescue (*Festuca arundinacea Shreb.*). Representative pedons of the minesoils at each site were described, sampled, and analyzed in 1981. The objective of this paper is to report an evaluation of the magnitude of soil development in minesoils under continuous forage cover from 1981 to 2001 at two of the earliest surface mines reclaimed according to the 1972 Ohio Stripmine Law.

Materials and Methods

Strip Mine Sites

The location of the two strip mine sites that were both reclaimed in 1975-76 are shown in Figure 1. In 1981, the minesoil at the Vinton County site was classified as Bethesda (loamy-skeletal, mixed,

Figure 1. Location of Bethesda and Fairpoint mine soils

acid, mesic, Typic Udorthent) whereas the minesoil at the Jackson County site was classified as Fairpoint (loamy-skeletal, mixed, nonacid, mesic, Typic Udorthent). Now more than 60,000 ha of each of these two series have been mapped in Ohio and nearby states following surface mining for coal. This region of Ohio receives an average of 1090 mm of precipitation per year, with 530 to 580 mm occurring during the May through September growing season. Average annual temperature is 11ºC and the number of days without killing frost ranges from 160 to 180 days. Replicated forage fertility experiments were superimposed on forage stands at both sites in the spring of 1977 with nine N-P-K treatment combinations. All topgrowth was removed during the 16 year (1977-94) trials using a three-cut hay management system.

Pedon Location and Sampling

One soil pit was excavated in 1981 to a depth of 76 cm at both sites which were selected as locations for representative pedons for the county soil surveys then in progress. Pits within 15 to 30 m of the original pits were excavated in 2001 to a depth of 100 to 125 cm in plots which had received the highest N-P-K fertilization rate during the 1977-94 period. Each season, these plots received 224 kg ha^{-1} actual N from ammonium nitrate (112 kg ha^{-1} in early April and 112 kg ha^{-1} after the first harvest in early June), 49 kg ha^{-1} P from 0-46-0, and 94 kg ha^{-1} K from 0-0-61 each April. Sites reverted to landowner control from 1995-2001, but were virtually abandoned insofar as management. Several 2 to 3 m bushes were found growing within each plot area when revisited in 2001. The minesoil pedons were described in 1981 by local USDA soil scientists and in 2001 by the authors using standard terminology in the *Soil Survey Manual* (Soil Survey Division Staff, 1993). Bulk samples were collected from all horizons for chemical and physical laboratory analyses. Multiple natural clods were collected and coated with saran for determination of bulk density (air dry) using the method of Brasher et al. (1966).

Laboratory Methods

Bulk samples were air dried and crushed to pass through a 2-mm sieve for the following analyses. Soil pH values were measured with a pH meter following equilibration for 1 h using a soil-to-water ratio of 1:1. Particle-size distribution was determined by a modification of the pipette method of Kilmer and Alexander (1949). Organic carbon content was determined by dry combustion (950ºC) using a method similar to that described by Allison et al. (1965). Calcium carbonate equivalents and calcite and dolomite contents of calcareous horizons were determined by the gasometric procedure of Dreimanis (1962). Extractable acidity was determined using $BaCl_2$-triethanolamine according to the method of Peech et al. (1947). Extractable bases were determined in 1N NH_4OAc (pH 7.0) extracts by atomic absorption (Ca, Mg) or flame emission (K) spectrophotometry. Cation-exchange capacity was determined by summation of cations.

<u>Results and Discussion</u>

The most striking morphological feature of the minesoils upon examination in 2001 was the accumulation of organic matter in the upper 9 to 11 cm of the replaced soil (Figures 2 and 3). The organic carbon content in the upper portion of the Ap horizons increased from 0.87% in 1981 to 2.38% in 2001 in the Bethesda minesoil and from 0.86% to 2.23% in the Fairpoint minesoil, a greater than 2.6-fold increase (Tables 1 and 2). The prominent increase in organic matter content undoubtedly influenced structural development in these minesoils (Tables 3 and 4). Structure in the upper 9 to 11 cm evolved from strong moderate platy to moderate fine granular in the Bethesda minesoil and from weak

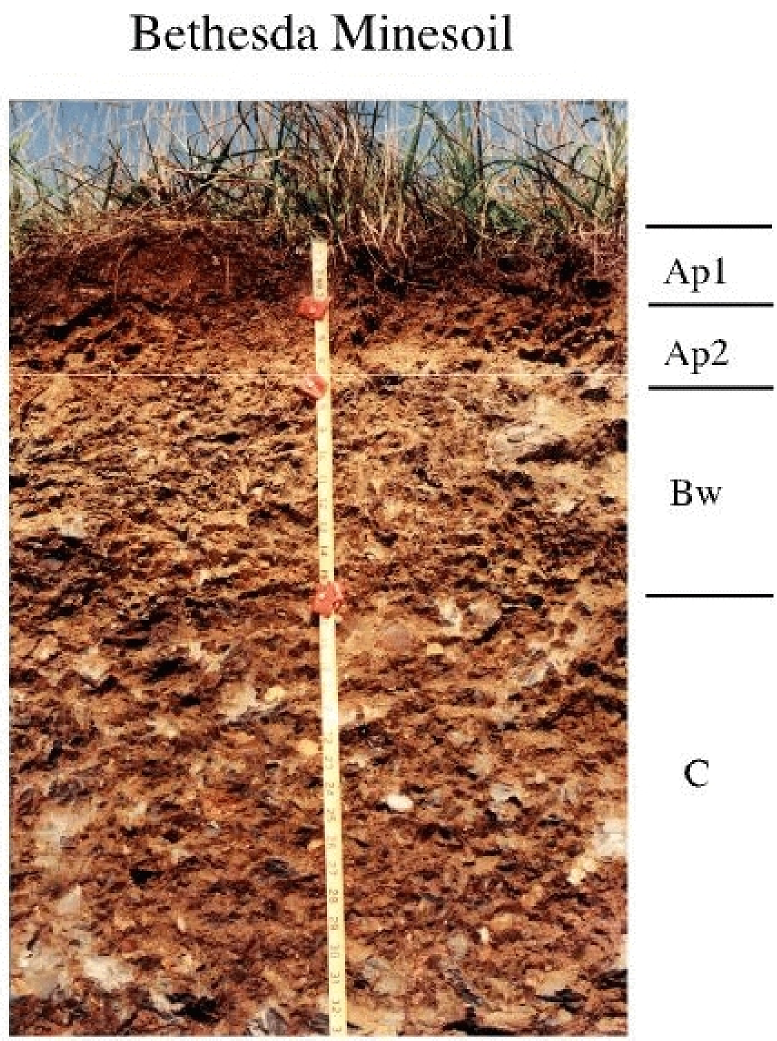

Figure 2. Profile of Bethesda minesoil sampled in 2001

moderate

Table 1. Chemical data for Bethesda minesoil in 1981 and 2001.

Horizon	Depth (cm)	pH	O.C. (%)	Extractable Cations (meq/100g)					Sum Cations (meq/100g)	Base Sat. (%)
				H	Ca	Mg	K	Na		
				5-year-old Bethesda Minesoil 1981						
A	0-10	6.4	0.87	4.0	5.9	2.0	0.36	.06	12.3	68
C1	10-18	6.1	N/AŦ	2.2	5.2	2.3	0.11	.08	9.9	78
C2	18-41	4.2	N/AŦ	9.5	3.2	3.0	0.17	.08	16.0	40
C3	41-76	3.9	N/AŦ	5.6	8.8	3.9	0.09	.06	18.4	70
				25-year-old Bethesda Minesoil 2001						
Apl	0-9	6.4	2.38	5.2	6.6	2.0	1.00	.08	14.9	65
Ap2	9-18	6.6	0.82	2.6	4.2	1.7	0.49	.12	9.1	71
Bw	18-41	5.4	N/AŦ	3.7	5.1	1.3	0.48	.12	10.7	65
C1	41-58	3.4	N/AŦ	11.2	6.7	1.2	0.52	.12	19.7	43
C2	58-76	3.8	N/AŦ	8.9	10.5	2.1	0.59	.13	22.2	60
C3	76-125	5.4	N/AŦ	4.6	6.0	2.9	0.69	.16	14.4	68

Ŧ N/A- organic carbon could not be determined due to coal contamination

Table 2. Chemical data for Fairpoint minesoil in 1981 and 2001.

Horizon	Depth (cm)	pH	O.C. (%)	Extractable Cations (meq/100g)					Sum Cations (meq/100g)	Base Sat. (%)
				H	Ca	Mg	K	Na		
				5-year-old Fairpoint Minesoil 1981						
Ap	0-23	7.1	0.86	4.1	16.8	0.9	0.29	0.04	22.1	81
C	23-76	6.2	N/AŦ	1.9	12.5	2.0	0.17	0.06	16.6	89
				25-year-old Fairpoint Minesoil 2001						
Apl	0-11	7.6	2.23	2.3	22.1	0.0	1.30	0.12	25.8	91
Ap2	11-24	7.5	0.75	3.1	10.5	0.0	0.81	0.23	14.6	79
CB	24-31	7.3	N/A Ŧ	1.2	8.4	0.9	0.73	0.44	11.7	90
CB	31-51	7.1	N/A Ŧ	1.3	17.8	3.3	0.88	0.81	24.1	95
C	51-76	7.1	N/A Ŧ	1.8	13.3	3.9	0.94	1.20	21.1	91
C	76-105	7.0	N/A Ŧ	1.0	11.7	3.2	0.94	1.19	18.0	94

Ŧ N/A- organic carbon could not be determined due to coal contamination

Table 3. Morphological and physical data for Bethesda minesoil in 1981 and 2001.

Horizon	Depth (cm)	Moist color	C. Frag >2mm (wt %)	Particle Size Distribution sand (%)	silt (%)	clay (%)	Text* Class	Bulk Density (Mg/m^3)	Structure**	Consist.***	Roots+
				5-year-old Bethesda Minesoil 1981							
A	0-10	70% 10YR4/3 30% 10YR5/4	3.5	26.2	56.5	17.3	SIL	1.74	Str-m-pl	fi	c
C1	10-18	5Y4/1	38.4	44.1	40.2	15.7	L		ma	vfi	n
C2	18-41	55% 10YR5/4 25% 10YR6/1 20% 10YR4/1	25.5	24.7	49.7	25.6	L	1.73	ma	fi	n
C3	41-76	10YR4/1	22.6	49.2	34.2	16.6	L	1.94	ma	vfi	n
				25-year-old Bethesda Minesoil 2001							
Apl	0-9	10YR4/2	9.8	40.3	41.9	17.8	L	1.45	mod-f-gr	fr	mm
Ap2	9-18	10YR5/4	3.3	24.4	54.0	21.6	SIL	1.69	wk-f-sbk	fr	mm
Bw	18-41	80% 2.5Y4/2 20% 7.5YR6/6	18.9	35.4	41.8	22.8	L	1.94	wk-m-abk	fi	cm
C1	41-58	10YR4/4	38.0	31.5	45.6	22.9	L	1.91	ma	vfi	n
C2	58-76	10YR4/4	38.0	32.2	46.0	21.8	L	1.86	ma	vfi	n
C3	76-125	10YR4/4	46.9	27.1	50.6	22.3	SIL	1.91	ma	vfi	n

* Textural Class: sil-silt loam; l-loam

** Structure Grade: wk-weak; mod-moderate; str-strong. Size: f-fine; m-medium
Type: pl-platy; gr-granular; sbk- subangular, blocky; abk- angular blocky; ma-massive.

*** Consistence: fr-friable; fi-firm; vfi- very firm.

\+ Roots: c-common; cm-common medium; mm- many medium; n- none evident.

Table 4. Morphological and physical data for Fairpoint minesoil in 1981 and 2001.

Horizon	Depth (cm)	Moist color	C.Frag >2mm (wt %)	Particle Size Distribution sand (%)	silt (%)	clay (%)	Text* Class	Bulk Density (Mg/m^3)	Structure**	Consist.***	Roots+
				5-year-old Fairpoint Minesoil 1981							
Ap	0-23	60% 10YR4/4 40% 10YR5/6	3.8	17.9	57.1	25.0	SI L	1.65	wk-m-sbk	fi	c
C	23-76	50% 2.5Y5/4 50% 5Y5/1	31.5	30.2	49.6	20.2	L	1.89	ma	fi	f
				25-year-old Fairpoint Minesoil 2001							
Ap1	0-11	80% 10YR4/3 20% 10YR5/6	7.0	20.5	53.2	26.3	SIL	1.58	wk-vf-sbk	fr	cm
Ap2	11-24	10YR5/6	7.1	16.5	54.6	28.9	SICL	1.70	wk-f-sbk	fi	cm
CB	24-31	60% 2.5Y5/2 40% 10YR5/6	20.1	24.9	48.9	26.2	L	1.99	wk-m-sbk	fi	cm
CB	31-51	60% 2.5Y5/2 40% 10YR5/6	10.2	24.0	49.6	26.4	L	1.99	wk-c-sbk	fi	cm
C	51-76	2.5Y4/2	15.8	24.2	48.1	27.7	CL	1.92	ma	fi	fm
C	76-105	2.5Y4/2	17.2	24.5	47.9	27.6	CL	1.92	ma	fi	fm

*Textural Class: sil-silt loam; sicl – silty clay loam; l-loam; cl- clay loam.

**Structure Grade: wk- weak. Size: vf-very fine; f-fine; m-medium, c-coarse. Type: sbk-subangular blocky; ma-massive.

***Consistence: fr- friable; fi- firm

\+ Roots – c- common; cm- common medium; f- few; fm- few medium subangular blocky to weak very fine subangular blocky structure in the Fairpoint minesoil. These changes in structure will increase infiltration of surface water into the minesoils, resulting in less runoff and increased water retention. Although there was no increase in organic carbon content in the lower portion of the Ap horizons, structural units also became smaller. Examination of the minesoils in 2001 also revealed weak medium or coarse subangular or angular blocky structure in the upper 23 to 27 cm of the spoil directly underlying the Ap horizons. In 1981, the spoils were described as massive C horizons. The consistence of the Ap horizon of Bethesda improved from firm to friable and the uppermost layer of spoil changed from very firm to firm; however, the only change in consistence in the Fairpoint minesoil was in the upper 11 cm of the Ap horizon which became friable. Although changes in structure and/or consistence were noted to 41 cm in Bethesda and 51 cm in Fairpoint, only the upper portion of the Ap horizon of Fairpoint and entire Ap of Bethesda showed any definitive decrease in bulk density (Tables 3 and 4). Due to improved structure and/or decrease in consistence, the abundance of roots in the Ap horizons and uppermost layer of spoil generally increased. The more restricted zone of rooting in the Bethesda minesoil results in it subjecting crops to more frequent droughts than the Fairpoint minesoil. However during seasons with ample, well distributed

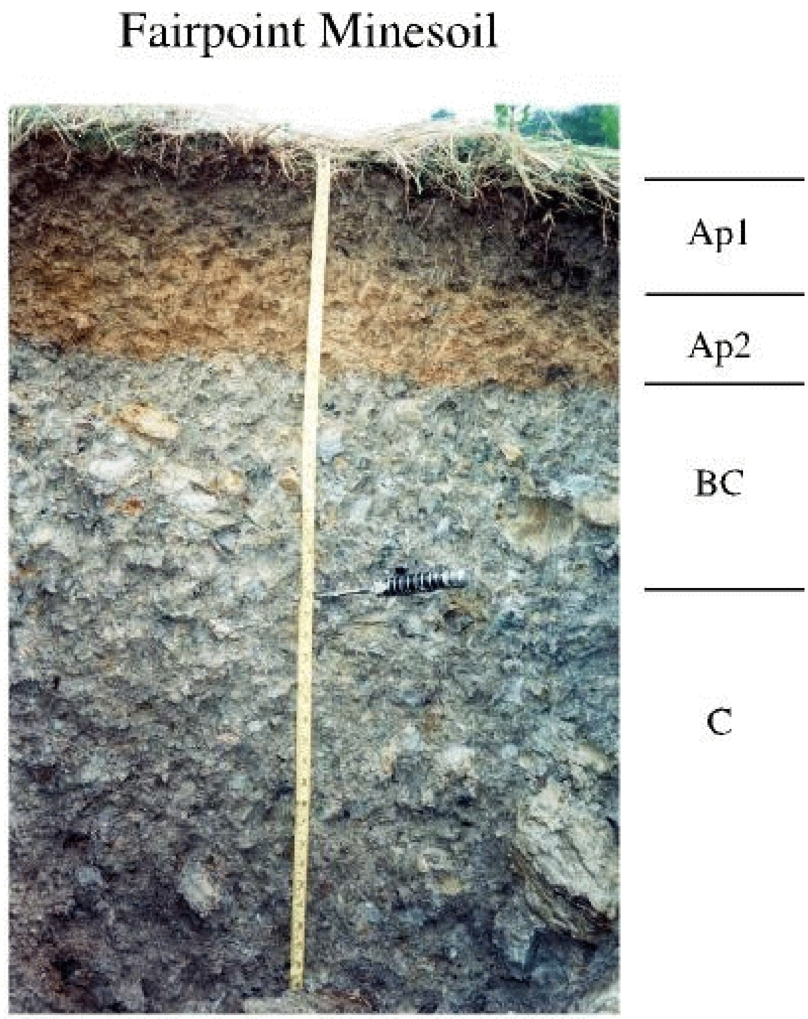

Figure 3. Profile of Fairpoint minesoil sampled in 2001

precipitation, forage yields from the Bethesda minesoil have equalled or exceeded the yields from the Fairpoint minesoil; consequently, field trials resulted in the decision to recommend Bethesda for forage production, but not for corn or soybean production.

Another evident morphological change during the 1981 to 2001 period, particularly in the Bethesda minesoil (Figure 2), was the oxidation of the spoil underlying the Ap horizon. The color of the upper 23 cm of the Bethesda spoil evolved from a 1 to 2 chroma and common (20%) reddish yellow 7.5YR 6/6 iron oxide concentrations formed. Although oxidation of the spoil in the Fairpoint minesoil (Figure 3) was not as evident, the upper 27 cm of the spoil immediately below the Ap horizon developed many (40%) yellowish brown 10YR 5/6 iron oxide concentrations where none were observed in 1981. The greater degree of oxidation of the Bethesda minesoil is related to its lower pH (Tables 1 and 2) which favors more rapid mineral weathering, resulting in greater release and oxidation of Fe.

Although one might expect physical weathering due to wet-dry and freeze-thaw processes to proceed more rapidly than chemical processes, there was no evident changes in particle-size distributions (Tables 3 and 4) during the twenty year period. In addition to increased oxidation, there were some changes in pH and extractable cation contents noted. Whereas the pH in the Bethesda minesoil showed only a slight decrease in the upper portion of the spoil below the Ap horizon, the pH throughout the Fairpoint minesoil increased. Both minesoils received a broadcast application of several tonnes of pulverized limestone prior to seeding of the forage trials and the Bethesda received a second lime application of 5 t ha^{-1} midway through the research period due to need as indicated by soil testing of the site (the Fairpoint site received only the initial application). Whereas the limestone applications undoubtedly maintained a pH suitable for plant growth in the Ap horizon, the rise in pH below the Ap horizon in the Fairpoint minesoil is more likely a consequence of the dissolution of residual limestone present in the replaced soil (Ap horizon) and leaching into the underlying spoil. The calcium carbonate equivalent of the Ap horizon of Fairpoint in 1981 was 1.8% (1.2% dolomite and 0.6% calcite); but in 2001, analytical data for the Ap horizon showed 1.2% calcium carbonate equivalent, 1.1% dolomite, and 0% calcite. The loss of calcite would be equivalent to about 15 t ha^{-1} of limestone.

There are no definitive changes in extractable H, Ca, or Mg contents or base saturation in either minesoil, but there is an evident increase in extractable K and Na in both the Ap horizons and underlying spoils at both sites (Tables 1 and 2). K contents increased 1.5 to 4-fold in the Ap horizons and 4 to 7-fold in the underlying spoils at both sites during the 20-year interval. Na contents increased 1.3 to 5-fold in the Ap horizons and 2 to 20-fold in the underlying spoils. The high contents of these cations are indicative of the weathering of minerals, such as biotite, muscovite, microcline, and orthoclase, that are freshly exposed during mining. Limited leaching since mining has slowed the removal of these two cations from the minesoils. The high potassium release by the minesoils contributes to the relatively high grass forage yields that were obtained throughout the 16 year research period and the high levels of K in harvested plant tissue. This occurred even though annual potassium fertilization was below crop removal levels. Whereas grass hay typically contains the equivalent of 16 kg K Mg^{-1} of hay (equivalent to 45 lbs K_2O per U. S. ton of hay; Beagle,1992), average annual harvest of grass forage from this 224-49-94 kg ha^{-1} fertilization program was 7.4 Mg ha^{-1} (hay equivalent) for the Bethesda site and 8.5 Mg ha^{-1} (hay equivalent) for the Fairpoint site. If high K release is typical of other minesoil locations, producers managing grass for hay/silage production may be able to shift some fertilizer expenditure from purchase of potassium to nitrogen, the most responsive nutrient in minesoil fertilization programs.

Summary

During the 20 year interval from 1981 to 2001, the minesoils have accumulated significant organic matter in the surface 9 to 11 cm, the development of soil structure has progressed to a depth of 41 to 51 cm, soil consistence has become more friable, rooting depths have increased, the release and oxidation of Fe has yielded higher chroma colors in the uppermost portion of the spoil, significant quantities of extractable Na and K have been released by mineral weathering, and calcite has been removed from the Fairpoint minesoil by dissolution. These changes indicate that significant soil development has occurred during this 20 year period. Whereas the minesoils were described in 1981 with only A and C horizons, the uppermost portion of the spoil in 2001 was described as a Bw horizon in Bethesda and as a CB horizon in Fairpoint. The upper spoil in Bethesda was designated as a Bw because that zone appeared to be a weakly developed B horizon whereas the CB designation was applied to the upper spoil in Fairpoint because it appeared to be more similar to the underlying spoil than a B horizon (Fig. 3), but enough structure was evident to identify some B horizon characteristics (Soil Survey Division Staff, 1993). Both the Bw of Bethesda and CB of Fairpoint qualify as cambic diagnostic horizons because the horizons 1) are ≥15 cm thick, 2) meet textural requirements, and 3) show evidence of alteration in the following forms: 1) soil structure is presence in more than one-half of the volume, and 2) higher chroma, higher value, or redder hue occur in these horizons than in underlying or overlying horizons (Soil Survey Staff, 1999). The redder hues and higher chromas and values developed in the upper spoils due to oxidation of Fe released by mineral weathering. Due to the presence of cambic diagnostic horizons, the current classification of these minesoils are: Bethesda- Dystric Eutrudept and Fairpoint- Typic Eutrudept. The evolution of these minesoils from Udorthents to Eutrudepts in 20 years indicates that early stages of soil development can occur rapidly in reclaimed minespoils under good forage grass cover.

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