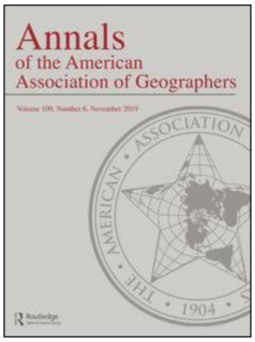

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Reconstructing Historical Forest Cover and Land Use Dynamics in the Northeastern United States Using Geospatial Analysis and Airborne LiDAR

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The northeastern United States experienced extensive deforestation during the seventeenth through twentieth centuries primarily for European agriculture, which peaked in the mid-nineteenth century, and followed by widespread farmstead abandonment and reforestation. Analysis of airborne light detection and ranging (LiDAR) data has revealed thousands of historical land-use features with topographic signatures across the landscape under the region's now-dense forest canopy. This study investigates two different types of features—stone walls and relict charcoal hearths—both of which are associated with widespread deforestation in the region. Our results demonstrate that LiDAR is an effective tool in reconstructing and quantifying the distribution and magnitude of historical forest cover using these relict land use features as a reliable proxy. Furthermore, these methods allow for direct quantification of cumulative land clearing over time in each town, in addition to the extent, intensity, and spatial distribution of cleared land and forest cover. *Key Words: airborne LiDAR, Anthropocene, historical land use, human–land use dynamics.*

The spread of agriculture and associated deforestation are two factors integral in considering the proposed geologic epoch termed the Anthropocene or the conceptual anthropocene, both of which contend that the landscape and environment have been measurably affected by humans, although the matter of timing continues to be debated (Crutzen and Stoermer 1999; Chin et al. 2013; Foley et al. 2013; Edwards 2015; Ruddiman et al. 2015; Zalasiewicz et al. 2015; Waters et al. 2016). Both agriculture and deforestation have occurred measurably on a global scale over the past 10,000 years, while varying regionally in their magnitude, extent, and timing (Foley et al. 2013; Ruddiman et al. 2015). These anthropogenic impacts have both been shown to drastically alter landscapes, with changes to forest structure and ecology (Delcourt and Delcourt 1987; Foster 1992; Hall et al. 2002; Motzkin, Bellemare, and Foster David 2002; Taverna, Urban, and McDonald 2005; McDonald, Motzkin, and Foster 2008; Hightower, Butterfield, and Weishampel 2014), geomorphology (Casana 2008; Merritts et al. 2011; Brown et al. 2013; Dotterweich 2013; Jefferson, Wegmann, and Chin 2013; Dotterweich et al. 2014), as well as historical climatology and outputs from associated modeling (Pitman et al. 2009; Burakowski et al. 2016; Lejeune, Seneviratne, and Davin 2017).

To study these regional impacts of historical agriculture and associated deforestation, it is critical to understand the distribution, magnitude, and properties of historical land use associated with agriculture and deforestation. This study uses high-resolution airborne light detection and ranging (LiDAR) data coupled with archival records to (1) examine the spatial distribution of stone walls and relict charcoal hearths (RCHs), both extant historical land use features associated with agriculture and deforestation that have topographic signatures, and (2) demonstrate that the distribution and location of these relict land use features can be used as a reliable indicator or proxy for reconstructing historical forest cover associated with the distribution of past land use. High-resolution LiDAR data have recently enabled identification and analysis of relict features of these past land use types usually not visible under the dense forest canopy of the U.S. Northeast (Johnson and Ouimet 2014, 2016; see Figure 1). Airborne LiDAR has become a frequently used instrument in historical and archaeological landscape studies, especially in forested regions, because of its ability to map topographic relief through vegetation

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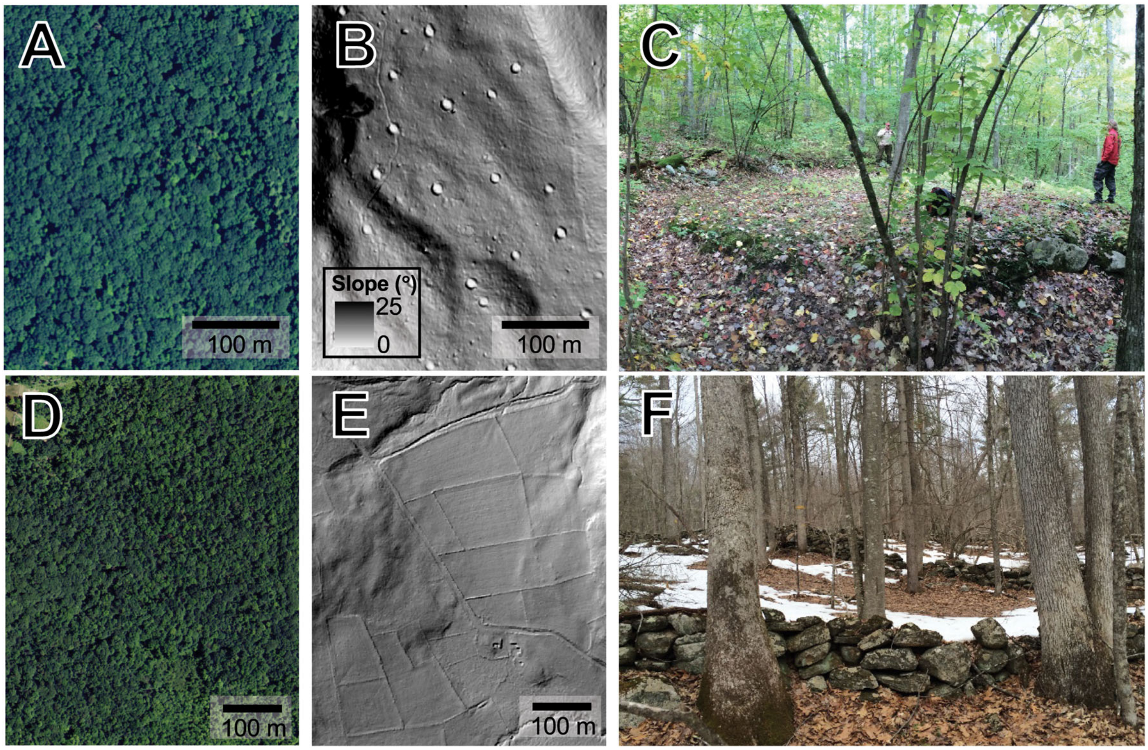

Figure 1. Relict charcoal hearths (C) and stone walls (F) are visible using both slope (B) and hillshade (E) products derived from LiDAR data in areas that have been reforested (A), (D). Aerial photos are from 2012 (Connecticut Environmental Conditions Online 2017) and LiDAR data from 2011 (Connecticut Environmental Conditions Online 2011). LiDAR digital elevation models used to generate both slope and hillshade rasters have a 1-m pixel resolution. LiDAR = light detection and ranging.

at extremely fine scales (e.g., Devereux et al. 2005; Chase et al. 2012; Rosenswig et al. 2013; Fernández-Lozano, Gutiérrez-Alonso, and Fernández-Morán 2015; Opitz et al. 2015).

In the northeastern United States, the drastic imposition of English-style agriculture on the landscape following European colonization in the seventeenth and eighteenth centuries initiated widespread deforestation for pasture and tillage land, resulting in erosion, changes in the transport and deposition of sediment in fluvial systems, and variation in the ecological distribution of species in the region (Cronon 1983; Thorson and Harris 1991; Foster 1992; Thorson et al. 1998; Walter and Merritts 2008). This process was a widespread departure from previous land use strategies by Native Americans, who first began to inhabit the region ~12,900 cal. BP (Boisvert 2012; Chapdelaine et al. 2012; Lothrop and Bradley 2012) and who practiced agriculture later in primarily coastal areas (Delcourt and Delcourt 1987; Chilton 2002; Petersen and Cowie 2002; Jones and Forrest 2003; Donahue 2004). By the mid-nineteenth century, English-style agriculture had reached its peak in southern New England (Cronon 1983; Thorson 2002; Donahue 2004; Foster et al. 2008) and began to decline as industrial change swept through the region. This caused the once-cleared agricultural landscape to become reforested as peripheral pastures and fields were gradually abandoned. In 1851, Henry David Thoreau, who documented this process of abandonment and subsequent reforestation, likened it to the fall of the Roman Empire (Foster 1999).

This classic story of historical land use change in New England often focuses comprehensively on the transformative forces of agriculture and husbandry, including cultivation, pasture, meadows, and woodlots (Cronon 1983; Bell 1989; Foster, Motzkin, and Slater 1998; Thorson 2002; Donahue 2004; Harrison and Judd 2011). There is little mention of industrial charcoal production, however, a form of land use introduced by Europeans in the seventeenth century that we now know occurred throughout the Northeast and that was also responsible for widespread deforestation in those portions of the region that supported the iron industry (Gordon 2001). In both the Mid-Atlantic and the northeastern United States, charcoal production has been correlated with

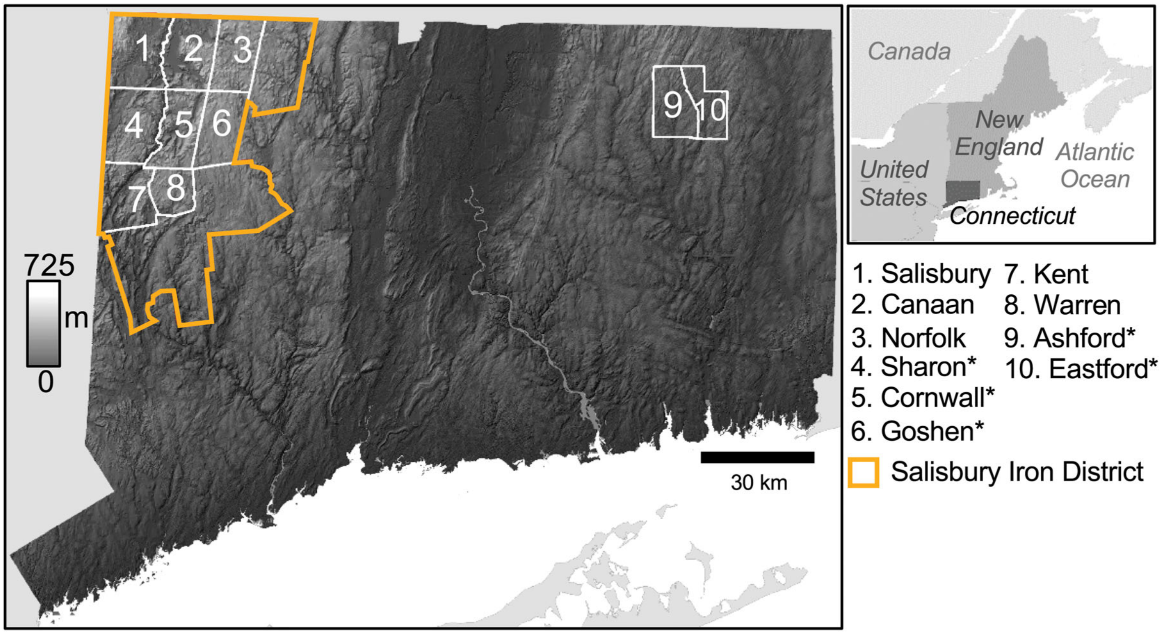

Figure 2. Overview of study region and towns with digital elevation models (U.S. Geological Survey National Elevation Dataset, 10 m). Town names with asterisks indicate those where both stone walls and relict charcoal hearths have been digitized (see Table 1).

erosion, alteration of soil properties, and ecological change (Mikan and Abrams 1995, 1996; Gordon 2001; Knowles 2013; Ignatiadis et al. 2016; A. Raab et al. 2019). Despite the wide range of studies across Europe that have used airborne LiDAR to locate and analyze RCHs (Crow et al. 2007; Crutchley and Crow 2009; Hesse 2010, 2013; Fruchart et al. 2011; Bollandsås et al. 2012; Mlekuž 2013; Risbøl et al. 2013; A. Raab et al. 2015), few published studies in the United States have done so to date (Potter, Brubaker, and Delano 2013; Johnson, Ouimet, and Raslan 2015; A. Raab et al. 2019; Carter 2019). The combination of agriculture and charcoal production during the eighteenth and nineteenth centuries would have resulted in extensive deforestation in this region and, as this study shows, much more than has been described previously.

Study Area and Historical Background

The primary focus of this study includes ten towns that comprise a majority of the historic Salisbury Iron District located in the northwestern part of Connecticut (Gordon 2001). The study also includes two comparative towns in northeastern Connecticut where charcoaling also occurred but on a much smaller scale (Figure 2, Table 1). All towns experienced widespread agricultural intensification during the seventeenth to twentieth centuries. The town of Canaan was divided into Canaan and North Canaan in 1858; for the purposes of this study the area encompassing both modern towns will be referred to as Canaan to consider pre-1858 sources within their proper political boundaries.

Topography in northwestern Connecticut is comprised of rugged, hilly uplands with northern hardwood and mixed deciduous–coniferous forest (Foster 1992; Foster et al. 2008; Parent and Volin 2014). Average elevation in this area is ~330 m above sea level but reaches >700 m in Salisbury. The area is bisected by the Housatonic River, the many tributaries of which were used for early industry in the area (Gordon 2001; Cooper 2003). This region was glaciated until ~17,000 to 18,000 years ago (Thorson 2002; Stone et al. 2005); these processes drastically shaped the land surface, and the resulting topography influenced subsequent land use by both Native Americans and later European groups (Bell 1985; Thorson 2002; Donahue 2004).

Historical accounts that discuss land use in this area often compared land qualitatively with regard to its capability to support English-style agriculture and suggest that certain topography was more or less suitable for different land use types. More specifically, steep or rough hilly lands were often described as better for growing or harvesting wood, whereas more even ground was better for agriculture, and

Table 1. Overview of study towns

	Year incorporated[a]	Average elevation (m)[b]	Town area (km^2)[c]	Features digitized
Ashford	1712[d]	203	102.3	RCH, SW
Canaan	1739	299	136.5	RCH
Colebrook	1729	344	85.2	RCH
Cornwall	1740	328	119.9	RCH, SW
Eastford	1712[d]	198	75.8	RCH, SW
Goshen	1739	394	117.0	RCH, SW
Kent	1739	260	128.4	RCH
Norfolk	1758	422	120.2	RCH
Salisbury	1741	305	155.5	RCH
Sharon	1739	299	154.2	RCH, SW
Warren	1786	350	71.3	RCH
Winchester	1771	330	87.5	RCH

Note: RCH = relict charcoal hearth; SW = stone wall.
[a]*Source:* Lewis (1881).
[b]*Source:* National Elevation Dataset (2016) 10m data.
[c]*Source:* University of Connecticut Map and Geographic Information Center, Connecticut Towns data set.
[d]Eastford was part of the town of Ashford until 1847 and reincorporated then.

lower, marshy areas were best for mowing or even grazing (see Warren 1914). Documents from 1807 to 1812 for three of the towns in this study reveal these views. In Goshen, the soil was “better adapted to grazing than to ploughing” with lower, moist lands “unfit for ploughing” and better suited for “mowing and grazing” (Norton 2003, 114), whereas in nearby Kent the “proportion of land unfit for cultivation” (125) was described as already being put to use producing charcoal for furnaces and forges (Slosson 2003). In Sharon, it was noted that the eastern side of the town had “so much broken ground favorable to the growth of trees, and at the same time wholly unfit for cultivation” (146) that residents could expect fuel wood for future generations (Smith 2003). This combination of steep, rough land coupled with more even terrain allowed for a combination of well-managed woodlots and pasture or tillage lands characteristic of English-style agriculture (Donahue 2004).

Agriculture and Stone Wall Construction

The most prominent and widespread type of seventeenth- to early-twentieth-century land use in southern New England was agriculture and pasture. The thousands of miles of stone walls that now cross the region are a testament to glaciations that occurred in this region and subsequently to the success of agriculture due to the well-drained and fertile lodgment till (Wessels 1997; Thorson 2002; Wessells 2010). As land was tilled and plowed, farmers discovered the ubiquitous stones in New England’s glacial till, and these were discarded over decades to the sides of fields or in the fields themselves as clearance piles or cairns, where they were eventually built into walls or left standing (Cronon 1983; Allport 1990; Thorson 2002; Ives 2015). Stone walls were said to be more durable and require less upkeep than wooden rails alone, but they were also an inescapable by-product of English-style husbandry in New England. It was reported that in 1871 New England states had the highest percentage of any type of fencing per 100 rods (~503 m), with stone comprising 30 percent to up to 79 percent of fencing in Connecticut, Massachusetts, and Rhode Island, with some counties as high as 100 percent (Dodge 1872). Thorson (2002) suggested that this is not a result of the need for fencing only, but a result of using stone walls as “linear landfills” to dispose of the large amounts of stone that appeared every year (Thorson 2002, 2005). Indeed, a resident of northwestern Connecticut commented in 1801, “Stone Wall is also made for Fence, which clears the Land of stone and also secures the Crops” (Allen 2003, 103).

Despite the ubiquity of stone walls throughout the landscape of the Northeast, stone comprised only a portion of the total fencing used in improved farmland, and fencing proportion types would have varied through time and space both as a result of the successive stages of settlement throughout the Northeast and availability of materials (Thorson 2002; Johnson and Ouimet 2016). Fencing during initial and early field clearance was built from brush, roots, and tree stumps that were then replaced with rail fences, stone and rail fences, or finally only stone over time in areas where it was available (Dodge 1872; Cronon 1983; Foster 1999). Farms in marginal areas might have been abandoned before this process could have occurred; stone piles are still extant in these areas that have now become reforested (Thorson 2005; Ives 2013, 2015). Most walls in this region were built between the late seventeenth and early twentieth centuries, although the distribution and timing of construction and land clearing depends on both settlement patterns and population (Allport 1990; Thorson 2002; Johnson and Ouimet 2016).

The advent of industrialization during the last half of the nineteenth and early twentieth centuries caused the abandonment of many farms during that time period, and their cleared fields and pastures slowly began to revert back to forest. This process occurred gradually as younger generations began finding work in cities, or moved west to find better farmland (Bell 1989; Barger 2013). The process is well documented in the landscape history of this region in both primary and secondary sources; for example, Thoreau documented this process of abandonment as early as the 1840s in his writings (Cronon 1983; Foster 1999; Harrison and Judd 2011).

Iron and Charcoal Production

Iron production began in New England with European settlement in the seventeenth century. Bog iron was used in Massachusetts and became a major manufacture in other eastern states such as Pennsylvania and New Jersey by the 18th century (Kury 1993; National Park Service 2021) Iron working on smaller scales in nearby Rhode Island made use of cumberlandite, an ore native to the area and high in titanium, in addition to bog ore, which was used elsewhere in the region (Ryzewski 2013).

The first forges in northwestern Connecticut were built by the 1730s, and the first blast furnaces in that area were built as early as 1762 (Kirby 1998, 2012; Gordon and Raber 2000; Gordon 2001). This hillier inland portion of New England was settled by Europeans much later than areas near the coast or major rivers. Towns in northwestern Connecticut were first surveyed by European settlers in the early eighteenth century, and those in the study area were incorporated between 1739 and 1786, becoming heavily settled in later years as a result of the discovery of iron ore (see Table 1). The height of iron production in this region, known historically as the Salisbury Iron District, occurred in approximately 1856, when about 80 percent of at least twenty known blast furnaces built between 1762 and 1872 were operating simultaneously; this time frame was also approximately during the height of agricultural clearance in southern New England (Lesley 1859; Harris 1885; Harte 1944; Foster, Motzkin, and Slater 1998; Kirby 1998; Gordon and Raber 2000; Gordon 2001; Knowles 2013; see Figure 3).

Northwestern Connecticut, along with adjacent New York and Massachusetts, provided an ideal location for iron production as a result of its geology and topography (Kirby 1998). The bedrock is a product of the Taconic orogeny (~550–440 ma) that resulted in the uplift of coastal carbonate sea floor sediments, later becoming valuable marble and limestone deposits stretching from northern Vermont down through New York (Bell 1985). Limestone was frequently used for flux in blast furnaces (Kirby 1998; Gordon 2001), and well-known limonite and goethite ore deposits exist along contacts of resulting calcite and dolomite marble and fine-grained schist. The location of the Housatonic and proximity to the Hudson allowed for easy transport of iron to New York's markets (Secretary of the Treasury 1833).

The regional-scale production of iron necessitated equally widespread production of charcoal to fuel blast furnaces, foundries, forges, and other iron-related manufactures. Charcoaling occurred at regional scales in western New England and along the Appalachians to Georgia during the eighteenth to early twentieth centuries to support the burgeoning iron industry in the United States (Gordon 2001; Knowles 2013; Potter, Brubaker, and Delano 2013), and also occurred at local scales as individual farmers produced it for sale or their own use (Barger 2013). Charcoal was produced by piling logs on top of a flat earthen platform and covering them with earth, leaves, and bark so that the wood would smolder slowly instead of fully burning (Svedelius and Anderson 1875; Barger 2013; see Figure 3). Since the nineteenth century, this type of feature has been variably referred to as a *meiler*, coal pit, log pit, charcoal mound, charcoal hearth, charcoal pit, charcoal kiln, or charcoal burning platform (Lesley 1859; Svedelius and Anderson 1875; Samuelson 1883; Harris 1885; Rolando 1992; Barger 2013; Deforce et al. 2013; Hesse 2013; Potter, Brubaker, and

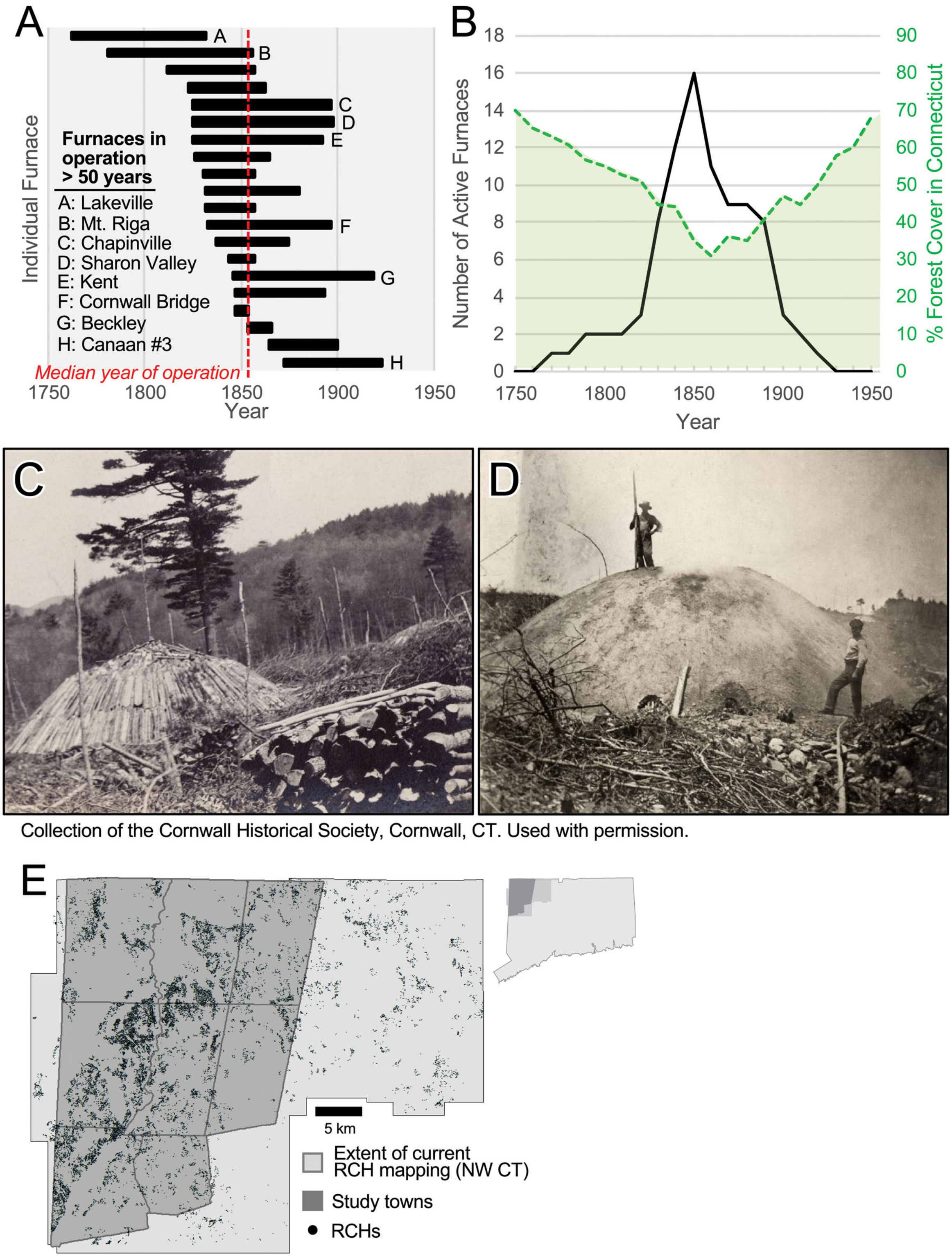

Figure 3. (A) Chart showing length of time and distribution of furnace operation in Connecticut where furnaces in operation more than fifty years are labeled. Data are derived from Gordon and Raber (2000). (B) Chart showing active furnace histogram from 1750 to 1950 against percentage of forest cover in Connecticut. Forest data derived from Foster, Motzkin, and Slater (1998) and furnace data from Gordon and Raber (2000). Late nineteenth-century and early twentieth-century photographs show relict charcoal hearths (RCHs) prior to being burned (C) and with burning in progress (D) in Connecticut. Used with permission courtesy of the Cornwall Historical Society. (E) The extent of RCH mapping at the time of writing in northwestern Connecticut. RCH = relict charcoal hearth.

Delano 2013; A. Raab et al. 2015). Typically in the United States, *charcoal kiln* or *retort* is used to refer to structures built from metal or brick that gradually replaced charcoaling by hand in the late nineteenth and early twentieth centuries (Massachusetts Historical Commission n.d.-a, n.d.-b; Rolando 1992). These allowed for more efficient production with predictable outcomes and also marketable by-products such as wood vinegar (Samuelson 1883). Today, despite the well-known work of Kirby (1998) and Gordon (Gordon and Raber 2000; Gordon 2001), the impacts of charcoaling and iron production, the number and locations of hearth sites, and quantity of deforested land remain relatively unstudied in New England and are rarely mentioned in broader studies of the region's landscape history.

Methods

LiDAR Processing and Feature Digitization

Two airborne LiDAR data sets were acquired through Connecticut Environmental Conditions Online (CTECO 2020) and National Oceanic and Atmospheric Administration Digital Coast (National Oceanic and Atmospheric Administration 2020) in the form of LAS tiles. The data were collected in December 2011 by Dewberry, Inc. for the U.S. Department of Agriculture Natural Resources Conservation Service in a 1,703 km^2 portion of northwestern Connecticut (CTECO 2011) and in November and December 2010 in a 4,589 km^2 area of eastern Connecticut (CTECO 2010). After downloading the LAS data, digital elevation models (DEMs) with a 1-m pixel resolution were then created from points classified as "2-Ground" using the "LAS Dataset to Raster" function in ArcGIS 10.2.2, using the "binning" method to assign each cell the maximum value of the points within it (ESRI 2020). There is a point spacing of ~0.7 m to ~1.0 m throughout the study areas for points classified as "2-Ground."

Historical land use features were digitized manually by examining both slope and hillshade rasters derived from the preceding DEM using the respective functions in ArcGIS 10.2.2. Visualization techniques for extracting cultural features from LiDAR data have been well studied, and although we have examined methods such as sky-view factor (Zakšek, Oštir, and Kokalj 2011) and others (Bennett et al. 2012), we found that slope and hillshade were satisfactory in identifying the types of topographic features in this study. RCHs were digitized by placing a point in the center of each circular or ovoid feature, and stone walls were digitized by placing a vertex at endpoints, abrupt changes in direction, or intersections with other walls. Several previous studies have used these methods in this region as well (Johnson and Ouimet 2014, 2016; A. Raab et al. 2019).

Geospatial Analyses

Analyses were performed using ArcGIS 10.2.2 and the R packages *spatstat*, *shapefiles*, and *maptools* to determine the spatial distribution of RCHs and stone walls in the study area with regard to topography and potential impacts on historical deforestation (Baddeley and Turner 2005; Stabler 2013; ESRI 2016; R Core Team 2020). The extent of clustering at regional and local scales was determined for RCHs using nearest neighbor ratios (NNRs) and associated nearest neighbor distances. The density of RCHs per square kilometer was calculated using the Point Density tool in ArcGIS 10.2.2, and the length of stone walls per square kilometer was calculated using the Line Statistics tool in ArcGIS 10.2.2. Both were calculated with an output cell size of 250 m using a circular neighborhood with a radius of 564.19 m to account for a search area of 1 km^2. Output raster data were clipped to town political boundaries, which have remained constant since the time period of study. Rasters were reclassified for each study town to calculate intensively improved or utilized land use areas based on visible feature density thresholds. Threshold ranges used are areas where the number of RCHs per square kilometer exceeded ten and fifteen hearths and where the length of stone walls per square kilometer exceeded 1, 2, 3, and 4 km. Threshold numbers were selected based on the amount of area that encompassed the highest number of features and based on visual inspection of feature distribution relative to raster values throughout the study area. Land that exhibits higher feature densities can be considered more intensively affected by that land use type but as feature density increases the amount of land affected becomes lower. For example, an area in a town where stone wall density measures 1 km/km^2 or greater would contain much more area than that of 4 km/km^2 or greater because it is less common for

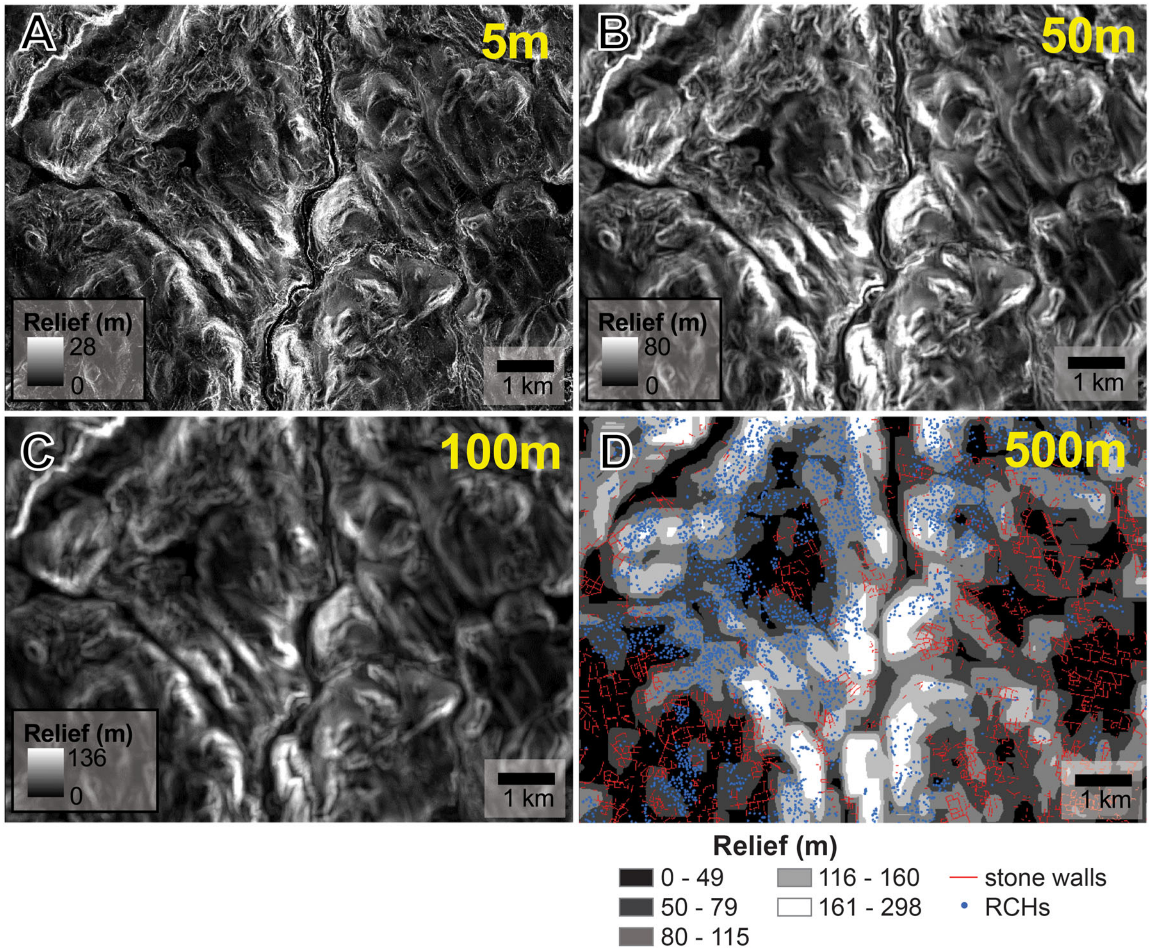

Figure 4. Varying scales of relief depict (A) 5 m, (B) 50 m, and (C) 100 m, compared with (D) 500 m, where values have been binned and features digitized. RCH = relict charcoal hearth.

the stone walls to be quite that dense. Water bodies in the study area are not included in this analysis, but we expect that their inclusion would only increase the proportion of land area encompassed by relict land use features and thus increase the area of intensive land use.

Characterizing Topographic Relief and Slope

In the study region the relief or roughness of the terrain varies in terms of its scale and ranges from areas with blocky, glacially deposited boulders that would have influenced land use decisions at human-perceived scales, to the first-order influences of geologic landforms, valleys, and bedrock ridges on much broader scales. To characterize these differences, a 1-m LiDAR-derived DEM was also generated in ArcMap 10.2.2 using the "LAS Dataset to Raster" tool, where each pixel contained the average of all LiDAR ground-classified elevation point returns within it. Focal statistics were calculated in ArcGIS 10.2.2 with rectangular window sizes of 3 m, 5 m, 10 m, 25 m, 50 m, 100 m, 250 m, 500 m, 1,000 m, and 5,000 m to determine the range in elevation values over various sampling distances (Figure 4).

Pixel statistics were extracted to 2-m-wide buffers that were generated 4 m away from each stone wall centerline and to 2-m buffers that were 8 m away from each RCH so as not to include the topographic signature of each feature in results (Figure 4). To further characterize the terrain in areas where only specific land use types occur, polygons were generated to encompass representative areas of only RCHs, only stone walls, or areas where there were no discernable relict historical land use types observed. Approximately 100,000 random points were generated within each of these zones and values from each of the relief rasters were extracted to these points to accurately characterize the terrain for each of the three categories.

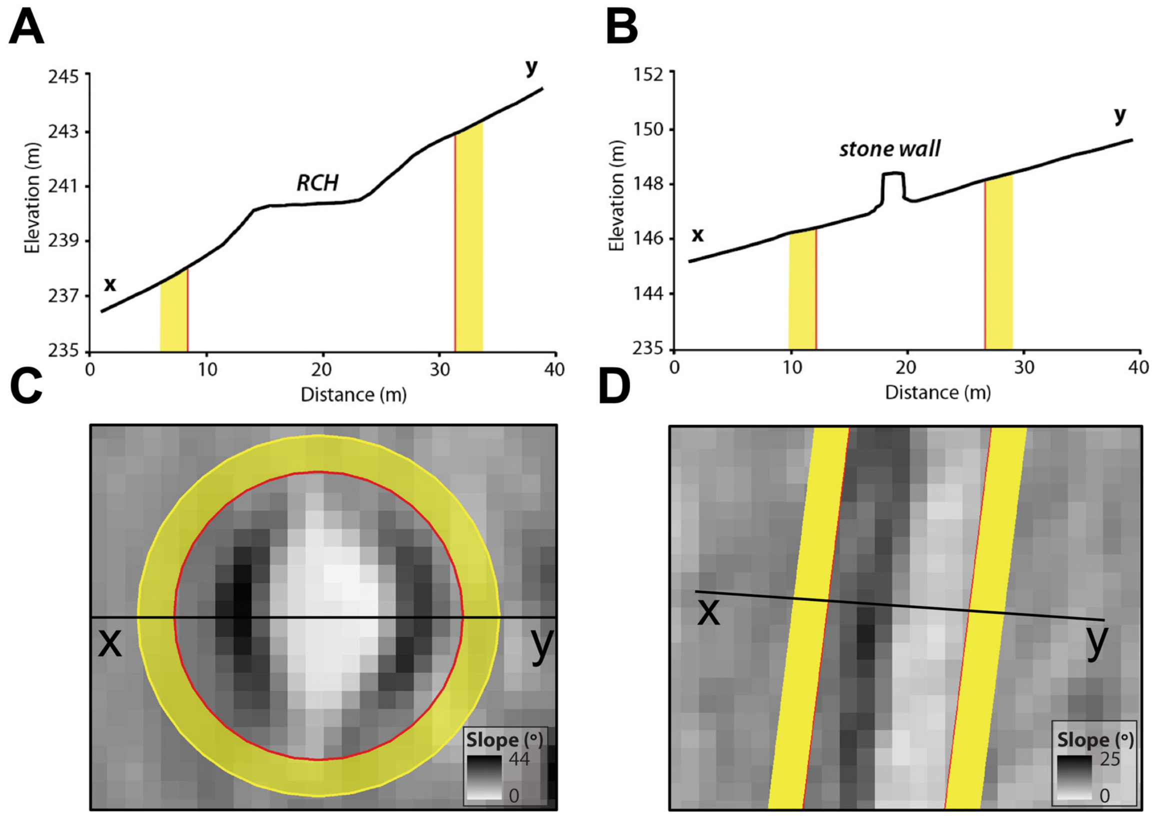

Figure 5. Methods of extracting slope for relict charcoal hearths and stone walls. (A) and (B) depict elevation profiles for each feature type respectively, and (C) and (D) do so in plan view, indicating where buffers extract the slope on either side of the feature itself.

Slope statistics for each feature type were also calculated in a similar manner. Minimum, maximum, and average slope for the area around each feature were extracted for about 10,000 features in each of the three categories (RCHs, stone walls, and areas with no visible relict land use types) using 2-m buffers that were 4 m and 8 m from stone walls and RCHs, respectively (Figure 5). To assess the significance of observed slope values for RCHs, the same number of points with 2-m-wide buffers were generated thirty times in random locations within the study area, and statistics for those values were also extracted.

Archival Research

The 1850 U.S. Federal Census Non-Population Schedule for Agriculture was used to calculate the total area of land in each town that was classified as "improved" or "unimproved" (Ancestry.com 2010). This decade, and just prior, during the nineteenth century is widely considered to be the peak of agricultural deforestation as well as iron furnace operation in southern New England (see Figure 3; Merchant 1989; Gordon 2001; Foster et al. 2008). The 1850 Census categorized the acreage of each farm in a town as either improved or unimproved, with the total of the two comprising the total amount of farmland. The Census defined improved land as "cleared and used for grazing, grass, or tillage, or which is now fallow," whereas unimproved land was defined as "a wood lot or other land at some distance but owned in connection with the farm, the timber or range of which is used for farm purposes" (Wright and Hunt 1900, 235).

We calculated the total amount of improved and unimproved land for each study town by transcribing the archival records into tabular data and adding the acreages of each farm to arrive at a total for the town, which was then converted from acres to square meters (1 acre = 4,046.86 m^2; Table 2). The total amount of reported farmland rarely equals the area of the town, however. Unreported areas have occurred in other documentary records for Connecticut (Waggoner 2003) and might indicate regions that were water bodies, unsurveyed or

Table 2. Summary of historical agricultural census data, 1850

	Town area (km^2)	Improved land (km^2)	Unimproved land (km^2)	Total farmland (km^2)	Unrecorded land (km^2)
Ashford	102.3	69.9	28.9	98.8	3.5
Canaan	136.5	50.7	30.3	81.0	55.5
Colebrook	85.2	58.2	21.5	79.6	5.6
Cornwall	119.9	54.8	33.6	88.4	31.5
Eastford	75.8	37.9	13.6	51.4	24.4
Goshen	117.0	74.5	19.2	93.7	23.3
Kent	128.4	56.9	34.7	91.5	36.9
Norfolk	120.2	69.0	26.2	95.2	25.1
Salisbury	155.5	68.9	33.0	101.9	53.6
Sharon	154.2	76.7	37.7	114.3	39.8
Warren	71.3	31.3	20.2	51.5	19.8
Winchester	87.6	56.7	16.3	73.0	14.6

uninhabited by European settlers, another type of land use, or generally a source of error (Ginsberg 1988; Steckel 1991). Additionally, the 1850 schedule states that it was "not intended to include the returns of small lots … where the productions are not $100 in value," although farms with less than $100 in production values and very small acreages (e.g., less than 10 acres of improved land, 0 acres of unimproved land) are frequently shown in the census regardless (Wright and Hunt 1900, 235; Ancestry.com 2010). The variation in possible omission of these farms by census takers in each town is one factor that could also account for variation in total farm area from total town area. Other studies have encountered issues with land use variability on larger continental scales when interpreting similar records, but the local scale of our study drastically decreases these errors (Ramankutty, Heller, and Rhemtulla 2010).

Results and Discussion

The results of these analyses establish that LiDAR is an extremely effective tool in reconstructing the distribution and magnitude of historical forest cover using relict land use features. A strong relationship between the distribution and magnitude of relict land use features with archival agricultural data demonstrates that features derived from LiDAR data can be used as proxies to reconstruct past deforestation extents in this region and generate estimates of past forest cover. The results also demonstrate that LiDAR provides additional information not available in historical documents and allows for mapping of the locations of past land use and direct quantification rather than just totals at administrative levels as archival data. There is also a strong relationship between the distribution of relict land use features with regard to topographic relief and slope, allowing for more comprehensive interpretations of the distribution and impacts of past land cover and land use. These results provide novel insights into the spatial distribution of relict land use features, reaffirm historical sources that discuss the merits of various topography for specific land use types, and provide further analysis of human–land use dynamics in Connecticut with implications for other regions that experienced widespread deforestation for agriculture and other historical land use.

Spatial Distribution of Land Use Features

The widespread distribution of RCHs and stone walls that are visible using LiDAR data reveals not only spatial variation but also the extent to which historical land use affected the landscape in this region. LiDAR data have revealed more than 20,000 RCHs in northwestern Connecticut and more than 15,000 stone walls totaling 1,340 km in Cornwall, Goshen, and Sharon, where both types of features are digitized completely (Johnson and Ouimet 2016). The densities of each type of feature vary across the landscape; the length of stone walls in some locations exceeds 11 km/km^2 and RCHs are as dense as 197 per square kilometer in others (Figure 6, Table 3). RCHs exhibit clustering at regional scales (NNR = 0.43; a value of one indicates randomly spaced, whereas a value above one indicates dispersed), which is likely a result of topographic controls and the prevalence of steep terrain in the

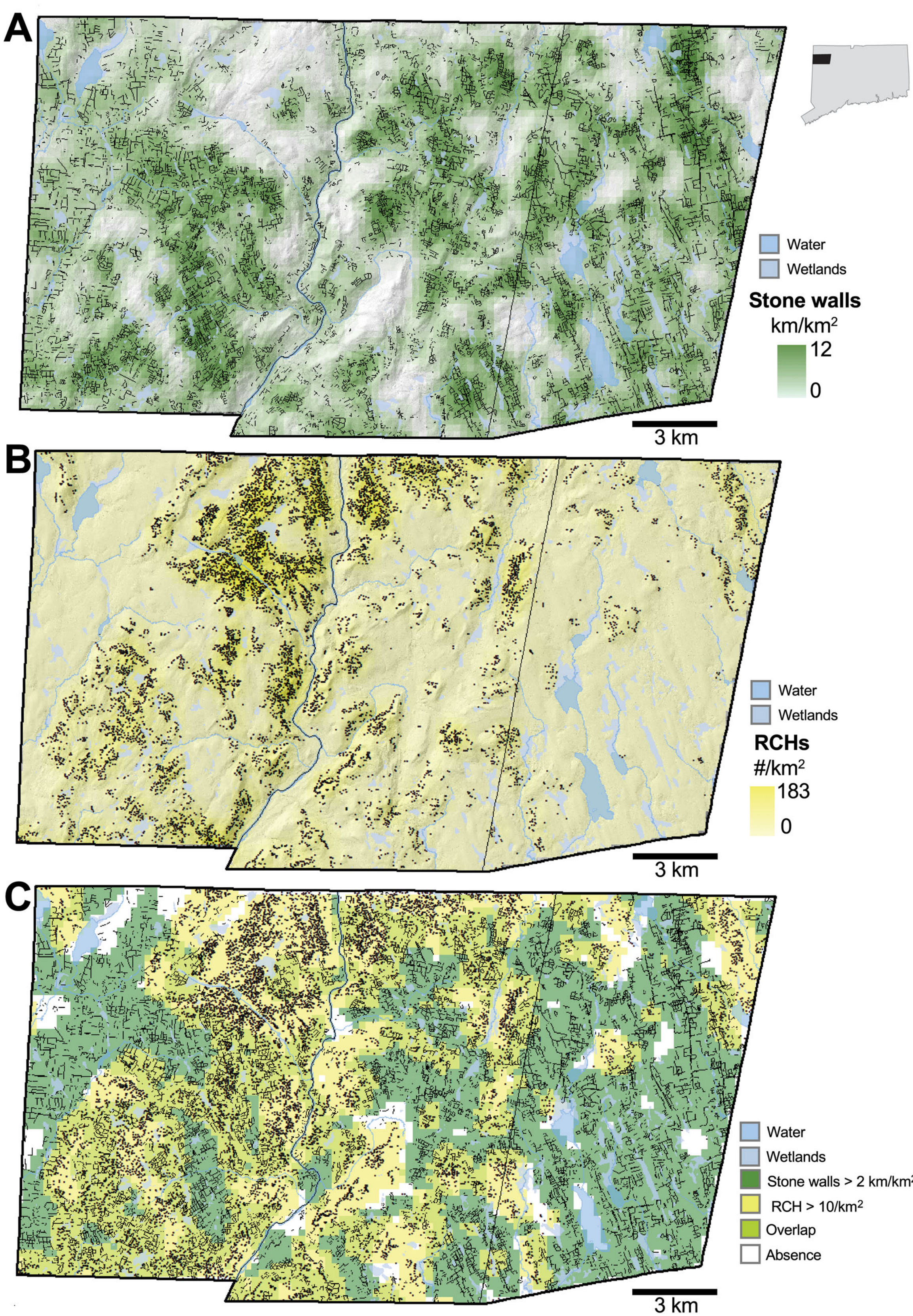

Figure 6. Density of (A) stone walls and (B) RCHs. From these, we derive (C) areas of high density ($>2\,km/km^2$ for stone walls and $>10/km^2$ for RCHs) for both feature types, areas where those areas overlap (contain both types of features), and where there is an absence of either feature type. RCH = relict charcoal hearth.

Table 3. Summary of geospatial data

	Town area (km^2)	Total stone wall length (km)	No. of RCHs	Stone wall density (km/km^2)[a]			RCH density ($number/km^2$)[b]		
				Minimum	M	Maximum	Minimum	M	Maximum
Ashford	102.3	436.6	9	0	4.2	9.8	0	0.1	5
Canaan	136.5	—	2,717	—	—	—	0	20.2	165
Colebrook	85.2	—	691	—	—	—	0	8.3	58
Cornwall	119.9	386.6	3,019	0	3.2	10.4	0	25.1	165
Eastford	75.8	336.8	97	0	4.3	12.0	0	1.2	32
Goshen	117.0	460.7	795	0	3.9	11.8	0	6.8	70
Kent	128.4	—	3,431	—	—	—	0	25.7	197
Norfolk	120.2	—	1,409	—	—	—	0	13.2	73
Salisbury	155.5	—	2,225	—	—	—	0	14.3	119
Sharon	154.2	493.6	5,648	0	3.2	11.4	0	35.7	183
Warren	71.3	—	777	—	—	—	0	10.7	56
Winchester	87.5	—	353	—	—	—	0	4.3	49
Total	1,354.0	2,113.9	21,432	—	—	—	—	—	—

Note: RCH = relict charcoal hearth.
[a]Values from Johnson and Ouimet (2016).
[b]Values based on raster statistics of density maps shown in Figure 6.

area. At finer scales, however, RCHs are regularly spaced and even dispersed (NNR = 1.36; Clark and Evans 1954). This suggests that although the overall regional distribution of RCHs is influenced by first-order trends such as topography, their regular or dispersed placement at finer scales is likely a result of individual decision-making processes by colliers or woodcutters and related to forest characteristics such as the location of old-growth or specific tree species types, as well as the number of times or length of time each RCH might have been used (Straka 2014; T. Raab et al. 2017; A. Raab et al. 2019).

High RCH density typically occurs in areas where the density of stone walls is low and vice versa. This demonstrates that the characteristics of specific areas of the landscape would have been amenable to each land use type as advocated in historical accounts (see further discussion on topography later). In some locations, there is an overlap between areas where RCH density is greater than $10/km^2$ and where stone wall density is greater than $2\,km/km^2$ (Figure 6C, Table 3), suggesting that some areas were not used exclusively for each type or they occurred at different time periods. Although features are not evenly dispersed throughout these overlapping areas and maintain discrete dispersal, in some instances we do observe RCHs that appear within the bounds of stone wall-lined fields (see Figure 2). It has been documented that abandoned agricultural fields were sometimes purchased by iron companies so that second-growth forest stands could be harvested and converted to charcoal (Thomas J. Dodd Research Center 2016). These areas of overlap also occur on more moderate slopes and areas of topographic relief, which were likely amenable to either land use type.

Influence of Topographic Relief and Slope

Topographic relief and slope significantly influence the distribution of both stone walls, which are representative of agricultural land, and RCHs, which are representative of charcoal production and timber harvesting (Figure 7). These results not only confirm historical accounts but provide quantifiable evidence that cultivated land was more likely to have occurred on flat, even terrain, whereas steep and rocky areas were best left for woodland (Allen 2003; Slosson 2003; Smith 2003). We find that there are also areas with no topographic evidence of relict land use features at all, suggesting that these areas might not have been amenable to either type of land use, were not in use for long enough periods of time to leave lasting traces (Johnson and Ouimet 2018), or were subject to land use that did not leave surface topography but might have left subsurface features that could be located archaeologically.

RCHs occur on slopes that average 10.1 degrees. This is significantly ($p = 0.03$) steeper than either stone walls (7.6 degrees) or the maximum slope for the area obtained after running thirty random simulations of more than 20,000 randomly placed points

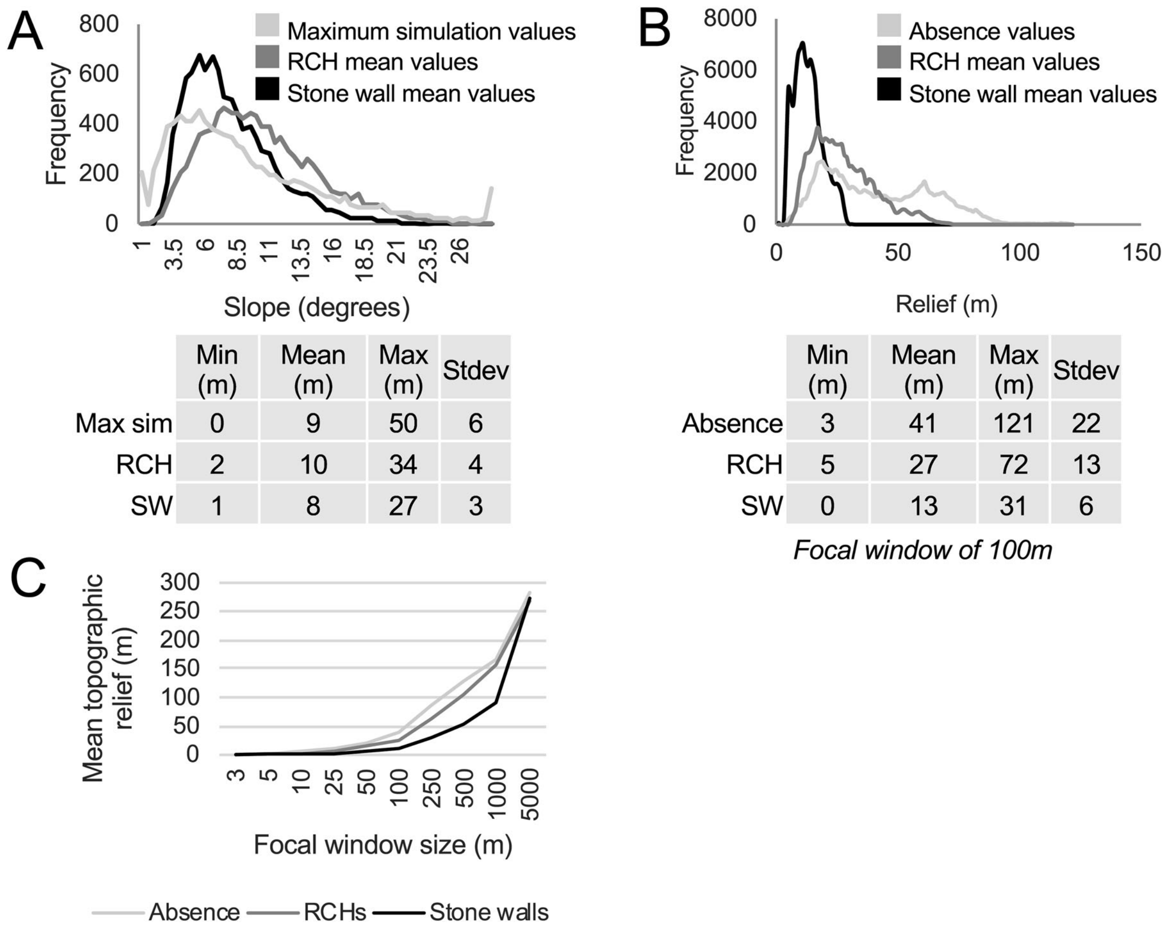

Figure 7. (A) The distribution of slope values extracted from ~10,000 randomly placed points throughout the study area with the mean slope values and mean SW slope values. (B) The distribution of relief values for ~100,000 randomly extracted points within representative areas of absence (neither feature type), mean relief values for RCHs, and mean relief values for stone walls. (C) The mean topographic relief for each feature type is discrete within a range of focal window sizes. RCH = relict control hearth; SW = stone wall.

(9.0 degrees; Figure 7A). The distribution of the data is different, which indicates a slight preference for building stone walls on lower slopes and RCHs on more moderate or steep slopes. Both of these distributions diverge from the distribution for randomly placed points throughout the region, suggesting that although the landscape in this area has steeper average slopes, relict land use features appear differentially within specific ranges.

In addition to slope, topographic relief influences the distribution of stone walls and RCHs in this area (Figure 7B). At all of the focal windows, we find differences between topographic relief for stone walls, RCHs, and areas where no relict land use features are observed. These differences are most pronounced at focal windows of 50 m to 1,000 m, suggesting that broader topography across the landscape influences the spatial distribution of these features more than scales of individual perception, which range from 3 m to 10 m (Figure 7C). The bimodal distribution of areas where neither feature occurs suggests that areas of lower relief in this category are likely marshy, wet areas, whereas higher relief areas are likely bedrock outcroppings or steep, rocky areas that were not amenable to either type of land use.

Topographic relief and slope are common metrics used to examine the land surface and have been calculated in a variety of ways, often to characterize the relationship between biological and physical factors of the landscape (Shepard et al. 2001; Black, Morgan, and Hessburg 2003; Benjamin, Domon, and Bouchard 2005; Sappington, Longshore, and Thompson 2007; Grohmann, Smith, and Riccomini 2009; Kreslavsky et al. 2013). Prior to this study, topographic characteristics such as slope and roughness were used in New England as one of many metrics to examine the relationship between historical land use and the current forest cover (Foster,

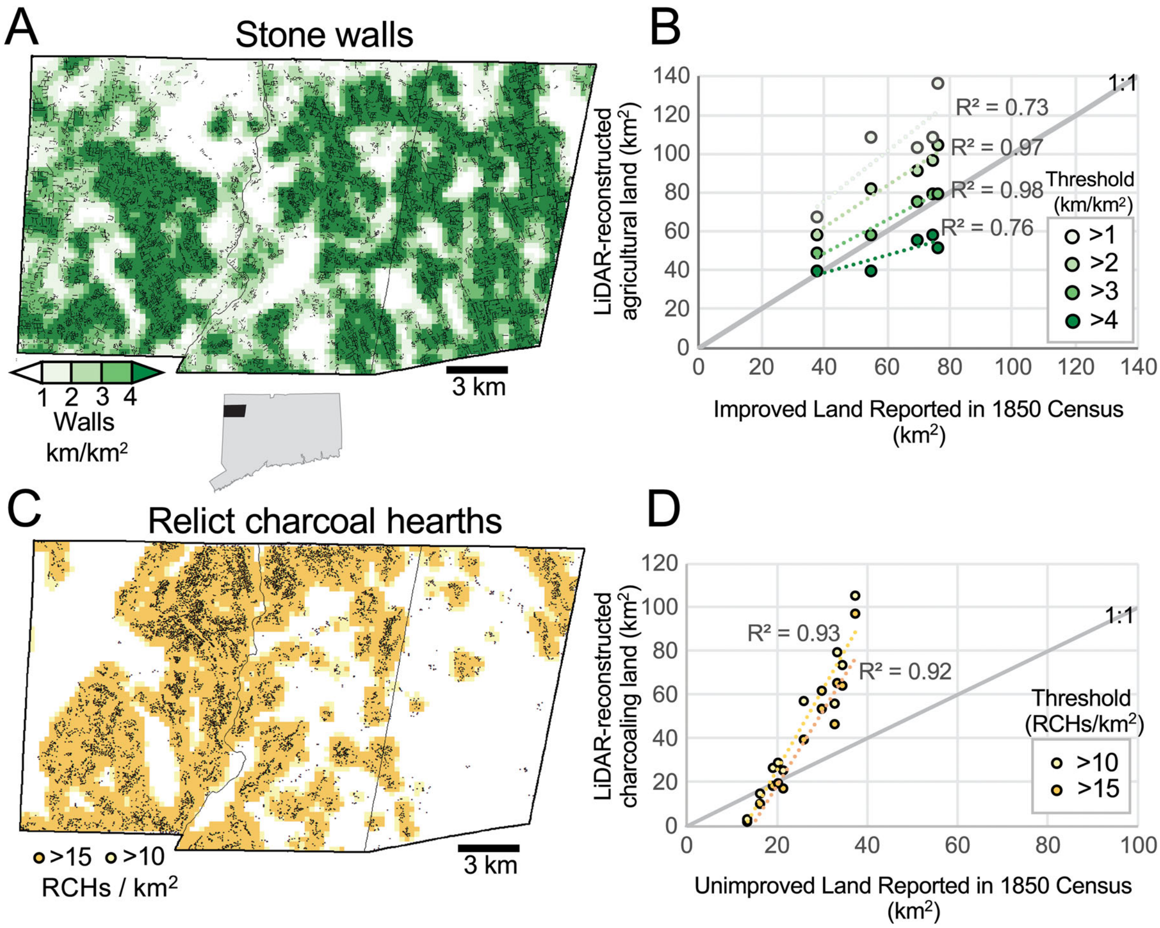

Figure 8. (A) Areas of stone wall density (km/km^2) (B) plotted against areas of improved land in 1850 and (C) areas of RCH density (D) plotted against unimproved land in 1850. RCH = relict charcoal hearth.

Motzkin, and Slater 1998; Cogbill, Burk, and Motzkin 2002) but sparingly in examining the distribution of historical land use alone (Eberhardt et al. 2003). One of the few other studies we are aware of that has examined slope with regard to the distribution of historical land use in this region (Eberhardt et al. 2003) also found a significant ($p = 0.004$) difference between degrees slope for plowed land (2.3), open land (9.3), and woodland (6.5) among nineteenth-century land use types on Cape Cod, Massachusetts.

Spatial Distribution of Land Use Features and Archival Agricultural Data

Our results show a strong relationship between improved land area calculated from the 1850 agricultural census and areas in towns where the density of stone walls is greater than 2 km/km^2 ($R^2 = 0.97$, $p < 0.01$) or greater than 3 km/km^2 ($R^2 = 0.98$, $p < 0.01$; Figure 8). Areas derived from stone wall densities greater than 1 km/km^2 or greater than 4 km/km^2 have less agreement with area reported in the 1850 census and fall further from a hypothesized 1:1 relationship. The total area of high-density walls comprises more land cleared per town in total than predicted by improved land in 1850 alone, as shown by the 1:1 line in the plot, indicating cumulative land cleared over time rather than at a single point. The best approximation of land clearing area during 1850 is the area where stone wall density is greater than 3 km/km^2, which exhibits good agreement but also appears to slightly overestimate the amount of land cleared at that time because it is above the 1:1 line. Other approaches for reconstructing intensive land use areas that have been preliminarily examined that we hope to expand on in the future include buffering certain distances from stone walls or delineating individual fields with polygons to extract specific properties.

Although there is a strong relationship between areas of dense stone wall construction and improved land in 1850, the distribution of stone walls is a more reliable indicator that specific areas of land were cleared for agriculture at some point in time rather than at a single date. Assigning a single specific date to a density threshold other than greater than 3 km/km^2 would also be challenging but might present an avenue of research in the future given that stone wall properties have been shown to vary temporally (Thorson 2002, 2005; Johnson and Ouimet 2016). Overall, stone walls are certainly a reliable marker of the spatial distribution of historical agricultural practice and can be used to derive estimates of past forest cover.

In contrast to the relationship between stone walls and improved land, areas that were listed as unimproved during 1850 have a strong relationship with areas where RCH density is greater than 15/km^2 ($R^2 = 0.92$, $p < 0.001$) and greater than 10/km^2 ($R^2 = 0.93$, $p < 0.001$; Figure 8). As with stone walls and improved land, we find a greater area (above the 1:1 line) for towns with extensive charcoaling. There is a much steeper slope to the trend, which indicates drastic levels of cumulative deforestation over time in some towns versus others where the area cleared is well below the 1:1 line. This means that much more land in these towns was cleared for charcoaling than appears in the 1850 census alone, suggesting that charcoaling occurred not only on recorded unimproved land but also in other forested areas of the towns as well. In towns where charcoaling occurred on smaller scales it is likely that the unimproved land would have been used for managed woodlots and likely not harvested at industrial-level scales.

Foster and colleagues (Foster, Motzkin, and Slater 1998) found similar relationships in adjacent areas of Massachusetts, where linear regression showed "agreement" between areas that had been mapped as woodland in 1830 and lands deemed "unimprovable" in 1830 census records. Their results denote that areas mapped as forest in 1830 were comprised of "wooded areas, cut-over and re-growing forest, and wooded wetlands and rocky areas unsuitable for agriculture" (Foster, Motzkin, and Slater 1998, 104). Other previous geospatial analysis and comparisons with historical documents have also shown a high correlation ($R^2 = 0.96$) between the total length of stone walls mapped using LiDAR and the area of cleared, improved farmland in the nineteenth century (Johnson and Ouimet 2016).

Spatial Distribution of Land Use Features and Historical Forest Cover

Using the low and high scenario intensive land use thresholds described earlier, we estimate that towns experienced land clearing ranging from 65 to 97 percent, with historical forest cover estimates ranging from 3 to 35 percent (Figure 9, Table 4, and Table 5). Estimates of cleared land and forest in northwestern Connecticut, where charcoaling played an important role in the eighteenth and nineteenth centuries, changed by as much as 30 percent when adding the land that had been cleared for RCHs to that of stone walls alone (see Figure 9B). In eastern Connecticut, where charcoaling occurred on a minor scale, stone walls are the best single indicator for reconstructing cleared land and therefore also historical forest cover. Due to the variation in RCH density throughout towns in Connecticut, we recommend that stone walls generally be used as a primary proxy for cleared land, with RCHs used as a secondary proxy to supplement the accuracy of such measurements.

Deriving land cover from relict land use features produces areas for cumulative change rather than just a single point in time and also suggests that the same land could have been cleared multiple times for agriculture and then again for charcoal production. These results deviate from typical methods of reconstructing land cover via archival records at town or county levels (see, e.g., Foster, Motzkin, and Slater 1998; Hall et al. 2002; Donahue 2004) and provide disaggregated spatial information about the actual variation and locations of deforested or forested land. The relationship to archival records demonstrates that it is not only a reliable method but also reveals new information about the process.

Implications and Conclusions

The spatial distribution of the preceding features with regard to topography is a reliable indicator of past land use practices, and the human–land use dynamics of southern New England becomes a much more nuanced process when including the widespread deforestation of the landscape for charcoal production into typical land use histories.

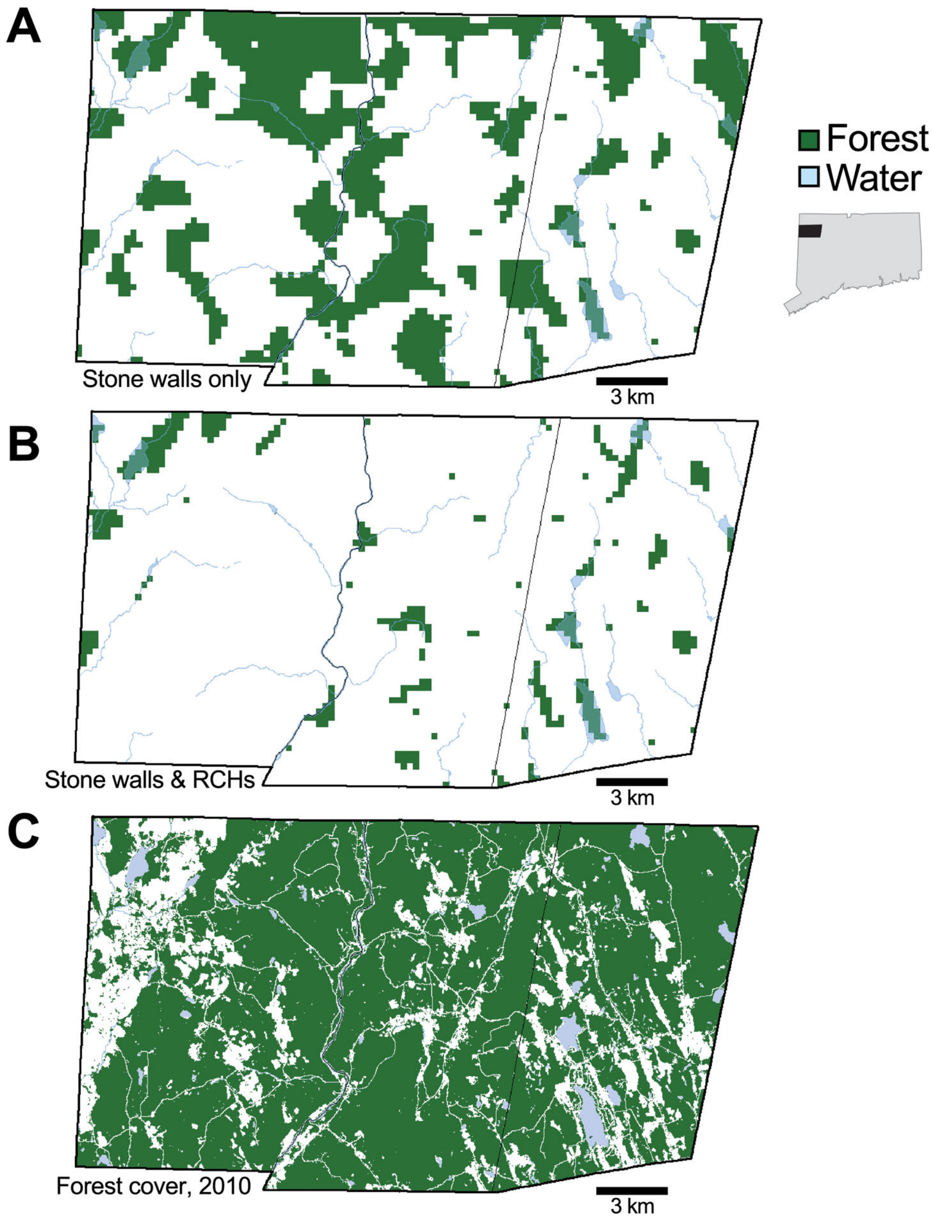

Figure 9. Reconstructed forest cover extents using (A) stone walls only (>2km/km^2), (B) stone walls and RCHs (10 hearths/km^2), and (C) forest cover extent in 2010 including wetlands (University of Connecticut Center for Land Use Education and Research [CLEAR] 2017).

Geospatial analysis of relict land use features derived from LiDAR also allows for interpretations of historical land use dynamics that are not possible using traditional archival research and historical data, especially with regard to both the cumulative use of land over multiple decades and the regional spatial distribution of the type and intensity of historical land use features. Our results have shown that the relationship of relict land use features is related to the dichotomy of improved versus unimproved land in northwestern Connecticut well, with improved relating to agriculture and unimproved relating to charcoal production or well-managed woodlots. LiDAR-based areal estimates correlate well with historical, yearly census data but vary in their magnitude, reflecting the cumulative nature of deforestation that this method shows.

This study has shown the utility of manually digitized features used in analysis on finer scales. Manual digitization of features in large regions to produce such estimates can indeed be time-consuming, but automated and semiautomated extraction algorithms for specific features are beginning to make this type

Table 4. LiDAR-reconstructed land used for charcoaling (km^2)

	Town area (km^2)	RCH density > 10/km^2	RCH density >15/km^2
Ashford	102.3	0.0	0.0
Canaan	136.5	61.1	52.9
Colebrook	85.2	24.4	16.5
Cornwall	119.9	79.1	64.8
Eastford	75.8	2.3	1.2
Goshen	117.0	26.0	18.0
Kent	128.4	72.3	63.2
Norfolk	120.2	56.4	38.9
Salisbury	155.5	55.2	45.8
Sharon	154.2	104.8	96.2
Warren	71.3	27.6	19.2
Winchester	87.6	13.8	8.9
Total	1,354.0	523.1	425.8

Note: LiDAR = light detection and ranging; RCH = relict charcoal hearth.

Table 5. LiDAR-reconstructed total land cleared and historic forest cover

		Low-threshold scenario								
		Area of intensive land use (km^2)					Historical forest estimates (km^2) using			
	Town area (km^2)	Stone wall density >2 km/km^2	RCH density > 10/km^2	Land above both thresholds	Total land cleared[a]	% of town	Stone walls only	RCHs only	Stone walls and RCHs	% of town
Ashford	102.3	91.7	0.0	0.0	91.7	89.6	10.6	102.3	10.6	10.4
Cornwall	119.9	82.0	79.1	45.0	116.1	96.8	37.9	40.9	3.8	3.2
Eastford	75.8	58.3	2.3	1.6	59	77.8	17.5	73.5	16.9	22.2
Goshen	117.0	96.1	26.0	13.9	108.2	92.5	20.9	91.0	8.8	7.5
Sharon	154.2	104.3	104.8	62.9	146.2	94.8	49.8	49.4	7.9	5.1
		High-threshold scenario								
		Area of intensive land use (km^2)					Historical forest estimates (km^2) using			
	Town area (km^2)	Stone wall density >3 km/km^2	RCH density >15/km^2	Land above both thresholds	Total land cleared[a]	% of town	Stone walls only	RCHs only	Stone walls and RCHs	% of town
Ashford	102.3	76	0	0.0	76.0	74.3	26.3	102.3	26.3	25.8
Cornwall	119.9	58.5	64.8	19.6	103.7	86.5	61.4	55.1	16.2	13.5
Eastford	75.8	48.4	1.2	0.7	48.9	64.5	27.4	74.6	26.8	35.4
Goshen	117.0	79.1	18	5.2	91.9	78.6	37.9	99	25.0	21.4
Sharon	154.2	79.6	96.2	39.1	136.7	88.6	74.6	58	17.5	11.3

Note: All values based on raster statistics of density maps shown in Figure 6. LiDAR = light detection and ranging; RCH = relict charcoal hearth.
[a](Area where stone walls exceed threshold + Area where RCHs exceed threshold) – (Area where both thresholds are exceeded).

of analysis more feasible to a wider range of projects and on broader scales (Cowley 2012; Schneider et al. 2015; Trier, Zortea, and Tonning 2015; A. Raab et al. 2019). Automatic detection algorithms have been developed in other regions for RCHs (Trier, Larsen, and Solberg 2009; Hesse 2010; Schneider et al. 2015) and linear features (Humme, Lindenbergh, and Sueur 2006; Bachofer, Quénéhervé, and Märker 2014). Although the rough terrain in the upland areas of southern New England has made similar efforts difficult for walls, preliminary research has shown promising results for RCHs (Witharana, Ouimet, and Johnson 2018).

Overall, the study also demonstrates the drastic extent to which European settlement altered this landscape, thus providing critical evidence in interpreting human–land use dynamics and the proposed Anthropocene geologic epoch in this region. These features demonstrate a lasting impact on the landscape and show that further studies are necessary to use the regional extent of LiDAR coupled with other data to ascertain the extent of impacts ranging from erosion and sediment transport, to alteration of soil properties, and changes in the distribution of various plant and animal species (Foster 1992; Mikan and Abrams 1995; Merritts et al. 2011). Coupled with intensive agriculture, charcoal production in support of the iron industry had a significant impact on the landscape in this region, as it did in other regions in the United States such as the Mid-Atlantic and the Southeast, where large-scale iron production also occurred (Lesley 1859; Merritts et al. 2011; Potter, Brubaker, and Delano 2013). These various impacts resulting from historical land use differ drastically from non-anthropogenic disturbance processes that are inherent to any landscape (Foster, Motzkin, and Slater 1998), and the use of LiDAR coupled with other regional data allows for the examination of the drastic land use change following European colonization of this region in the seventeenth century.

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