Historical land use and stand age effects on forest soil properties in the Mid-Atlantic US

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ABSTRACT

The conversion of agriculture lands to forest has been occurring in parts of North America for decades. The legacy of management activity during this transition is reflected in soil physical and chemical properties years after abandonment. This study was conducted at the Smithsonian Environmental Research Center, Maryland, USA, to determine land-use history and forest age effects on soil nutrients, carbon, pH, and bulk density. Soils in young and old successional forests and forests with no evidence of historical disturbance were sampled. The young forest stands were abandoned from agriculture 50–70 years ago and the old forest stands had been abandoned from agriculture or grazing 120–150 years ago. The oldest forest stands had no recorded history of disturbance even though it is likely they were at least disturbed by tree removal or grazing of animals in the colonial era. Young forest soils had higher concentrations of Mg, Ca, NO_3 and a higher pH than old, which may be an age effect. The old forest soils that had been abandoned from agriculture and grazing had higher bulk density and lower C content than undisturbed stands indicating a land-use effect. In the stands that were formally agriculture there was evidence of erosion, indicated by a Bt horizon closer to the surface. The most evident difference between stands of different land-use history was the absence of a well-developed O horizon, which we attribute to the presence of earthworms. Land-use legacy set the forest ecosystem in a different trajectory of soil evolution.

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1. Introduction

Land-use history has long term, if not permanent, effects on vegetation and soil properties (e.g. Compton and Boone, 2000; Dupouey et al., 2002; Foster and Aber, 2003; Verheyen et al., 1999). The duration and type of land use, e.g., woodlot, agriculture, and grazing, determines the current soil chemical and physical properties. Provided with detailed land-use records of European land, 700 years of land-use change has rendered differences in soil properties directly related to the duration of forest, grassland, cultivated, and arable land (Verheyen et al., 1999). In the U.S., the recorded land-use history, although not as extensive, is around 400 years but only for the northeastern coastal areas of the country. Within this time frame these effects have been measured and have shown a long lasting signature in the soil (Foster and Aber, 2003) and vegetation (Thompson et al., 2013) due mostly to the impact of agriculture introduced during European settlement (Cronon, 1983; Foster and Aber, 2003). Based on these studies in New England and Europe, it is clear that historical land uses profoundly altered soil chemical and physical properties, including patterns of surface soil horizon development.

Some of the earliest colonial settlements were in the Chesapeake Bay region of Maryland. Before European settlement, 95% of Maryland was covered with forests (Besley, 1916). In the Chesapeake Bay watershed, 40–50% of the land was under agriculture by 1840 (Cooper, 1995), increasing to 80% by the end of the 19th century (Brush, 1986). Currently the forest cover in Maryland is estimated to be 43% of the land area (Stolte et al., 2012). The vast majority of forests in Maryland are secondary at different stages of succession with varying tree species composition (Brush, 1986). At the Smithsonian Environmental Research Center (SERC) in Anne Arundel County, MD, where our research was conducted, there are uncut forest stands which provide a rare opportunity to study the effects of land-use history on the trajectory of soil recovery post anthropogenic disturbances. Here we report on a comparative study in thirteen forest stands at SERC focusing on the changes in soil physical and chemical properties over a 150-year period.

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SERC lies within the watershed of the Rhode River sub-estuary of Chesapeake Bay. The Smithsonian owns 1072 ha on the Rhode River watershed and the land is maintained in a mix of land-uses, including forest stands that have no physical evidence of previous disturbance, stands of mature forests with evidence of previous disturbance and forests that have been undergoing succession since the stands were abandoned from agriculture in the 1940s. Advantages of conducting our study at SERC include: (1) Information on historical uses of the SERC land goes back to the time of European colonization in the 1600s, (2) SERC soil, land use, and vegetation history has been documented (Correll, 1974; Higman, 1968; Pierce, 1974), (3) SERC upland forests are a patch-work of stands of different ages reflecting different times of agri-cultural abandonment, and (4) small stands of uncut, old growth exist on the property.

Soil formation and soil evolution is a slow process, thus most chronosequence studies have implemented a space-for-time sub-stitution. This approach has been criticized for the lack of consis-tency in controlling for abiotic and biotic conditions through time (Johnson and Miyanishi, 2008; Pickett, 1989). Despite these difficulties, we believe detailed knowledge of historic land-use pat-terns can provide a valuable platform for evaluating ecosystem structure and function, especially as they related to differences in soil characteristics.

Our approach was to characterize and compare physical and chemical soil properties of forest stands that differed in age and land-use histories on the SERC property. Our objectives were to determine: (1) the degree to which forest soils retain legacy impacts from past agricultural practices and (2) the degree to which the legacy impacts change over time. We developed a con-ceptual model to separate the complex interaction effects of stand age, land-use legacy, and other disturbances to understand the present-day soil characteristics and therefore, the trajectory of soil evolution (Fig. 1). The well-documented history of the upland for-est mosaic of SERC are a great opportunity to advance our under-standing of how forest soils recover in this region. During colonial times and later, many of the forest stands in the area were converted into agriculture fields. This conversion from forest to long-term crop production introduced physical disturbance associ-ated with annual cultivation, nutrient amendments from fertilizer and manure, and bioturbation by introduced soil fauna, mainly non-native earthworms, should have resulted in a transformation of soil properties. To examine how this transformation in soil prop-erties varied by differences of age, we compared young and old for-est soils, and for differences related to land use, we compared soils in the young/old to the uncut forests. Unique aspects of this study compared to existing land-use history studies are the comparison of land-use histories, forest ages, and uncut forest stands on similar soil types; and the establishment of non-native earthworm com-munities in both the young and old forest soils but not the uncut forest soils.

Based on the conceptual model shown in Fig. 1, to compare age effects, we expected that old forest stand soils would have higher carbon, lower nutrient concentrations, bulk densities and pH than the young forest soils. Exposure to weathering and vegetation dif-ferences would cause the net loss of nutrients in the old forest soils compared to the young forest soils. To compare land-use effects, we expected that uncut forest soils would contain more SOM related to a thicker O horizon than the old forest stands. We also predicted that uncut forest would have less nutrients, and lower bulk densities and pH than the old forest soils through a combina-tion of weathering, lower quality leaf litter, lack of additional nutri-ent input from historical cropping and grazing practices, and lack of earthworm mixing and feeding activity.
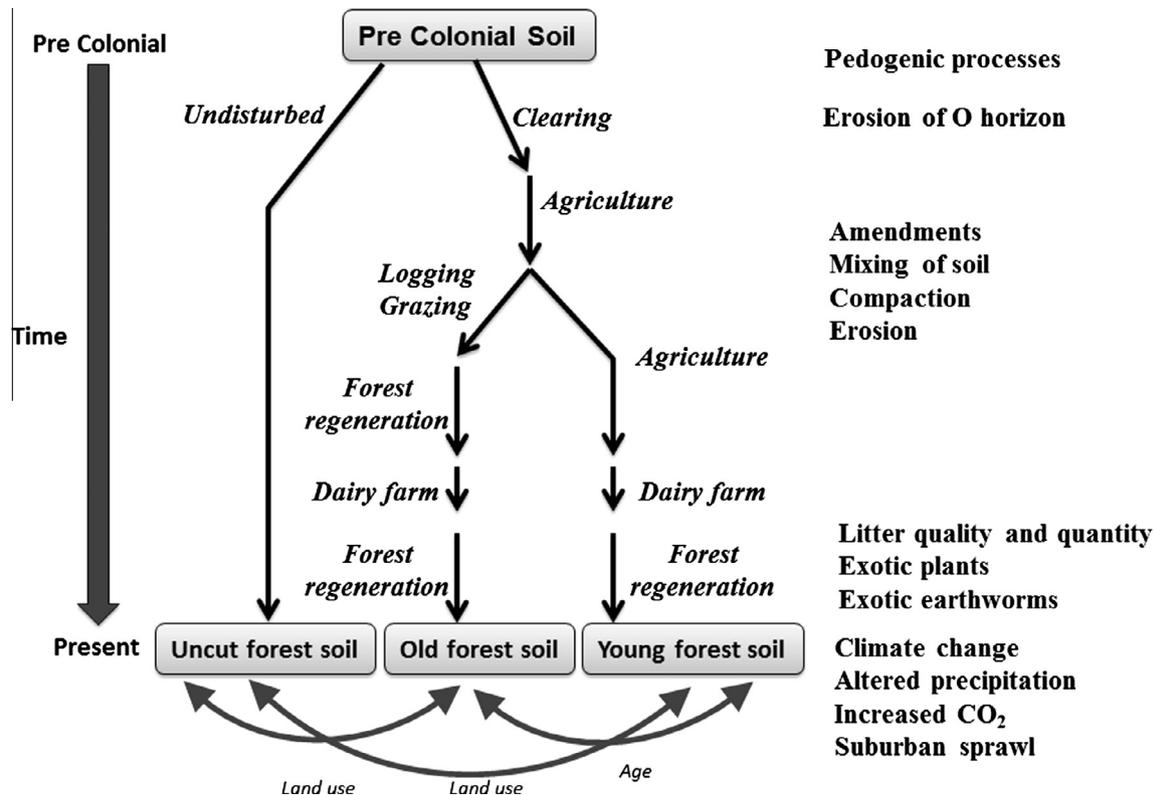

Fig. 1. The general history of the uncut, old, and young forest soils and the comparisons between land use and age, i.e., for land-use comparisons, uncut was compared to old and young forest soil; for age comparisons, old was compared to young forest soils. The evolution of these soils is affected by pedogenic processes.

2. Methods

2.1. History and description of the Smithsonian Environmental Research Center

The Smithsonian Environmental Research Center (SERC) is located along the western shore of the Chesapeake Bay in southern Anne Arundel County, Maryland on the Rhode River estuary (38°53′N, 76°33′W) (Fig. 2). The major soils at SERC are Collington sandy loam (fine-loamy mixed, active, mesic Typic Hapludult), Annapolis fine sandy loam (fine-loamy, glauconitic, mesic Typic Hapludult) and Donlonton fine sandy loam (fine-loamy, glauconitic, mesic Aquic Hapludults) (Supplementary material Appendix A) (NRCS, 2015, Dec 1). The parent material is glauconitic marine sediments lying on the Nanjemoy formation. The mean precipitation in the region is 114.6 cm and the mean annual temperature is 13 °C (D. Correll, T. Jordan, and J. Duls, unpublished data). Elevation change across SERC is minimal, 15–30 m (Correll, 1974).

Land use, vegetation, and management history (Higman, 1968) and soils (Correll, 1974; Pierce, 1974) have been examined and measured at SERC. Land-use maps were available from 1846 and more recently from 1925 and the late 1960s. The earliest pictorial record in 1846 of the Rhode river watershed is a topographic map published by the US Coast and Geodetic Survey (Table 1). These maps distinguish between forests (deciduous and conifer), farmland, wetland and residential areas. Later, aerial photos taken by the USDA, US NAVY and NASA, and vegetation and soil surveys were used to construct vegetation and land use maps by the staff of the Smithsonian Environmental Research Center (Higman, 1968; Jenkins et al., 1971; Correll, 1974; Pierce, 1974). Oral history of the property was recorded in 1970s and compiled by Daniel Higman (unpublished). The 13 sites selected for this study were comprised of 5 young, 5 old and 3 uncut forest stands using vegetation survey data and map prepared by Higman (1968) (Fig. 2). We used age-range categories because (1) we would have replicates for statistical analysis, and (2) the exact ages of the forest stands are unknown. Based on historical documents and examination of tree rings of trees that had been felled, it was possible to place the stands into distinct age categories. Both young and old forest stands have been classified as part of the Tulip poplar Associations (Brush et al., 1980), but they differ in age and tree species composition.

The young forest stands developed on land that had been previously cleared for agriculture, planted with diverse crops fertilized with manure, marl, and gypsum (Higman, 1968) until the mid-20th century, then abandoned (Table 1). Details about timing, frequency, and exact location of the amendment are not known. Today these stands are at least 50 years old, dominated by tulip poplar (*Liriodendron tulipifera*) and sweet gum (*Liquidambar styraciflua*), with red maple (*Acer rubrum*), black cherry (*Prunus serotina*) and box elder maple (*Acer negundo*) being the secondary species. The first two species comprises 71% of the leaf litter production (Szlavecz unpublished data). The old forest stands developed on lands that were abandoned from management about 120–150 years ago and have a mixed history of agriculture and logging. Tulip polar and sweet gum are still important canopy species in these stands but the dominant trees are several species of oaks, (*Quercus* spp.), American beech (*Fagus grandifolia*), and hickories (*Carya* spp.); making up 62% of the leaf litter production (Szlavecz unpublished data). The uncut forest stands were classified and mapped as the Chestnut oak-Chestnut Association (Brush et al., 1980). They are considered to be the oldest forests on the SERC property and there is no evidence of previous management activities such as agriculture and logging (Higman, 1968). The uncut forests are dominated by several species of oak (*Quercus*) with the dominant species being chestnut oak (*Q. prinus*) which contributes 70% of the total litter input (Szlavecz unpublished data).
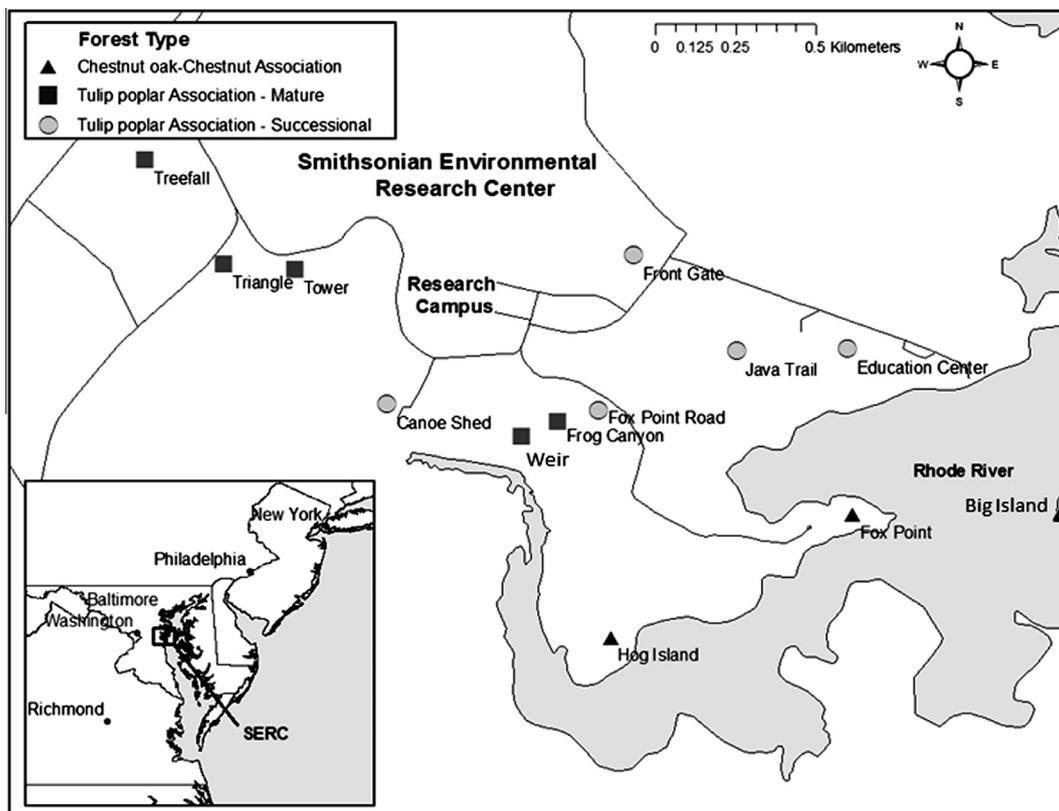

Fig. 2. Map of site locations within the Smithsonian Environmental Research Center in Edgewater, Maryland.

Table 1
Historical land use, vegetation and soil type for 13 forest stands at the Smithsonian Environmental Research Center. More information on sites and soil is given in the Methods and in Supplement A.

Age of stand	Site name	Vegetation – Land use maps[a]			Soil[b]	Tree leaf litter[c]
		1846	1925–45	1965		
Young 50–70 years	Java trail	Improved land[d]	Alfalfa	Regenerating forest and pasture (*Solidago-Aster*)	Annapolis	Tulip poplar, Oak, Maple, Sweetgum
	Front gate	Improved land	Barley/Wheat/ Corn or Orchard	Sweetgum	Donlonton	Tulip poplar, Maple, Sweetgum
	Fox point road	Improved land	Corn/Alfalfa	Regenerating forest and pasture (*Rubus/Lonicera/Rhus*)	Annapolis	Tulip poplar, Sweetgum
	Canoe shed	Improved land	Corn/Alfalfa	Regenerating forest and pasture (*Rubus/Lonicera/Rhus*)	Annapolis	Tulip poplar
	Education center	Improved land	Alfalfa	Regenerating forest and pasture (*Solidago-Aster*)	Annapolis	Sweetgum, Tulip poplar
Old 120–150 years	Tower	Woodland	Forest	Hardwoods	Adelphia/Holmdel	Tulip poplar, Beech, Sweetgum
	Frog Canyon	Improved land	Forest	Hardwoods	Annapolis	Tulip poplar, Maple, Oak
	Weir	Woodland	Forest	Hardwoods	Annapolis	Beech, Tulip poplar, Oak
	Triangle	Woodland	Forest	Hardwoods	Collington/Annapolis	Tulip poplar, Beech, Sweetgum
	Treefall	Woodland [e]	Forest	Hardwoods	Collington/Annapolis	Tulip poplar, Beech, Oak
Uncut >200 years	Fox Point	Woodland	Forest	Hardwoods	Collington/Wist	Oak, Sweetgum
	Big Island	Woodland	Forest	Hardwoods	Collington/Annapolis	Oak
	Hog Island	Woodland	Forest	Hardwoods	Donlonton	Oak

[a] Sources of maps: US Coast Guard and Geodetic Surveys (Higman, 1968; Higman, unpublished; Correll, 1974).
[b] NRCS, Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. http://websoilsurvey.nrcs.usda.gov/ accessed 11/19/2015.
[c] Leaf litter was collected using six 20L buckets per site between September–December 2010, and sorted to major types.
[d] This term was used in map and possibly means agriculture. All terms in the table were taken from the original maps.
[e] This site was outside of the 1846 map boundary. Vegetation was inferred from the neighboring forest areas and written history (Higman, 1968).

Previous research by our group has demonstrated that non-native earthworms are an important component of SERC forests (Crow et al., 2009; Filley et al., 2008; Ma et al., 2013; Szlavecz and Csuzdi, 2007; Szlavecz et al., 2011). In the context of this study, the uncut forests on Hog Island, Fox Point and Big Island are earthworm-free while non-native earthworms are abundant in soils at the old and young forest stands (Szlavecz and Csuzdi, 2007; Szlavecz et al., 2011).

There is no evidence that the forests at the Frog Canyon and Weir sites were ever cleared for agriculture but they were grazed by cattle from 1915 to 1940 when SERC operated as a dairy farm (Java Dairy Farm, n.d.). The understory vegetation at the Frog Canyon and Weir sites lack the understory herbs and shrub species that are found in mature forests at the Tower, Treefall and Triangle sites (Fig. 2) where there is no evidence of grazing during the period of time that the dairy farm operated. The Tower, Triangle and Treefall sites, however, show evidence that they may have been grazed prior to the Civil War. All three sites have very large canopy trees which have canopy growth forms typical of trees that grew in the open (i.e., not in a closed forest). The other canopy trees at those sites are, however, large and based on size and age probably colonized the site about the time that the Civil War. If these historical interpretations are correct, the young and old forest stands were both grazed. There is also some historical evidence, stumps and information from the previous land owner of the Treefall site that trees may have been selectively removed from that part of the forest within the past 50–100 years, however, it does not appear that it was ever clear cut.

2.2. Soil sampling and analysis

Soil was sampled from five young five old and three uncut forest stands. The uncut forest stands although somewhat different is tree composition, represent undisturbed conditions, and thus were used to compare soil properties to those soils once supporting agriculture or other human activities such as logging and grazing. The soils series catena and topography are similar throughout the study area in order to minimize confounding conditions. For example, the soil series of Annapolis fine sandy loam, Collington sandy loam, and Donlonton fine sandy loam are similar enough for comparison purposes even though there is different vegetation in the young, old, and uncut forest stands. All sampling sites were on slopes less than 5% except for Weir where it was greater.

In order to determine the depth of the Bt horizon, a representative 10 × 10 m area of the particular forest stand was selected and 9 soil samples 5 m apart were cored per site. The depth of the Bt was determined using texture analysis by the feel method. Slope was also taken using a clinometer both in the direction of greatest slope and perpendicular to account for the influence of topography on Bt depth.

For texture and chemical analysis, composite samples, which combined fifteen 3.5 cm diameter soil cores from each of the 13 stands, were taken of the mineral soil from 0–10 cm and 10–20 cm. Additionally, 25 × 25 cm quadrats of the organic horizons of the uncut forest soils were collected and placed in a drying oven at 70 °C until constant weight. Mean values per site were used to calculate mean and standard error on Table 2. Morgan-extractable chemical characteristics (P, K, Mg, Ca, Fe, Al, Mn, Zn, and NO_3) were determined at the Cornell Soil Analysis Laboratory. Bulk density for the top 0–5 cm was determined by a gravimetric coring method (Blake and Hartge, 1986); texture was determined by the hydrometer method (Wilde et al., 1972); pH was determined in 1:1 H_2O. Soils were analyzed for C and N content using an EAI CE-440 elemental analyzer (Exeter Analytical Inc.) at the Analytical Services Laboratory at SERC. Carbon for the organic O horizon layer was determined by loss on ignition. Carbon content was calculated using C percentage and bulk density and summing the O horizon layer (where present) and the mineral layer.

Table 2
Physical and chemical soil properties in 13 forest stands at the Smithsonian Environmental Research Center. Mean values and standard error (in parentheses) are given. Significant differences (Proc MIXED) among the forest stands are in boldface. Different letters indicate significant differences between forest stands at $P < 0.05$. Carbon content includes O layer in the uncut stands.

Physical properties	Depth (cm)	Young ($n = 5$)	Old ($n = 5$)	Uncut ($n = 3$)	P value
O layer mass (kg m^{-2})		n/a	n/a	3.6 (0.6)	n/a
Bulk density (g cm^{-3})	**0–5**	**1.00 (0.05)^a**	**0.82 (0.06)^a**	**0.43 (0.08)^b**	**0.0009**
Depth to Bt (cm)		**18 (3.7)^a**	**25 (2.0)^{ab}**	**40 (2.0)^b**	**0.012**
Clay (%)	0–10	19 (1.1)	19 (2.1)	15.0 (0.69)	0.30
	10–20	23 (1.5)	24 (3.6)	17 (2.0)	0.30
Sand (%)	0–10	48 (2.7)	52 (2.9)	46 (8.5)	0.63
	10–20	46 (2.3)	47 (4.9)	45 (6.1)	0.97
Silt (%)	0–10	34 (3.1)	32 (0.74)	40 (7.7)	0.47
	10–20	31 (3.2)	34 (2.5)	39 (4.0)	0.38
Chemical properties					
C content (kg m^{-2})		**2.6 (0.29)^{ab}**	**2.31 (0.07)^a**	**3.4 (0.22)^b**	**0.025**
O layer organic matter content (%)		n/a	n/a	65.0 (4.78)	n/a
C (mineral layer, %)	**0–10**	**2.6 (0.21)^a**	**2.8 (0.10)^{ab}**	**4.2 (0.69)^b**	**0.017**
	10–20	0.93 (0.02)	1.2 (0.26)	1.4 (0.40)	0.27
N (%)	0–10	0.22 (0.03)	0.17 (0.019)	0.17 (0.035)	0.34
	10–20	0.09 (0.01)	0.08 (0.02)	0.06 (0.05)	0.67
C:N	**0–10**	**12.2 (0.79)^a**	**17 (2.0)^{ab}**	**25.1 (1.5)^b**	**0.0011**
	10–20	10.9 (0.99)	27 (13)	70 (55)	0.26
pH	**0–10**	**5.4 (0.16)^b**	**4.9 (0.23)^a**	**4.17 (0.03)^a**	**0.0009**
	10–20	4.8 (0.12)	4.7 (0.19)	4.6 (0.18)	0.050
Ca (mg kg^{-1})	**0–10**	**2400 (280)^b**	**700 (180)^a**	**50 (12)^a**	**<0.0001**
	10–20	**1600 (290)^b**	**160 (56)^a**	**23 (8.8)^a**	**0.0003**
Mg (mg kg^{-1})	**0–10**	**470 (49)^b**	**220 (66)^a**	**60 (10)^a**	**0.0017**
	10–20	**360 (55)^b**	**90 (46)^a**	**27 (4.4)^a**	**0.0016**
Al (mg kg^{-1})	**0–10**	**80 (10)^b**	**300 (63)^{ab}**	**500 (120)^a**	**0.0038**
	10–20	**210 (31)^a**	**500 (120)^{ab}**	**700 (140)^b**	**0.020**
P (mg kg^{-1})	0–10	3 (1.5)	3.3 (0.84)	7 (2.7)	0.24
	10–20	1.0 (1.0)	4.2 (0.73)	9 (5.9)	0.11
K (mg kg^{-1})	0–10	250 (19)	210 (28)	170 (49)	0.21
	10–20	160 (11)	110 (18)	100 (22)	0.067
NO$_3$ (mg kg^{-1})	**0–10**	**50 (7.4)^b**	**7 (7)^a**	***bdl^a**	**0.0004**
	10–20	bdl	bdl	bdl	n/a
BC:Al	**0–10**	**43 (9.0)^b**	**4 (1.1)^a**	**0.58 (0.037)^a**	**0.0010**
	10–20	**12 (3.7)^b**	**0.74 (0.14)^a**	**0.23 (0.020)^a**	**0.0113**

Texture analysis in the Uncut stands was carried out for two sites.
Depth of Bt was determined for four "Young", three "Old", and two "Uncut" sites.
Ca, Mg, Al, P, K and NO$_3$ are Morgan extractable concentrations. BC: Base cations
* Below detection level.

2.3. Statistical analysis

Principle Component Analysis (PCA) was used as a data reduction tool to explain variability and to visualize the comparison of forest stands spatially using SAS Proc FACTOR. The number of soil chemical variables chosen to represent each principle component was determined using the eigenvalue for a given principle component. Due to high degree of autocorrelation, which is common in soils, and low replication of study sites ($n = 13$ composite samples), a subset of the 16 variables was selected for the surface depth and of the 13 for the lower depths (Table 2). For the surface depth, P, pH, Ca, clay, bulk density, C content (the C content accounted for the O horizon layer and the bulk density of the O horizon and mineral soil layer), and N were chosen. For the lower depth P, pH, Ca, clay, C percent, and N were selected. These variables serve as surrogates for the other measured soil variables, for example, divalent Ca was used in lieu of divalent Mg; clay for sand and silt, C content for C percent and C:N ratio, and pH for Al. Differences in soil characteristics between young, old, and uncut forest stands were analyzed using the restricted likelihood estimation technique SAS Proc MIXED and GT2 Hochbergs pair-wise comparisons. The fixed effects were forest stands, there were no random effects in this completely randomized design, and each of the two soil depths was run separately (SAS, 2010). Residual evaluation for normality and homogeneity of variance were not tested due to low sample

size per group, i.e., young $n = 5$, old $n = 5$, and uncut $n = 3$. Normality tests have little power, when the sample size is low, to determine if a sample comes from a Gaussian population. Small sample sizes do not provide reliable inferences about the shape of the distribution in the entire population. Regression analysis was done in GraphPad Prism. For Fig. 5, a second order polynomial equation, $Y = 632 + (-283) * X + 31.53 * X^2$, was used to create the regression line.

3. Results

3.1. Soil physical properties

The old and young stands had an Ap horizon and the uncut stands had an A horizon. All had a clay-rich Bt horizon, with soils at some sites also having a transition horizon. The transition to the Bt horizons (Table 2) in the old forest stands was deeper (25 ± 2.0 cm) than the young forest stands (18 ± 3.7 cm). The deepest transition from surface to subsurface horizons was in soils at the uncut forest stands (40 ± 2.0 cm). There was a negative correlation ($r^2 = 0.45$, $p = 0.049$) between the percent clay in the surface soils and the depth of the top of the Bt horizon (Fig. 3).

All of the young forest stands had a similar pattern of clay accumulation throughout the profile starting at the surface (9%) and

increasing to the 25 cm depth (33%). This same pattern was found in soils at the old forest stands but the variance in the percent clay was higher. Along with clay content or, in part, due to the amount of clay, there were forest stand differences in bulk density. The uncut forest soils had significantly ($p = 0.009$) lower bulk density than the old (48%) and young (57%) forest stands, respectively (Table 2).

3.2. Soil chemical properties

For the surface 10 cm, Ca, pH, bulk density explained 46% of the variability, followed by carbon content and N which accounted for 19% (Fig. 4A). The forest sites formed three distinct groups with uncut forest stands separated from the young and old stands that had been historically managed. The young forest soils with a history of agriculture use have higher pH, Ca, and bulk density (Table 2). The uncut forest soils had the lowest pH, Ca, and bulk density with the old forest soils falling between the young and uncut forest soils. For the 10–20 cm depth, Ca and P explained 39% of the variability, followed by clay which accounted for 23% (Fig. 4B). One distinction between the young forest and the old and uncut stands was that the young stands have higher concentrations of Ca and lower P. However, it did not appear that texture, e.g. clay, in the 10–20 cm soil layer explained the differences related to forest age, even though there were differences in the depth to the Bt horizon (18 cm for young, 25 for old, and 40 for uncut) between forest stands; soil samples for the texture analysis were taken above the Bt horizon.

The pH in the surface 0–10 cm at the young forest stands was 5.4; this was 13% and 41% log units higher than pH in the old and uncut forest soils, respectively (Table 2). Calcium concentrations of soils at the young forest stand (2400 mg kg^{-1}) were 58% and 98% higher than soils at the old and uncut forest stands, respectively. A C:N of 12.2 in the young forest soils was 32% and 53% lower compared to soils at the old and uncut forest stands, respectively. Bulk density in the young forest soils (1.0 g cm^{-3}) was 18% and 57% higher than the old and uncut, respectively. The 10–20 cm soils showed the same trends except for the C:N ratio which was not statistically different (Table 2). The carbon content in the uncut forests soils was significantly higher than the old forest soils. The uncut forest had an O horizon mass of 3.6 ± 0.6 kg m^{-2}, whereas the old had a small or absent O horizon, and the young forest had no O horizon.

Soils at the young forest stands for the surface 0–10 cm had 74 and 11 times higher base cation (BC): aluminum (Al) ratios than soils from the uncut and old stands respectively (Fig. 5A, Table 2).
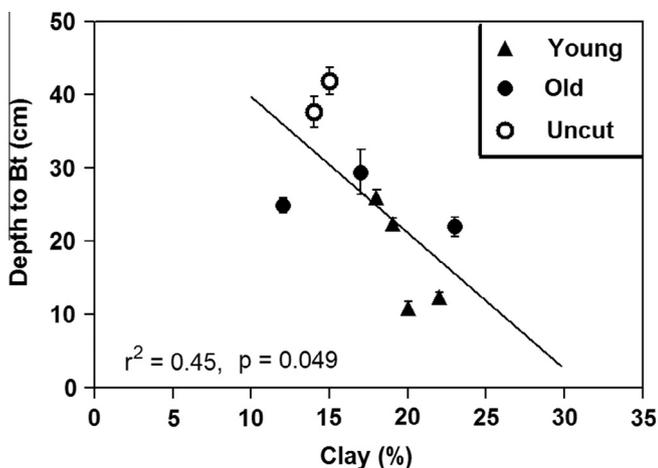
Fig. 3. The depth of the top of the Bt horizon versus clay percentage. Mean ± std err, $n = 9$ for each site. Not all forest stands were sampled for depth of Bt horizon.
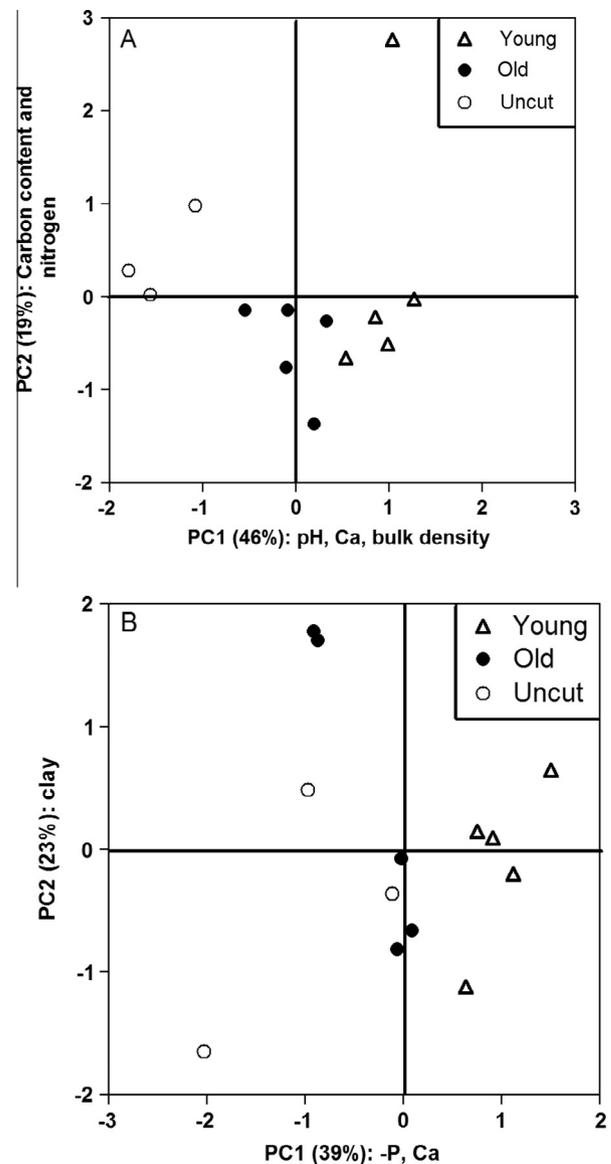
Fig. 4. Principal component analysis. (A) is the surface depth at 0–10 cm and (B) is the lower soil depth at 10–20 cm.

The base cations were the sum of Ca, Mg, and K. Both the uncut and old forests had BC:Al ratios that did not change with an increase in pH, however, the young forest BC:Al ratio increased with pH. This ratio increased after a pH of approximately 5.2 in the surface 0–10 cm depth. The BC:Al ratios were also significantly higher at the 10–20 cm depth interval at the young forest stands compared to the old and uncut (Fig. 5B, Table 2). In the 10–20 cm lower depth, there was less of a response between pH and the BC:Al ratio in the young forest stands.

4. Discussion

Soils integrate long- and short-term history through soil physical and chemical characteristics, biological activity, and spatial landscape arrangement (Fanning and Fanning, 1989). Important ecosystem processes, such as C storage and N retention, are influenced by soil properties and reflect historical patterns of land use (Compton and Boone, 2000). This integration over various time scales complicates the interpretation of the influences from different land-use histories and cover types even if other soil forming factors are held constant. Given the inherent drawbacks of
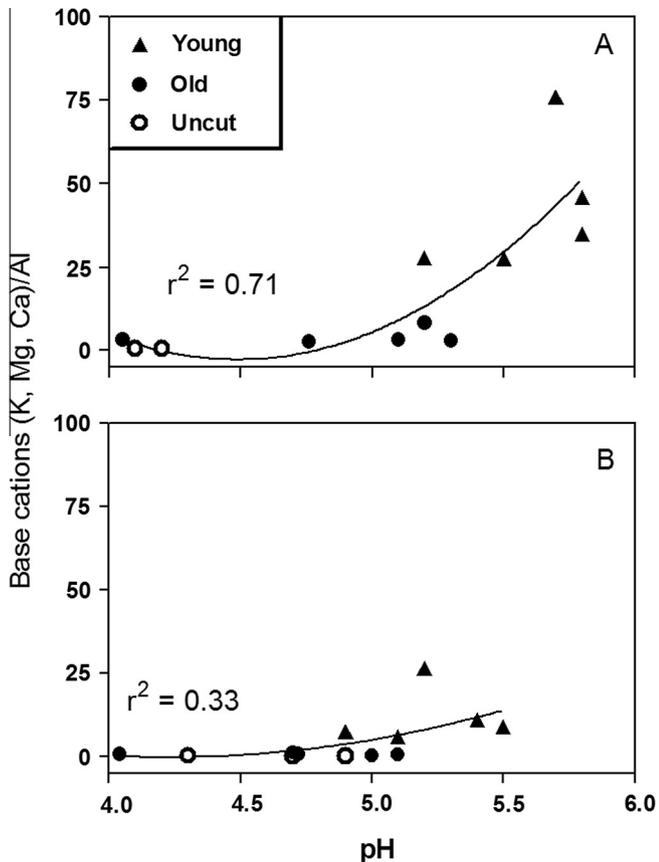
Fig. 5. The soil pH versus base cation aluminum ratios. For the surface soil depth, Hog Island and Big Island are both pH 4.2. For the lower soil depth, Frog Canyon, Weir, and Fox Point all have a pH of 4.7. (A) is the surface depth at 0–10 cm and (B) is the lower soil depth at 10–20 cm.

space-for-time studies (Pickett, 1989), our study area was distinct because soils from stands with no previous land-use history represented a baseline for comparison with soils that had different patterns of land-use management and different recovery times.

At SERC, three of the five main factors related to soil formation were similar: parent material, climate, topography (Jenny, 1941). The primary differences between the three sets of stands were time since disturbance and organisms that include vegetation and soil biota that affect soil development in multiple ways (Fig. 1). The three forest stands have had different histories related to agriculture or use such as grazing. The young forest stands had been previously cleared and managed as agricultural fields for many decades. The old forest stands had a wider range of historical land uses including agriculture and grazing. Verheyen et al. (1999) showed historical grassland combined with other land-use classes affected soil chemistry. Both Frog Canyon and Weir (old forest sites) were grazed by cattle when the sites were a dairy farm; however, we found no differences in soil nutrient concentrations between the two grazed forest sites compared to the other old forest sites, which were similar to what Fraterrigo et al. (2005) found between historic land use that was pasture and a forested reference. Franzluebbers and Stuedemann (2013) suggested that animal grazing had no effect on C or N after six years.

4.1. Soil physical properties

Our results demonstrate that, within the 150-year time frame, both land-use history and forest age have an influence and long-term effects on soil physical properties. The depth of the top of

the Bt horizon, which is defined as a layer of soil with increased clay content compared to the layer above, may be an indication of erosion of the surface horizons such as the O, Ap, and AB (Reganold et al., 1987) for the young and old stands. Erosion in the early stages of agriculture at SERC, i.e., 1670 (Java Dairy Farm, n.d.), resulted in local laws being passed in 1704 and 1743 to prevent siltation of streams (Higman, 1968). The Bt horizon in young forest soils was closer to the surface compared to the uncut forest soils (Table 2); this may indicate more wind or water erosion in combination with possible loss of organic matter due to oxidation. These results suggest that the physical effects of historic erosion may still be present in these soils today. As the depth to the Bt decreases, the percent of clay in the surface horizons increased (Fig. 3). We propose that the depth of Bt horizon has the potential to be an indicator for similar chronosequence studies focusing on old field succession. The timing and duration of the erosion is speculative but regardless of when these events occurred, the soil horizons are reflective of the cumulative effect of erosion.

The young forest soils have higher bulk density values compared to the old and uncut forest stands which may be related to recent cultivation (Tiessen et al., 1982), to the foot and equipment traffic (Lyon et al., 1952; Tiessen et al., 1982) related to sowing and harvesting, or, earthworm activity. Earthworms can both compact and decompact soil (Blouin et al., 2013). The effects of earthworms on bulk density will depend on (1) the initial conditions (e.g. highly compacted soil will become more loose by earthworm activity), and (2) the earthworm species composition. Decompaction can be the result of constant burrowing through the soil thus loosening it. Bulk density on the surface may increase when species consistently deposit their loose, globular cast on the surface. Compaction on the surface happens when the entire annual leaf litter input is consumed by the earthworms, and the casts are mixed into the mineral layer. This has been observed in temperate, originally earthworm-free forests in North America (e.g. Alban and Berry, 1994; Hale et al., 2005). At SERC, all leaf litter is consumed within a year in the young forests.

4.2. Soil chemical properties

We expected old forest soils to have higher C; lower nutrients, bulk densities, and pH than the young forest soils. We found that only Mg, Ca, NO_3, and pH were significantly different between young and old forest soils. For the land-use effect, C content and bulk density were the only variables that differed significantly between old and uncut forest. Differences in soil chemical properties may be the result of the complex interactions of land use and forest age. Forests were cleared for agricultural use, and after abandonment, succession led to the establishment of secondary forests. Consistent with results from this study, others have demonstrated that during succession from abandonment of agricultural fields to forests, carbon increases (Brunet et al., 2012; DeGryze et al., 2004; Falkengren-Grerup et al., 2006; Flinn and Marks, 2007), pH decreases (Falkengren-Grerup et al., 2006; Schrijver et al., 2012) and the C:N ratio increases (Compton and Boone, 2000). The young soils at the SERC stands were less acidic and contained less Al compared to the old forest soils in both the surface and lower depths. The pH of the uncut forest surface soil depth was very low, 18% lower than the average of the old and young soils, and 14% lower than the NRCS web soil survey (NRCS, 2015, Dec 1) estimations of 4.9 (Collington has an estimated pH of 4.7, Annapolis, 5.4, and Donlonton, 4.5). The low pH in uncut forests pH are probably due to a combination of decades of soil leaching in and lack of leaf litter input high in nutrients such as calcium. Also, earthworms that have been shown to increase pH (Burtelow et al., 1998; Szlavecz et al., 2006) are absent in the uncut sites. In the previously managed sites additional factors influencing soil pH and Ca levels

include amendment of manure, marl, and gypsum (Higman, 1968). To complicate matter at SERC, several oyster middens have been discovered (Cook-Patton et al., 2014), which would directly increase pH and Ca; however to our knowledge, none of our sampling locations overlapped with these relic middens.

There was a general increase in Mg and Ca concentrations in soils between the uncut, old, and young forest stands, however, there were no differences in P concentration. This finding was not consistent with the results of Bellemare et al. (2002) and Switzer et al. (1979) who found that Mg and Ca concentrations in the surface soil increased with forest age. A possible explanation for the differences between our study and the others may be related to earthworm activity and vegetation differences, including understory (Higman, 1968) and herbaceous plants (Parker et al., 2010) thereby influencing the quantity and quality of leaf litter input, and therefore the nutrients to the soils. The young stands at SERC were dominated by tulip poplar (L. tulipifera) which has leaves with higher concentrations of Mg and Ca compared to oaks (Mudrick et al., 1994) which dominate the forest at the old and uncut stands. Unlike studies that have found differences in P concentrations between historic agricultural land and a reference forested stands (e.g.,Compton and Boone, 2000; Honnay et al., 1999; Koerner et al., 1997; Verheyen et al., 1999), it was surprising to find no differences between the historical agricultural stand, i.e., young and old, compared to the uncut stands especially since the agricultural fields would have additional applications of manure high in P. The soil nutrient status has been shown to be important to tree community organization in northeastern forest (Bigelow and Canham, 2002), to diagnose nutrient deficiencies for sugar maple (Ouimet et al., 2013), and to model coarse-scale plant species distribution in combination with climate variables (Coudun et al., 2006).

One difference between the old and uncut stands was that C content was lower because clearing and logging may have created more erosion in the old forest stands, and the earthworm population prevented redevelopment of the O horizon (Ma et al., 2013). In uncut forest, cation concentrations may be underestimated and may not be representative of the total cation content because the cation content was not measured in the O horizon.

The old and uncut forest soils have a BC:Al ratio close to 1.0 in contrast to the higher ratio of the young forest soils. The vegetation, both understory and canopy, of the uncut forest are adapted to low pH conditions, as well as a low cation aluminum ratios. Soil solution BC:Al ratios less than 1.0 has been suggested possible root damage and stress for some tree species (Cronan and Grigal, 1995; Sverdrup et al., 1996). However, in general, there is little evidence to support that low BC:Al ratios are indicators of potential stress in forest ecosystems (e.g., Wargo et al., 2003). Soil fertility can be maintained across a range of cationic ratios; in other words, there is no ideal basic cation saturation ratio or range (Eckert, 1987; Eckert and McLean, 1981; Kopittke and Menzies, 2007).

4.3. Organisms

The amount, diversity and type of litter determine the annual organic carbon input into temperate deciduous forests. Soil fauna is the driver that connects, integrates, and mixes above- and below-ground parts of the ecosystem and earthworms are a keystone group in this process (De Deyn and Van der Putten, 2005; Wardle et al., 2004). Although not directly included in the present study, we have sampled earthworm abundance and activity in many SERC forests stands, including the sites reported here. In general, earthworms are abundant in the secondary forest stands, but are absent on the uncut stands. The species composition and biomass of the earthworm communities differ between old and young stands, even though there is temporal variation at each site that

has earthworms (Szlavecz and Csuzdi, 2007; Szlavecz et al., 2011). Non-native earthworms may have been established after the creation of agriculture fields. Most species are common both in forests and in open habitats, including arable fields. The earthworms most likely remained in the recovering forests. Altered carbon chemistry and storage due to selective feeding has been attributed to earthworms (Filley et al., 2008) and has a lasting legacy in the soil (Crow et al., 2009; Ma et al., 2013). Earthworms can indirectly affect understory plants as has been shown for orchids at SERC (McCormick et al., 2013), ferns in Minnesota (Gundale, 2002), eventually modifying the structure and function of the entire plant community (Forey et al., 2011; Hale et al., 2006; Nuzzo et al., 2009).

One of the greatest differences among stands that could be related to historical events was soil organic matter content, which was highly related to the presence or absence of O horizons. In the uncut forest soil, the O horizon mass averaged 3.6 ± 0.6 kg m^{-2}, whereas in the old forest soils, there was no measurable O horizon (Table 2). The O horizon contributes a significant amount of C and was the reason that uncut forest soils had a higher C content in the surface depth, which included the O horizon and the 0–10 cm mineral soil layer. Soil carbon was reduced by an average of 30% or higher through cultivation of temperate forest soils (Davidson and Ackerman, 1993; Johnson, 1992) which was similar to the reduction of 32% from the uncut to the old carbon content in SERC soils. The disappearance of the O layer was also the most visible effect of non-native earthworm activity (Alban and Berry, 1994; Eisenhauer et al., 2007; Fahey et al., 2013). Regardless of the reason of the original loss of O layer, the C content had not increased after 75 years of succession, i.e., from the young versus old forest stands, which was similar for carbon content in the plow layer 10–115 years after agricultural abandonment for a Rhode Island forest (Hooker and Compton, 2003). On a subset of our sampling sites, Ma et al. (2013) has shown distinct differences among soil carbon aggregate fractions and attributed these to past land use in combination with earthworm presence. In Belgium, Muys et al. (1992) showed that as long as palatable leaf litter was available, earthworms prevented the development of organic layer and moder humus during afforestation. Additionally, bioturbation magnifies the nutrient concentration difference between the old and uncut surface layers because the nutrient rich O horizon is incorporated into the old forest soil's 0–10 cm layer in contrast to the uncut forest soil. While agricultural legacies are still detected in old forest soils, present nutrient concentrations may be more strongly affected by the ongoing mixing of leaf litter with mineral soil. Detailed chemical analyses of plant litter residue and different fractions of soil organic matter at a subset of our sites strongly support the latter mechanism (Filley et al., 2008; Crow et al., 2009; Ma et al., 2013).

4.4. Forest soil trajectory

Time was central to this study, as our questions address soil recovery after agricultural abandonment and as forests age. When and if a forest recovers in either function or form is subject to interpretation but once a forest is disturbed, a new trajectory is created and this new trajectory affects future composition and structure both for vegetation and soils (Cramer et al., 2008; Foster et al., 2003; Huggett, 1998) and soil biota. Some soil properties, such as carbon content may return to pre-disturbance levels. However vertical distribution in the soil profile and proportion of C in different aggregate fractions (Ma et al., 2013) may be modified; both can affect microbial activity and thus nutrient availability. Biotic properties, such as vegetation and soil biota, could recover in biomass but not in species composition. For instance, total annual leaf litter input is similar in the uncut and old forests at SERC (Szlavecz

unpublished), but composition of litter is different (Table 1). Litter chemistry of a forest composed of mostly Tulip poplar and red maple affect soil properties differently than one dominated by species of oak. Also, forest soil without non-native earthworms could shift to one with abundant earthworms as is the case at SERC. These confounding factors may drive the trajectory of the ecosystem, including the soil subsystem to an alternative stable state.

5. Conclusions

Quantifying and separating the effects of past history and forest stand age on soil characteristics is challenging. The chemical and physical factors that were important in showing an age effect between young forest and old forest soils at SERC were pH, Ca, Mg, and NO_3, which may be related to weathering, leaf litter quality inputs, and agricultural inputs such as manure, marl, and gypsum. Evidence of a historical land-use legacy, the soils of the uncut forest stands had an O horizon that was not found in the young and old forest soils, and a lower bulk density. The surface horizon differences were affected by agriculture practices and inputs due to cultivation, to the foot and equipment traffic related to sowing and harvesting, erosion due to clearing and logging, mixing caused by introduced organisms, e.g. earthworms, and nutrient-rich leaf litter quality input. The Bt horizon was generally closer to the surface in the young forest soils which we interpret as an indication of erosion during the time that the stands were used for agricultural practices. Given our results, we predict that the young forest soil will become more like the old forest soil with a decrease in pH, loss of nitrate and cations such as Ca and Mg; along with a corresponding increase in Al. We believe that the results of this study, which were conducted in a restricted area to reduce variability, can be generalized to a larger area especially in the Chesapeake Bay region with similar land-use history and current vegetation, such as the Tulip poplar association (Brush et al., 1980).

Anthropogenic influences may keep forest ecosystems and their soils evolving, and create different and permanent trajectories which will affect forest soils irreversibly. McMahon et al. (2010) showed that the growth rate of trees at SERC has recently increased presumably due to CO_2 fertilization. Additionally, climate models project increased frequency and intensity of precipitation for the Mid-Atlantic region (Meehl et al., 2005) that may profoundly affect carbon cycling both above- and belowground. Increasing human population on the region leads to increased N-deposition and new species introduction. As an example, in one of our old forest stands, Treefall, several Asian earthworm species are currently invading from the neighboring residential areas (Chang et al., 2016). These future influences will cause trajectories of forest soils to diverge further away from the pre-Colonial states even affecting those forests that have not been cut or managed previously.

Acknowledgements

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2016.03.046.

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