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Acid soil indicators in forest soils of the Cherry River Watershed, West Virginia

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Abstract Declining forest health has been observed during the past several decades in several areas of the eastern USA, and some of this decline is attributed to acid deposition. Decreases in soil pH and increases in soil acidity are indicators of potential impacts on tree growth due to acid inputs and Al toxicity. The Cherry River watershed, which lies within the Monongahela National Forest in West Virginia, has some of the highest rates of acid deposition in Appalachia. East and West areas within the watershed, which showed differences in precipitation, stream chemistry, and vegetation composition, were compared to evaluate soil acidity conditions and to assess their degree of risk on tree growth. Thirty-one soil pits in the West area and 36 pits in the East area were dug and described, and soil samples from each horizon were analyzed for chemical parameters. In A horizons, East area soils averaged 3.7 pH with 9.4 $cmol_c\ kg^{-1}$ of acidity compared to pH 4.0 and 6.2 $cmol_c\ kg^{-1}$ of acidity in West area soils. Extractable cations (Ca, Mg, and Al) were significantly higher in the A, transition, and upper B horizons of East versus West soils. However, even with differences in cation concentrations, Ca/Al molar ratios were similar for East and West soils. For both sites using the Ca/Al ratio, a 50% risk of impaired tree growth was found for A horizons, while a 75% risk was found for deeper horizons. Low concentrations of base cations and high extractable Al in these soils translate into a high degree of risk for forest regeneration and tree growth after conventional tree harvesting.

Keywords Acid deposition · Ca/Al molar ratio · Extractable acidity · Extractable bases · Soil acidification

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Introduction and objectives

Declining forest health has been observed during the past several decades in the eastern USA

(Bailey et al. 2004; Binkley et al. 1998). A number of factors influence the productivity and sustainability of forests, including species composition, disease, insect infestations, soil moisture, nutrient status, and acid deposition, all of which tend to be interrelated (Duchesne et al. 2003). For example, nutrient availability and growth of forest trees can decrease in areas subject to chronic high levels of acid deposition, which in turn makes these same trees susceptible to diseases or insect damage (Federer et al. 1989).

Concentrations of base cations (Ca, Mg, K, Na), effective cation exchange capacity (ECEC), and metal concentrations such as Al and Mn are three soil chemical factors which influence tree growth (Adams et al. 2000). Calcium and N are particularly important, because these elements are primary components of biomass (Auchmoody and Smith 1977), affect cell function (Yanai et al. 2005), and influence juvenile growth of many tree species (Bigelow and Canham 2007). Base cations also aid in counteracting the effects of soil acidity and Al toxicity at low pH (Federer et al. 1989; Juice et al. 2006).

The main inputs of Ca to soils are weathering and atmospheric deposition (Huntington 2000). However, the rate at which Ca is replaced by weathering tends to be very slow compared to rates of deposition, biomass immobilization, and leaching (USGS 1999). Schnably (2003) found that replenishment of soil Ca in Appalachia is low due to the highly weathered status of these soils and because many of these soils formed from base-poor geology (Huntington et al. 2000).

Atmospheric deposition has been linked to soil acidification and Ca depletion. Markewitz et al. (1998) reported that the upper 60 cm of soil in the Calhoun Experimental Forest in South Carolina has shown accelerated acidification caused by atmospheric deposition from 1962 to 1990. In England, Blake et al. (1999) determined from a century-long study that acid deposition was the main cause of soil acidification in the Geescroft Wilderness Area. In the Panola Mountain watershed in Georgia, Ca has leached faster in forest soils affected by acid deposition, and if leaching continues at current rates, within 150 years, only enough Ca will be available in the soil for one hardwood rotation to reach marketable size (Joslin et al. 1992; USGS 1999). Using a model simulation, Gbondo-Tugbawa and Driscoll (2003) found that a 20% depletion of soil Ca has occurred over the past 40 years in the Hubbard Brook Experimental Forest in New Hampshire.

Between 1967 and 1999, Bailey et al. (2005) found that forest soils in the Allegheny National Forest in northern Pennsylvania decreased in pH and exchangeable Ca and Mg and increased in exchangeable Al over those 30 years. They also showed that the majority of the change in Ca and Mg could not be accounted for by tree growth, and they concluded that acid deposition was the driving force behind cation leaching from the soil. Drohan and Sharpe (1997) re-sampled soils in Pennsylvania that had been initially sampled 14 to 36 years before. The O and A horizons decreased in pH and exchangeable Ca and Mg and increased in exchangeable Al in the A horizon, which they attributed to biomass immobilization and acid deposition.

The Ca/Al molar ratio of soils has been used to indicate the risk of impaired tree growth due to Ca losses and Al antagonism and toxicity (Cronan and Grigal 1995; Lyon and Sharpe 1999), and degrees of risk were assigned to different ratios Table 1. Lyon and Sharpe (1999) compared Ca/Al molar ratios using 0.01 M $SrCl_2$ extraction in forest soils of Pennsylvania to the vigor of

Table 1 Acid risk assessment criteria proposed by Cronan and Grigal (1995) and which we used for soils in the Cherry River watershed to assess risk (see also Lyon and Sharpe 1999)

% risk[a]	Ca/Al molar ratio
0	>2.0
< 50	1.1–2.0
50	0.6–1.0
75	0.2–0.5
100	<0.2

[a] % Risk = soils with low Ca/Al molar ratios have higher risks for reduced tree growth due to Al antagonism and toxicity. The composite relationship Cronan and Grigal (1995) found in their review of over 300 references is largely based on seedling responses under controlled conditions

sugar maple (*Acer saccharum* Marsh.) where soil samples were taken. For declining maple stands, the median Ca/Al molar ratios were 13.2, 0.7, and 0.3, respectively, for the O, A, and B horizons. For non-declining stands, the median Ca/Al molar ratios were 17.6, 1.9, and 1.1 for these same horizons. Schaberg et al. (2006) found only a weak correlation between Ca/Al molar ratios and basal growth for sugar maple trees in Vermont (see also Huber et al. 2004). More research is needed to correlate acid soil indicators, such as the Ca/Al molar ratio, with tree growth, species-specific effects, and foliar chemistry.

The Cherry River watershed, within the Monongahela National Forest, is located downwind of some of the highest SO_2 emissions in the nation (NADP 2005). Because acid deposition rates are high in the watershed, the potential risk for soil acidification is also high, which could lead to impacts on tree growth and overall forest health. Two areas (East and West) within the watershed, which showed differences in precipitation, stream chemistry, and vegetation composition, were selected to (1) determine the chemical properties of soils in each area and (2) to assess the current degree of risk on tree growth using the Ca/Al molar ratio.

Materials and methods

Site description

The Cherry River watershed is located in Nicholas, Webster, and Greenbrier Counties of West Virginia (Fig. 1) and has been predominantly forested since the turn of the twentieth century (Reger 1921). The rugged terrain of the watershed limits land use, though small family farms are scattered throughout the watershed in valleys and on ridge tops.

Two areas within the Cherry River watershed were selected based on differences in elevation, precipitation, stream chemistry, and vegetation. Average elevation is 785 m for the West area and 1,000 m for the East area. Annual precipitation in the West area averages 125 cm (49 in.), and the East averages 137 cm (54 in.). A National Atmospheric Deposition Program (NADP) monitoring station is located at Cedar Creek State Park, 100 km northwest of the Cherry River watershed, and wet sulfate deposition in the Cherry River watershed ranges from 25 to 30 kg ha^{-1} year^{-1} (Grimm and Lynch 2004; NADP 2005). From the US Forest Service unpublished stream data sampled during spring periods (high flow),

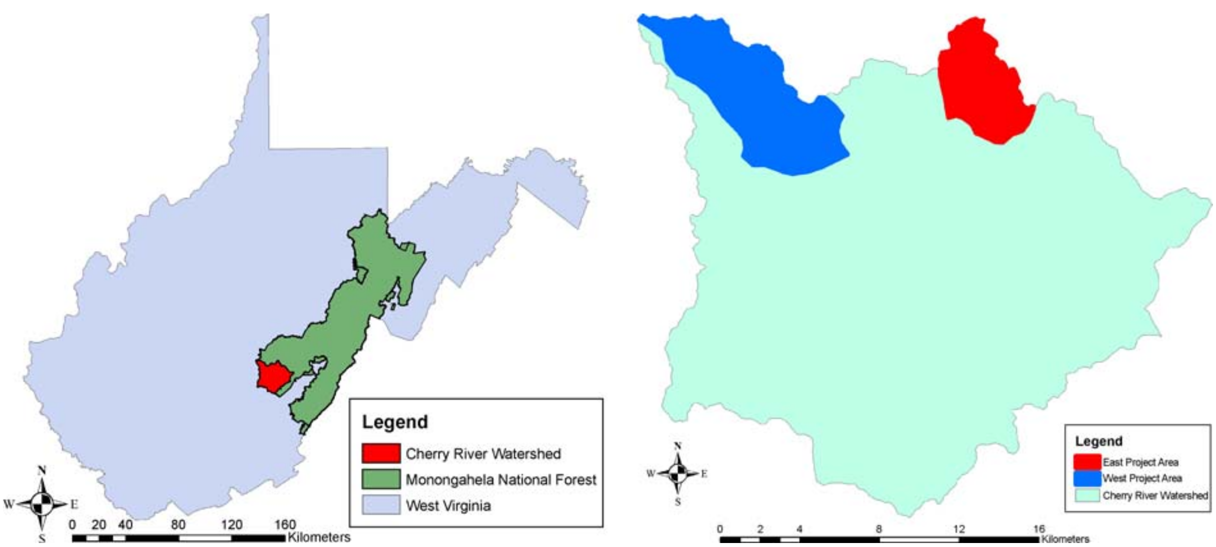

Fig. 1 The location of the Cherry River watershed within the Monongahela National Forest in West Virginia and the location of East and West areas within the watershed

Table 2 Average values for water chemistry from several streams in the Cherry River watershed in the East and West areas during springs of 2002, 2005, and 2007 (see Fig. 2)

Area	Stream	pH	Alkalinity	Ca	Mg	NO_3	SO_4
			μeq L^{-1}				
East	Bear run	5.3	−0.6	52.0	39.1	46.4	281.1
	Rabbit run	4.5	−44.0	27.4	14.9	42.8	101.4
	Hunters run	5.1	−24.2	45.5	30.7	27.1	82.5
	Windy run	4.5	−34.9	41.0	23.2	29.3	97.6
	Average	4.7	−25.9	41.5	27.0	36.4	140.6
West	Morris creek	6.2	22.8	71.5	44.8	27.1	92.2
	Holcomb run	5.6	−0.6	50.0	41.2	25.7	93.7
	Desert branch	5.3	1.2	52.5	39.8	25.6	89.1
	Buckheart run	5.5	−5.5	56.5	34.9	23.6	87.0
	Coal siding run	5.9	14.5	60.0	44.0	30.7	121.0
	Curtain run	5.5	−3.5	45.6	35.6	18.6	98.3
	Average	5.6	4.8	56.0	40.1	25.2	96.9

This is unpublished data from the US Forest Service
Alkalinity = the capacity of a water to neutralize strong acid, titrated to pH 4.2

West area streams had an average pH of 5.6 and alkalinity of 5 μeq L^{-1}, while East area streams showed an average pH of 4.7 and alkalinity of −26 μeq L^{-1} (Table 2 and Fig. 2).

Surface geology of these areas is comprised of the Kanawha and New River Formations of the Pottsville Group (Rice et al. 1992), Pennsylvanian Period, Paleozoic Era. Both formations are composed of 60–70% sandstone and 25–30% shale, with smaller amount of coal and limestone (Reger 1921). Pottsville geology in this region is known to be acid-bearing with few alkaline components, and soils forming from these parent materials are acid (Price 1939). Major soil series in the West area are Buchanan (fine-loamy, mixed, semiactive, mesic Aquic Fragiudults) and

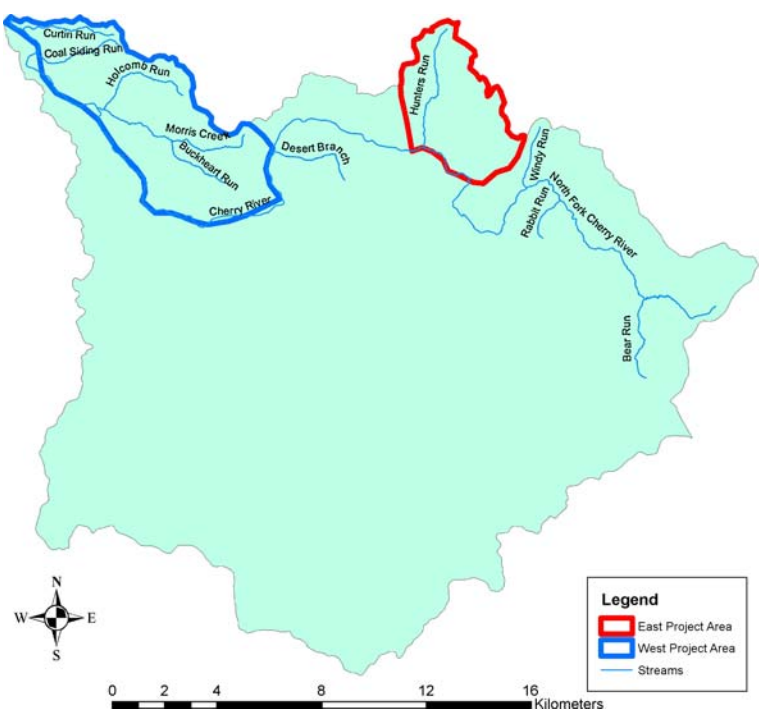

Fig. 2 Location of streams sampled in the Cherry River watershed

Table 3 A comparison of site characteristics between the West and East areas

Parameter	West area	East Area
Elevation	570–1,000 m (1,875–3,135 ft)	790–1,210 m (2,600–3,925 ft)
Precipitation	125 cm (49 in.)	137 cm (54 in.)
Average stream acidity[a]	pH = 5.6, alkalinity = 5 μeq L^{-1}	pH = 4.7, alkalinity = −26 μeq L^{-1}
Bedrock types	Sandstone, gray shale	Sandstone, black shale
Dominant soil mapping unit	Gilpin, Buchanan (mesic)	Mandy, Snowdog (frigid)
Dominant tree species	Red Oak (*Quercus rubra*)	Black cherry (*Prunus serotina*)
	White Oak (*Quercus alba*)	Sugar maple (*Acer saccharum*)
	Hickory (*Carya* spp.)	Red maple (*Acer rubrum*)
		American beech (*Fagus grandifolia*)
		Yellow-poplar (*Liriodendron tulipifera*)

[a]See Table 2

Gilpin (fine-loamy, mixed, active, mesic Typic Hapludults). East area soils are Mandy (loamy-skeletal, mixed, active, frigid Typic Dystrudepts) and Snowdog (fine-loamy, siliceous, active, frigid Typic Fragiudepts). East soils have frigid soil temperatures, and West soils are mesic (Mount and Paetzold 2002).

The predominant forest type in the Cherry River watershed is Eastern Deciduous hardwoods. The West area is dominated by red oak (*Quercus rubra* L.), white oak (*Quercus alba* L.), and hickory (*Carya* spp. Nutt.). Dominant trees of the East area are black cherry (*Prunus serotina* Ehrh.), sugar maple, red maple (*Acer rubrum* L.), American beech (*Fagus grandifolia* Ehrh.), and yellow-poplar (*Liriodendron tulipifera* L.). Table 3 summarizes the differences between the West and East areas. Because of these differences in elevation, precipitation, stream chemistry, and vegetation, we hypothesized that the East area may be more sensitive to acid deposition than the West area.

Field and laboratory methods

Sixty-seven soil pits (31 in the West area and 36 in the East area) were dug in the summer of 2004. Criteria for selecting soil pit locations were as follows: (1) The site was not close to a road or other structure that influenced drainage across the site, (2) it showed no signs of recent disturbance, and (3) the area was representative of the landscape position on which it was found. The pits were located on one of six major landscape positions (ridge top, shoulder, back slope, bench, foot slope, and floodplain), were situated across all aspects, and were found across a variety of slopes (1% for floodplains to 40% for shoulders and back slopes). At each pit, soil profiles were described (Soil Survey Division Staff 1993) to the depth of bedrock or to the C horizon (pit location data and profile descriptions are not shown here but are available in Sponaugle 2005). About 2 kg of soil was obtained from each described horizon and air-dried. Sub-samples were sent to laboratories at the University of Maine and The Pennsylvania State University.

The soil laboratory at the University of Maine determined soil pH (1:1 soil/water), total carbon (%C) by dry combustion, extractable Ca, K, Mg, Na, and Al by 1 M NH_4Cl (unbuffered), and extractable acidity by 1 M KCl (Soil Survey Staff 1996). ECEC was calculated by summing extractable bases by NH_4Cl and extractable acidity by KCl, while base saturation of the ECEC (BSECEC) was calculated by total base cations divided by ECEC. At The Pennsylvania State University laboratory, Ca and Al were determined by 0.01 M $SrCl_2$ extraction, which has been reported to be a good index of soluble, plant-available Ca and Al concentrations in soil solution (Joslin and Wolfe 1989). This $SrCl_2$ extraction technique is the method used to determine Ca/Al molar ratios in soils for risk assessment of tree growth (Lyon and Sharpe 1999). Risk was determined using the criteria set by Cronan and Grigal (1995) and Lyon and Sharpe (1999; Table 1).

Soil chemical values in East and West areas for each horizon were statistically analyzed by *t* tests

Table 4 Average values in 2004 of acidity-related analytes for soils by horizon for East and West areas

Area	Horizon	Soil pH	Acidity ($cmol_c$ kg^{-1})	ECEC ($cmol_c$ kg^{-1})	BSECEC (%)	%C (g 100 g^{-1})
East	A	3.7[a]	9.4[a]	10.7[a]	12[a]	8.1[a]
West	A	4.0[a]	6.2[a]	7.2[a]	15[a]	7.5[a]
East	Transition	4.1	8.5[a]	9.0[a]	5[a]	3.4[a]
West	Transition	4.3	4.3[a]	4.7[a]	9[a]	2.6[a]
East	Upper B	4.3	6.9[a]	7.3[a]	6	2.4[a]
West	Upper B	4.5	3.7[a]	4.0[a]	7	1.3[a]
East	Lower B	4.6	4.7	5.0	6	1.0
West	Lower B	4.5	4.2	4.5	7	0.6
East	BC	4.6	4.2	4.5	9	0.7
West	BC	4.5	3.3	3.6	10	0.3

Horizon values are averages of $n = 36$ in the East area and $n = 31$ in the West area
Horizon designations: *A* A, A_1, and A_2 horizons, *Transition* AB, BA, and E horizons, *Upper B* B_w and B_t horizons, *Lower B* B_x horizons, *BC* means BC horizons
[a]Analyte values within a horizon are significantly different between areas at $\alpha = 0.05$

to determine significant differences between areas by horizon (SAS 1989).

Results

Chemical properties

Average pH was significantly lower in A horizons of East area soils (pH 3.7) compared to West soils (pH 4.0; Table 4). Average acidity and ECEC were significantly higher in A, transition, and upper B horizons of the East area compared to the West area. Higher C values were found in A, transition, and upper B horizons of East soils compared to West soils. Johnson (2002) also found high ECEC in forest soils with high %C contents, where carboxyl groups in humus provided H^+ , thereby decreasing the pH and increasing the ECEC. The higher C values in East soils could be due to frigid soil temperatures, where C compounds are not degraded as quickly as in mesic soil temperatures. But other reasons for higher C contents in East soils could be higher precipitation, greater biomass production from trees and understory species, a longer elapsed period since the last timber harvest, as well as other conditions such as slope, aspect, and soil moisture differences.

Calcium and Mg were significantly higher in East A horizons compared to West A horizons (Table 5). The lower pH and higher acidity of the East soils would be expected to coincide with lower base cation concentrations, but this was not the case. Even with greater Ca and Mg concentrations, the high levels of extractable acidity and Al in A and transition horizons of East soils caused the BSECEC of these soils to be significantly lower than West area soils (Table 4). The dominant trees in the canopies of East areas were maples (*Acer* spp.) and black cherry compared to oaks (*Quercus* spp.) in the West area (Table 2). Maples prefer moist soil conditions and high Ca and N concentrations (Finzi et al. 1998a, b; Prescott 2002; Schwartz et al. 2003), which is reflected in higher amounts of base cations in maple leaf litter than oak leaf litter (Washburn and Arthur 2002).

Aluminum was present in significantly higher amounts in the upper three horizons of East versus West soils (Table 5), and this Al accounted for 70% to 90% of the ECEC in these soils. Jenkins (2002) found similar levels of Al (5 to 10 $cmol_c$ kg^{-1}) in soils formed from the same geology in other areas of West Virginia.

Ca/Al molar ratios

Using $SrCl_2$ extraction, Ca and Al concentrations (Table 6) in East and West soils were much lower than those obtained by NH_4Cl extraction (Table 5). The 0.01 M $SrCl_2$ technique is believed to extract soluble, plant-available levels of these elements (Joslin et al. 1988), which is used to indicate the acid soil condition and potential

Table 5 Average extractable cation concentrations in 2004 for soils by horizon for the East and West areas by 1 M NH_4Cl extraction

Area	Horizon[a]	Ca	Mg	K	Na	Al
		$cmol_c\ kg^{-1}$				
East	A	0.80[b]	0.31[b]	0.21	0.05	7.2[b]
West	A	0.68[b]	0.22[b]	0.20	0.05	6.0[b]
East	Transition	0.22	0.12[b]	0.12	0.03	6.8[b]
West	Transition	0.20	0.07[b]	0.10	0.03	3.7[b]
East	Upper B	0.17	0.08	0.09	0.04[b]	5.6[b]
West	Upper B	0.14	0.05	0.08	0.02[b]	3.6[b]
East	Lower B	0.10	0.05	0.09	0.02	3.9
West	Lower B	0.13	0.09	0.08	0.02	3.3
East	BC	0.13	0.08	0.08	0.02	3.4
West	BC	0.18	0.09	0.08	0.02	2.8

Horizon values are averages of $n = 36$ in the East area and $n = 31$ in the West area
[a]See horizon designations in Table 4
[b]Analyte values within a horizon are significantly different between areas at $\alpha = 0.05$

impacts of Ca and Al on tree growth (Cronan and Grigal 1995; Lyon and Sharpe 1999). The 1 M NH_4Cl extraction is more aggressive and removes some portion of exchangeable Ca and Al, as well as soil solution concentrations, and therefore should extract greater amounts than 0.01 M $SrCl_2$ extraction.

Based on these concentrations extracted by $SrCl_2$ and the resulting Ca/Al molar ratios, risk was assigned according to the categories of Cronan and Grigal (1995) shown in Table 1. The A horizons had the highest ratios, which related to a 50% risk of tree growth decline, while almost all of the deeper horizons showed a 75% risk (Table 6). Transition and lower B horizons differed slightly in risk categories between East and West areas, but actually were quite similar in absolute values of Ca/Al molar ratios.

Discussion

We began this research because of concerns with soil acidification in the Monongahela National Forest. In 2002, West areas streams had higher pH and alkalinity than East area streams. Lawrence et al. (1999) found alkalinity of streams in the

Table 6 Average values of Ca and Al by horizon for the East and West areas as determined by $SrCl_2$ extraction

Area	Horizon[a]	Ca	Al	Ca/Al ratio	Risk[b] (%)
		$cmol_c\ kg^{-1}$			
East	A	0.095[c]	0.256	0.8	50
West	A	0.180[c]	0.200	0.9	50
East	Transition	0.130	0.354[c]	0.4	75
West	Transition	0.121	0.205[c]	0.6	50
East	Upper B	0.069	0.290	0.2	75
West	Upper B	0.063	0.243	0.3	75
East	Lower B	0.033	0.325	0.1	100
West	Lower B	0.060	0.278	0.2	75
East	BC	0.052	0.276	0.2	75
West	BC	0.075	0.294	0.3	75

Ratios were calculated based on Ca and Al values, and risk categories were assigned based on Table 1. Horizon values are averages of $n = 36$ in the East area and $n = 31$ in the West area
[a]See horizon designations in Table 4
[b]Risk categories are shown in Table 1
[c]Analyte values within a horizon are significantly different between areas at $\alpha = 0.05$

Catskill Mountains of New York correlated well with acid soil conditions and acid deposition trends. We therefore hypothesized that East area soils were more acid than those in the West area of the Cherry River watershed, and hence, these soils may pose a greater risk of tree decline. Vegetation differences between areas also supported this hypothesis; large patches of hay-scented fern (*Dennstaedtia punctilobula* (Michx.) Moore), which has been suggested as an indicator of soil acidification (Demchik and Sharpe 1999), were found in the East area but not in the West area.

Significantly greater acid soil conditions existed in the East compared to the West areas based on pH, base saturation, and Ca, Mg, and Al concentrations. For comparison, we found soil chemistry data (unpublished data from the US Forest Service) in both areas from samples taken in 1981. The A horizon of an East area soil pit in 1981 showed Ca, Mg, and Al concentrations of 2.8, 0.6, and 5.6 $cmol_c\ kg^{-1}$, compared to 0.8, 0.3, and 7.2 $cmol_c\ kg^{-1}$ in 2004 (Table 5). Similarly, the A horizon of a West area soil pit in 1981 showed Ca, Mg, and Al levels of 12.3, 1.6, and 1.8 $cmol_c\ kg^{-1}$, compared to 0.7, 0.2, and 6.0 $cmol_c\ kg^{-1}$ in 2004. These 1981 data show a similar trend of more acid conditions in the East versus West soils. This finding also corroborates the results of similar studies where Al has increased and Ca and Mg have decreased over time in eastern US forest soils (Bailey et al. 2005; Drohan and Sharpe 1997).

If base cations were lost during the past 23 years in these forest soils as has been found with other forest soil studies in the eastern USA, the reasons could be due to several factors, including normal leaching by rainfall and soil development, enhanced leaching by acid deposition, organic matter decomposition, nutrient uptake and release by vegetation, erosion, slow rates of base input from parent material weathering, and slow cycling of nutrients. Markewitz et al. (1998) studied soil acidification over three decades in the Calhoun National Forest in South Carolina and found decreases in soil pH and depletion of base cations. Those authors found that about 60% of the acidity increase was due to natural soil processes and organic matter inputs, and about 40% was due to acid deposition. Based on Ca/Al molar ratios between areas in our study, risks were very similar between areas and showed a 50% to 75% risk.

The acidic character and the acid risk assessment of soils in the Cherry River watershed illustrate a potential risk of impaired tree growth and poor regeneration after harvesting. As mentioned, the risk criteria in forest soils as proposed by Cronon and Grigal have shortcomings with limited correlation and testing to forest tree growth (Huber et al. 2004; Schaberg et al. 2006). And indeed, we did not collect foliar samples of trees on these two areas to correlate to acid soil parameters, nor did we determine tree growth changes over time to demonstrate the effects of increasing acidification of soils. We will be collecting tree foliage samples for analysis as part of our continuing forest soils research in the Monongahela National Forest.

We know that decreases in soil pH and base cation concentrations, as well as increases in Al, can negatively impact forest health and productivity (Bigelow and Canham 2007; Lyon and Sharpe 1999). Therefore, recognizing that soils in the Cherry River watershed have acid soil conditions that suggest a 50% to 75% risk of impaired tree growth upon harvesting based on Ca/Al molar ratios, we can propose some simple and easy strategies to temper soil acidification and lessen the potential impacts on tree growth, and some of these approaches can be implemented at low cost or written into timber harvesting plans.

For example, on areas where soil pH is <4.5 and the Ca/Al molar ratio is <1 in upper horizons, harvest methods like stem-only removal can be assigned so that branches, leaves, and tree crowns are left on site (Elliott and Knoepp 2005; Mann et al. 1988). Rather than clearing or removing downed trees and debris for firewood, this material can be left on the ground to decompose, thereby releasing Ca and other nutrients into the soil upon decomposition.

Short harvest rotations can decrease base cation availabilities in soils due to shorter times to accumulate organic matter through leaf and litter fall (Blanco et al. 2005; Grigal 2000). Because the Cherry River watershed soils have low base cation concentrations, the longest reasonable harvest rotation should be used to encourage base cation replenishment via litter fall and weathering.

Soil liming may be warranted in locations where high risk might hinder tree harvesting, but where harvesting is necessary to meet land owner desires. The benefits of liming acid, agricultural soils are well known (McLean 1982). Liming increases calcium concentrations, raises soil pH, and neutralizes the acidity and aluminum toxicity in acid soils (Sims 1996; Thomas and Hargrove 1984). There have been several research projects focusing on the liming of forest soils, but the results from these studies have been mixed, and many findings could not be replicated (Rengel 2003). For example, liming can elevate leaching of organic carbon and nitrogen from forest soils due to increased microbial activity (Rengel 2003), thereby negating some of the positive effects of liming. Research indicates that dolomitic limestone, pelletized lime, and limestone sand are the most effective liming products, which are slow reacting and can be applied by ground-spreading equipment economically (Mizel 2005). The use of liming for mitigation of these high risk soils requires more research to understand the conflicting results and to determine where liming will be most effective and the rates and types of lime best suited to different types of site and soil conditions. Given the possible extent of at-risk forest soils in the Appalachians, research into these questions should be a high priority.

Conclusions

Soils of East and West areas in the Cherry River watershed had low pH (3.7 to 4.6), high levels of extractable acidity (3.3 to 9.4 $cmol_c\ kg^{-1}$), low levels of Ca (0.1 to 0.8 $cmol_c\ kg^{-1}$), and high levels of Al (2.8 to 7.2 $cmol_c\ kg^{-1}$). East area soils were significantly more acidic than West area soils, and soil conditions appear to have become increasingly acidic since 1981 in both areas. Using the Ca/Al molar ratio proposed by Cronan and Grigal (1995), soils of both East and West areas within the Cherry River watershed had a 50% risk of impaired tree growth in A horizons and a 75% degree of risk in lower horizons. These degrees of risk imply a potential for impaired tree growth and poor regeneration after tree harvesting. The use of acid soil indicators in forest soils can help direct better management decisions to lessen soil acidification and potentially reduce the impacts of tree harvesting on forest health. Management strategies for alleviating some problems associated with soil acidification include adjusting timber harvesting techniques, leaving wood on site, lengthening rotations, and liming forest soils.

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