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An Anthropocene chronosequence study on upland soils in the northeastern USA☆

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ABSTRACT

Intensive land use from agricultural activities fundamentally affects the physical structure and nutrient cycling of soils and can lead to increased erosion of sediment that gets stored downslope in legacy deposits. The northeastern USA provides the opportunity to study anthropogenic-induced changes to soils, with a well-documented ~300-year history of land modification. In this study, we investigate impacts on upland soils in northeast Connecticut at two sites used extensively in the 17–20th centuries that are now abandoned and forested along with two modern agriculture sites. We use stone walls present in LiDAR and aerial imagery from 1934 to 2019 to develop an Anthropocene chronosequence with four land use classes (T_0, T_1, T_2, and T_3) that vary in terms of duration of land use and time since abandonment. The two abandoned sites differ primarily in terms of average hillslope gradients, and we use transects at the steeper site to investigate the effect of *catena* position on sediment mobilization and downslope changes. Soil profiles within each class were described and sampled for standard soil analyses and trace metals using pXRF to address the processes of erosion and mixing in the soils. At both sites, A horizon thicknesses increase and B horizon thicknesses decrease with increasing land use duration. The consistent depth to the C horizon across all classes, lack of soil truncations and accumulation of sediment at the base of slopes, and inventories and patterns of Pb in soil profiles all suggest land use impacts led to soil mixing and redistribution along hillslope catenas, but no substantial erosion and soil loss. Therefore, depositional areas such as wetlands, floodplains and millponds in low relief deglaciated landscapes may not contain large quantities of legacy sediment. Furthermore, widely available LiDAR and aerial imagery datasets have the potential to scale up the chronosequence approach and soil impacts described here.

1. Introduction

Humans have long altered the land surface and utilized soils to sustain life. Globally, humans are viewed as agents of erosion and soil loss, with agriculture as a primary driver, and modern human-induced erosion rates commonly outpace background soil erosion rates by 1–2 orders of magnitude (Montgomery, 2007; Wilkinson and McElroy, 2007). Physical modifications to soils and increased erosion began ~10,000 years ago with the onset of agriculture and these impacts have varied both spatially and temporally throughout the Holocene as humans have spread across the globe and agricultural practices evolved (Dotterweich, 2013; Vanwalleghem et al., 2017). Examples of accelerated erosion rates are seen in legacy sediment deposits associated with episodic anthropogenic disturbance (James, 2013) and core records from ~4000 years ago in the U.K. and Europe, ~2000 years ago in Central America, and more recently within the past ~400 years resulting from European settlement in North America and Australia (Hoffmann et al., 2013; Macklin et al., 2014; Dotterweich, 2013; Beach et al., 2018; Jenny et al., 2019). In addition to sedimentary records, high resolution topographic datasets have been used globally to quantify volumes of legacy sediment deposits in valley bottoms (e.g., Johnson et al., 2019), as well as identify anthropogenic landforms on hillslopes indicating the location and extent of areas contributing to soil erosion, such as agricultural terraces and stone walls (Johnson and Ouimet, 2016; Brown et al., 2021; Cucchiaro et al., 2021). Due to human-induced changes to soils being seen around the globe, recent studies have proposed soils as a marker of the Anthropocene, and in fact, humans may be acting as soil forming agents, rather than just causing erosion and soil loss (Richter, 2020; Certini and Scalenghe, 2021). Furthermore, given the range of human impacts on soils, classifications for anthropogenic soils have

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been proposed based on the degree of modification (Volungevičius and Skorupskas, 2011).

On the broad scale, human land use influences both physical and chemical properties of soils. Physical changes to soil horizon thickness may include truncations associated with compaction and erosion, development of a plow horizon through mixing via humans and animals (Costa, 1975; Marsh and Siccama, 1997), or significant addition of topsoil due to activities such as charcoal production (Hirsch et al., 2017). Cultivation can alter nutrient cycles in soils, which can have ecological implications (McLauchlan, 2006; Matlack, 2009). Soils can also become enriched in trace metal concentrations (Hg, Pb, Mn, Cd, Zn) through atmospheric deposition due to increased atmospheric input from industrialization and human activity (Brantley et al., 2007; Holmgren et al., 2010; Zhang, 2003; Herndon et al., 2011). These metals are a concern due to their toxicity to plants and humans and can persist in soils on the order of decades to centuries (Ma et al., 2014; Kraepiel et al., 2015). Soil mixing and erosion has been addressed using additives to soil, including fallout radionuclides (Wallbrink and Murray, 1996; Matisoff, 2014; Silverhart, 2019) and ^{10}Be (Jelinski et al., 2019) in addition to metals, which have been used to address localized or systematic erosion and deposition associated with 20th century agriculture. Previous soils work associated with historic land impacts has generally focused on physical (e.g., redevelopment of forest soils) and geochemical changes (e.g., changes to carbon and nitrogen stocks) in the period following abandonment (Compton and Boone, 2000; Hooker and Compton, 2003; Matlack, 2009; Yesilonis et al., 2016); less work has focused on evaluating changes caused due to varying duration and intensity of land use activity.

In North America, the intensity of land use impacts increased dramatically on the east coast starting in the 17th century following European settlement, as vast areas were deforested and converted into agricultural land for cultivation and pasture. As westward expansion began, these agricultural practices migrated across the country. Legacy sediment deposits resulting from historic activity have been identified and studied throughout the U.S., including in the southeast (Happ, 1945; Trimble and Penney, 1975; Trimble, 2008; Dearman and James, 2019; Spell and Johnson, 2019), northeast (Costa, 1975; Bierman et al., 1997; Thorson et al., 1998; Walter and Merritts, 2008; Pizzuto and O'Neal, 2009; James, 2013; Johnson et al., 2019), and Midwest (Pavlowsky et al., 2017). However, the quantity of legacy sediment stored greatly varies by region. Studies in the Mid-Atlantic Piedmont have directly quantified heightened soil erosion of up to 15 cm from historic agriculture (Costa, 1975), and in the lower Midwest, post-settlement erosion rates on cultivated hillslopes are up to two orders of magnitude greater than background erosion (Trimble, 2008; Jelinski et al., 2019). In the northeast region, meanwhile, there appears to be less legacy sediment stored in river valleys (Snyder et al., 2017; Johnson et al., 2019), and very little work has been done in this region on upland soil erosion from historic land use. One of the key differences in the northeast may be the influence of glaciation, which affects the distribution and availability of fine-grained sediment throughout the landscape; the other regions studied may have experienced colder, periglacial conditions but were generally not directly impacted by glaciers.

In this study, we investigate 17–20th century land use impacts on upland soils in northeastern USA. Specifically, we establish four land use classes of agricultural impacts over the past ~250 years (i.e., an Anthropocene chronosequence) that allow us to examine physical and geochemical changes in soil profiles in relation to varying duration of intense agricultural activity and time since abandonment. We also examine whether agricultural activity is associated with significant erosion of upland soils in the region and whether higher sloped areas used for similar lengths of time experienced greater soil erosion. Overall, measurements of soil horizon thickness and vertical distribution of trace metals in soils provide a better understanding of the processes of anthropogenic mixing versus erosion on upland soils in the region, as sediment derived from upland sources has generally been acknowledged as the source of legacy sediment from 17–20th century EuroAmerican land use.

1.1. Study location

1.1.1. Regional setting

The northeastern USA is a tectonically inactive and generally low-relief landscape. The current climate is temperate, with mean yearly average temperatures of ~9 °C and average precipitation of ~1200 mm (NOAA, 2021). The Laurentide Ice Sheet retreated from the region between 21 and 17 ka, leaving a diverse array of glacial landforms and sediments throughout the landscape (Stone et al., 2005). More recently, the region underwent extensive land use beginning in the 17th century following European settlement and has a well-documented history of up to 70–90% deforestation, with peak land clearance occurring in the mid-19th century, ca. 1850 (Francis and Foster, 2001). Stone walls are ubiquitous features throughout the northeast that reflect the combination of glaciation and agricultural activity associated with 17-20th century land clearance. Cobble and boulder sized stones that are abundant within glacial till were moved to the edges of fields and property boundaries during initial land clearance and annually as agricultural activity and freeze thaw cycles brought additional stones to the surface (Thorson, 2002). Widespread reforestation began in the late 19th-early 20th centuries as agricultural fields were abandoned due to westward migration and urbanization (Francis and Foster, 2001).

1.1.2. Study sites

Two study sites were chosen in eastern Connecticut in the towns of Mansfield and Woodstock (Fig. 1) – each is representative of the region, with intensive land use beginning in the late 17th–early 18th century and a progression of reforestation through the 19th and 20th centuries. The two primary sites of the study, Wormwood Hill (WH) and UConn Forest (UF), are each located in the town of Mansfield. Wormwood Hill is a ~3 km^2 site characterized by two drumlinoid features separated by a wetland with slopes <7°. Soils at Wormwood Hill are developed in lodgment till and overlie metamorphic schist and gneiss (Stone et al., 2005) and are classified as Inceptisols (Aquic and Typic Dystrudepts) within the Woodbridge, Charlton, and Canton series (Soil Survey Staff, 2014). UConn Forest is a ~ 1 km^2 site characterized as low to moderate slopes (7–20°) adjacent to the Fenton River, an upland river within the Thames watershed, which drains into Long Island Sound. Soils at UConn Forest are developed in melt-out till overlying schist and gneiss (Stone et al., 2005) and are classified as Inceptisols, primarily within the Woodbridge, Canton, and Charlton series (Soil Survey Staff, 2014). Vegetation at the sites is similar, and is primarily a deciduous mix (oak, maple, ash, etc.) with some conifers (pine, spruce, etc.). Soils located in areas with mostly coniferous cover were not sampled.

In addition to the primary sites, field work was conducted at corn and hay fields located on two modern farms in the region, one in Mansfield, CT (Stearns Farm — SF), and one in Woodstock, CT (Valleyside Farm — VS) (Figs. S1 and S2). These sites were chosen as part of a larger USDA-NRCS soil health survey and were utilized in this study due to similar soil types and parent material. Stearns Farm is a conventionally tilled farm, and the hay and corn fields sampled have been used as such for the past 100 years, and likely used for longer. Soils are developed on a drumlinoid feature composed of lodgment till and are characterized as Inceptisols within the Woodbridge series. The fields sampled at Valleyside are located on a hillslope, and the corn field was switched to no-tillage practice for the past 6–10 years following conventional practices that were in place for more than 40 years. Soils at this site are developed in lodgment till and characterized as Inceptisols within the Montauk series. Corn fields at both farm sites display evidence of sheet and rill erosion.

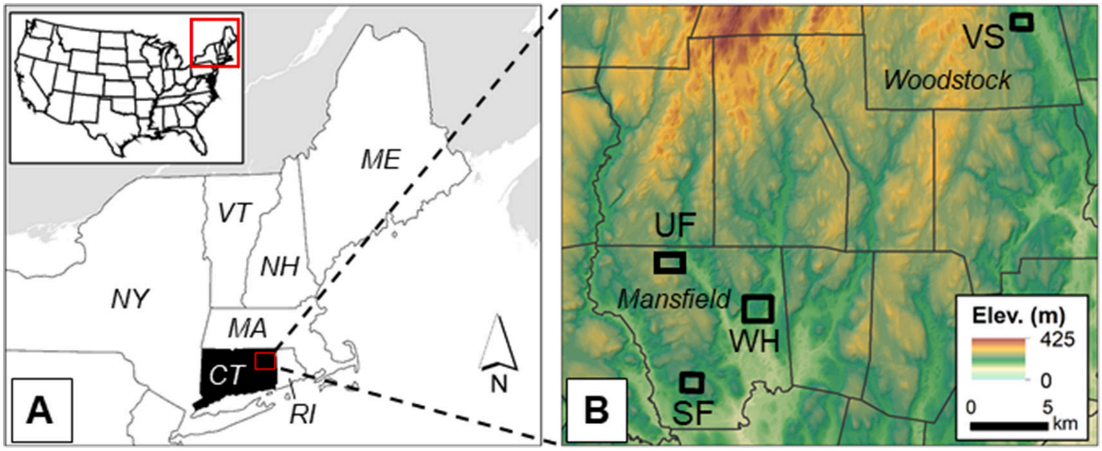

Fig. 1. Site map showing A) regional area, inset in B indicated by red box, B) location of all sampling sites in eastern Connecticut (VS — Valleyside Farm; UF — UConn Forest; WH— Wormwood Hill; SF — Stearns Farm).

2. Methods

2.1. Historical census analysis

U.S. Federal Census Non-Population Schedule for Agriculture records for the years 1850, 1860, 1870, and 1880 were obtained for the town of Mansfield (National Archives, 2021). 1850 is the first year such records exist. Categories on improved and unimproved land were transcribed and tabulated from this census data to calculate the area of cleared and forested land for 1850, 1860, 1870, and 1880 for the town of Mansfield following methods of Johnson et al. (2021).

2.2. Geospatial mapping of land use classes

Stone walls present in LiDAR data and aerial imagery from 1934 to 2019 provide direct evidence for land use change through time. Stone walls for the town of Mansfield were manually digitized using 2016 1-m LiDAR hillshade derivatives (CTECO, 2021) following methods of Johnson and Ouimet (2014, 2016) (Fig. 2). Repeat aerial photographs from 1934, 1951, 1970, 1986, and 2019 were used to map areas cleared for agriculture in each time interval (CTECO, 2021). Geospatial analysis also included slope analysis for individual soil pits. Slope maps were generated using 1-m LiDAR Digital Elevation Models (DEMs) and USGS National Elevation Dataset (NED) 10-m DEMs. 10-m NED data was used for slope analysis because slope calculations using LiDAR can often be biased by small scale roughness and point cloud quality.

Together, stone wall datasets and extent of cleared land in the aerial imagery were combined to develop a chronology constraining the duration of land use activity and time since abandonment for four classes described in Section 2.2.1 (Fig. 2). Stone walls were built to support agricultural practices and therefore serve as a direct indicator for land cleared at some point in the past. In many cases, stone walls are mapped in terrain that is forested by 1934, indicating that stages of duration and timing of land use activity can be constrained in the study area. Areas with a high density of stone walls have been shown to approximate maximum land clearance at the height of historic land use ca. 1850, after which land was successively abandoned and reforestation took place throughout the late 19th and early 20th centuries (Johnson and Ouimet, 2016). It follows that areas with a sparse, low density of stone walls were likely cleared for a short amount of time and had likely already been abandoned by 1850. After 1934, areas cleared for agriculture can be directly mapped through time based on presence in the imagery. Image resolution varies slightly in the aerial images studied (0.5–2 ft. per pixel), but quality is consistently high enough to see individual stone walls within cleared fields when present.

2.2.1. Land use classification

The four following land use classes constrain the timing and duration of land use and were developed based off of LiDAR-derived stone wall maps and aerial imagery, described in Section 2.2. These classes were mapped at the Wormwood Hill and UConn Forest sites (Fig. 3).

T_0— Minimal agricultural activity with abandonment prior to 1850: Topography that shows minimal evidence of stone wall construction and implied agricultural activity. If they occur, walls in these areas are

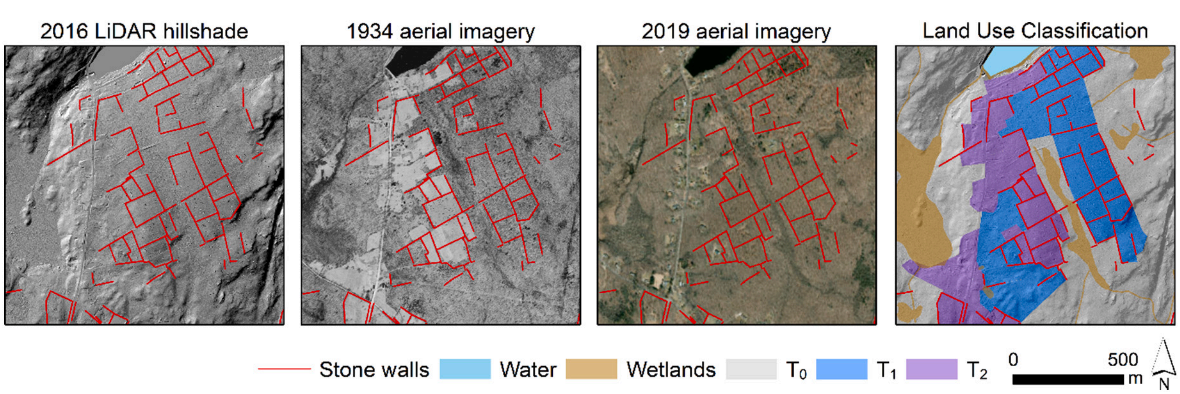

Fig. 2. Methods for determining the timing and duration of land use and delineation of land use classes. T_3, continuous agriculture up to present, exists nearby in Mansfield, but not for the Wormwood Hill study area shown here (see Fig. 11). Datasets used include LiDAR hillshade derivatives, stone wall maps, and aerial imagery such as 1934 and 2019. 2019 aerial imagery is leaf-off, taken in March–April.

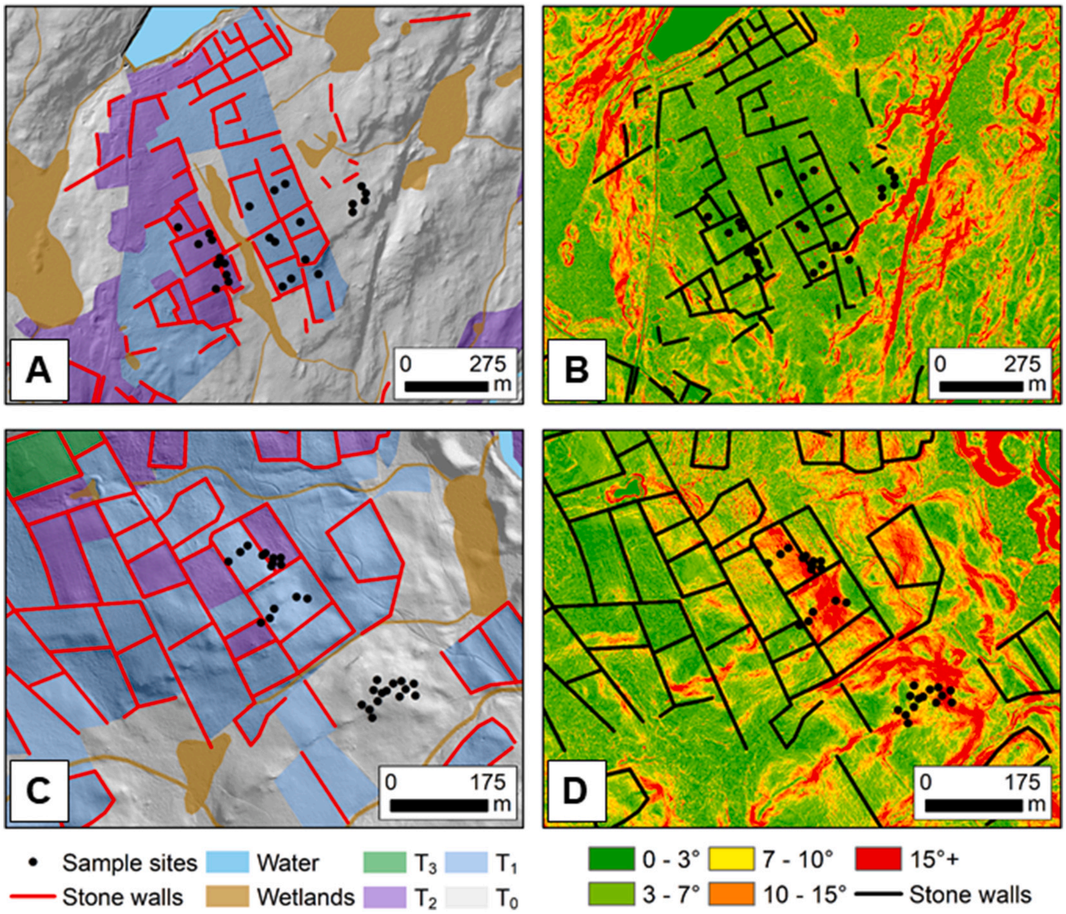

Fig. 3. Detailed site maps showing sample locations, land use classification, and slope maps for Wormwood Hill (A, B) and UConn Forest (C, D). Underlying base maps are hillshades (A, C) and slope maps (B, D) derived from a 1-m LiDAR DEM.

sparse, and are single, isolated features, and often exhibit signs of disintegration in field observations (Manandhar et al., 2021). The land was likely cleared and may have been used as a pasture or woodlot but was not likely used for sustained agriculture. It underwent the shortest duration of use (0–25 years) and longest abandonment (225+ years) of the agricultural activity associated with the walls. Select woodlot (land managed as a source for fuel or lumber) activity could also have occurred in this land class before the early 20th century and first imagery in 1934.

T_1—Abandonment prior to 1934: Areas where prior agricultural activity is evident by the presence of well delineated stone wall lined polygonal fields but was clearly abandoned well before the early 20th century as these areas are reforested in 1934 aerial photographs. This land was likely cleared at the height of land use clearance in the region, ca. 1850 (Johnson and Ouimet, 2016), was used for a shorter duration (75–150 years) and has been abandoned for 85–150 years.

T_2—Mid- 20th century abandonment: Areas where stone walls are evident, land was cleared and actively being used for agriculture up through the 1930–1970s but reforested from 1980s onward. Locations of these areas can be clearly determined using aerial imagery. Most of the time, these locations occur within well delineated stone wall lined fields, indicating that land use activity likely extends back to the 18th century. This land was used for an intermediate duration (150–250 years) and has a short abandonment period (25–85 years).

T_3— Continuous agriculture with short or no abandonment: Areas where stone walls are evident, land is cleared in 1934, and is still presently cleared for agriculture. This land has likely been used continuously or semi-continuously from the time of town establishment (assuming this date follows not too long after first settlement) through modern day, for the longest duration (>250 years), and has a very short abandonment period following use if any (0–25 years). In this study, Valleyside Farm, Stearns Farm, and a lawn site at Wormwood Hill represent this category.

Overall, estimates for land use duration and abandonment are based on town establishment (1702 for Mansfield, CT), evidence of wall development in LiDAR and in the field, and direct observations using aerial imagery. Constraints for both the duration and abandonment periods for the T_0 and T_1 classes are more uncertain, as the onset of land use activity is estimated to be around the time of town incorporation. Stone walls, however, were built continuously through time, and in some areas, may have been built later. However, wall development, type of wall, and completeness of the structure also provide information on the length of land use, as farmers continuously added stone to the walls as new stones were unearthed each year due to freeze-thaw cycles and plowing (Thorson, 2002). Walls within the T_1 and T_2 classes are more well-developed (taller, better maintained) implying longer land use duration (Manandhar et al., 2021), whereas walls within the T_0 class are often lower, and may show signs of higher degradation, supporting a rapid and brief land use period.

Constraints on abandonment periods for the T_2 and T_3 have less uncertainty, as the timing of reforestation can be directly observed using repeat historic aerial imagery. Timing of land use onset is less certain and is estimated as the timing of town incorporation. In this study, T_2 areas at WH were still cleared, but showed signs of abandonment in 1951 aerial photographs. These areas were mostly to completely reforested by 1970. At the UF site, the T_2 areas were also cleared and remained cleared through 1970 aerial imagery. These areas were completely reforested prior to 1986 aerial images. These differences highlight the error and range in timing associated with T_2. Other classes may exhibit similar issues when comparing across sites or with different landowners through time.

In considering these four categories of land use, the term agriculture is used broadly, as it is often difficult to know in most areas the exact distribution of which land parcels were used for cultivation, pasture, woodlot, or a transitioned from one land use type to another over time (e.g., cultivation converted to pasture). Land use records at these sites may provide some information about the types of crops and animals at the location but are limited, are subject to landowner reporting, and could be missing for individual properties (Johnson et al., 2021). They also do not provide spatial information. Since the State of Connecticut is known to have small patches of old growth forest in the western part of the state, true control areas (with no land clearing or land use activities at all) were not available for this study and are rare this far south in the region. At the same time, estimates of improved land clearance for the state in the middle to late 19th century only reach 60–70% (Foster et al., 2008; United States Department of Agriculture, 2021). Areas such as T_0, with minimal evidence of substantial agricultural activity, were likely cleared or selectively cleared once to remove old growth forest, which can increase soil erosion, but was never used to such a degree as to be included in estimates of cleared land. T_1, T_2, and T_3, meanwhile, clearly lie within terrain dominated by well-defined stone walls visible in LiDAR, and stone walls have been shown to correlate well with cleared and/or improved land in historical census data (Johnson and Ouimet, 2016). Overall, while it is likely true that all land was fully or partially cleared at some point between the 17th and 19th centuries, leading to new growth forest throughout the state and in particular our study site, land was not used equally, and specific soil impacts will likely vary greatly.

In our mapping, we also incorporate the presence of modern waterbodies and wetlands (U.S. Fish and Wildlife Service, 2021). Wetlands may have been historically ditched and converted, or may have been unsuitable for use, and therefore likely align with the T_1 or T_0 class. However, due to vastly different characteristics of wetland soils to those used in this study, we exclude these areas from the land use classification. We also acknowledge human modifications such as road crossings or dams may have altered the presence or size of waterbodies and wetlands through time, which likely results in minor error in our mapping.

2.3. Field methods

LiDAR-derived stone wall maps were checked and field verified at the Wormwood Hill (WH) and UConn Forest (UF) sites (Leonard et al., 2021; Manandhar et al., 2021). At both sites, five to ten soil pits ~1 m depth) for each class were described in the field following NRCS protocol (Schoeneberger et al., 2012). Horizon thickness, boundary type, color, texture, structure, rock fragments, consistence, and root density were determined for each horizon, and used to characterize the soil morphology for each land use class. At the Stearns Farm (SF) and Valleyside Farm (VS) fewer 1-m deep soil profiles were sampled (only one hay, one corn for each) but the same protocols were followed. One-way ANOVA tests were used to statistically assess differences in horizon thickness between the classes. At the UF and minimum of four 1-m deep soil pits were sampled for each land use class at each site for general soil and geochemical analyses. In areas were additional or replicate A horizon measurements or samples for geochemical data were needed, a minimum of two additional 20–30 cm shallow pits were used. The top 20 cm was sampled in 2 cm increments, 20–50 cm depth was sampled in 5 cm increments, and below 50 cm depth was sampled in 10 cm increments. This strategy was used to get a higher resolution profile of Pb near the surface. At the UF site, three downslope transects were employed in a *catena* style approach, with 3–5 soil pits covering different hillslope positions to capture variation and changes in soil horizon thickness and slope (for sample locations and corresponding data refer to Table S1).

Several additional shallow soil pits at the WH and UF sites were included in the dataset and statistical analysis comparing horizon thicknesses. These shallow pits all result in measurements for the A horizon thicknesses, but do not necessarily provide data for the B_w and C_d horizons due to depth constraints (see Table S1). In the statistical analysis, only A and B horizons where the thickness from the top to the bottom of the horizon and C_d horizons where the depth to the top of the horizon could be measured were included. In addition, data available on horizon thicknesses from duplicate and triplicate profiles at the T_3 sites collected by the NRCS were used to supplement the analysis.

2.4. Lab analyses

Soil pit samples were dried for 40 °C for 24 h and analyzed for standard soil analyses, including pH measured as 1:1 soil to water, and bulk density using the core method (Soil Survey Staff, 2009). One aliquot of each soil sample was analyzed for Loss-on-ignition (LOI) by ignition in a muffle furnace at 550 °C for four hours following standard protocol (Dean, 1974). Weight lost during LOI can be used to determine percent soil organic matter. A second aliquot of each sample was homogenized using a mortar and pestle and sieved with a 2 mm mesh. The geochemistry of the <2 mm fraction was analyzed for a suite of 30 elements using an Olympus Vanta portable X-ray fluorescence (pXRF). Results for Pb concentrations are presented here.

2.5. Calculation of Pb inventory

Pb inventories were calculated for each profile analyzed for pXRF using an inventory calculation modified from Jelinski et al. (2019). An average concentration of 20 ppm was used to subtract background Pb (Pb_{back}) values from the total Pb (Pb_{tot}) value to determine the amount of accumulated Pb inventory (Pb_{acc}). Any small or negative values were set to equal 0. The concentration of Pb was then multiplied by the average bulk density of the soil layer and the thickness of the sampled interval, and were summed to calculate the Pb inventory (Eq. (1)):

$$Pb_{acc} = \Sigma\left[(Pb_{tot} - Pb_{back})^{*}\rho^{*}t\right] \quad (1)$$

where ρ is bulk density and t is thickness of the sample interval. A one-way ANOVA test was then used to assess statistical significance in Pb inventory between the different land use classes.

3. Results

3.1. Historical Census Summary

At the Wormwood Hill site from 1850 to 1880, non-population agricultural census records for nearby landowners report ~80% of the property was listed as "improved," including cultivated land and pasture that is tilled or mowed regularly or in rotation, and land lying fallow; approximately 20% was listed as "unimproved", which includes woodland/woodlots, brushland, rough or stony land, swamp land, and any other land that does not fall under the improved or forested category (see Table 2). Crops produced at Wormwood Hill property included corn, potatoes, rye, oats, barley, and hay, and sheep and cows were the primary livestock. 1850–1880 census records for percent improved and unimproved land, crop type, and livestock kept are similar for landowners near the UConn Forest site. While the census provides information on types and quantity of agricultural products produced, it does not provide spatial context on exactly where specific types of activity were occurring at the site. Reports from individual landowners only encompass part of each of the study areas and do not necessarily line up with study area boundaries. However, it is assumed that crops were grown closer to the house, and pastoral activities occurred farther from the house.

3.2. General soil characteristics and horizon thickness

For both sites, the primary soil horizons that were characterized were O, A, A_p, B_w, and C_d (Fig. 4). The O horizon (10YR 2/2) is characterized by decomposing leaf litter and humus and its thickness ranges between 1 and 4 cm. The A horizon (10YR 3/3–3/6) is primarily characterized by mineral soil mixed with accumulated organics. The A_p (plow) horizon is created by tilling the soil, resulting in a 20–30 cm layer of homogeneously mixed soil (Marsh and Siccama, 1997). However, we use the term A_p broadly in this study to include other disturbances, such as pastoral activity (Soil Science Division Soil Science Division Staff, 2017). While the T_2 and T_3 classes often showed little or no development of an O horizon, they have clear development of an A_p horizon, and the T_2 classes sometimes showed development of a new A horizon above the A_p. The T_1 classes had clear O horizon development, and sometimes also showed evidence of the development of a new A horizon above the A_p horizon. The transition between the A_p (10YR 3/3–3/4) and underlying B_w horizon across all classes is generally a smooth and abrupt transition that may also show evidence of plow scars at the boundary, marking the depth of tillage. The B_w horizon is highly weathered and characterized by a distinct red color (7.5YR 4/6–10YR 4/6) from iron oxidation. The C_d horizon (2.5Y 4/3–4/4) is a densic layer consisting of unweathered glacial till. Overall, the soils are strongly to very strongly acidic (pH 4.4–5.5) and organic content measured using LOI ranges from 7 to 11% at 2–4 cm depth to 1–2% at >50 cm depth. While these soils are developed in till, which can have spatially variable grainsize, the A and A_p horizons were characteristically fine sandy loam with 1–3% mixed rock fragments, while the B_w and C_d horizons were characterized as sandy loam, with 5–25% mixed rock fragments.

At both sites, the total combined thicknesses of the A horizons increase with an increase in land use duration, while the thickness of the B horizon decreases (Figs. 4 and 5). From here on in the text, we will refer to the combined A and A_p horizons present in the T_1-T_3 classes solely as the A horizon. At the WH site, the A horizon increases from 5 ± 3 cm in the T_0 class to 21 ± 4 cm in the T_2 class (Table 1). A similar increase is seen at the UF site, where the A horizon increases from 9 ± 6 cm in the T_0 class to 30 ± 15 cm in the T_2 class. The thicknesses of both the A and B horizons are greater across all the classes at the UF site. One-way ANOVA test results indicate that the difference in the A horizon thickness across the three classes at both sites is statistically significant (Table 1).

The depth to the C_d horizon is consistent across the classes at both sites, however, the depth to this horizon is overall greater at the UF site. At the WH site, the depth to the C_d horizon increases slightly from 59 ± 6 cm for T_0 to 63 ± 10 cm for T_2 (Table 1). However, across all three classes, the depth is not statistically significant based on the one-way ANOVA test, and the average depth to the C_d horizon combining all classes at the WH site is 61 ± 9 cm. Depths to the C_d are similar at the UF site, with the C_d depth increasing from 72 ± 18 cm in the T_0 class to 87 ± 15 cm at the T_2 class, and these differences are not statistically significant based off ANOVA results. The average depth across all the classes at the site is 84 ± 14 cm, and soils developed at the UF site are ~24 cm thicker than the WH site.

3.3. Geochemical results

Pb in the T_0 class is concentrated in the upper 5–10 cm at both sites, consistent with the average thickness of the A horizon (~5–9 cm). It is the most concentrated within the upper 3 cm, up to ~80 ppm, and decreases exponentially with depth. Pb follows a similar pattern in the T_1 class, also concentrated up to ~60 ppm in the upper 10 cm, despite the A horizon being 15–24 cm thick on average. For the T_2 class, Pb is distributed more uniformly throughout the upper 20 cm, and the A horizon is on average 21–30 cm (Fig. 6). This profile shows a more diffuse peak, with values generally not exceeding ~40 ppm. In the T_3 class, Pb is distributed relatively uniformly throughout the upper 30 cm, consistent with the average depth to the A horizon at 27 cm, and Pb values ~30 ppm consistently throughout this depth. Background Pb concentrations at depth are 15–20 ppm, consistent with findings in other studies (Zimdahl and Skogerboe, 1977; Sterckeman et al., 2000).

Calculated Pb inventories across all classes average 272 ± 110 μg/cm^2. Inventories average 236 ± 52 μg/cm^2 for the T_0 class, 248 ± 64 μg/cm^2 for T_1, 332 ± 160 μg/cm^2 for T_2, and 272 ± 110 μg/cm^2 for T_3 (Figs. 7 and S3). One-way ANOVA does not result in a statistical significance between the four classes ($p = 0.145$).

4. Discussion

4.1. Changes to pedostratigraphy and implications for soil erosion

Morphologic modifications to soils are primarily reflected as changes in soil horizon thickness. While a true control site was not used, it is expected that the A horizon at a control would be ~1–10 cm thick; soil profiles beneath stone walls could potentially serve as a proxy for undisturbed soil. As the duration of land use increases, the development of an A_p horizon occurs and the combined thicknesses of the A horizons observed today increase (Fig. 8). At the same time, the thickness of the B horizon decreases, and these patterns are best explained through the incorporation of lower B horizon material with the more organic O and A horizons as land is mixed through plowing, animal hooves, and root growth. Overall, at the UF site, both the A and B horizons, and depth to the C_d horizon is greater, but more variable. Thicker horizons are

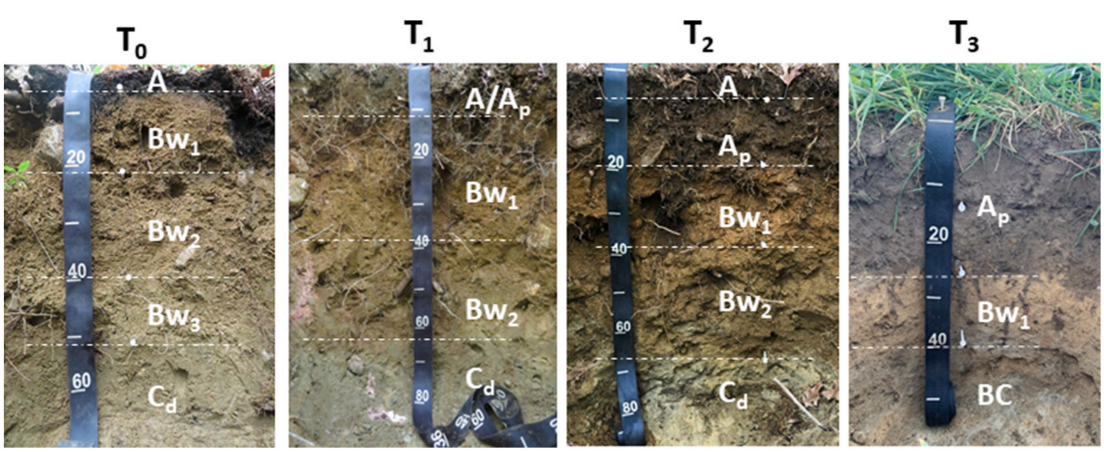

Fig. 4. Photos of a characteristic soil profile for each land use classification (T_0–T_3). The notation A/Ap in photo for T_1 refers to uncertainty in determining the type of A horizon seen in that particular soil pit.

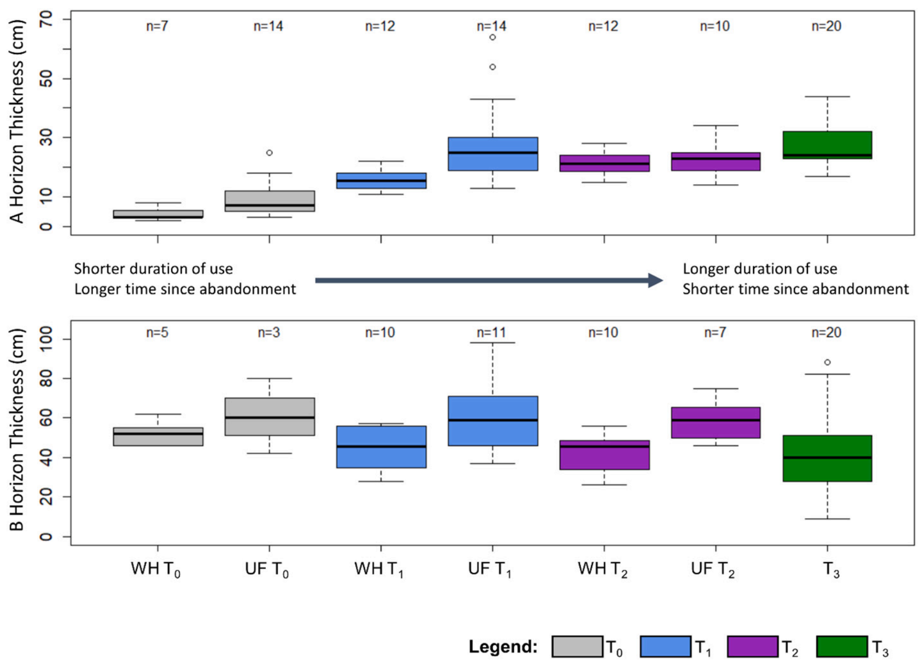

Fig. 5. Boxplots of A horizon thicknesses and B horizon thicknesses for each class at the UF, WH, and modern agriculture (T_3) sites.

Table 1
Average soil horizon measurements (1σ standard deviation) and statistical analysis. Measurements of A (combined A and A_p for T_1-T_3) and B_w horizons are the thickness of the soil horizon, where the measurements for C_d are the depth to the top of horizon. (Note: Depth to bedrock below the C horizon was not reached; in some profiles, the C horizon was not reached and exceeded 1 m depth). ANOVA results that are statistically significant are marked with an asterisk (*). See supplemental Table S1 for full data set.

Site	Horizon	Number of measurements (all classes) (n)	T_0 horizon measurements (cm)	T_1 horizon measurements (cm)	T_2 horizon measurements (cm)	T_3 horizon measurements (cm)	ANOVA test F-value ($p = 0.05$)
UConn Forest	A	38	9 ± 6	24 ± 8	30 ± 15	N/A	9.57 e − 06*
	B_w	22	61 ± 19	63 ± 17	56 ± 12		0.498
	C_d	22	72 ± 18	86 ± 13	85 ± 15		0.192
Wormwood Hill	A	31	5 ± 3	15 ± 3	21 ± 4	N/A	4.31 e-08*
	B_w	25	52 ± 7	45 ± 10	42 ± 10		0.062
	C_d	25	59 ± 6	60 ± 10	63 ± 10		0.458
Modern Agricultural	A	20	N/A	N/A	N/A	27 ± 8	N/A
	B_w	20				43 ± 22	
	C_d	7				66 ± 12	

generally positively correlated with higher slopes, however, the profiles on the higher slopes are at the UF site. Thicker soils at the UF site may be due to inherent characteristics, such slight differences in parent material (melt-out vs. lodgment till) or soil formation processes.

At the Wormwood Hill site, the depth to the C_d horizon is consistent across all the classes, and there is no statistical significance in average depth (Table 1). There is more variation in average C_d horizon depth between the T_0 and the T_1/T_2 classes at the UF site, however, this difference is not statistically significant. Overall, at both sites, there is a slight increase in average depth from T_0 to T_2, possibly indicative of organic material from land use being added to the soil and mixed in, continuing to thicken the A horizons through time. The uniformity in depth and slight increase in the A horizons suggest that there has not been significant erosion, as removal of topsoil would reduce the thickness of the A horizons. Rather, soils historically have been more influenced by addition of organic material and mixing, especially in low slope areas.

The *catena* style approach employing three transects (Fig. 9) was used at the UF site to further evaluate the role that downslope movement may have on changes to the thickness of the A horizons, which in highly erosive areas, may signify evidence of erosion through truncation and thinning of the A horizon. Typical catena style approaches have shown that upper areas of hillslopes are erosive, and downslope areas are cumulic (Bird, 1957). At the UF site, the A horizon thickness generally increases from upper positions (crest/shoulder) on the slope to lower positions (footslopes) by about 10–15 cm (Fig. 9), however, this pattern is consistent across the T_0–T_2 classes. The exception is directly adjacent to a stone wall built across the hillslope, where the thickest A horizons are located on the upslope side of stone walls bisecting hillslopes, and the thinnest A horizons are located on the downslope side of the wall.

Two soil profiles directly upslope of a stone wall built perpendicularly across a hillslope were used to investigate the role that orthogonal walls have on trapping sediment on the hillslope. Field evidence suggests the buildup of sediment behind the walls. One profile had an overthickened A horizon of 64 cm and the other was 49 cm, likely resulting from the incorporation and buildup of eroded soil overtime behind the wall. This is approximately double the thickness of the A horizon in the T_2 and T_1 areas. The horizon was homogenous in color and texture throughout in both profiles, without evidence of layering. Mixing likely incorporates eroded/accumulating organic and mineral A horizon soil rather than B horizon material, therefore, it is difficult to differentiate between cumulic and mixing. Roots near the surface likely have some impact on mixing, but the majority is likely due to cultivation or pasture animals. At both soil pits, the C_d horizon was not reached and

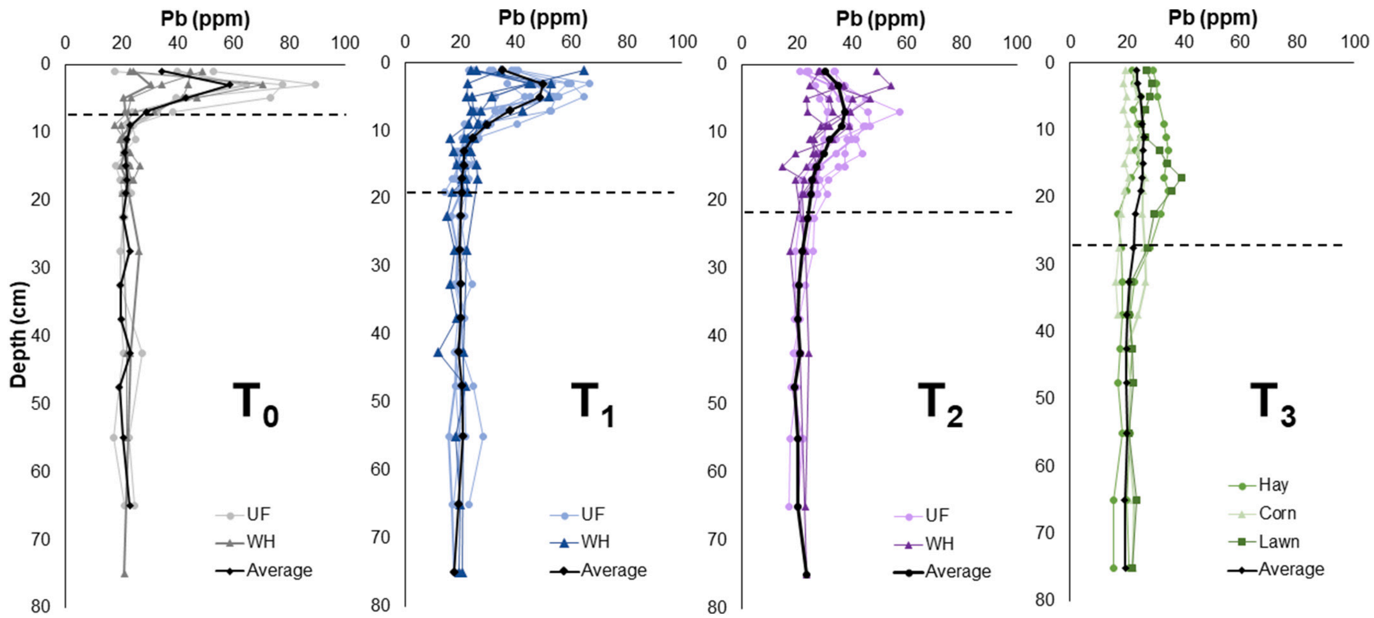

Fig. 6. Pb concentration with depth for the four classes across all sites. Horizontal dashed black line represents the average depth to the transition between the A and B horizons.

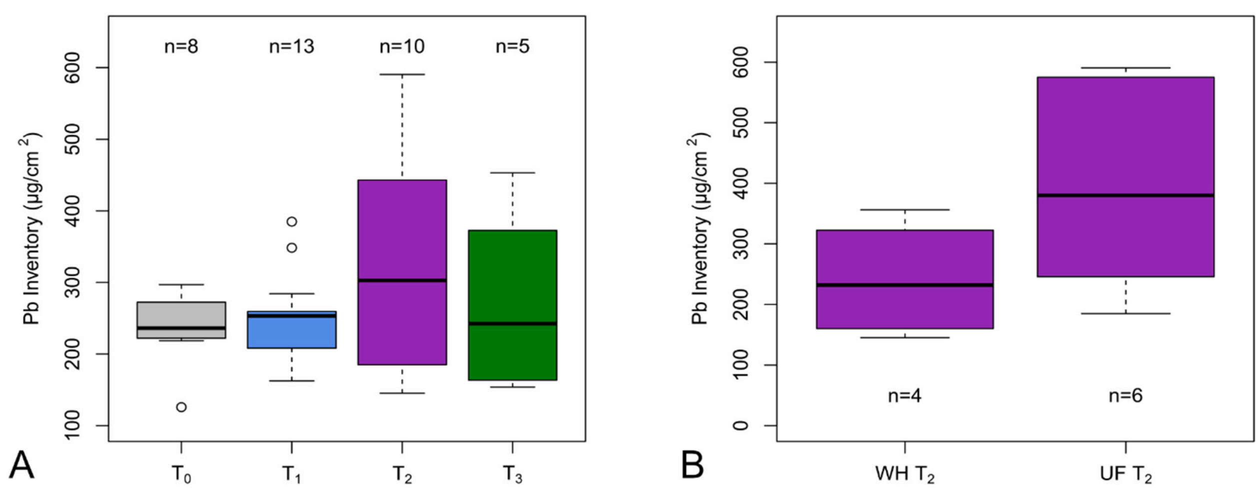

Fig. 7. (A) Boxplots of Pb inventory for each of the land use classes and (B) for the T_2 land use class for Wormwood Hill and UConn Forest.

exceeded a depth of 1 m; the depth to this horizon exceeds the average C_d horizon depth of 84 cm across all classes, also suggesting the accumulation of sediment. Two profiles located within 5 m downslope of the wall had A horizons of 14 cm, approximately half the average thickness for the UF T_2 class (Table 1), and some erosion may have occurred causing these horizons to be thinner. However, the scope of these findings is limited, as both profiles upslope of the wall were located within the T_1 class, about 25 m apart along the same wall. Additional work investigating other high slope sites and within the T_2 or T_3 classes is necessary to fully address the role of stone walls in quantifying sediment stored directly on hillslopes.

Overall, we observe similar changes to pedostratigraphy and behavior at both sites, regardless of slope differences. The UF site does not appear to display evidence of significant soil mobilization, except in the soil profiles located directly above and below stone walls that run perpendicularly across moderate to steep hillslopes. This is evidence for redistribution and storage on hillslopes, due to long durations of land use activity at these sites, rather than significant soil loss. Since most agricultural practices in the region occur in lower slope, smoother terrain, it is expected that land use soil impacts would behave similarly, and influence of slope on erosion may be relatively minimal.

4.2. Trace metal (Pb) incorporation in soil

Mixing of different metals in the soil is directly related to the timing of deposition of the metal, as well as the timing of land use. It is assumed that metal deposition at our study sites is primarily through wet or dry atmospheric deposition and is linked to metal specific increases in the atmosphere due to industrial activity and combustion of leaded gasoline. Increases in atmospheric Pb through the early 20th century related to leaded gasoline have been well documented, and EPA legislation passed in the 1970s subsequently led to reduced concentrations (Richardson et al., 2014). Pb accumulates in humus and upper mineral horizons in forests (Siccama and Smith, 1978; Wang et al., 1995) and is relatively immobile in soil, with residence times of up to 500 years (Haack et al., 2003). In uncultivated soils and formerly cultivated soils abandoned and reforested prior to the early 20th century, most of the accumulated Pb is stored within the upper 10 cm (Miller and Friedland, 1994; Marsh and

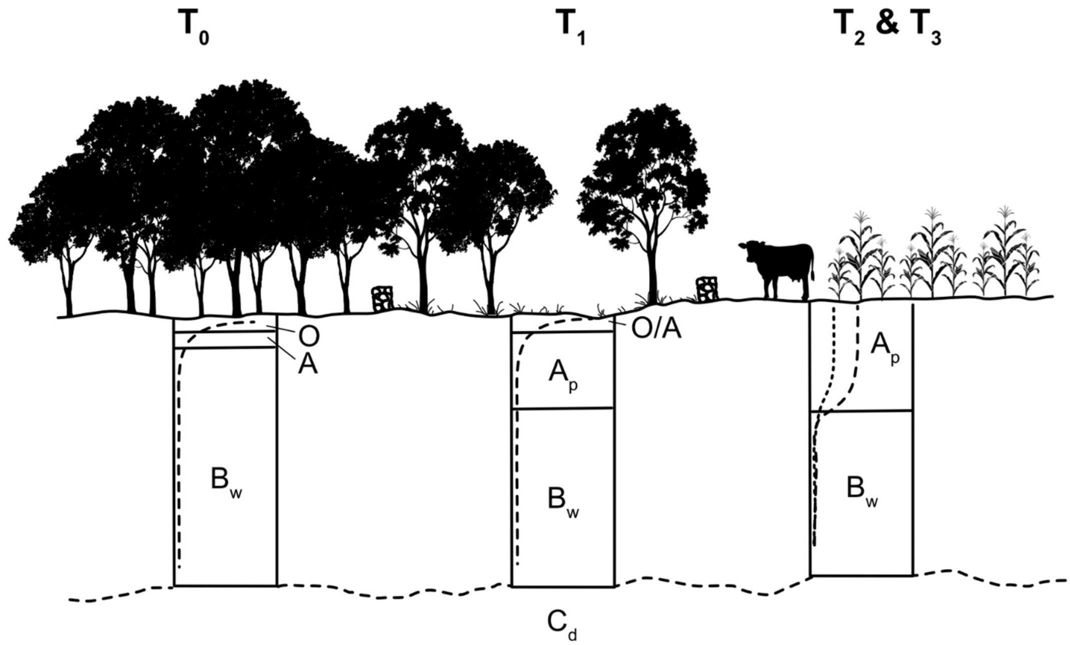

Fig. 8. Conceptual diagram showing physical changes to soil horizon thicknesses and the vertical distribution of Pb for different durations of land use. Dashed lines in the soil profile represent patterns of Pb distribution (within the T_2/T_3 profile, the dashed line on the right represents T_2 and the dashed line on the left represents T_3).

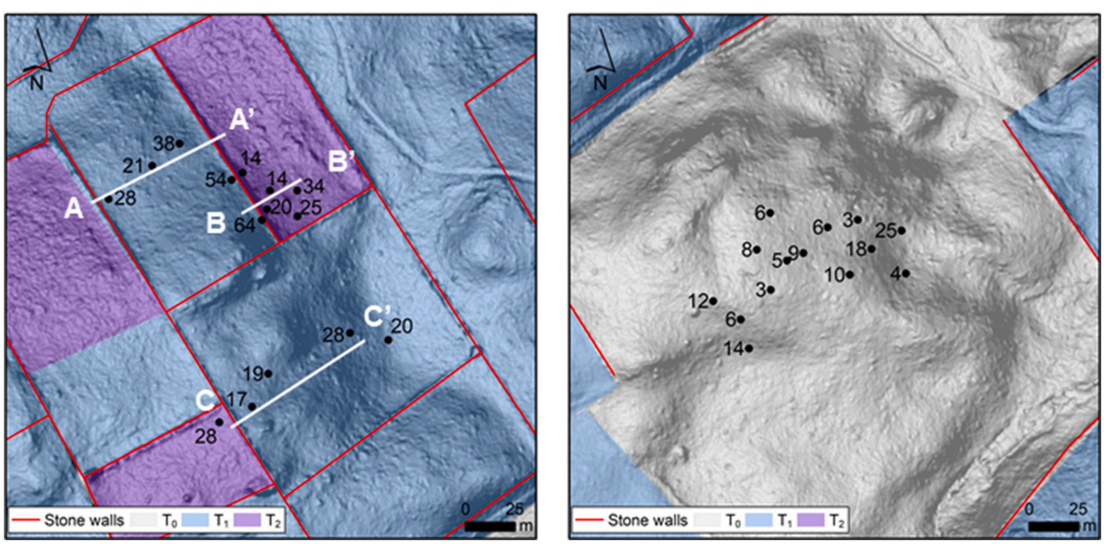

Fig. 9. Map of soil profiles with A horizon thicknesses (cm; black dots) indicated at the UF site for T_1 and T_2 class (left) and the T_0 class (right). White lines represent transects A–A', B–B′, and C–C′ for the catena approach. Underlying base map is a slope map derived from 1-m LiDAR.

Siccama, 1997; Svendsen et al., 2007). Therefore, the distribution of Pb concentrations within the upper 20–30 cm of soils can provide information about soil mixing and erosion through the 20th century.

In the T_0 and T_1 class, Pb is concentrated in the upper 7–10 cm and decreases with depth to ~7–10 cm before reaching background levels (Fig. 6). These areas were abandoned and reforested prior to the early 20th century, preceding increased Pb usage from leaded gasoline. The pattern of Pb within the T_1 class is consistent with findings of Marsh and Siccama (1997), where in formerly cultivated soils abandoned prior to the early-20th century, Pb concentrations in the newly developed forest soil and A horizon decrease with depth and reach background values at ~10 cm down from the top of the A horizon. In this context, our findings suggest that the pattern within the T_0 and T_1 classes is representative of the Pb profile being influenced by natural diffusion processes, such as leaching or bioturbation, rather than land use related soil mixing due to plowing, pastural activity, or enhanced bioturbation associated with crop cycles.

On the other hand, the T_3 sites which were used through the 20th century, display patterns of uniform concentrations of Pb through the A horizon, consistent with continuous mixing and incorporation of Pb through the A horizon due to cultivation. The T_2 sites which were used through part of the 20th century have more elevated Pb concentrations in the A horizon but display blunter and more diffuse profiles than T_1 or T_0 with depth. Pb within the upper 20–30 cm of the T_3 is class is overall lower than the T_2 class, and is almost a vertical line, with concentrations in the A horizon slightly above background levels. This difference in the pattern between T_2 and T_3 is likely a result from Pb deposited atmospherically in the early to mid-20th century being mixed deeper into the

A horizon, as more recent Pb concentrations decreased due to EPA restrictions in the 1970s. As a result, Pb concentrations in T_3 could simply be more diluted, as more recently there has not been a significant influx of atmospheric Pb added to the top of the soil to maintain a higher concentration (e.g., Richardson et al., 2014). In addition, there could be some erosion affecting the T_3 pits studied. This may help explain the corn fields at the Stearns site, where conventional till practices are used and there is evidence of sheet and rill erosion. The depth to the C_d horizon between the corn and hay field (located ~60 m apart), was a 10 cm difference suggesting this site may have experienced higher erosion, and combined with lower Pb input, may help explain the lower A horizon Pb levels. However, the difference in C_d depth at the Stearns site could also be due natural variation, as closely located soil profiles at the UF and WH sites displayed similar depth variations.

Our results concerning the mixing patterns of Pb due to cultivation are similar to patterns exhibited by studies done using fallout radionuclides (Walling et al., 1999; Matisoff, 2014). We also find consistency with studies of recent erosion in other areas of the northeast. For example, in Pennsylvania, Silverhart (2019) found that ^{137}Cs is concentrated in the upper 5–10 cm of soils that were forested prior to the 1950s, and land cultivated from ~1960 onwards displays uniform mixing of the radionuclide in the upper 25–30 cm, and was minimally redistributed over the hillslopes, pointing to minimal erosion over the past 50–60 years. In undisturbed soils in northern New England, ^{210}Pb and ^{137}Cs is contained primarily in the upper 10 cm and profile shapes coupled with advection-diffusion models suggest natural diffusion processes, including animal burrowing and freeze-thaw, have minimal effect on recent, short-term soil mixing (Kaste et al., 2007).

Inventories using fallout radionuclides or atmospherically derived metals have utility in quantifying soil transport, with deviation from reference inventories signifying erosion or deposition (Matisoff and Whiting, 2012; Silverhart, 2019). For the Pb inventories calculated in this study, classes with significantly lower inventories would suggest erosion or loss of Pb accumulated previously through atmospheric deposition. Across both the UF and WH sites, Pb inventories are similar across the T_0–T_3 classes (Fig. 7a); results from the one-way ANOVA tests suggest that there is no statistical significance between the classes, and this similarity suggests minimal soil erosion or deposition. At the UF site, there appears to be no evidence of a spatial pattern signifying an accumulation of Pb along downslope transects (Fig. S4). However, there is more variability within the T_2 and T_3 classes, and average T_2 inventories at the UF sites are higher than the others, as there are three profiles with inventories over 400 μg/cm^2 (Fig. 7b), although these high inventories are not likely to be influenced by soil mobilization; they are located at upper slope positions and/or directly downslope of stone walls (position 1 on Fig. 10), where lower Pb inventories and erosion would be expected. Therefore, they may be related to a lack of vegetation cover during increased atmospheric Pb deposition. Overall, the similarity of Pb inventories between classes at both sites and the lack of clear downslope loss and accumulation at UF suggests minimal erosion over the 20th century.

Overall, Pb and short-lived fallout radionuclides such as ^{137}Cs cannot speak to soil mixing and hillslope sediment transport that occurred prior to the 20th century. Longer-term systems, such as meteoric ^{10}Be has a much longer half-life and has utility for investigating post-settlement erosion and works well alongside recent radionuclides like ^{137}Cs (Jelinski et al., 2019). Therefore, it may be possible that using other geochemical systems and metals related to anthropogenic activity, such as Hg or ^{10}Be, used in combination with Pb could offer insight into sediment accumulation behind walls and soil mixing associated with the T_1 and T_0 classes, which experienced land use impacts in the 17th–19th centuries.

4.3. Scaling up historic soil impacts using stone wall maps

The terrain used in this study is very common for wide swaths of the region, with agriculture in many upland areas occurring in low slope areas where the soil has been developed in glacial till. To explore this, we begin by scaling up at the town level. Land use classifications were mapped for the entire town of Mansfield (118 km^2) to determine the amount and progression of land use (Fig. 11; see supplemental for additional methods). The T_0 class is approximately 38% of the town area, T_1 class ~16%, and T_2 is ~12%. The T_3 class accounts for about ~26% of the town area, divided between 11% for agricultural land and 15% for developed (residential) land (Table 2). The remaining 11% of the town area is water or wetlands. The sum of T_1–T_3 classes with water/wetland (65%) is consistent with 65–70% farmland between 1850 and 1900 throughout Connecticut (National Archives, 2021), as well as estimates of land clearance between 70 and 90% in other areas of New England during the mid-19th century (Francis and Foster, 2001). More specific to Mansfield, agricultural non-population census records indicate that improved land was 80% in 1850 and had decreased to 59% by 1880 (Table 2).

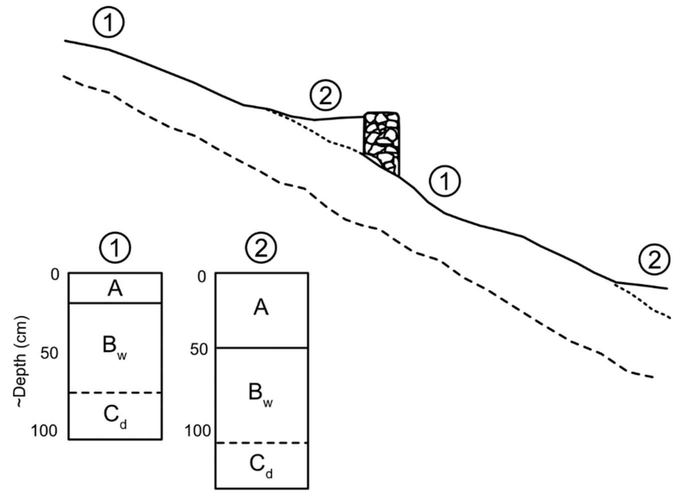

Fig. 10. Conceptual diagram showing redistribution of sediment and changes to soil horizon thickness on hillslopes containing stone walls. The dashed line represents the boundary between the B_w and C_d horizons, the dotted line represents the original land surface elevation.

Although the general agreement between our scaling up results and historical census data is promising, it is worth discussing sources of error associated with mapping stone walls, delineating land use classes, and scaling up. Stone walls are generally linear features, but can be either under or over-mapped, either due to the quality of the LiDAR data, or from user interpretation (Leonard et al., 2021). Under-mapping is particularly important when interpreting and differentiating earlier time periods, which are generally characterized by shorter duration of land use activity and stone walls that may be sparse or not well built, and results in larger uncertainty for the T_0 and T_1 classes. This error in the stone wall maps can therefore propagate error in land use class mapping, as both stone wall maps and aerial imagery are relied upon for determining the classification. On the other hand, the least uncertainty exists in the T_2 and T_3 land use classes, where locations and the extent of land use can be directly observed (see supplemental for additional detail).

Comparison between the 1850 and 1880 census data and town level results should take these issues into account. For example, non-population census records for improved land in 1850 suggest 80% of the town was cleared, as compared to a total of 54% of cleared land for the T_1–T_3 classes completed using this method for mapping (Table 2). While cleared land in the 1880 census decreases to 59%, it is possible that our mapping methods underestimate peak of land clearance occurring ca. 1850.

Variations in topography can also influence mapping the land use classes. There is generally a relationship between slope and agriculture,

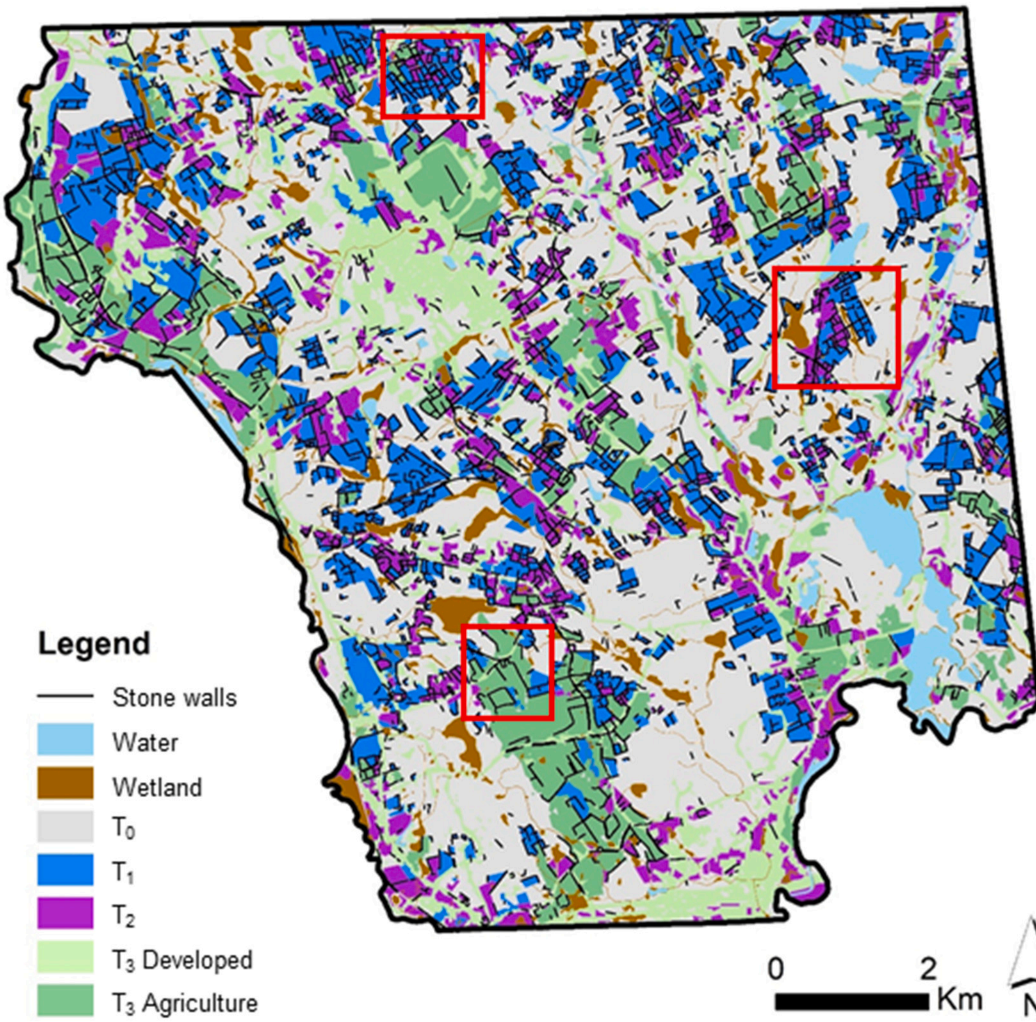

Fig. 11. Map of land use classes, stone walls, and wetland/waterbodies for the town of Mansfield (118 km^2). Red boxes show locations of study sites (Fig. 1).

Table 2
Area and percent of each land use class for the town of Mansfield and amount of improved and unimproved land from agricultural non population census records.

Land use class		Area (km^2)	Percent
T_0		44.7	38
T_1		19.1	16
T_2		13.6	12
T_3 Agriculture		12.5	11
T_3 Developed		17.7	15
Wetlands		7.1	6
Water		3.2	3
1850 Census	Improved	95	80
	Unimproved	23	20
1860 Census	Improved	86	73
	Unimproved	21	18
1870 Census	Improved	49	42
	Unimproved	65	55
1880 Census	Improved	70	59
	Unimproved	21	18

where agricultural activities, especially areas that have been farmed longer, primarily occur on low-slope, smooth terrain (Johnson and Ouimet, 2021), and are therefore mapped within the T_1–T_3 classes due to the high presence of stone walls. Some areas in the town that are especially steep, rugged, or have a shallow depth to bedrock were less suitable for agricultural activities. These areas often lack the presence of stone walls and are classified within the T_0 class.

Many regions throughout the northeast where extensive stone walls exist and mapping have LiDAR coverage and repeat aerial imagery taken since the 1930–40s, allowing for our land use classes and Anthropocene chronosequence approach to be applied around the region. In addition, methods involving machine learning may allow for the automation of stone wall mapping and the development of classes, as digitizing by hand is time consuming. Overall, when combined with soil data like that which has been presented here, being able to scale up has important implications for calculating soil impacts from historic land use, such as changes to carbon and nitrogen stocks at the regional scale.

4.4. Implications for legacy sediment storage in northeastern USA

Overall, our results suggest that historic, 17th–20th century, land use impacts in northeastern USA led to soil mixing primarily from cultivation and pasture animals and downslope movement in the A horizon along hillslope catenas, but no substantial erosion and soil loss, especially in low-slope areas. Therefore, depositional areas such as wetlands, floodplains and mill ponds in low to moderately sloped deglaciated landscapes may not store vast quantities of legacy sediment. This is consistent with previous studies in the northeast that have proposed low amounts of legacy sediment may be stored in river valleys due to the presence of other depositional environments such as lakes and wetlands (Thorson et al., 1998; Johnson et al., 2019), or may be influenced by the availability of fine-grained sediment in glacial deposits (Dow et al., 2020). Thorson et al. (1998) found anthropogenic sediment stored in wetlands may be sourced from swales and streambeds and coupled with the lack of evidence for surface erosion on hillslopes in this study, suggests that sediment mobilization may be a result of return flow or saturated overland flow rather than surface runoff.

In contrast, unglaciated regions farther south like the Mid-Atlantic Piedmont store vast amounts of legacy sediment, which pose environmental concerns to streams through increased sediment and nutrient loads (Walter and Merritts, 2008; Jiang et al., 2020). Differences in legacy sediment between the northeast and the Mid-Atlantic may also be due to slope, parent material and soil type in the areas studied, which could have influenced the availability and mobility of sediment. Furthermore, Silverhart's (2019) work on soil erosion in an upland catchment in PA occurred in a catchment with very little legacy sediment stored behind mill dams and suggests that material is being redistributed and remaining on the hillslope. This watershed may be operating similar to our study sites in New England despite its different glacial history and parent material.

5. Conclusions

In northeastern USA, 17th–20th century land use activity significantly impacted soil development and mixing but did not necessarily lead to widespread soil loss. Overall, the region is relatively low-relief, and most historic agriculture took place on gently sloped, smooth terrain where soil was less rocky than on steeper more bedrock-dominated slopes, but the parent material consisted of glacial till. The consistent depth to the C horizon across all classes at both sites, the lack of field evidence of thin A horizons and soil truncations and accumulation of sediment at the base of slopes, along with the inventories and patterns of trace metal mixing in the soils, all suggest that surface erosion of soil is minimal and any material that is moving is remaining on hillslopes. Therefore, erosion of soils from historic agricultural activity may have been a result of localized indirect runoff (e.g., from channelized erosion accessing deeper sediment in gullies, (Hill, 2019)), rather than widespread direct surface erosion on hillslopes. Additional work is needed on the role of stone walls directly trapping sediment on hillslopes, and while overthickened A horizons exist directly behind walls on slopes, it suggests some sediment is being redistributed, but most is remaining in upland areas. The majority of the focus area in this study is on low slopes, and only samples a small subset of higher slopes; there may be greater erosion and truncations of the A horizon in areas with steeper slopes. For low to moderately sloped terrain, therefore, our results suggest that inland wetlands, floodplains, mill ponds, and other depositional areas adjacent to areas used for 17th–20th century agriculture in this region may not store vast quantities of legacy sediment.

In addition, the use of widely available LiDAR and aerial imagery datasets used to develop the land use classification here have the potential to scale up soil impacts related to historic land use in areas where similar features and datasets exist. Stone wall maps exist for large regions throughout the northeastern U.S., and these areas also have aerial imagery dating back to the 1930–40s. While there are limitations to these datasets, they more precisely locate where land use took place in comparison with traditional methods such as land use records, and therefore have the potential for scaling up soil impacts such as total changes to carbon and nitrogen stocks.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2022.108304.

Data availability

The datasets used in the findings of this study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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