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ORIGINAL PAPER

Investigating Surficial Geologic Controls on Soil Properties, Inorganic Nutrient Uptake, and Northern Hardwood Growth in Western Massachusetts, USA

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Abstract

The influence of glacial geologic materials on soil properties, tree nutrient acquisition, and tree growth rates in New England is not well-constrained. Here, our research investigates the effect of two dominant surficial deposits, glacial till and glaciofluvial deposits, on soils and northern hardwood trees in western Massachusetts. We investigated sixteen paired glaciofluvial and glacial till sites located on the perimeters of glacial lake Hitchcock sediments, which drained 12,400 years ago. At each site, a 12.2-m-radius circular plot was selected, a soil pit was excavated, and all trees within the plot were sampled for foliage and cored with an increment borer. Our analyses found glaciofluvial soils to have significantly higher pH, clay fraction, and water field capacity than glacial till soils. Glaciofluvial soils also had less rock fragments and lower sand content than glacial till soils. We observed significantly higher pseudo-total K, Ca, Mg, and Mn concentrations in glacial till soils, but found similar foliar concentrations for five of the six tree species. Tree cores showed Black Birch, Red Maple, and Red Oak grew 1.3 to 2.1 times faster on glaciofluvial soils. Our study found that glaciofluvial soils, which exhibit greater water retention, less rocks, more fine particles, and higher soil pH than glacial till soils, promote faster growth of Black Birch, Red Maple, and Red Oak. However, the growth of American Beech, White Oak, and Eastern Hemlock was not impacted by surficial deposits, implying adaptation to nutrient limitations, coarser rocky soils, and potential water stress. Thus, the growth of some common tree species is affected by geologic materials, but others are not affected.

Keywords Glacial till · Glaciofluvial · Soil parent material · Forest nutrients

1 Introduction

In the northeastern USA, forests are critical resources for harvesting timber, building materials, and biomass as biofuel for domestic heating. While the demand for timber and biofuel is increasing, forest lands dedicated to timber harvesting management plans are simultaneously decreasing (Robertson et al. 2011; Joshi and Mehmood, 2011). Thus, it is increasingly important for public and private forest and land managers to consider the longevity of nutrients and soil properties for sustainability of production rates of managed forested lands (Deal et al. 2012; Paré and Thiffault, 2016). Soil fertility is central to the sustainability of forestry, but few studies have explored the link between soil properties to their geologic parent materials in the northeastern USA (e.g., Li et al. 2017). Here, we investigate the link between geologic materials and physical and chemical properties of soils, and their subsequent influence on nutrient uptake and tree growth.

Glacial geology dominates the formation of soils in the northeastern USA, including the state of Massachusetts. Most of Massachusetts' soils derive from either glaciofluvial or glacial till deposits. During the last glacial maximum from 19,000–22,000 years ago, the Laurentide Ice Sheet covered Massachusetts (Dyke and Prest, 1987; Dyke et al. 2002). As the ice sheet moved southward, it deposited a heterogeneous mix of rock fragments, ranging from sand to boulders > 4 m diameter, forming lodgement glacial till (Dyke and Prest, 1987). Glacial till is the most common geologic material on upslope, elevated topographic positions in the northeastern USA. The Laurentide Ice Sheet retreated and glacial till-derived soils began forming approximately 19,000 to 15,000 years ago in Connecticut and Massachusetts (Balco

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and Schaefer 2006) or as late as 11,000 years ago in Vermont and New Hampshire (Ridge and Larsen, 1990), as determined by studies of varved lake sediments and cosmogenic radionuclide dating. Fluvial systems weathered, eroded, and re-deposited the glacial till-derived soils as glaciofluvial deltaic and lacustrine deposits. In the Connecticut River Valley of western Massachusetts, much of the deltaic and lacustrine deposits correspond with Glacial Lake Hitchcock sediments deposited between 16,500 and 12,400 years ago (Dyke and Prest, 1987; Ridge and Larsen, 1990; Uchupi et al. 2001).

Surficial geology can control many edaphic properties of their overlying soils. Glaciofluvial deposits are typically well-sorted and dominated by fine sands and coarse silt while lacustrine deposits, particularly the varved materials, may be dominated with fine silts and clays (Hartshorn and Young, 1969; Ashley, 1975). Soils formed from poorly sorted glacial deposits have higher boulder, stone, and gravel content. The sandy loam, rocky glacial till soils of western Massachusetts are excessively well-drained while silt loams formed from finer glaciofluvial deposits are commonly poorly drained (Villholth et al. 1998; Soil Survey Staff, 2008). These differences have important implications for tree growth as excessively drained soils are drier during late-summer droughts, but finer soil textures can decrease oxygen diffusivity to roots and increase surface area for weathering and sorption (Mohanty and Mousli 2000; Taylor and Blum 1995; Miller et al. 1993). Moreover, there may be mineralogical differences in glacial till and glaciofluvial deposits, due to the heterogeneity of material deposited by the Laurentide Ice Sheet (Bailey and Hornbeck 1992) or preferential losses of carbonates and increases in feldspars and quartz during sediment transport (Eberl 2004).

Soils derived from glacial till and glaciofluvial deposits may influence tree growth differently due to differences in their reservoirs of inorganic nutrients and the release rates of these nutrients. Paoli et al. (2007) found that surface soil P, K, and Mg concentrations and percent sand content were significantly related to forest stem density and aboveground biomass in a tropical forest. Paoli et al. (2007) also determined that 31% of the aboveground biomass variance observed was due to P availability and percent sand content. As another example, Royer-Tardif and Bradley (2011) found evidence that soil nutrient availability controlled the relative abundance of Jack Pine and Trembling Aspen in Quebec, Canada. They also found that fertile clay deposits fostered a more heterogeneous forest tree species composition than on nutrient-poor glacial till sites (Royer-Tardif and Bradley, 2011). Calvaruso et al. (2017) found that soils underlying European Beech (*Fagus sylvatica*) stands inherited key physical and chemical soil properties from their geologic materials. Analysis of plant data from the U.S. Forest Service "Tree Chemistry Database" revealed differences in foliar chemistry based on the geologic materials(Pardo et al. 2005); fluvial K (6.2 ± 0.1 mg g^{-1}) and Ca (7.5 ± 0.1 mg g^{-1}) concentrations were lower than glacial-till K (7.7 ± 0.1 mg g^{-1}) and Ca (9.2 ± 0.1 mg g^{-1}) concentrations, respectively. However, few studies have examined the impact of geologic materials on tree growth on the northern hardwoods that dominate the forests of New England (Finzi et al. 1998).

The primary objective of this study was to explore the influence of geologic materials (glaciofluvial and glacial-till) on soil properties and assess if they significantly affect tree nutrient acquisition and growth rates in unmanaged northern hardwood forests of western Massachusetts. Our first hypothesis was that glaciofluvial soils would promote greater tree growth than glacial till soils due to their physical properties(less rocks, higher water field capacity, more clay) and chemical properties (higher pH, higher concentrations of Ca, K, Mg, Mn, Cu, Zn). Our second hypothesis was that glaciofluvial soils would promote greater tree nutrient uptake and growth rates than glacial till soils due to their edaphic properties (higher pH, greater water field capacity, higher nutrient availability). The information may be useful for forest ecosystem researchers and forest resource managers to determine differences in site productivity influenced by surficial geology.

2 Materials and Methods

2.1 Site Descriptions

We studied 16 paired forested sites across the two dominant surficial deposits in the Connecticut River Valley of western Massachusetts (Table 1, Fig. 1). Each pair consisted of a glaciofluvial and glacial till forest site, within 400 m of each other, on the edge of Glacial Lake Hitchcock lacustrine deposits and Wisconsonian glacial till. Each pair of forest sites had comparable elevation, aspect, and geomorphic position. The glacial material for each site was first identified using the United States Department of Agriculture Natural Resource Conservation Service's web tool Web Soil Survey (https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm, accessed June 2018) and the USGS 1:24,000 Surficial Geology Map (https://docs.digital.mass.gov/dataset/massgis-data-usgs-124000-surficial-geology, accessed June 2018) and further confirmed through soil pit excavation. The location of each forest site is detailed in (Table 1, Fig. 1). Each potential pair was inspected for forest composition, geologic material, and hydrology. Forests with human disturbances, recent forest management activities, boulder fields, exotic tree species, and poor drainage were deemed unsuitable for this study. Forest sites also needed to be well-drained, on slopes < 10°, and at least 50 m from any human roads or structures. At forest sites deemed suitable, we denoted a circular forest stand with a 12.2-m (40 ft) diameter for study.

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Table 1 Location of forest stands, their tree species composition, and stand age estimate

Site #	Material	Soil series	Latitude	Longitude	Elevation a.s.l. (m)	Tree species†	Stand age‡ (years)
1	Glaciofluvial	Belgrade	42° 17′ 16.98″ N	72° 32′ 39.55″ W	93	AB, WO	44 ± 5
	Glacial Till	Narragansett-Holyoke	42° 17′ 27.20″ N	72° 32′ 44.66″ W	110	RM, WO	47 ± 5
2	Glaciofluvial	Belgrade	42° 17′ 9.42″ N	72° 34′ 34.83″ W	51	EH, RO	58 ± 8
	Glacial Till	Holyoke	42° 17′ 21.95″ N	72° 34′ 36.26″ W	93	EH, RO	48 ± 11
3	Glaciofluvial	Hinckley	42° 17′ 2.26″ N	72° 36′ 1.01″ W	49	BB, EH, RM, RO	71 ± 21
	Glacial Till	Holyoke	42° 17′ 4.07″ N	72° 36′ 8.34″ W	47	BB, EH, RM, WO	60 ± 5
4	Glaciofluvial	Hinckley	42° 18′ 25.85″ N	72° 34′ 23.12″ W	171	BB, EH, RM	67 ± 15
	Glacial Till	Narragansett-Holyoke	42° 18′ 20.81″ N	72° 34′ 21.68″ W	203	BB, EH, RM	55 ± 12
5	Glaciofluvial	Hinckley	42° 18′ 38.27″ N	72° 33′ 22.97″ W	138	AB, EH	78 ± 13
	Glacial Till	Narragansett-Holyoke	42° 18′ 40.39″ N	72° 33′ 19.04″ W	147	AB, EH, RO	56 ± 11
6	Glaciofluvial	Belgrade	42° 17′ 41.50″ N	72° 39′ 31.86″ W	64	EH, RM	67 ± 17
	Glacial Till	Narragansett-Holyoke	42° 17′ 53.63″ N	72° 39′ 37.30″ W	95	BB, WO	58 ± 10
7	Glaciofluvial	Hinckley	42° 16′ 20.90″ N	72° 36′ 44.86″ W	55	BB, EH, RM	78 ± 19
	Glacial Till	Narragansett-Holyoke	42° 16′ 20.21″ N	72° 36′ 49.68″ W	56	AB, RM	68 ± 20
8	Glaciofluvial	Hinckley	42° 14′ 21.98″ N	72° 39′ 28.40″ W	76	BB, RM, WO	48 ± 12
	Glacial Till	Narragansett-Holyoke	42° 14′ 13.45″ N	72° 39′ 16.52″ W	150	BB, WO	64 ± 21
9	Glaciofluvial	Hinckley	42° 14′ 4.70″ N	72° 39′ 27.68″ W	117	BB, WO	81 ± 17
	Glacial Till	Narragansett-Holyoke	42° 14′ 1.14″ N	72° 39′ 25.74″ W	151	AB, BB	56 ± 13
10	Glaciofluvial	Hinckley	42° 21′ 2.74″ N	72° 39′ 22.14″ W	82	BB, EH	69 ± 22
	Glacial Till	Charlton-Rock outcrop-Hollis	42° 21′ 5.36″ N	72° 39′ 28.69″ W	97	BB, EH	68 ± 23
11	Glaciofluvial	Belgrade	42° 21′ 14.00″ N	72° 40′ 5.22″ W	74	BB, EH, RM, WO	41 ± 9
	Glacial Till	Charlton-Rock outcrop-Hollis	42° 21′ 22.00″ N	72° 40′ 2.75″ W	80	EH, BB, RM, WO	39 ± 9
12	Glaciofluvial	Belgrade	42° 22′ 52.24″ N	72° 38′ 39.92″ W	58	EH, BB, WO	60 ± 13
	Glacial Till	Charlton-Rock outcrop-Hollis	42° 22′ 52.89″ N	72° 38′ 36.97″ W	67	EH, BB, RM, WO,	81 ± 20
13	Glaciofluvial	Hinckley	42° 22′ 27.77″ N	72° 39′ 50.47″ W	86	AB, EH, RO	88 ± 16
	Glacial Till	Woodbridge	42° 22′ 32.67″ N	72° 39′ 56.88″ W	113	AB, EH, RO, BB	85 ± 16
14	Glaciofluvial	Hinckley	42° 27′ 55.12″ N	72° 30′ 11.74″ W	149	BB, EH, RO	77 ± 15
	Glacial Till	Holyoke-Yalesville	42° 27′ 50.40″ N	72° 30′ 18.11″ W	148	AB, EH	70 ± 13
15	Glaciofluvial	Hinckley	42° 29′ 59.31″ N	72° 31′ 47.28″ W	133	AB, BB, RO	68 ± 11
	Glacial Till	Holyoke-Yalesville	42° 29′ 57.16″ N	72° 31′ 49.80″ W	145	BB, EH, RO	73 ± 14
16	Glaciofluvial	Scio	42° 32′ 57.30″ N	72° 34′ 28.67″ W	81	BB, EH, RO	80 ± 12
	Glacial Till	Holyoke-Yalesville	42° 33′ 5.29″ N	72° 34′ 31.37″ W	116	AB, EH, RO	71 ± 17

† Forest species codes: AB = American Beech, BB = Black Birch, EH = Eastern Hemlock, RM = Red Maple, RO = Red Oak, WO = White Oak

‡ Stand age was estimated to be the average tree age using counted tree core rings

Current land management of all sites is single-tree selection harvesting and reforestation conservation.

2.2 Tree Species, Tree Coring, and Foliar Analyses

Tree species present at glacial till and glaciofluvial sites are given in Table 1. All trees with > 10 cm diameter were measured for diameter at breast height (DBH) and identified. Leaf foliage and bolewood samples were collected from American Beech (*Fagus americana*), Black Birch (*Betula lenta*), Eastern Hemlock (*Tsuga canadensis*), Red Maple *(Acer rubrum*), White Oak (*Quercus alba*), Red Oak (*Quercus rubra*), White or “paper” Birch (*Betula papyrifera*), and White Ash (*Fraxinus americana*) in triplicate from each forest stand in the summer of 2018. Species were identified using the *Trees of Eastern North America* dichotomous tree guide (Nelson et al. 2014). Foliage was collected from branches in the middle to upper canopy, 4 to 25 m above the ground, using a stainless-steel pole saw (see Richardson and Friedland, 2016) or an arborist throw-ball. For the throw-ball technique, a 0.4-kg arborist throw-ball was lobbed over upper canopy branches and the branches were forcibly removed at the connection to

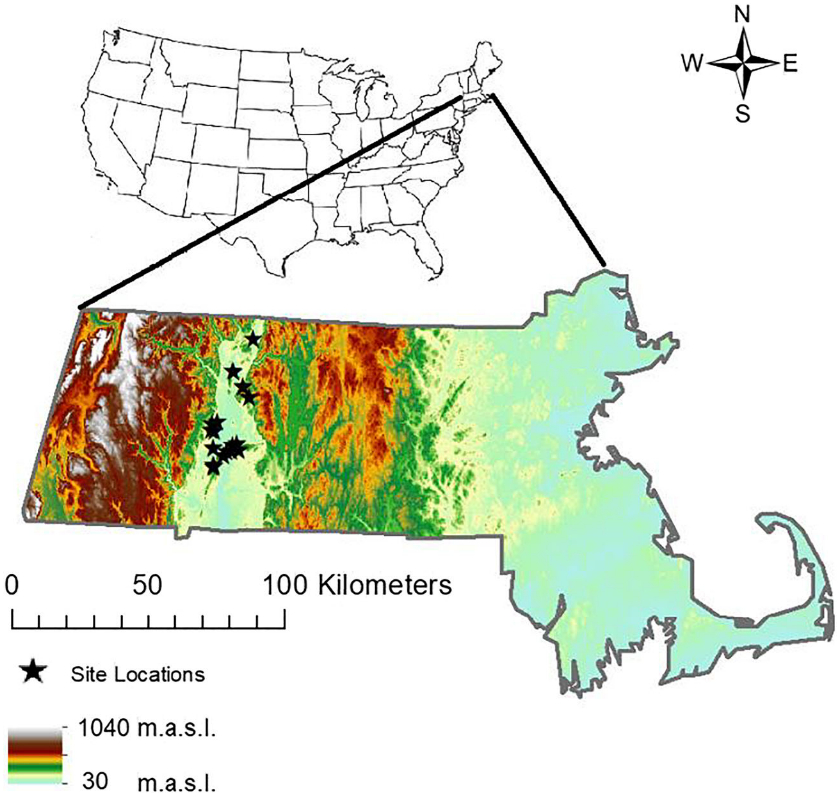

Fig. 1 Location of sampling sites indicated by stars across the state of Massachusetts, USA, with meters above sea level (m.a.s.l.) from a digital elevation map. The Connecticut River Valley closely corresponds with glacial lake Hitchcock and former fluvial sediments

the main trunk. For shorter trees, a stainless steel pole saw was extended, and a branch was collected from the main trunk. In both cases, branches collected were between 3 and 10 cm in diameter.

Trees were cored using an 18.3-cm-long increment corer with a 4.3-mm width. Trees with a DBH of 10 cm and under were not cored. In the laboratory, all cores were secured to a 30-cm-long wood board with glue. Tree cores were polished starting with sandpaper at 40 grit and continued down to 800 grit. The polished tree cores were analyzed by dissecting microscope to count and measure each annual tree ring. Using the tree ring data, we estimated the age of the tree, annual growth rate, and minimum stand age (Table 1).

To determine macro- and micronutrient concentrations, digestions were carried out using a modified EPA 3050B Method (Chen and Ma, 1998; Rechcigl and Payne, 1990), in which samples are combusted prior to strong acid, pseudo-total digestion. To begin the process, plant material was dried to a constant weight at 90 to 105 °C for a period of 24 h. Foliage was then ground up to reduce heterogeneity, and for larger leaves, the mid-vein was removed prior to grinding. The ground-up foliage was then transferred to a ceramic vessel and combusted at 550 °C for 8 h. The ashes were transferred to 50-mL centrifuge tubes and digested with 5 mL of reverse aqua regia (9:1 HNO_3:HCl) and lightly capped to degas overnight. After 12 h, the digest was diluted to 50 g using deionized water. Samples were further treated by diluting 3 g of the plant tissue digest to 15 g using 2.5% HNO_3 solution for analysis by inductively coupled plasma-mass spectrometry (ICP-MS). While this method can cause issues for measuring insoluble, high field strength elements (e.g., Ti or Si), it is effective for measuring base cations and micronutrient trace elements (see Rechcigl and Payne, 1990).

2.3 Soil Sampling and Analysis

Soils at each site were sampled between June and August 2018. A 1-m-wide by 1-m-deep soil pit was excavated in the center of each forest stand. One side of the pit was designated for pedon description, to avoid any compaction, and described following U.S. Soil Taxonomy using the National Soil Survey Center NRCS USDA Field Book for Describing and Sampling Soils Version 3.0 (Schoeneberger et al. 2012). Starting from the bottom of the pit, soil cores were collected from each of the horizons using a 15-cm-diameter steel cylinder to capture soil bulk density. For soil horizons with large rocks (> 5 cm) that prevented the steel cylinder from being hammered into the soil pit face, the % rock volume was visually estimated with a 15 × 15 grid, and collected by trowel. This visual estimation of rock fraction occurred for 20 of the 148 total soil horizons and exclusively for glacial till soils. One soil sample was obtained from each soil horizon and collected in polyethylene bags. In total, 32 soil pits were excavated in this study and 148 soil horizons sampled.

All mineral soil samples and organic horizons were air-dried. Mineral soil samples were then weighed and sieved to ≤ 2 mm and then re-weighed. A 2:5 soil–water slurry was used to determine soil pH. Slurries were shaken for 1 h using a wrist-action shaker and vacuum extracted through a Whatman 40 filter. The pH of the supernatant extract was measured with a pH meter (8015 VWR). For organic-rich horizons, samples were filtered using a Whatman 1 filter. Loss on ignition was used to estimate % soil organic matter (SOM) and measured by combusting a 4-g oven-dried subsample at 550 °C for 8 h. Every 20 samples included one blank and duplicate. To determine the soil particle size distribution, we weighed ~ 30 g of dried soil into a 250-mL glass beaker. Organic matter was removed and we added 100 mL of 1 M sodium hexametaphosphate (HMP) solution to the soil for at least 8 h to disperse soil particles. This HMP–soil slurry was washed out into a 1000-mL graduated cylinder with DI water. We utilized a modified Bouyoucos hydrometer method with hydrometer readings at 60 s and 1.5 h after mixing to the closest 0.5 g L^{-1} (Gee and Bauder, 1986). To examine differences in soil water retention of the soils, we performed a field capacity test (Rawls et al. 1991). We performed the test by adding 20 g of soil to a funnel with Whatman 1 filter paper, then saturating the soil with DI water. Once all the water had passed through the sample, we weighed the wet soil at field capacity following cessation of gravimetric water draining and compared the wet mass to the soil's dry mass to determine the percent field capacity. Field capacity is reported as a percentage of the wet weight divided by the soil dry weight.

For macro- and microelement analysis, soil samples were dried at 105 °C for 24 h and 0.5 g was weighed into 50-mL centrifuge tubes for acid digestion. Soils were not ground to avoid creating fresh surfaces for dissolution of silicate minerals. Soil samples were extracted using a strong acid, pseudo-total digestion with 5 mL of 9:1 HNO_3:HCl acid heated to 90 °C for 45 min. This method allows for quantification of metals that are sorbed to organic matter and secondary Al and Fe oxides not within crystalline silicates, providing an estimate of metals that are bioavailable or mobile (Chen and Ma, 1998). With every 20 samples, a preparation blank, a duplicate, and a standard reference material (SRM) was included. Montana Soil 2711a and Peach Leaves 1547a from the National Institute of Standards and Technology (NIST) were used as SRMs for soil and plant samples, respectively. The digests were then diluted to 50 mL using deionized water.

2.4 ICP-MS Analyses

Soil extracts and plant digests were diluted with deionized water and analyzed for macro- and micronutrients (Ca, K, Mg, Fe, Mn, Cu, Zn) with an Agilent 7700x Inductively Coupled Plasma Mass Spectrometer (Agilent Technology, Santa Clara, CA, USA). Recoveries for pseudo-total digests of Ca, K, Mg, Mn, Cu, and Zn were 82–111% of their certified values. The metal concentration coefficient of variation between intra-sample duplicates was < 7%, and metal concentrations in the preparation blank samples were < 0.1% of their analyte concentrations.

2.5 Statistical Analyses

Descriptive statistics were calculated in Matlab (Mathworks, Natick, MA, USA). Average values are presented in text and in figures ± 1 standard error. Data were tested for normal distribution using the Kolmogorov-Smirnov test (Lilliefors, 1967) and logarithmically transformed when necessary to establish normality. Foliar and mineral soil macro- and micronutrient concentrations and soil properties (pH, %LOI, field capacity, bulk density) were compared between glaciofluvial and glacial till sites for both soil horizon and tree species using paired sample t tests. Differences among tree species were determined using two-way analysis of variation (ANOVA) tests with post hoc t tests. For tree cores, time-series analysis was performed using ANTEVS 1.4.1 software to determine the detrended averages (Rayburn and Vollmer, 2013).

3 Results

3.1 Soil Physicochemical Properties Across Glacial Till- and Glaciofluvial-Derived Soils

Our measurements across the 16 paired sites show that there are significant differences in soil physical and chemical properties between soils derived from glaciofluvial materials and soils derived from glacial till materials. According to U.S. Soil Taxonomic information from Web Soil Survey and field observations, glacial till soils were all Dystrudepts, primarily of the Narragansett, Holyoke, Charlton, Hollis, and Yalesville soil series, while glaciofluvial soils were predominantly of the Belgrade, Hinckley, and Scio soil series. Rock fraction, %sand, %silt, and %clay were significantly different between glaciofluvial-derived and glacial till-derived soils for each soil horizon across the forest sites (Fig. 2). Glacial till soils had a significantly higher rock fraction (2 mm to 5 cm in diameter) and %sand than glaciofluvial soils for all horizons by > 10% w/w (Fig. 2). Furthermore, the glacial till soils had a significantly lower clay fraction than glaciofluvial soils for all horizons (Fig. 2). The %silt fraction in the A horizons (0 to 30 cm depth) was significantly lower for the glacial till soils compared with glaciofluvial soils, but not for the other horizons.

Surface soil horizon bulk density did not differ between surficial geologic materials; however, the C horizons of glacial till soils were significantly more dense than the C horizons of glaciofluvial soils ($P < 0.05$, Fig. 3). Field capacity was significantly greater for glaciofluvial soils compared to glacial till

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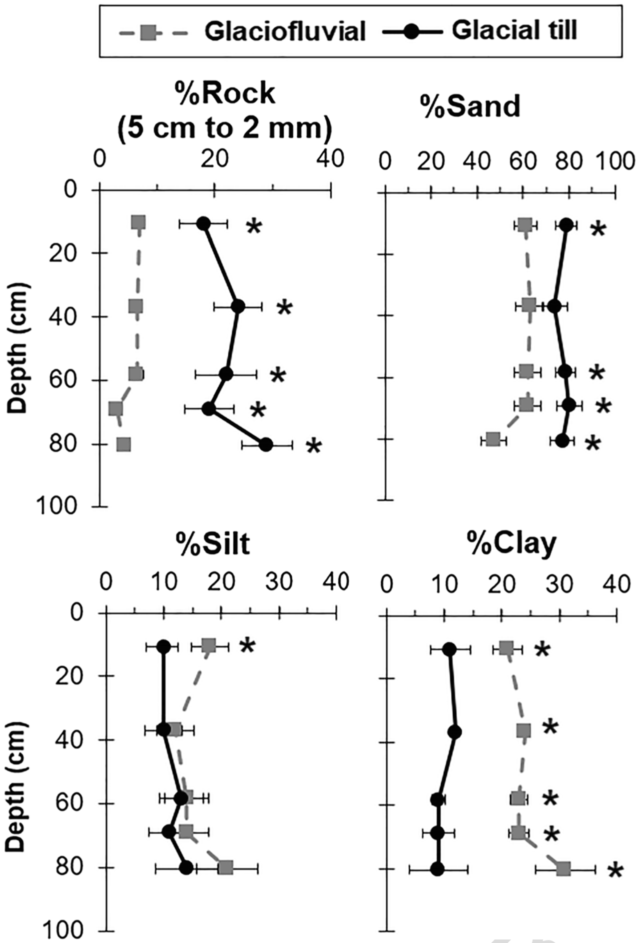

Fig. 2 Average rock and soil particle size distributions for each horizon at glaciofluvial and glacial till. Error bars are ± 1 standard error. (*) indicates a significant difference ($P < 0.05$) using paired *t* test

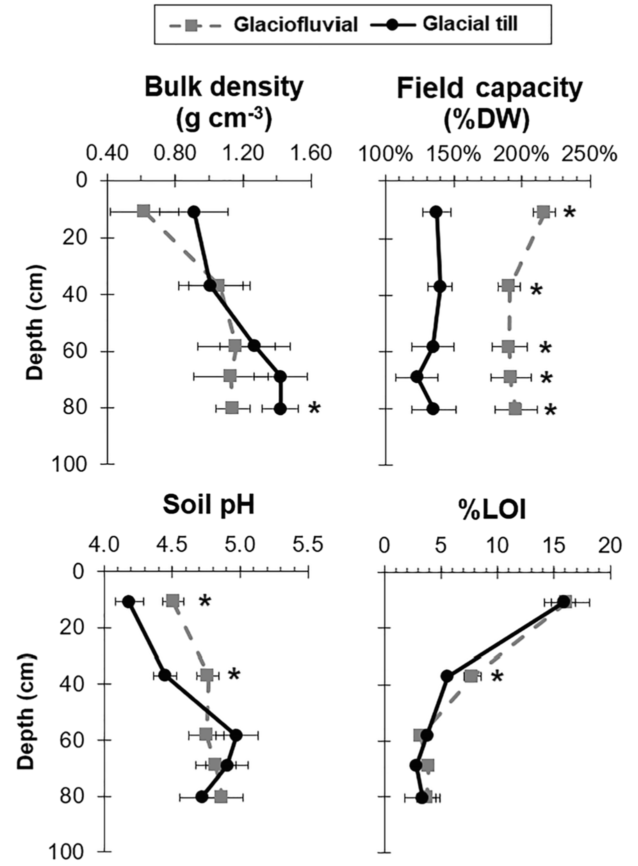

Fig. 3 Average bulk density, field capacity, soil pH (1:2.5 soil to water ratio), and loss on ignition (%LOI) for each horizon at glaciofluvial and glacial till. Error bars are ± 1 standard error. (*) indicates a significant difference ($P < 0.05$) using paired *t* test

soils for all soil horizons ($P < 0.05$, Fig. 3). A horizon and upper B horizon soil pH was significantly higher for glaciofluvial soils compared to glacial till sites (Fig. 3). However, %LOI in glaciofluvial soils was only greater than %LOI in glacial till soils in the upper B horizons (~ 40 cm depth) and lower B horizons (~ 70 cm depth) (Fig. 3).

Nutrient concentrations were determined using a pseudo-total digestion, allowing for measurement of nutrients that are readily plant available or non-crystalline silicate forms that may become plant available (e.g., organic complexed, sorbed to secondary oxides) (see Chen and Ma, 1998). Using the pseudo-total extractions, we found that glacial till soils had significantly higher concentrations of Ca, K, Mg, Mn, and Zn in their A and upper B horizons (Fig. 4).

3.2 Tree Nutrient Uptake and Growth Rates

Mid-season foliage was collected and analyzed for inorganic nutrients to determine if nutrient acquisition differed between glaciofluvial and glacial till deposit sites (Fig. 5). A two-way ANOVA and post hoc *t* tests ($P > 0.10$) revealed no significant relationship between surficial geology and nutrient acquisition. However, our data did show that Red Maple exhibited significantly higher foliar Ca, K, and Cu concentrations ($P < 0.05$, Fig. 5) while growing on glacial till.

We examined tree age and annual tree growth using tree cores. To better quantify non-site-specific effects of growth rate, data were grouped among geologic materials and averaged by calendar year for each tree species and compared across surficial geologic material. From our data shown in Fig. 6, Black Birch, Red Maple, and Red Oak had faster annual growth rates on the glaciofluvial soils than glacial till soils. However, American Beech, Eastern Hemlock, and White Oak grew at similar rates for both surficial geologic materials.

4 Discussion

4.1 Soil Physicochemical Properties Between Glacial Till- and Glaciofluvial-Derived Soils

Our analyses support our first hypothesis that soils derived from glacial till and glaciofluvial geologic materials have

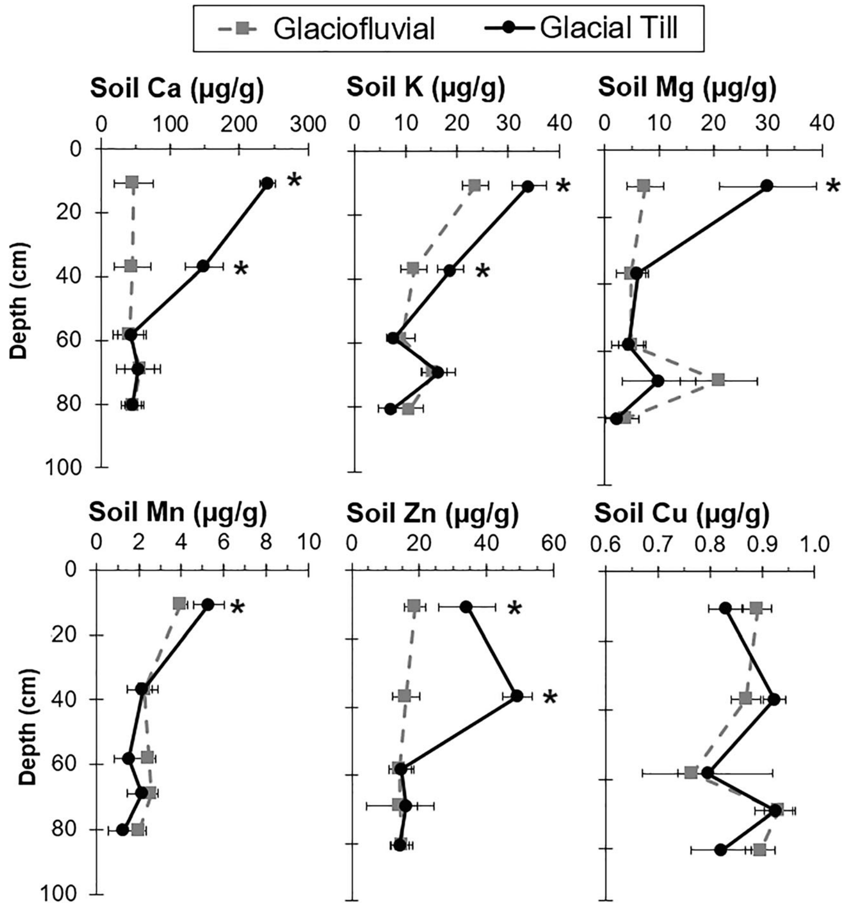

Fig. 4 Average pseudo-total metal soil concentrations for each soil horizon at glaciofluvial and glacial till sites. Error bars are ± 1 standard error. (*) indicates a significant difference between glaciofluvial and glacial till soils

significantly different physical and chemical properties. Glacial till soils had higher pseudo-total macro- and micronutrient concentrations, but glaciofluvial soils had higher pH and finer textures. The finer, well-sorted particle size distribution for glaciofluvial soils led to higher water field capacity and less rock fragments, which can decrease water stress in trees during precipitation-limited summer months and increase volume for rooting (Li et al. 2010; Keller and Håkansson 2010;

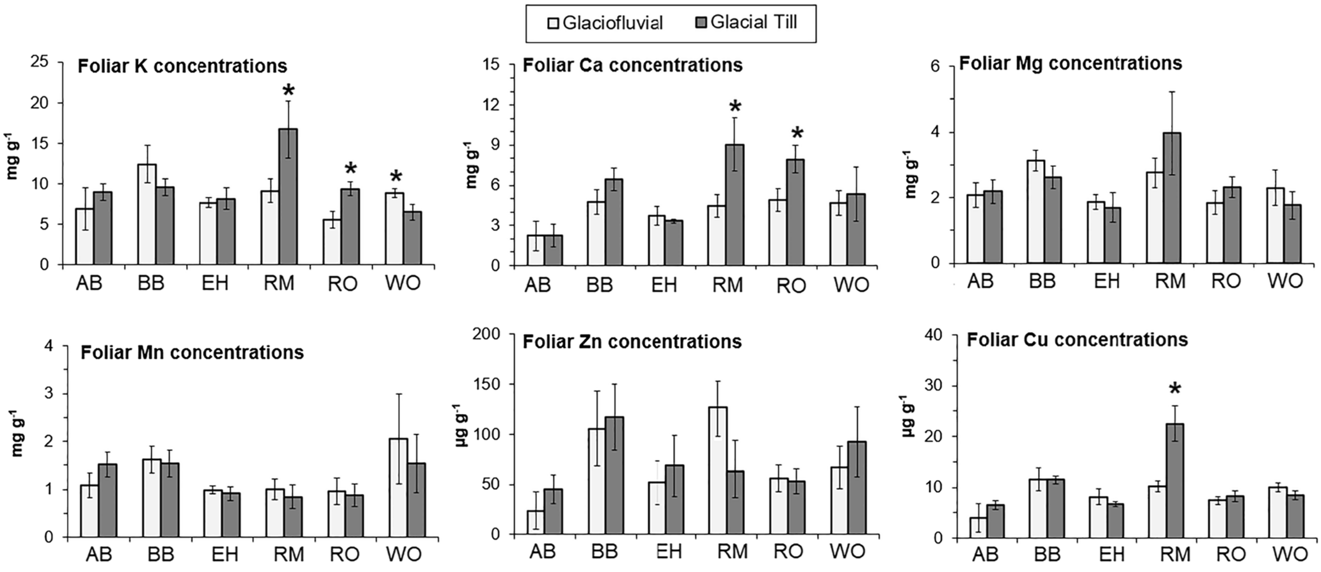

Fig. 5 Average foliar metal concentrations for dominant tree species found across both glaciofluvial and glacial till sites. Error bars are ± 1 standard error. (*) indicates a significant difference between glaciofluvial and glacial till soils. Forest species codes: AB = American Beech, BB = Black Birch, EH = Eastern Hemlock, RM = Red Maple, RO = Red Oak, WO = White Oak

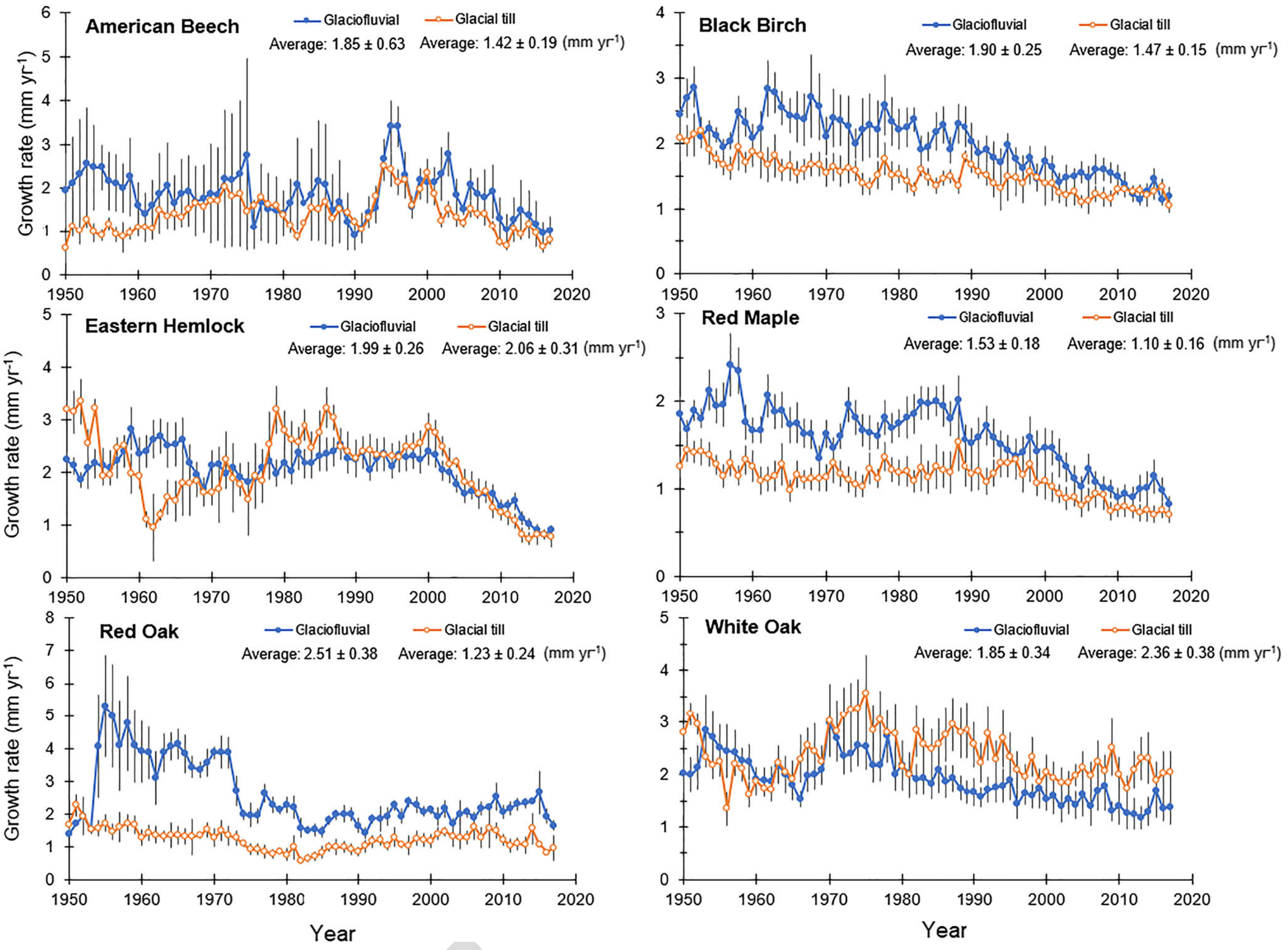

Fig. 6 Average annual growth rate estimate from tree cores annual ring measurements for dominant tree species found across both glaciofluvial and glacial till sites. Error bars are ± 1 standard error and $N = 9$ tree cores for each species at across surficial deposit

Rab et al. 2011; Olson 2012). Greater clay contents are typically associated with greater cation exchange and higher surface area for weathering (Miller et al., 1993; Taylor and Blum, 1995), but we observed greater inorganic nutrient concentrations in the sandy glacial till soils. Greater amounts of fine particles can increase aggregation and stability of C compounds for nutrient retention, particularly in agroforest systems (e.g., Rocha et al. 2018). The greater inorganic nutrient concentrations in glacial till soils was likely due to their lower pH, which agrees with the observations of previous studies (e.g., Taylor and Blum 1995; Finzi et al. 1998; Nikodemus et al. 2013) that greater acidity can increase dissolution and leaching of inorganic nutrients from silicates. Further, we hypothesize that glacial till soils had greater Ca, K, and Mg than the glaciofluvial soils because fluvial materials are typically more extensively weathered due to reworking by fluvial action. During this weathering and erosional transport, Ca, K, and Mg-bearing minerals such as carbonates and apatite are lost, leaving behind a greater proportion of resistant, nutrient-poor feldspar and quartz (see Harley and Gilkes 2000; Eberl 2004; Viers et al. 2009). These results support our hypothesis that geologic materials control soil properties important for tree growth; rocky, glacial soils common in uplands can provide greater inorganic nutrients, but low-lying, glaciofluvial soils can provide greater water and nutrient retention for northern hardwood trees.

4.2 Tree Nutrient Uptake and Growth

Our findings demonstrate that higher pseudo-total Ca, K, Mg, Mn, and Zn concentrations in glacial till soils (Fig. 4) did not correspond with greater acquisition and uptake of nutrients implied through foliar tissue concentrations (Fig. 5) for most tree species. These results are novel as, to the authors' knowledge, this is the first report on geologic material controls on northern hardwood nutrient acquisition of macronutrient and micronutrient concentrations in temperate forests of New England. An analysis of foliar data from the Tree Chemistry Database by the U.S. Forest Service (Prado et al. 2002) Q3 showed that foliar K and Ca concentrations, but not Mg concentrations, may be different when compared among soil parent materials. The discrepancy between our findings and data

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from Prado et al. (2002) may be due to a broader climatic sampling region, wider range of geologic materials included, or greater number of tree species analyzed. Erdmann et al. (1988) observed variations in foliar concentrations in Red Maple across sites but attributed variations to tree physiological properties rather than soil properties. Previous research has primarily focused on N or P cycling in hardwood forests, but our results show that Red Maple uptake of K, Ca, and Cu can be affected by geologic material. However, foliar nutrient concentrations for American Beech, Black Birch, Eastern Hemlock, Red Oak, and White Oak were similar between glaciofluvial- and glacial till-derived soils. Acquisition of inorganic nutrients is essential for chemical signaling, cellular metabolism, enzyme production, and photosynthesis (Schaberg et al. 2001; Guo et al. 2016; Zhao et al. 2001; Wang et al. 2013). One possible mechanism is that soil inorganic nutrient concentrations were adequate for most tree species but not low enough to see an effect as observed in the tropical forests studied by Paoli et al. (2007). An alternative hypothesis is that most trees were able to acquire similar amounts of nutrients, regardless of the soil parent material, due to rhizosphere interactions. As described by Zemunik et al. (2015), under nutrient-limiting conditions, plants can adapt for more effective nutrient acquisition through increasing exudate release, stimulating mycorrhizal fungal or bacterial associations, or altering belowground root traits (in addition, see Uroz et al. 2011; Yin et al. 2014).

Our results also demonstrate a non-linear relationship between soil nutrient concentrations and plant uptake rates, as represented by foliar concentrations. This could be due to either the pseudo-total digestion procedure used or the more likely possibility that trees adapted to increase uptake under low nutrient availability and limit "luxury" uptake under high nutrient availability. One possible reason is that pseudo-total extractions were unable to capture nuances in bioavailability or type of sorption (such as carbonates, oxide bound, and organic matter occulted fractions), which can alter the availability of inorganic nutrients such as Ca and Mg (see Park and Ro 2018). However, Calvaruso et al. (2017) showed that tree acquisition and uptake of nutrients are dynamic; trees can readily adapt to overcome inorganic nutrient constraints in soils. Thus, we argue that trees obtain nutrients in spite of lower concentrations in glaciofluvial soils or "luxury uptake" of nutrients that are limited on glacial till soils. Mineral weathering of feldspar and apatite has been identified as a key factor impacting long-term timber harvesting sustainability (Vadeboncoeur et al. 2014; Zetterberg et al. 2016). Silicate minerals can be weathered by secretion of organic compounds from tree roots (e.g., chelators; see Uroz et al. 2011; Zhu et al. 2014; Yin et al., 2014), or tree-supported microbial communities may dissolve silicate minerals present (Harley and Gilkes 2000; Uroz et al. 2009, Ahmed and Holmström 2015). As an example, Zemunik et al. (2015) demonstrated that increased exudation of chelating compounds and stimulation of mycorrhizal fungi increased access of total inorganic P by plants, not just operationally defined bioavailable P forms.

Lastly, we found the first evidence, to the authors' knowledge, that geologic materials may control northern hardwood tree growth in New England. Instead of nutrient limitations, our data suggests tree growth rates (annual ring thickness mm year^{-1}) were between 1.3 to 2.1 times greater for Black Birch, Red Maple, and Red Oak on glaciofluvial deposits. This occurred even though Red Maple and Red Oak had lower K and Ca soil and foliar concentrations at glaciofluvial sites than on glacial till sites (Fig. 4). We hypothesize that faster Black Birch, Red Maple, and Red Oak growth on glaciofluvial soils than on glacial till was due to soil physical properties, specifically the significantly greater field capacity, lower rock fraction, and greater fine fraction (Fig. 3). Previous literature has focused on light, predation, and diseases as primary controls on Birch, Maple, and Oak growth rates (e.g., Johnson and Abrams, 2009; Parker and Dey 2008). Kirkpatrick (1981) recognized moisture can control Black Birch growth but observed their growth across New England was greater in well-drained, dry soils than on poorly drained, wet soils. Thus, we demonstrate for the first time that tree growth for three common northern hardwoods was affected by the geologic material that served as soil parent material, which was not related to nutrient uptake or accessibility.

5 Conclusions and Implications

Our study confirmed our hypothesis that geologic materials can affect tree growth. Black Birch, Red Maple, and Red Oak were more adept at growing on glaciofluvial geologic deposits than glacial till. One important implication is that harvesting common tree species on coarse glacial till materials in western Massachusetts may affect subsequent tree growth after timber harvesting. Thus, harvesting Black Birch, Red Maple, and Red Oak on glacial till may result in slower regeneration while harvesting these three species on glaciofluvial materials may result in faster regeneration. Another implication is that tree species can acquire similar nutrient concentrations, even with lower available nutrient concentrations. This implies that limitations from mineral weathering and soil retention between geologic materials can be overcome by mineral–biological interactions, improving long-term nutrient acquisition. Thus, operationally defined soil extraction procedures may not accurately capture nutrient availability, particularly when considering effects from exudates, chelators, and microbial symbionts. Our study only focused on a specific region of western Massachusetts and Glacial Lake Hitchcock sediments. For future studies, a greater sampling area across New England states will greatly enhance the ability to examine if our results are more broadly applicable to and separate from glacial outwash, alluvial fans and deltaic deposits and glacial lacustrine deposits.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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