

Article

Forest Soil Cation Dynamics and Increases in Carbon on the Allegheny Plateau, PA, USA Following a Period of Strongly Declining Acid Deposition

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Location: The four study sites are located on the Allegheny National Forest, Warren County, PA, USA. Figure 1 shows the location of the Allegheny National Forest in the northeastern USA. The four study sites are designated: Dew Drop (DD), Fools Creek (FC), Hearts Content (HC), and North Branch (NB).

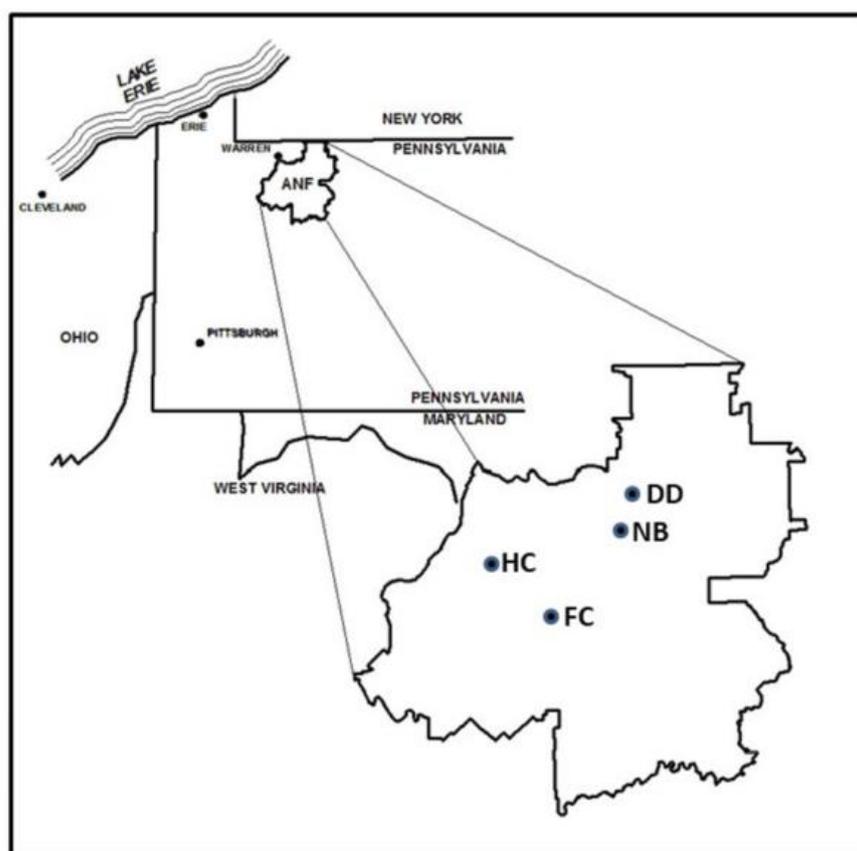


Figure 1. Location of the four soil sampling sites on the Allegheny National Forest (ANF), north-western PA, USA.

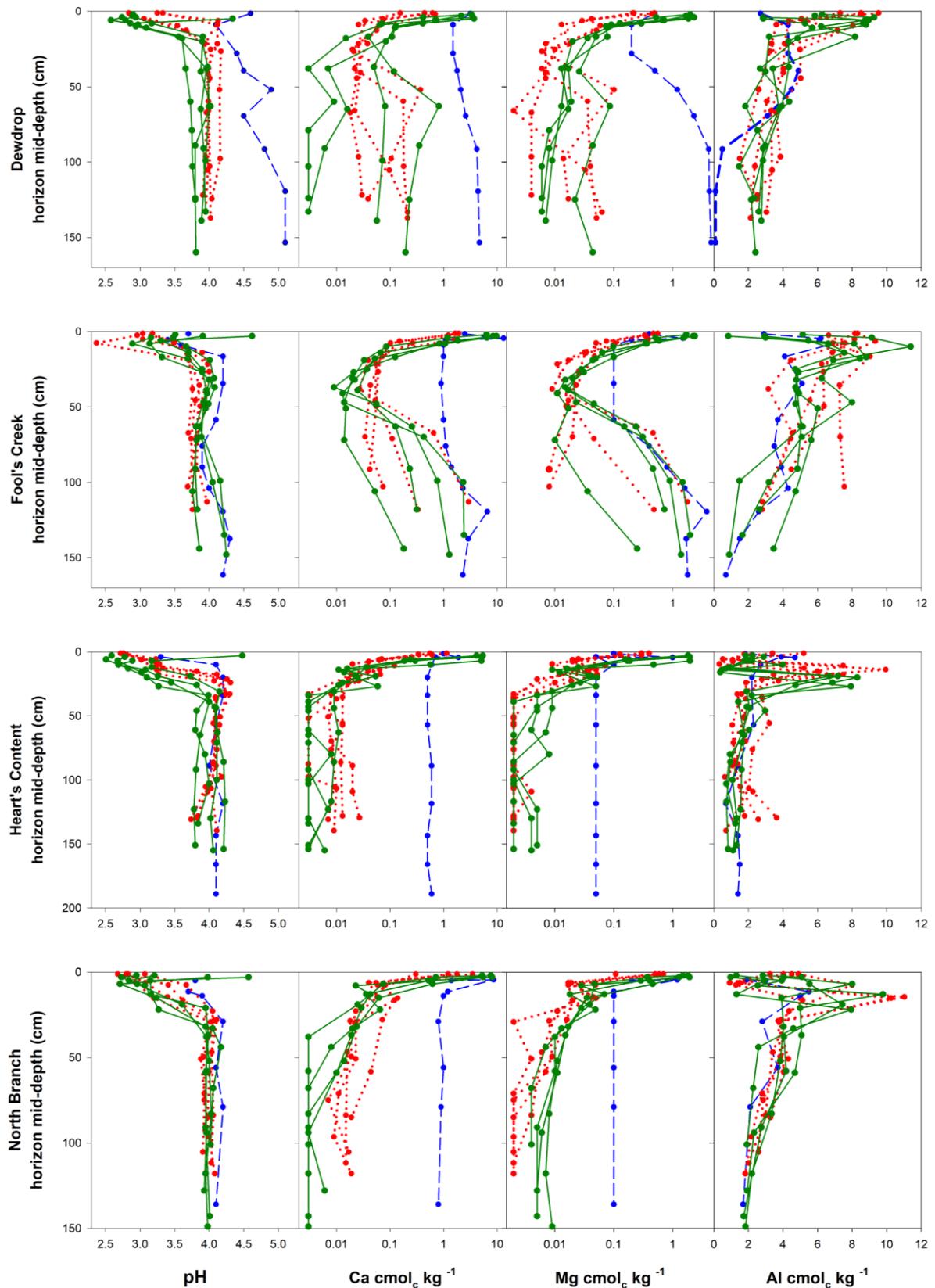


Figure S2: Profile chemistry for pH, and exchangeable Ca, Mg, and Al. Genetic horizon samples are plotted at the depth of the middle of each horizon. Year sampled is 1967 (blue, dashed line), 1997 (red, dotted line), 2017 (green, solid line).

Vegetation History: The original forest on these sites was 75% Hemlock – Beech with other Northern hardwood species (black cherry, sugar maple, red maple, white ash) not making up more than 5% each of the remaining 25% of the trees [22]. Between 1890 and 1930, improved access to the Allegheny Plateau top, where our study plots are located, resulted in removal of all but 1% of the trees; these trees were typically <1 inch in diameter. The large trees went to sawmills, while the smaller trees were processed at chemical wood plants. The forest has regrown since this initial cutting. During this regrowth period, deer population dynamics have strongly influenced the composition and regeneration of the second growth forest as deer have strong preferences for and against certain species as forage. Thus, between the extensive early logging and the influence of deer the current forest composition is much different than that of the original forest.

In 1967, vegetation species lists were noted by the original soil surveyors, including: Dewdrop (DD): red maple, red oak, American beech, white ash, cucumbertree, birch, quaking aspen, bracken, serviceberry; Fools Creek (FC): red maple, black cherry, American beech, birch, quaking aspen, white ash, ironwood; Hearts Content (HC): white oak, red oak, red maple, quaking aspen, sassafras, mountain laurel, white pine, bracken; and North Branch (NB): black cherry, white ash, birch, red maple, ironwood, bracken. Species common names, Latin binomials, and abbreviations are given in table S5.

Stand Composition and Structure in 1997 and 2017: We cored several dominant and co-dominant trees at each study site in 1997 and read the increment cores to determine stand age. Stand composition and structure data were collected in 1997 and 2017 using three 0.04-hectare plots at each of the four soil survey sites. Plots were randomly selected around the soil pits in undisturbed areas, so the 2017 sample points were not exactly in the same spots used in 1997. All standing trees ≥ 10 cm diameter breast height (1.3 m on the bole) were measured and crowns were evaluated. All four sites supported mature, fully stocked [21] second growth northern hardwood and mixed oak forests that originated following forest removals between 1890 and 1930 [22]. Allegheny National Forest records were consulted to note any management or disturbances that had occurred at the stands since the original 1967 soil survey.

In 1997, the overstory trees at DD (basal area: $38.7 \text{ m}^2 \text{ ha}^{-1}$) (Table S1) were dominated by 90-year-old northern red oak. A few trees were removed from the stand about 1977, and a light gypsy moth defoliation occurred in 2013. By 2017 basal area increased to $45.2 \text{ m}^2 \text{ ha}^{-1}$ and the stand continued to be dominated by overstory northern red oak and red maple. This increase was due to increased basal area of northern red oak, red maple, and American beech. The number of trees per hectare increased dramatically from 447 trees ha^{-1} in 1997 to 1070 in 2017. This was mainly due to many small American beech and striped maple stems now present at this site. Both black cherry and cucumber-tree present in 1997 are now gone.

Table S1. Dew Drop (DD) stand composition and structure. Species abbreviations are northern red oak (NRO), red maple (RM), birch (BIR), black cherry (BC), cucumbertree (CUC), sugar maple (SM), striped maple (STM), serviceberry (SVB), and American beech (AB).

	ALL SPP	NRO	RM	BIR	BC	CUC	SM	STM	SVB	AB
TOTAL BA 1997	38.7	25.3	6.3	3.0	1.8	1.1				1.2
TOTAL BA 2017	45.2	30.1	10.0	0.8			0.2	0.1	0.4	3.6
PERCENT BA 1997	100	65	16	8	5	3				3
PERCENT BA 2017	100	66	22	2			<1	<1	1	8
TREES/HA 1997	447	148.2	123.5	56.8	17.3	7.4				91.4
TREES/HA 2017	1070	131.6	131.6	65.9			8.0	172.9	24.7	535.2

At FC, in 1997, the overstory was dominated by 90-yr-old black cherry and red maple containing $33.9 \text{ m}^2 \text{ ha}^{-1}$ of basal area (Table S2). By 2017, the basal area had decreased slightly to $32.7 \text{ m}^2 \text{ ha}^{-1}$. The 1967 pit site was included in a fertilizer study in 1972, requiring us to locate 1997 and 2017 sample points approximately 30 m from the outer edge of the

fertilizer treatment isolation zone. By 2017 small stems of birch (both sweet birch and yellow birch) and American beech increased significantly in the stand. The other major change at this site is the decrease in basal area of white ash and sugar maple. The basal area of white ash decreased from 4.3 m² ha⁻¹ in 1997 to zero in 2017, likely due to mortality from emerald ash borer (*Agrilus planipennis* Fairmaire). Sugar maple basal area also decreased from 5.1 m² ha⁻¹ in 1997 to 3.9 m² ha⁻¹ in 2017. The number of trees ha⁻¹ also increased from 632 in 1997 to 1055 in 2017. This was mainly due to increased numbers small birch, and American beech stems.

Table S2. Fools Creek (FC) stand composition and structure. Species abbreviations as in Table S1, with the addition of sweet birch (SB), yellow birch (YB), and white ash (WA).

	ALL SPP	BC	RM	SB	SM	AB	YB	BIR	STM	WA
TOTAL BA 1997	33.9	12.8	9.0		5.1	1.9		0.9		4.3
TOTAL BA 2017	32.7	12.6	9.3	3.9	3.9	2.4	0.4	0.1	<0.1	
PERCENT BA 1997	100	38	27		15	5		3		13
PERCENT BA 2017	100	39	29	12	12	7	1			
TREES/HA 1997	632	155.6	106.2		205.0	74.1		24.7		66.7
TREES/HA 2017	1055	90.6	57.6	272.7	115.3	461.1	16.5	8.1	32.8	0

The overstory at HC was a 100-yr-old mixed oak forest dominated by white oak, northern red oak, and red maple with a basal area of 32.5 m² ha⁻¹ in 1997 (Table S3). By 2017 northern red oak basal area had increased from 3.3 m² ha⁻¹ in 1997 to 18 m² ha⁻¹ in 2017. The only apparent disturbance at this site since 1967 was a gypsy moth (*Lymantria dispar* L.) defoliation in 1988 that resulted in mortality of some oak; most of these trees remained standing dead in 1997 but were gone by 2017. Changes at HC include increased number of trees ha⁻¹ from 487 in 1997 to 872 trees ha⁻¹ in 2017. However, the bigger change was the increased species diversity with six new species tallied in these plots in 2017. The new species in these plots included sugar maple, cucumbertree, American beech, eastern hemlock, white pine, and mountain holly.

Table S3. Hearts Content (HC) stand composition and structure. Species abbreviations are the same as the previous tables with the addition of white oak (WO), black gum (BGUM), sassafras (SAS), eastern hemlock (EH), white pine (WP), and mountain holly (MTH).

	ALL SPP	NRO	RM	WO	SM	BIR	CUC	BGUM	SAS	AB	EH	WP	MTH
TOTAL BA 1997	32.5	3.3	20.2	7.7		0.6		0.1	0.7				
TOTAL BA 2017	41.3	18.0	14.0	3.7	0.2	1.5	1.5		0.8	0.6	0.5	0.3	0.1
PERCENT BA 1997	100	10	62	24		2		0.0	2				
PERCENT BA 2017	100	44	34	9	0.0	4	4		2	2	1	1	0.0
TREES/HA 1997	487	7.4	353.2	74.1		9.9		9.9	32.1				
TREES/HA 2017	872	82.2	238.8	32.8	16.5	81.5	8.2		16.5	140.0	16.5	181.1	57.6

The forest stand at NB was dominated by 90-yr-old (in 1997) American beech, black cherry, and red maple with a basal area of 40.9 m² ha⁻¹ (Table S4). The original pit site was obliterated by a small gravel pit; 1997 sample points were approximately 30 m away, within the same soil and vegetation. Basal area increased modestly at North Branch from 40.9 m² ha⁻¹ in 1997 to 42.5 m² ha⁻¹ in 2017. The increased basal area was mainly due to growth of black cherry which in 2017 accounted for 53% of the total stand basal area compared with only 37% in 1997. There was a decrease in the number of trees ha⁻¹ from 551 in 1997 to 395 in 2017. Both red maple and American beech had decreased numbers of trees

ha⁻¹ in 2017 compared with 1997, but birch increased from zero in 1997 to 41.2 trees ha⁻¹ in 2017. Some of these changes may be due to different plot placement in 1997 and 2017.

Table S4. North Branch (NB) stand composition and structure. Species abbreviations are the same as the previous tables.

	ALL SPP	BC	RM	AB	WA	STM	BIR
TOTAL BA 1997	40.9	15.2	12.8	11.9	0.9	0.1	
TOTAL BA 2017	42.5	22.5	11.3	8.0			0.7
PERCENT BA 1997	100	37	31	29	2	0	
PERCENT BA 2017	100	53	27	19			2
TREES/HA 1997	551	74.1	123.5	338.4	7.4	7.4	
TREES/HA 2017	395	90.6	82.2	181.0			41.2

Table S5. Abbreviations, common names, and Latin binomials for all vegetation species.

Abbreviation	Common Name	Latin Name
AB	American beech	<i>Fagus grandifolia</i> Ehrh.
BC	Black cherry	<i>Prunus serotina</i> Ehrh.
BGUM	Blackgum	<i>Nyssa sylvatica</i> Marsh.
BIR	Birch	<i>Betula</i> spp. Britt.
	Bracken fern	<i>Pteridium aquilinum</i> (L.) Kuhn
CUC	Cucumbertree	<i>Magnolia acuminata</i> L.
EH	Eastern hemlock	<i>Tsuga canadensis</i> L. (Carr.)
	Ironwood	<i>Ostrya virginiana</i> (Mill.) K. Koch
MTH	Mountain holly	<i>Illex mucronata</i> (L.) Powell, Savol. & Andrews
	Mountain laurel	<i>Kalmia latifolia</i> L.
NRO	Northern red oak	<i>Quercus rubra</i> L.
	Quaking aspen	<i>Populus tremuloides</i> Michx.
RM	Red maple	<i>Acer rubrum</i> L.
SAS	Sassafras	<i>Sassafras albidum</i> (Nutt.) Nees
SB	Sweet birch	<i>Betula lenta</i> L.
SM	Sugar maple	<i>Acer saccharum</i> Marsh.
STM	Striped maple	<i>Acer pensylvanicum</i> L.
SVB	Serviceberry	<i>Amelanchier</i> spp. (Michx. f)
WA	White ash	<i>Fraxinus americana</i> L.
WO	White oak	<i>Quercus alba</i> L.
WP	White pine	<i>Pinus strobus</i> L.
YB	Yellow birch	<i>Betula alleghaniensis</i> Britt.