LAKE SEDIMENTATION AND LAND USE CHANGE IN MEDOMAK AND SENNEBEC WATERSHEDS, COASTAL MAINE

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An Undergraduate Senior Thesis Presented to

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Chestnut Hill, MA

April 20th, 2021

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The purpose of this study is to quantify land use change in two coastal New England watersheds using lake core analysis, orthorectified historic aerial imagery, and data from the National Land Cover Database (NCLD). The study covers Sennebec and Medomak ponds in coastal Maine, which lie between the Penobscot Bay and the southern stretch of the Kennebec River. With lake cores recording >800 years (Sennebec) and >1600 years (Medomak), the timeframe of this study spans from the era of Indigenous populations, through the period of EuroAmerican settlement, and into the modern day, to provide insight into the interactions between humans and watershed dynamics through time.

Results from lake-core analysis show changes in mass accumulation rates (MARs) and corresponding suspended sediment yields (SSYs) for Sennebec and Medomak Ponds in the early-19th century, which coincides with a period of population growth and its associated land-use changes in Maine. In Sennebec Pond, average MAR over the most recent 200-year interval was 0.070 +/- 0.0072 g/cm^2/yr (5.2 +/- 0.54 Mg/km^2/yr) compared with 0.056 +/- 0.0026 g/cm^2/year (4.1 +/- 0.19 Mg/km^2/yr) over the previous ~670 years. The changes were smaller in Medomak Pond, with the average MAR over the most recent 200 years being 0.043 +/- 0.0027 g/cm^2/yr (3.0 +/-0.19 Mg/km^2/yr) compared to 0.042 +/- 0.0043 g/cm^2/yr (2.9 +/- 0.30 Mg/km^2/yr) over the previous ~670 years. Differences in watershed characteristics and the radiocarbon control points could account for the smaller changes in the Medomak Pond record. Compared to results from similar studies of lakes in more mountainous regions of New England (e.g., Cook et al., 2020), the recent changes in MAR and SSY appear more muted. With different watershed characteristics, including relatively high percentage of open water and wetlands (17% in Sennebec and 19% in Medomak), the capacity of these low-relief coastal watersheds to trap sediment could potentially dampen the signal visible in lake cores.

GIS analysis of 1950s orthoimagery compared with 2016 NLCD data was used to quantify more recent land use change. Despite challenges in distinguishing land cover on mid-20th century greyscale images, analysis demonstrated a -12.03% (Medomak) and -12.23% (Sennebec) decrease in non-forested land, and at least a 2.39% and 5.38% increase in forested land, following similar trends of reforestation seen in New England in the past half century.

The results of the study demonstrate that human behavior does have a quantifiable effect on watershed sediment transport, but this effect may be muted or obscured by the geomorphic characteristics of the watersheds and lake basins.

ACKNOWLEDGEMENTS

First and foremost, thank you to Noah for an incredible year of research and growth. I could not have asked for a better mentor in these strange and challenging times, and your guidance in research and life has been invaluable every step of the way.

My sincerest thanks to Tim for the consistent support and counsel as well, so much of this research would not have been possible without you.

To my parents, for nurturing my curiosity for the natural world and without whom my education would not be possible, I love you dearly.

To the Surface Processes lab group, our biweekly zoom meetings have been a consistent highlight of my week, thank you for all your support along the way!

To Gramps, for all the love and enthusiasm for learning that you instilled in me, I miss you every day.

TABLE OF CONTENTS

CHAPTER 1. INTRODUCTION

1.1 Background

First coined at the turn of the century, the concept of the Anthropocene has gained momentum in the scientific community over the past two decades. In an attempt to understand the lasting effect of human activities on earth systems and the environment, the Anthropocene Working Group (AWG) was formed as a body of the Subcommission of Quaternary Stratigraphy, and voted in favor of defining the Anthropocene as a formal geologic unit in 2019 (AWG, 2019). While the status of the term has yet to be ratified by the AWG's parent bodies, the term has been adopted informally within earth and environmental sciences in an effort to better understand the impact of anthropogenic activity on our planet. Within this communal effort, an extensive literature is being developed to understand how human land clearance and use impacts terrestrial and marine ecosystems and environments (e.g., Bürgi et al. 2017; Ge et al. 2019; Sanderman et al. 2017). The consequences of anthropogenic land alteration can be vast, including— but not remotely limited to— changes in atmospheric composition, reduction of biodiversity, and the deterioration of water resources (e.g., Vitousek et al. 1997, Foley et al. 2005). Uncovering substantial data about the dynamics between land use and the environment is critical to mitigating negative effects and understanding how humans can develop a more sustainable relationship with the ecosystems within which they operate.

Following along this vein, this study examines the impact of anthropogenic land use on watershed dynamics at two adjacent sites in coastal Maine through the accumulation of extensive lake core data and geographic information systems (GIS) analysis. By building a comprehensive chronology, this study analyzes land use change at Sennebec and Medomak watersheds from the time of Indigenous American populations, through EuroAmerican settlement, and up to present land use dynamics. This study is part of a larger effort to quantify regional landscape evolution in New England over the Holocene and into the Anthropocene, and offers complimentary research to work done in more mountainous regions of Maine to provide comparable analysis across watersheds of different land use history and watershed structure (Cook et al. 2020).

Although the first reported European contact with Maine forests dates as far back as 1497, permanent EuroAmerican settlement did not begin until over a century later, during the 1620s (Barton et al. 2012). Due to sporadic fighting between the settlers and Indigenous Americans, the Seven Years War, and the onset of the American Revolution shortly after, EuroAmerican populations did not move into Maine in large quantities until the end of the 18th century. However, the modest colonial settlement leading up to accelerated EuroAmerican settlement and land clearance at the end of the 18th century was important as it reframed the primary perception of land as means for sustenance to land as means for commercial utilization and profit, a concept that would stretch through the colonial era and into modern day (Barton et al. 2012).

By 1790, the population of Maine was estimated at 100,000, which grew to 300,000 by the time Maine gained statehood in 1820, and continued to increase to around half a million only 20 years later. This onset of settlement was coupled with land clearance, with the 1760 estimate of 10,000 acres cleared rising to 650,000 by 1820, and a million by 1840 (Barton et al. 2012). The exact level and timing of this clearance varied with location, moving from the coast farther inland with time (Barton et al. 2012, Cook et al. 2020). The watersheds of this study belong mainly to Knox and Waldo counties, which reached their land clearance zenith towards the 1880s (Barton et al. 2012, Fig. 4.7). By the mid-nineteenth century, the American agricultural sector had begun to move west, the population in the northeastern United States became more concentrated, and large swaths of land in New England were abandoned, making way for the "century of natural reforestation and forest growth" that would follow (Thompson et al. 2013, p. 1). The percent land clearance dropped steadily in southern Maine from the 1880s on, and percent forest cover of Maine has risen back to near pre-colonial levels since the late 19th century (Barton et al. 2012).

1.2 Study Area

The study area spans two adjacent watersheds of Sennebec and Medomak ponds (Figure 1). The watersheds are located in the Midcoast region of Maine, situated primarily within Waldo and Knox counties (Figures 1 and 2). The adjacent low-lying coastal watersheds were chosen as areas of interest for this study to offer comparable data to a previous study done in the more mountainous inland watershed of Little Kennebago Lake (Cook et al., 2020). By pairing the analysis of both watersheds rather than selecting just one, we could develop a better understanding of how both land use history and individual watershed characteristics may impact the sedimentation in these watersheds. The ratio of the lake area to the watershed area is similar for both Sennebec and Medomak (0.0074 and 0.0070, respectively). Sennebec Pond and its associated watershed are approximately twice the size of Medomak Pond and its respective watershed (Table 1). The average depth and annual inflow rate is higher in Sennebec than Medomak, and the residence time of water— which is the volume of the water body divided by the inflow rate— is longer in Sennebec Pond (~23 days) than Medomak (~13 days). The mean elevation, relief, mean slope, and mean annual precipitation are similar in both watersheds, although all are slightly higher in Sennebec (Table 1). Populations within Waldo and Knox counties have remained relatively similar and constant since 1860 (Table 2). The upstream area of Sennebec was included in the 1847 expansion of the St. George Canal, which was once a mode of transport for lumber between the late 1700s and mid 1800s.

Bedrock geology in the region includes areas of Precambrian-Ordovician marine sedimentary rocks, metamorphosed to gneiss and schist, as well as Cambrian-Ordovician schist, marble, and gneiss, and Silurian-Devonian volcanic rocks (Maine Geological Survey, 2002) Surficial geology of the region is predominantly till and glacial-marine silt and clay deposits (Maine Geological Survey, 2003).

Regional forest cover in the coastal and interior area of central Maine is defined as Laurentian Mixed Forest (Thompson et al. 2013; U.S. Forest Service, 1994), which is a transitional forest between boreal and broadleaf deciduous zones (U.S. Forest Service, 1995). Northeastern spruce-fir, northern hardwood-spruce, and northern hardwoods are common (U.S. Forest Service, 1994). Of the farmland in Knox and Waldo, 57% and 54% (respectively) are actively used for agricultural practices such as crop cultivation, pasture, or grazing. The other 43% and 46% of farmland in the counties is designated as woodland, and is considered part of the farm operation but is not currently being cultivated for agricultural production (U.S. Department of Agriculture, 2017, *Knox County*; U.S. Department of Agriculture, 2017, *Waldo County*).

1.3 Purpose & Scope

This study uses a combination of lake core and GIS analysis to quantify the impact of land use on sedimentation rates at these two coastal Maine watersheds across time. Cultivating an understanding on this relationship between land use and watershed dynamics is critical to developing a more complete picture of how the interactions between humans and their environment have evolved over time, and the impact that anthropogenic land use can have on natural processes and environments.

In order to quantify the impact of land use on the chosen watersheds, I developed a two-pronged study that included lake cores from both Sennebec and Medomak ponds, as well as a GIS analysis of aerial imagery and land cover data for both watersheds. I used radiocarbon dates from samples collected from the lake core by Professor Tim Cook at University of Massachusetts Amherst to develop age-depth models for each watershed. The lake core analysis gave me a comprehensive volume of data for both Sennebec and Medomak dating back ~880 years and ~1620 years, respectively. This yields a chronology over which I estimate sediment yield of both watersheds. GIS analysis spanned a narrower window of time, with the earliest available aerial imagery over the study area in 1953 to the most recent orthoimages collected in 2018. This gave me the opportunity to analyze more recent land use trends to observe anthropogenic land over the last half century. The findings of this study contribute to the growing body of literature that aims to quantify and understand the complex interactions between humans and their environment by analyzing land use change through time.

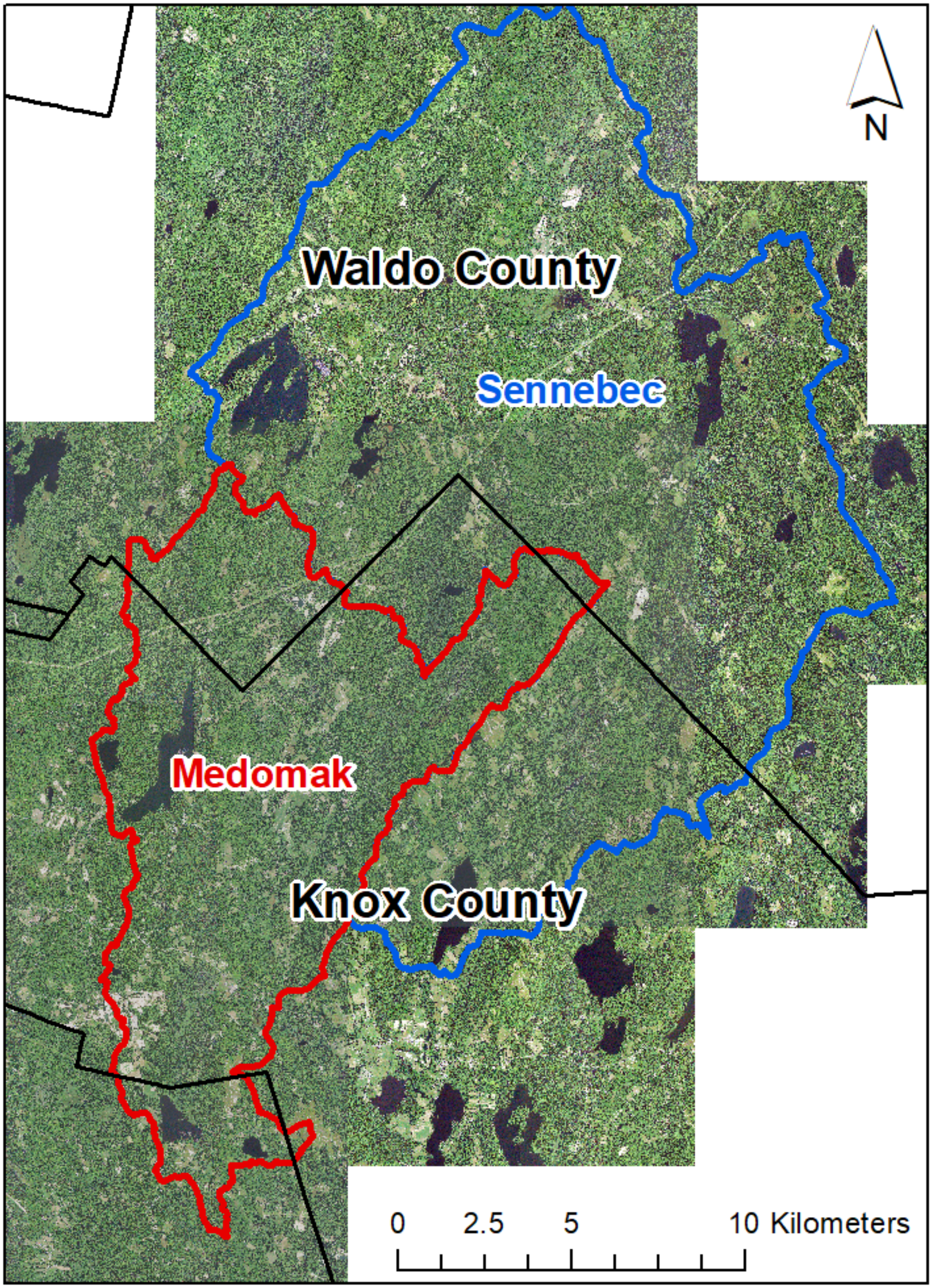

Figure 1. The Medomak (outlined in red) and Sennebec (outlined in blue) watersheds shown over a mosaic of 2018 NAIP orthoimages. The borders of Waldo County (above) and Knox County (below) indicated in black.

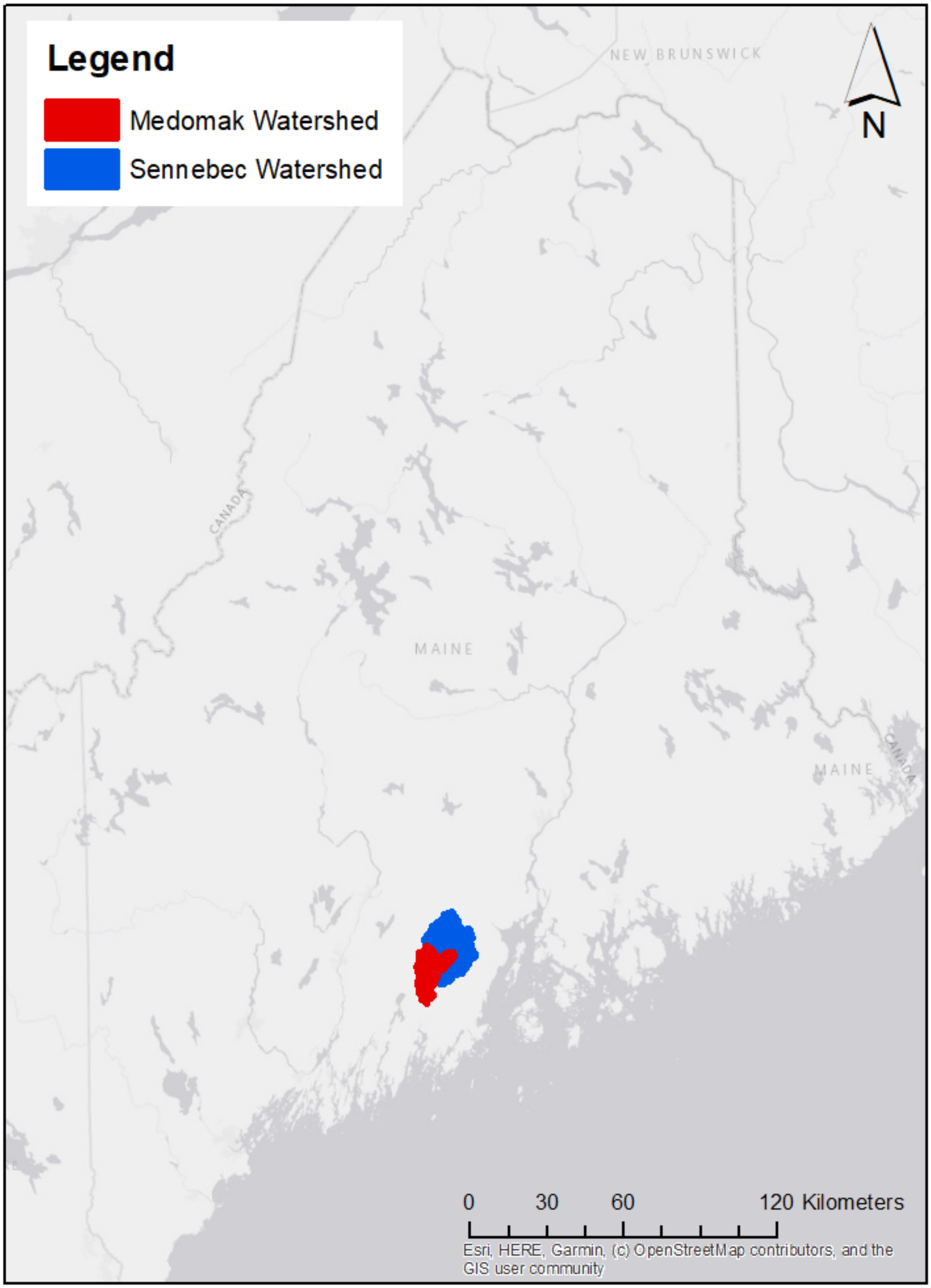

Figure 2. The Medomak (red) and Sennebec (blue) watersheds shown on a greyscale base map of Maine.

Table 1. The relevant characteristics of Sennebec and Medomak watersheds.

	Lake Area, LA (km^2)	*Watershed Area, CA (km^2)*	*Ratio, Lake Area to Watershed Area*	*Mean Depth (m)*	*Mean Annual Inflow Rate (m^3/s)*	*Residence Time (days)*	*Mean Elevation (m)*	*Relief (m)*	*Mean Slope (degrees)*	*Mean Annual Precipitation (cm/year)*
Sennebec (44°15'N, 69°16'W)	2.17	292.7	0.0074	5.79	6.37	22.83	116	319	4.18	120
Medomak (44°11'N, 69°22'W)	0.967	137.8	0.0070	3.66	3.06	13.43	96	231	3.84	115
Source	Lake Stewards	*NHDplus*		Lake Stewards	*StreamStats*		*NHDplus*	*NHDplus*	*NHDplus*	*StreamStats*

Source key: Lake Stewards, Lake Stewards of Maine (2021); *NHDplus,* U.S. Geological Survey (2012), *NHDplus*; *StreamStats,* U.S. Geological Survey (2016) *StreamStats.*

Table 2. The population data of Knox County, ME and Waldo County, ME, from 1860 to 1950, and 2019.

	1860	*1870*	*1880*	*1890*	*1900*	*1910*	*1920*	*1930*	*1940*	*1950*	*2019*
Knox County	32,716	30,823	32,863	31,473	30,406	28,981	26,245	27,693	27,191	28,121	39,772
Waldo County	38,447	34,522	32,463	27,759	24,185	23,383	21,328	20,268	21,159	21,687	39,715
Source	Social Exp.	Social Exp.	Social Exp.	Social Exp.	Social Exp.	Social Exp.	Social Exp.	Social Exp.	1950 Census	1950 Census	Quick facts

Source key: Social Exp., Social Explorer (2021); 1950 Census, U.S. Census Bureau (1950); Quick facts, U.S. Census Bureau (2019, July 1).

CHAPTER 2. METHODS

2.1 Lake Core Analysis

Professor Tim Cook of University of Massachusetts Amherst, along with Professor Noah Snyder of Boston College, Jim LeNoir, and Sarah Johnson, collected two separate sediment cores at each pond, so that both Sennebec and Medomak had a core section 18-1 which included the water-sediment interface, and another core section 18-2 which extended further into the lake sediment cross section (Figures 3 and 4). The 18-2 Medomak core was split into two sections, 18-2-1 and 18-2-2 (Figure 4). Professor Cook then measured magnetic susceptibility at 0.5 cm intervals using a Bartington MS2E surface sensor, and used an ITRAX scanning X-ray fluorescence (XRF) core scanner to collect down-core elemental abundances. He scanned cores 18-1 with a Mo X-ray source operating at 30 kV and 55 mA with a 20 second exposure time, and cores 18-2 with a 10 second exposure time. Raw counts for the 18-1 cores were then divided by two so that they were comparable with the results from the 18-2 cores. Samples of organic material were collected at UMass Amherst along the cores of both ponds, and source material was recorded by Professor Cook. Accelerator mass spectrometry (AMS) radiocarbon dating was performed at the Woods Hole NOSAMS facility. The resulting radiocarbon ages were then calibrated to calendar years using the IntCal20 calibration curve (Reimer et al., 2020) (Table 3).

At Boston College, I measured the loss on ignition (LOI; or percent of organic matter) and dry bulk density (ρ_{db}) of the sediment by collecting sediment samples at 1-cm intervals down the sequence of the lake cores. Samples were weighed at the time of sampling, and then dried for a minimum of 16 hours at 100°C. Once they had cooled from the drying oven, they were weighed once more. Finally, they were combusted in a muffle furnace at 550°C and weighed again once they were completely cooled. LOI (%) and ρ_{db} (g/cm^3) were derived from these measurements using the following equations:

$$LOI = \frac{mass\ dry\ sediment - mass\ combusted\ sediment}{mass\ dry\ sediment} * 100. \tag{1}$$

$$\rho_{db} = \frac{mass\ dry\ sediment}{volume\ of\ sample}. \tag{2}$$

At each pond, the offset between the 18-1 and 18-2 core was determined using sections of overlapping LOI, ρ_{db}, XRF, and magnetic susceptibility data. Composite sequences of 175.5 cm and 183.5 cm were then available for analysis for Sennebec and Medomak, respectively.

I used a linear regression to create an age-depth model for each pond in CLAM using the calibrated radiocarbon samples, discussed further in section 3.1.1 (Blaauw & Christen, 2011). The slope of these age-depth models was interpreted as the instantaneous bulk sedimentation rate (SR), which was used to determine down-core values of the mass accumulation rate of clastic sediment ($MAR_{clastic}$) using the following equation:

$$MAR_{clastic} = \frac{\rho_{db} * (100 - LOI)}{SR}. \tag{3}$$

$MAR_{clastic}$ (g/cm^2/yr) was then converted to suspended sediment yield (SSY) with the units Mg/yr/km^2 using the equation:

$$SSY = MAR_{clastic} * \frac{LA}{CA} * 10{,}000\ Mg\ g^{-1}\ cm^2\ km^2, \tag{4}$$

where LA and CA are the lake area and catchment area, respectively, of each watershed in question.

2.2 GIS Analysis

In order to quantify more recent land use change, historical aerial single frame imagery from the years 1953-1956 and 2018 NAIP orthoimagery were downloaded from USGS

EarthExplorer (Table 4). The 1950s single frames were orthorectified in AgiSoft Metashape using the 2018 NAIP orthoimagery to find reference points. Reference points were placed on each historic single frame using UTM coordinates with a NAD83/UTM zone 19N projection to distinguish the northing and easting in meters, and using LiDAR data downloaded from the USGS National Map to distinguish elevation coordinates. Both the downloaded NAIP imagery and the historic aerial orthomosaics covered 100% of both watersheds (Figures 1 and 5).

For recent land cover information, the 2016 National Land Cover Database (NLCD) was accessed and cropped to the watershed boundaries of each watershed in ArcGIS (NLCD 2016) (Figure 6). The subsections of land cover included in both cropped datasets were summed and taken as a percentage of a whole. The subsections were then further simplified by the following conditions: deciduous, mixed, and evergreen forests were summed under the category of "forested land." Emergent herbaceous wetlands, woody wetlands, and open water were summed and classified under the category of "water and wetlands." The remaining categories were summed under the classification of "Non-Forested Land." These categories were developed land of low to high intensity, developed open space, barren land, shrub/scrub, herbaceous, hay/pasture, and cultivated crop land.

For historic land cover, orthomosaics assembled from the 1953-1956 imagery were interpreted by eye, and sections of land were determined to be either "forested," "non-forested," or "water and wetlands." These categories were chosen to simplify land cover into the three most general land cover characteristics of these watersheds, which also have their own distinct sediment trapping or source potential. Features were distinguished using a combination of observations including greyscale, texture, shadows, roads, and tree cover density. Because the aerial imagery was captured in April and May, some deciduous trees could have been sparse of leaves and therefore lacking the features necessary to visually distinguish forested land from non-forested. Therefore, areas where texture and elongated shadows alluded to the presence of tall, bare tree trunks were assumed to be covered in deciduous trees and thus were distinguished as forested land (Figure 7). Although historic aerial imagery was relatively high resolution (Table 4) it was often difficult to discern vegetation and land cover type on greyscale images. This was particularly challenging when identifying the difference between forest cover and water and wetlands in the historic photographs.

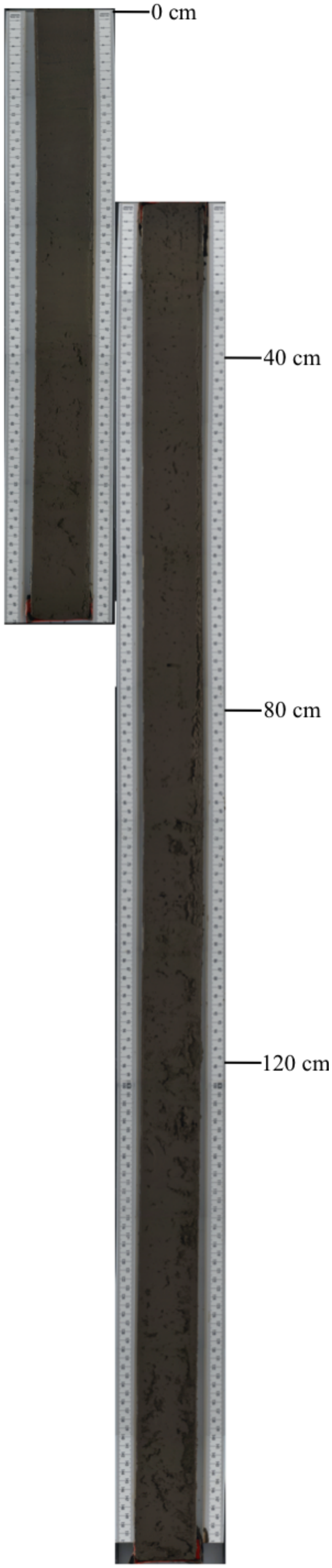

Figure 3 (left). Core 18-1 (left) and 18-2 (right) for Sennebec Pond, shown with the 22.5 cm offset derived from a combination of overlapping magnetic susceptibility, XRF, LOI and ρ_{db} data. 0cm marks the water-sediment interface. Photos courtesy of Tim Cook, UMass Amherst.

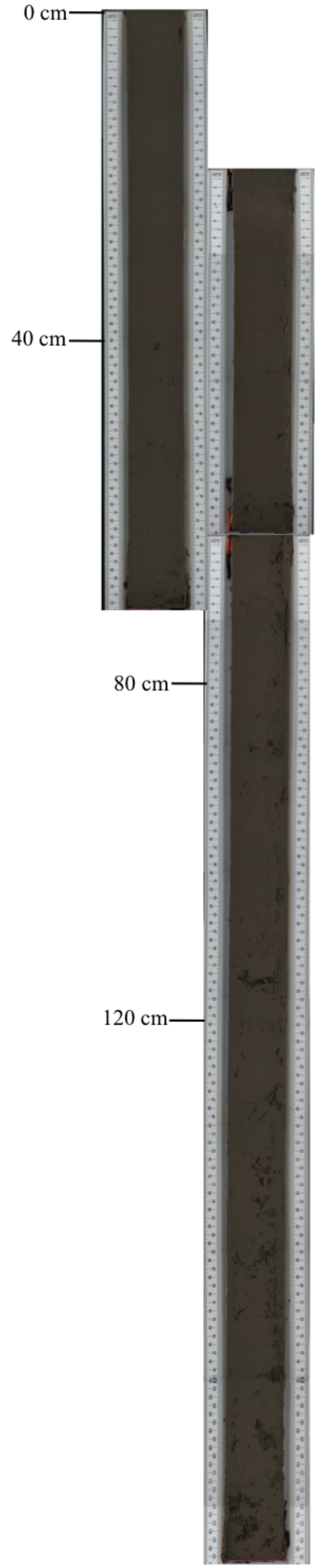

Figure 4 (right). Core 18-1 (left), 18-2-1 (right, above) and 18-2-2 (right, below) for Medomak Pond, shown with the 19.5 cm offset derived from a combination of overlapping magnetic susceptibility, XRF, LOI and ρ_{db} data. 0cm marks the water-sediment interface. Photos courtesy of Tim Cook, UMass Amherst.

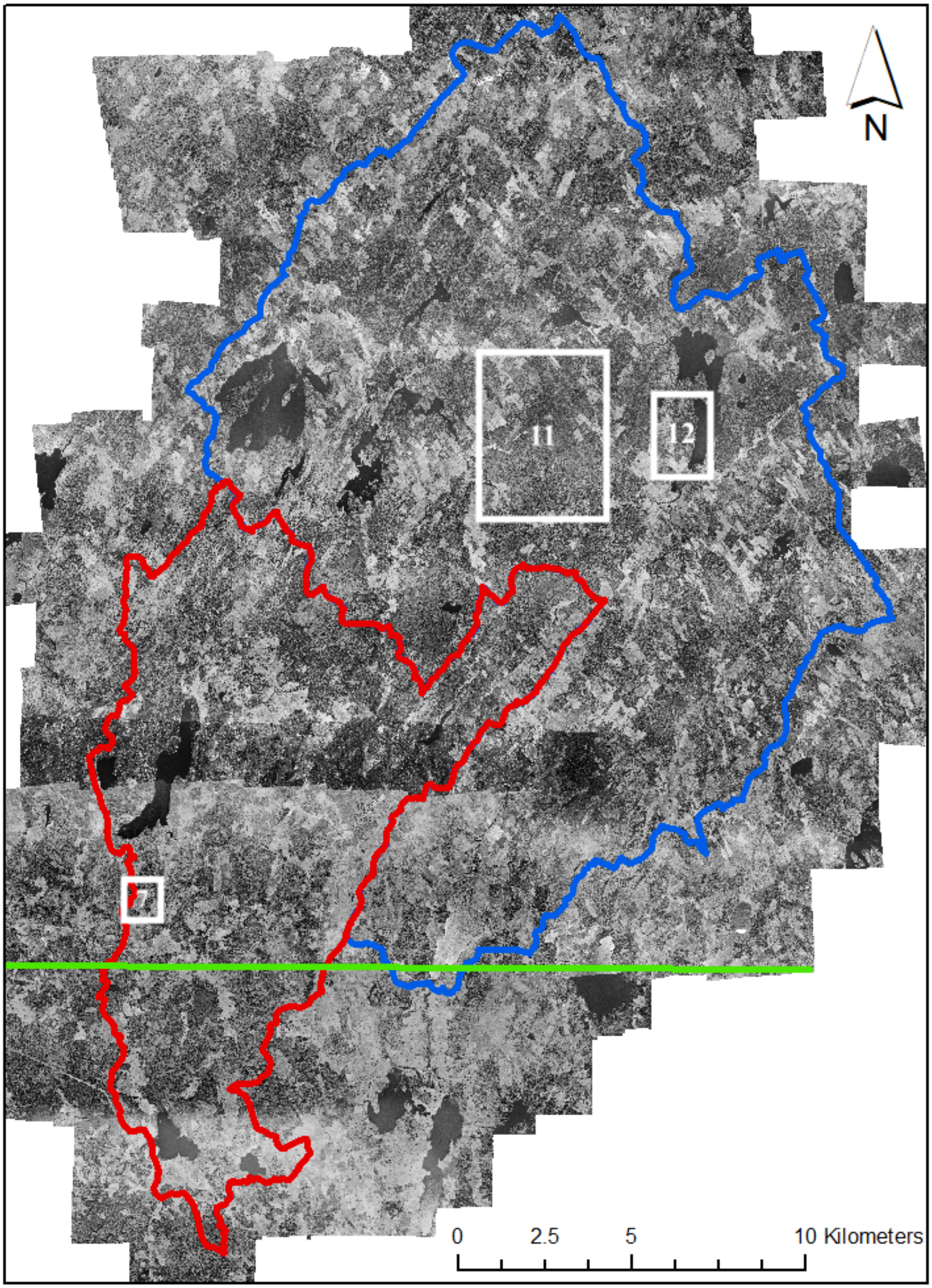

Figure 5. The orthorectified mosaic of 173 aerial single frame images downloaded at 1:17000 and 1:24000 resolution, with 0.4-0.6 pixel resolution. Medomak watershed is outlined in red and Sennebec in blue, with the areas represented in Figures 7, 11, and 12 outlined approximately with white borders. The green line demarcates the area above which photos were taken in May 1956, and below which photos were taken in April 1953.

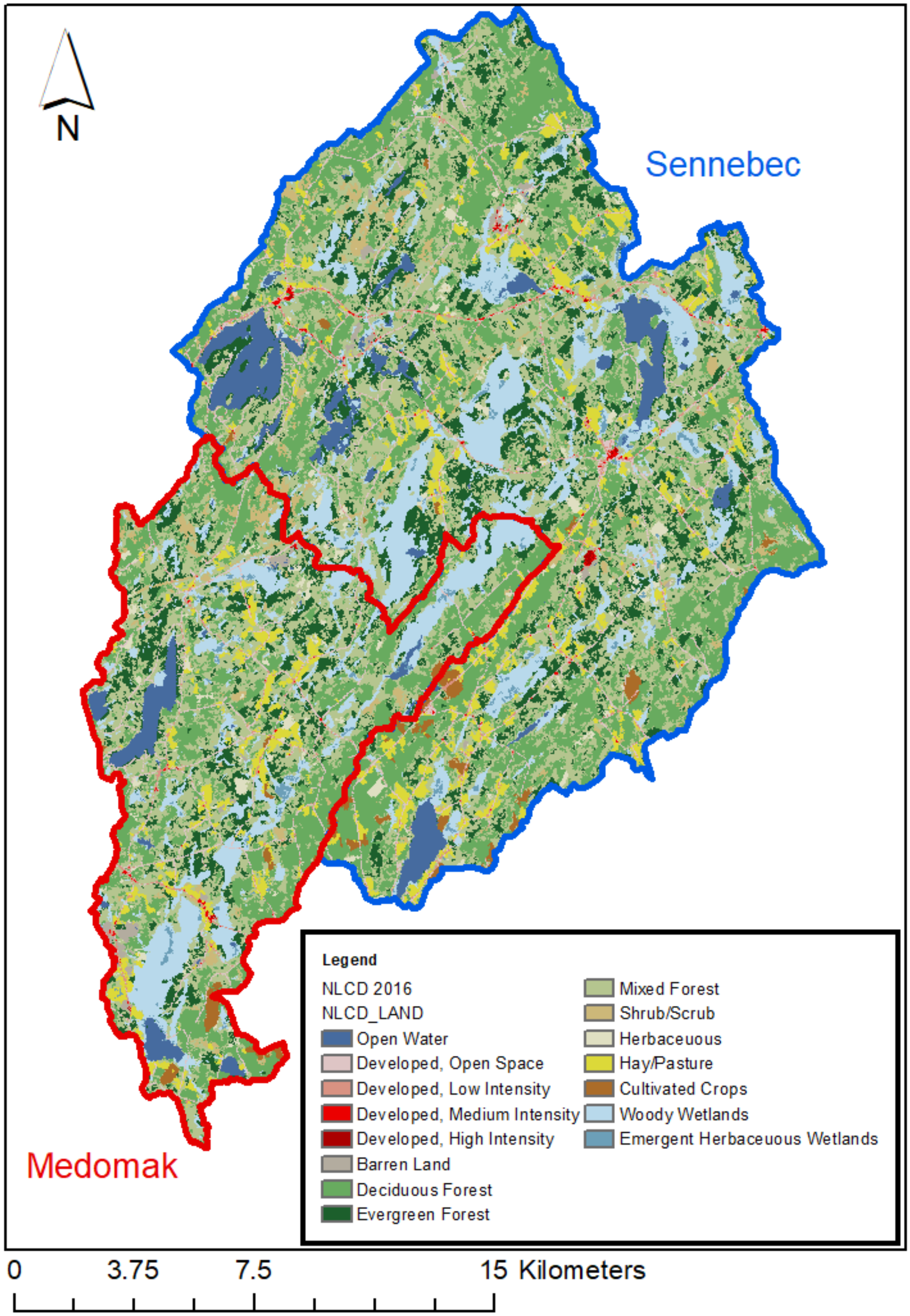

Figure 6. The National Land Cover Database (NLCD) data for Medomak (outlined in red) and Sennebec (outlined in blue), clipped to watershed boundaries in ArcGIS.

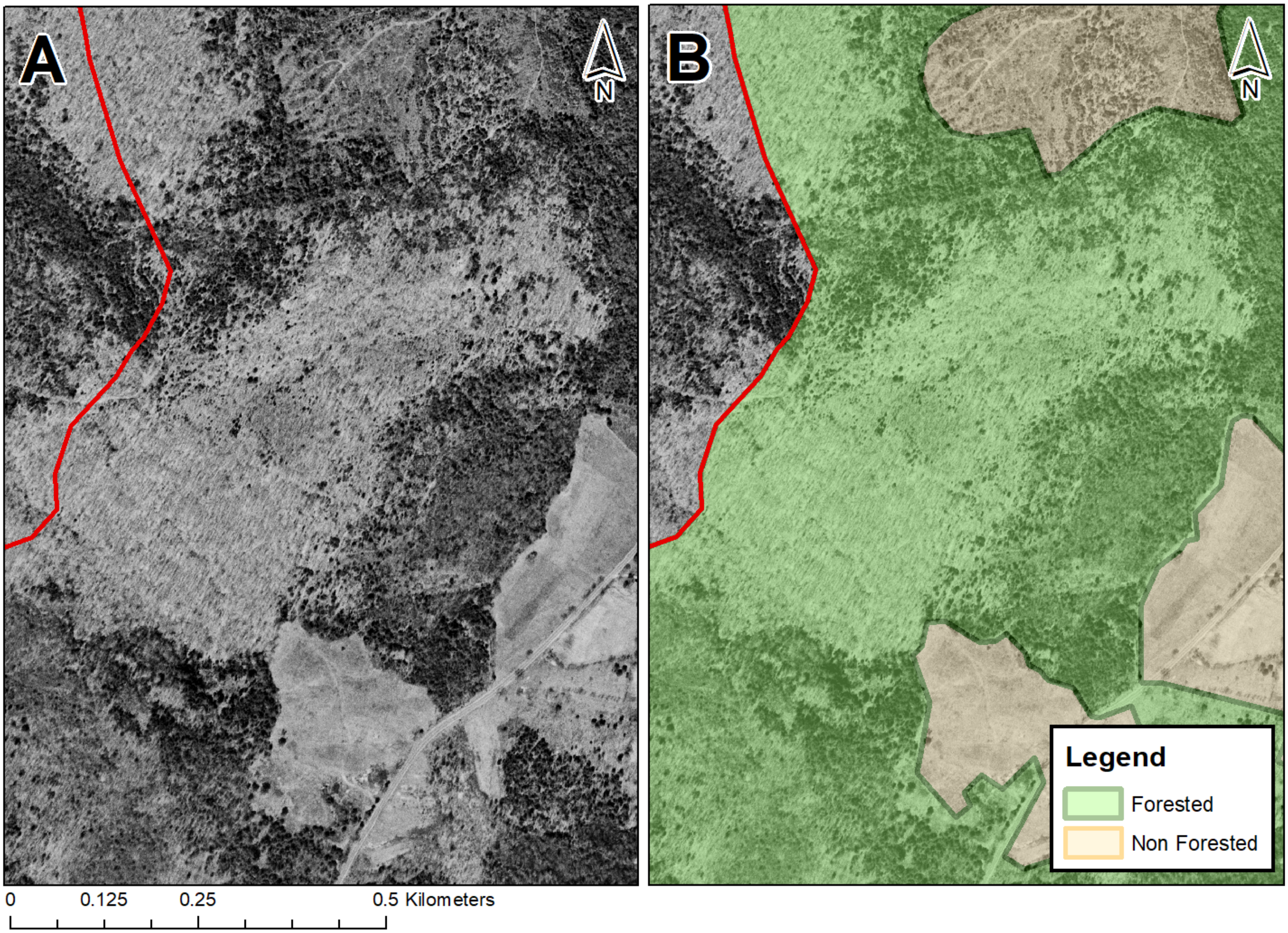

Figure 7. An example of how texture and shadows were used to distinguish between deciduous, leafless trees and nonforested land for 1956 aerial imagery.

Table 3.
The information for collected radiocarbon samples, as well as the calibrated age ranges and calibrated range probabilities based on a 95% confidence interval.

	Composite Depth	*Source Material*	*^{14}C Age (Years BP)*	*^{14}C Age Error*	*Calibrated Age Min (Years BP)*	*Calibrated Age Max (Years BP)*	*Calibrated Range Probability*
Medomak							
	114.5	Plant/Wood	340	23	1478 1538	1529 1635	32.5 62.3
	123	Sediment Organic Carbon	1380	15	604 752	677 757	93.4 1.6
	131	Plant/Wood	955	15	1032 1077	1052 1156	18 76.8
	182	Sediment Organic Carbon	1900	20	80 109	99 211	10.8 84
Sennebec							
	75	Plant/Wood	215	15	1649 1742 1765 1777 1942	1677 1750 1773 1798 1950	34.9 2.2 4.6 41.9 10.1
	93.5	Leaves	431	31	1424 1600	1501 1616	90.6 4.3
	102	Twig	968	31	1023 1057	1054 1158	23.7 71.3
	127	Plant/Wood	505	15	1410	1436	95

Table 4.
The aerial imagery source and scale information.

Original Data Type	*Source*	*Date*	*Scale/Resolution*
42 Aerial Single Frames	Earth Explorer	04/04/1953	0.4 meter resolution
131 Aerial Single Frames	Earth Explorer	05/1956	0.6 meter resolution
29 NAIP orthoimages	Earth Explorer	07/2018	0.6 meter resolution

CHAPTER 3. RESULTS

3.1 Lake Core Analysis

3.1.1 Age-Depth Models

^{14}C dates from the four control points at each watershed were not straightforward, as younger sediment must necessarily overlie older layers, but the samples in both records did not follow this rule (Figure 8). A potential explanation for this anomaly is that some of the organic samples were older than the sediment layer they resided in. Because it was not possible to identify which control points were anomalous, a simple linear regression was used to perform the age-depth analysis. Any model that incorporated an incomplete set of the control points and excluded one or more as outliers required large changes in accumulation rate inconsistent with the sedimentology. Instead, we equalized the differences between points of potential error by using this relatively conservative approach, and all radiocarbon control points were incorporated in the final models. The resulting age-depth models for Sennebec and Medomak ponds indicate that the chronological records span ~900 years and ~1600 years, respectively (Figure 8). The instantaneous bulk sedimentation rates (SR) used in equations 3 and 4 were derived from the slope of the age depth models.

3.1.2 Magnetic Susceptibility, LOI and ρ_{db}

The sediment in the cores taken from both lakes appear massive, with no distinct layering and almost completely homogenous gyttja throughout the depths of both cores (Figures 3 and 4). Results from the magnetic susceptibility, LOI, and ρ_{db} analysis in both watersheds show a reversal of trends around the turn of the nineteenth century (Figure 9). A peak in LOI data around 1300 CE in Medomak is likely a result of human error in the sampling process.

Over the available time span for Sennebec, the average magnetic susceptibility is 4.88 +/- 1.97 SI • 10^5. This broke down to an average of 8.36 +/- 0.94 SI • 10^5 over the most recent ~200 years (2018 to ~1820 CE), and an average of 3.86 +/- 0.27 SI • 10^5 over the remaining ~670 years of the sediment record (before 1820 to ~1140 CE), showing a 116% change over these two intervals. For Medomak, the overall average magnetic susceptibility was 4.39 +/- 0.82 SI • 10^5. For the most recent ~200 year interval (2018 to ~1820 CE), the average magnetic susceptibility was 5.97 +/- 1.07 SI • 10^5 and the average over the ~670 preceding years (before 1820 to ~1140 CE) was 3.82 +/- 0.26 SI • 10^5, an 56% increase between the two intervals.

For LOI, Sennebec averaged 15.91% +/- 1.8%, which broke down to an average of 12.80% +/- 0.77% in the most recent ~200 years, and 16.82% +/- 0.65% over the remaining ~670 years, a 4.02% decrease between the two intervals (note the flipped axis of the LOI data in Figure 9B). Medomak had an overall average of 11.73% +/- 1.02%, with an average of 11.92% +/- 0.71% over the most recent ~200 years— a 0.64% decrease from the average of 12.57% +/- 0.93% over the preceding ~670 years.

The dry bulk density values of Sennebec averaged 0.36 +/- 0.04 g/cm^3 over the entire time span. The most recent ~200 year average was 0.42 +/- 0.04 g/cm^3, an increase of 20% from the average 0.35 +/- 0.02 g/cm^3 average of the remaining ~670 years. For Medomak, ρ_{db} averaged 0.47 +/- 0.05 g/cm^3 overall, with an average of 0.440 +/- 0.02 g/cm^3 over the most recent ~200 year interval and 0.437 +/- 0.04 g/cm^3 over the ~670 preceding years, an 0.65% increase.

3.1.3 $MAR_{clastic}$ and SSY

Because SSY is a function of the $MAR_{clastic}$ results (Equations 3-4), the patterns demonstrated in the results are identical (Figure 10). For simplicity, $MAR_{clastic}$ will be described with the corresponding SSY quantity in parenthesis, where applicable. Both lakes show a reversal in $MAR_{clastic}$ trends around the early 19th century, although it is more apparent in the Sennebec record. Over the ~880 year time span of the Sennebec record, the average $MAR_{clastic}$ was 0.059 +/- 0.0073 g/cm^2/yr (4.4 +/- 0.55 Mg/km^2/yr). Over the most recent ~200 year interval, average $MAR_{clastic}$ was 0.070 +/- 0.0072 g/cm^2/yr (5.2 +/- 0.54 Mg/km^2/yr), a 26% increase from the ~670 year interval that preceded, which had an average $MAR_{clastic}$ of 0.056 +/- 0.0026 g/cm^2/year (4.1 +/- 0.19 Mg/km^2/yr). Medomak Pond shows more modest changes, with average $MAR_{clastic}$ values varying less between these same time intervals. The ~880 year average for Medomak Pond was 0.042 +/- 0.0040 g/cm^2/yr (2.9 +- 0.28 Mg/km^2/yr) for the Medomak record. Over the most recent ~200 year time interval, average $MAR_{clastic}$ was 0.043 +- 0.0027 g/cm^2/yr (3.0 +/- 0.19 Mg/km^2/yr) compared to an average of 0.042 +/- 0.0043 g/cm^2/yr (2.9 +/- 0.30 Mg/km^2/yr) over the previous ~670 years, a 1.87% increase.

3.2 GIS Analysis

GIS analysis revealed a modest increase in forested land between the 1950s and 2016 NLCD data, with Medomak demonstrating a 2.39% increase and Sennebec a 5.38% increase. GIS analysis of imagery from the 1950s against modern day orthoimages also demonstrated an decrease in non-forested land in both Medomak (-12.03%) and Sennebec (-12.23%) (Table 5). This combination of increasing forest land and decreasing non-forested land between the 1950s and modern day is not isolated to this study area, and has been observed around New England over the past half-century (Foster et al. 2008; Barton et al. 2012).

It was difficult to discern areas of water and wetlands from forested area in the greyscale aerial imagery. Areas that were classified as "woody wetlands" in the NLCD data were hard to distinguish visually from forested land in the historic aerial imagery (Figures 11 and 12). This challenge likely resulted in an underestimate of 1950s woody wetlands. Since woody wetlands are a large proportion of the water and wetlands category from the NLCD 2016 data (Table 5), an underestimate of woody wetlands in the historic imagery would potentially result in a large underestimate of total water bodies and wetlands in the 1950s. Although results demonstrate an increase in water and wetland area between the 1950s (9.76% and 10.17%) and 2016 (19.42% and 17.05%), formation of new water bodies or wetlands to the magnitude demonstrated by these results is unlikely. Instead, these numbers are likely impacted by the limitations of the methodology, as discussed further in Chapter 4. With areas that were potentially woody wetlands included under forested land cover, an underestimate in 1950s water and wetlands was likely paired with an overestimate of 1950s forested land, resulting in an underestimate of the magnitude of forest cover change.

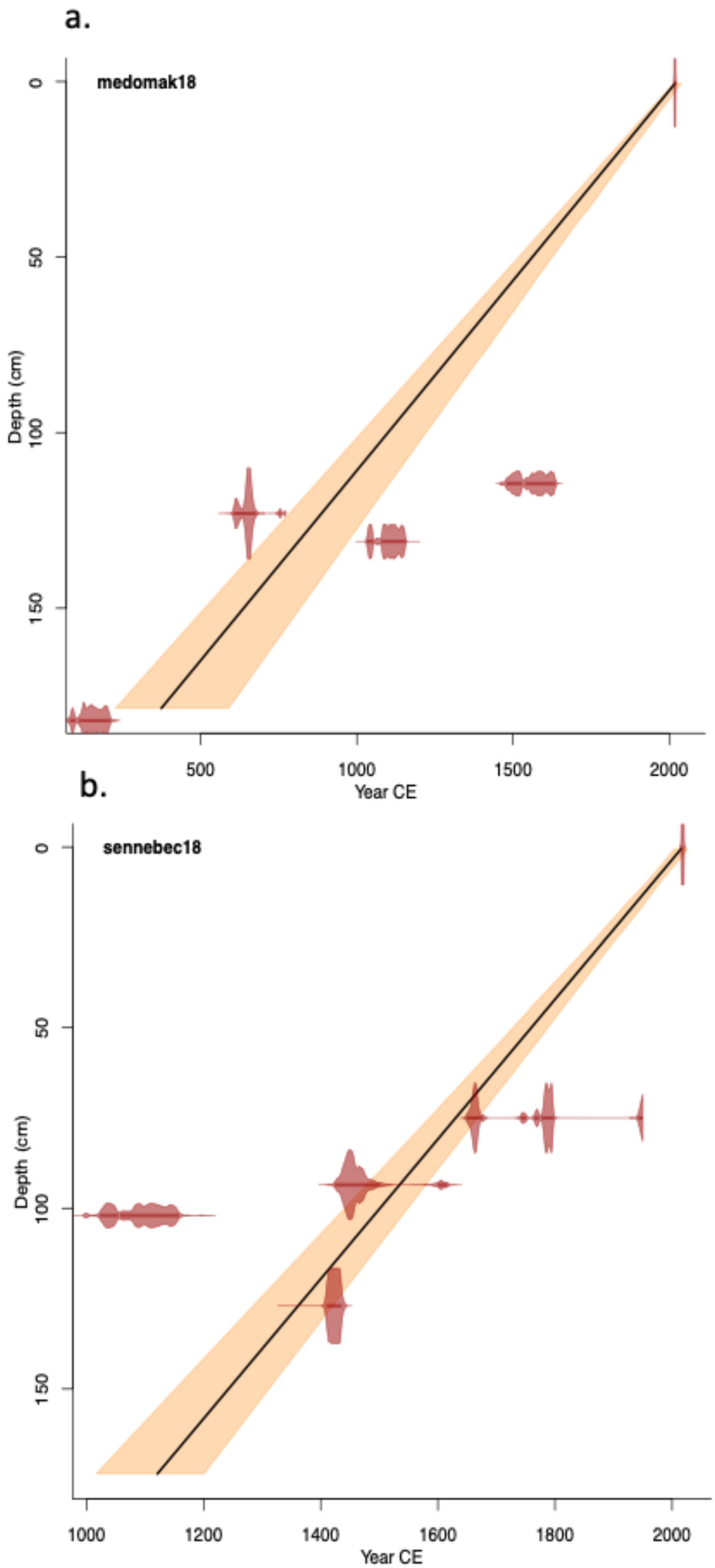

Figure 8. Age-depth models for Medomak (above) and Sennebec (below), calculated using CLAM (Blaauw & Christen, 2011) and a linear regression.

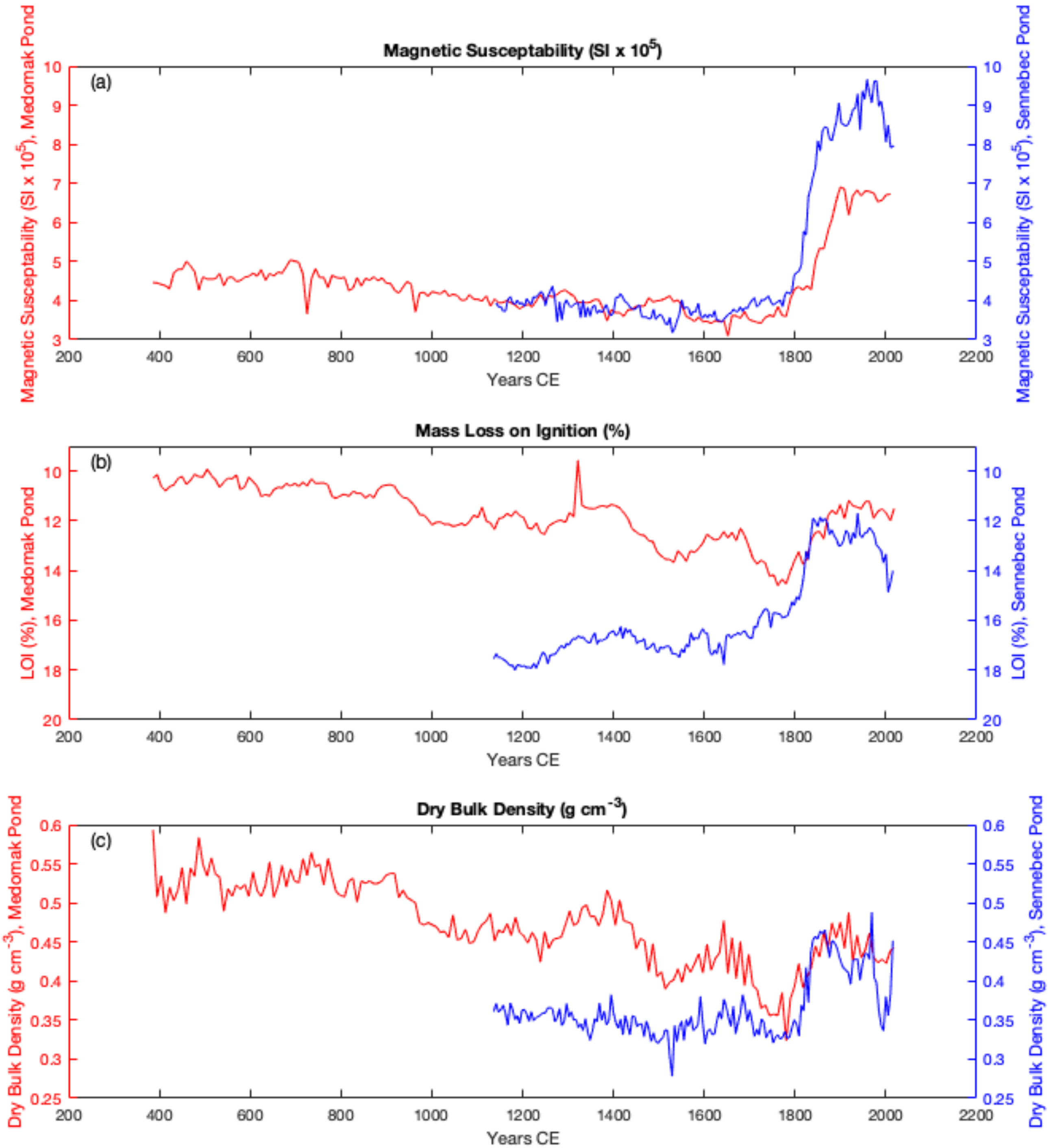

Figure 9. The magnetic susceptibility, percent LOI, and dry bulk density for Medomak (red) and Sennebec (blue) ponds.

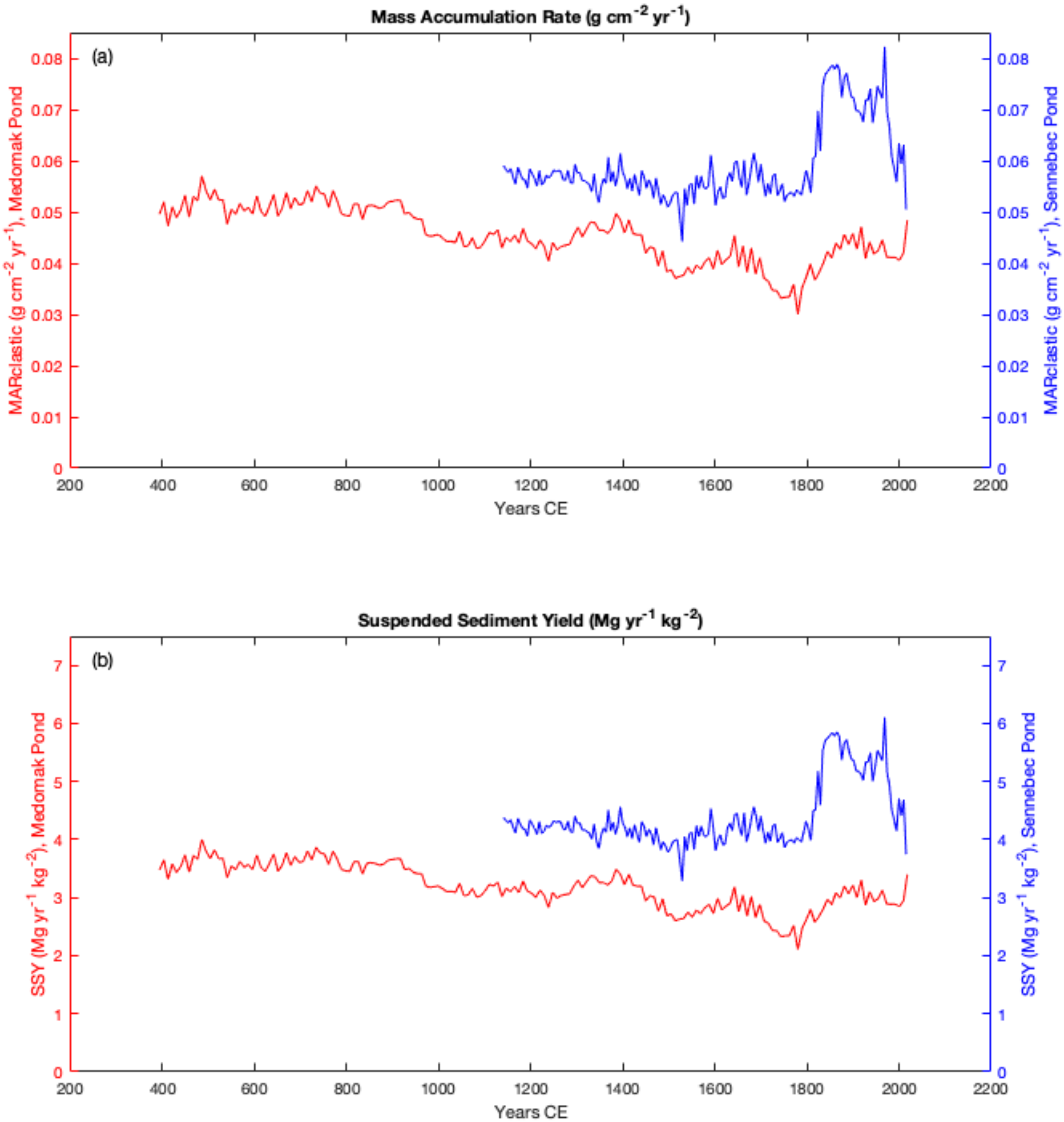

Figure 10. The $MAR_{clastic}$ (above) and SSY (below) values for Medomak (red) and Sennebec (blue) ponds.

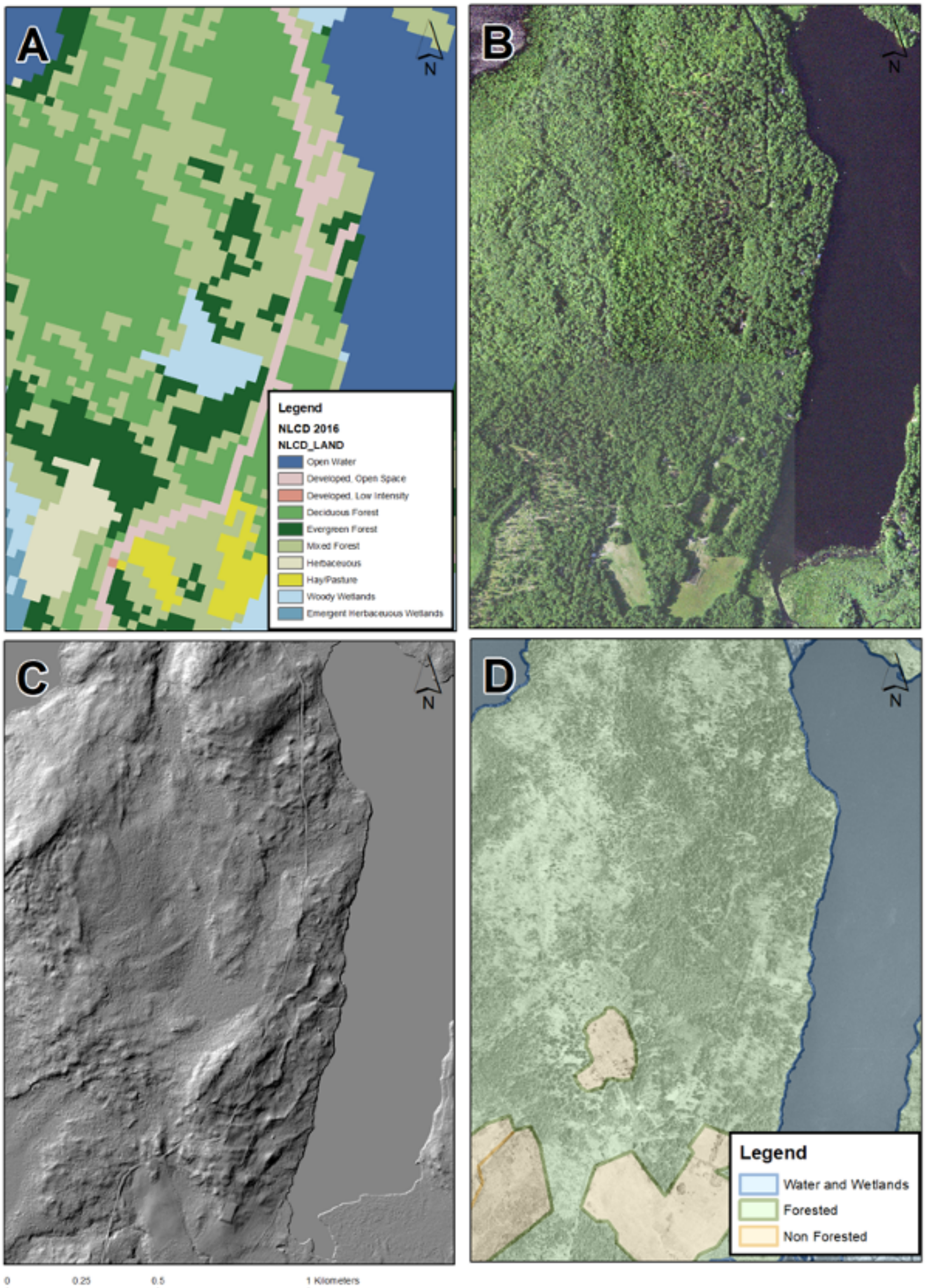

Figure 11. One sample of imagery analyzed, demonstrating difficulty in discerning woody wetlands from forested area. The data displayed is from A) NLCD 2016 B) 2018 NAIP orthophotograph C) LiDAR D) 1956 orthorectified images. 1956 image includes land-cover interpretations.

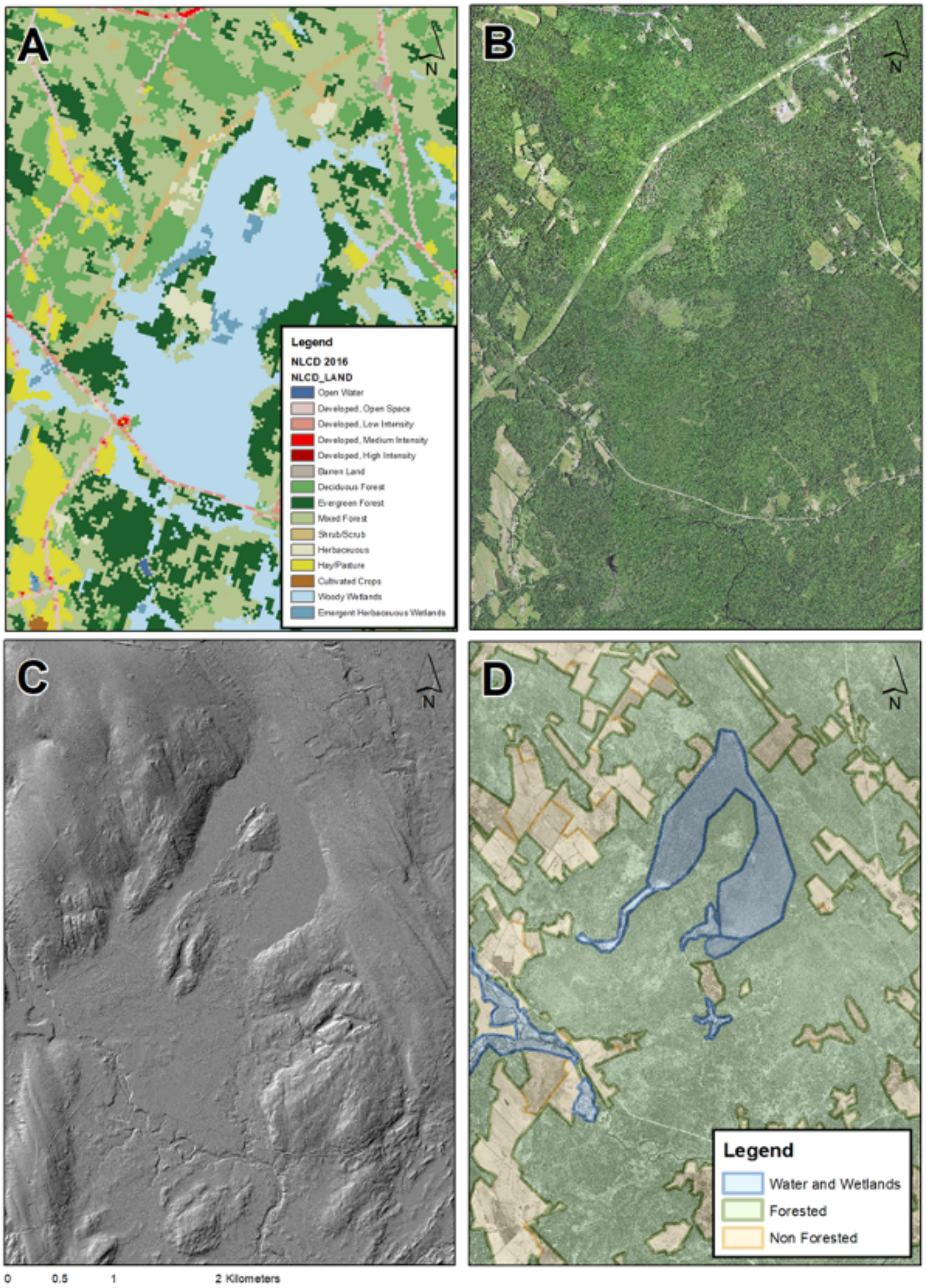

Figure 12. A second sample of imagery analyzed, demonstrating difficulty in discerning woody wetlands from forested area. The data displayed is from A) NLCD 2016 B) 2018 NAIP orthophotograph C) LiDAR D) 1956 orthorectified images. 1956 image includes land-cover interpretations.

Table 5.
The results from GIS analysis of aerial imagery for land cover change. Woody wetlands, which was a category of the NLCD 2016 data and summed under the category of Water and Wetlands for the purposes of this study, is separated out and shown here.

Medomak		*1953-1956*	*NLCD 2016*
	Water and Wetlands	9.76%	19.42%
	Woody Wetlands (NLCD)		*15.13%*
	Non-Forested	27.93%	15.90%
	Forested	62.29%	64.68%
Sennebec		*1953-1956*	*2018*
	Water and Wetlands	10.17%	17.05%
	Woody Wetlands (NLCD)		*11.55%*
	Non-Forested	26.99%	14.76%
	Forested	62.90%	68.18%

CHAPTER 4. DISCUSSION

The temporal ranges of the most recent 200 years and the preceding 670 years used in the lake core analysis were chosen as intervals of importance because of this study's interest on the period of accelerated EuroAmerican settlement, as well as qualitative observations of the trends demonstrated in Figures 9 and 10. Although EuroAmerican settlers began establishing permanent settlements in Maine as early as the 1600s, populations remained relatively small until Maine gained statehood approximately 200 years ago, when sporadic warfare ended and the densely forested state was admitted into the Union (Barton et al. 2012). Both core records show a reversal of trends around this time (Figures 9 and 10). Thus, an interval of 200 years was chosen as a reasonable period over which to quantify more recent changes in the sediment record of both lakes. Although the radiocarbon analysis revealed that the Medomak record extends longer than the ~880 year Sennebec cores, the intervals of quantitative analysis were kept consistent between both watersheds for inter-watershed comparability. For this reason, the interval for pre-colonial analysis was designated as the ~670 years preceding the modern interval for both watersheds.

Magnetic susceptibility, percent loss on ignition, and dry bulk density are all metrics for distinguishing clastic sediment content in the lake core. The volume of clastic sediment being delivered to the lake is important because it provides insight into how fast clastic sediment is being weathered and transported from the watershed to the water body. Because of this, it was expected that ρ_{db} and magnetic susceptibility would increase during periods of heightened land clearance, and %LOI would decrease due to a higher volume of clastic material being delivered to the lakes. In order to calculate actual mass accumulation rates and the total yield of suspended sediment to the lake over time, LOI and ρ_{db} are important factors in calculating $MAR_{clastic}$ and SSY (equations 3 and 4).

While the magnitude of the changes between the two identified intervals of time at Sennebec are relatively greater than those demonstrated at Medomak, similar trends were observable in both datasets. In particular, between the most recent 200 year interval and the preceding 670 year interval, both watersheds experienced higher values of magnetic susceptibility and dry bulk density (ρ_{db}) and lower percentages of mass lost on ignition (LOI) (note flipped axis of LOI data) (Figure 9). The concurrence of a trend reversal in all three datasets suggests that both watersheds experienced a period of heightened minerogenic sediment accumulation, which is a reflection of increased delivery of clastic material to each lake around 1800 CE.

Although this trend reversal is evident in both qualitative observations and quantitative analyses of each dataset, the difference in the magnitude of change experienced at each watershed is interesting because of their proximity to one another. Because they are geographically adjacent, they have similar population histories (Greenleaf, 1829) (Table 2) and similar distribution of public use buildings such as school houses and infrastructure reliant on land clearance such as saw mills (Maine State Archives, 1884, *Knox County*; Maine State Archives, 1884, *Waldo County*) (Figures 13 and 14). These similarities allude to a similar historic pattern of both population and land clearance in both watersheds. The similarities of land use between the watersheds are further evidenced in more recent years by the results of the GIS analysis, as both the aerial imagery and NLCD 2016 data suggest similar recent land cover changes in both watersheds (Table 5).

Therefore, it is likely that the different magnitude of change experienced between the two watersheds is not due to different land use histories, but instead a consequence of different watershed characteristics. Although they have very similar ratios of lake area to watershed area, the smaller lake area, shallower mean depth, and lower annual inflow rate of Medomak Pond could all contribute to a smaller sediment input to the lake (Table 1). The residence time of water within the lake (volume of lake / inflow rate) is consequently shorter in Medomak Pond (approximately 13 days) than it is in Sennebec Pond (approximately 23 days) (Table 1). This likely leads to lower retention of sediment in Medomak Pond than Sennebec Pond, which could potentially contribute to the more muted changes in indicators of clastic input, such as LOI and dry bulk density.

The potential consequences of these watershed characteristics on percent LOI and dry bulk density measurements could have further implications for the clastic mass accumulation rates ($MAR_{clastic}$) and suspended sediment yield (SSY) estimates (Figure 10). While there is a similar change in $MAR_{clastic}$ and SSY trends for both Medomak and Sennebec ponds around the turn of the nineteenth century, it is notably more muted in the Medomak core. The aforementioned watershed characteristics can impact this, as both LOI and dry bulk density are factors in deriving $MAR_{clastic}$ (Equation 3) and SSY (Equation 4).

The age control points for Medomak Pond are generally concentrated towards older dates, while those in Sennebec Ponds are relatively younger (Figure 8). A linear regression was used to develop the age-depth plots because neither set of control points were straightforward, i.e. samples were not always older than those at shallower depths. This was the best possible option to create an age-depth model without making any assumptions about which control points were outliers. However, by running a linear regression through all control points, this age-depth model inherently reduces variability of the dataset. Because SR is a direct factor in calculating both $MAR_{clastic}$ and SSY (Equations 3-4), the underestimate of the variability with a linear regression would result in an underestimate of the variability of both of these values. With a constant SR, the variability that is observed in the $MAR_{clastic}$ and SSY results is solely a consequence of compositional changes of the sediment and not changes in the rate of sediment delivery to the lake. In particular, because there are no recent age control points for Medomak, when the sedimentation rate (SR) was likely higher, the sedimentation rate derived from the age-depth model is likely an underestimate of the overall linear trend for more recent years. It is likely that some combination of watershed characteristics and the conservative choice of age-depth model contributed to the lower magnitude of changes in the trends observed at Medomak Pond. It is important to note that there is some uncertainty about the recent age constraints on both ponds, as additional analysis such as ^{210}Pb, ^{214}Pb or ^{137}Cs dating were not performed within the scope of this study. However, while this makes the precise timing of the observed trend reversal slightly more uncertain, it likely falls around the reported times.

Results from the GIS land cover analysis demonstrate an increase of forest cover and decrease in non-forested land over the past half century. It was difficult to discern water and wetlands from forested land in the 1950s imagery, particularly with regards to the distinction of woody wetlands from forested land (Figures 11 and 12). This led to a probable overestimate of historic forested land and subsequent underestimate of forest coverage change between 1950s and modern land cover measurements. I initially included woody wetlands under the category of water and wetlands when summing the NLCD 2016 data. While this categorization was logical in grouping land cover by similar sediment trapping potential, it made it difficult to maintain the same classification when identifying land cover in the 1950s imagery. Because woody wetlands is a high percentage of the composite water and wetlands category (Table 5), misclassification of woody wetlands as forested land in the 1950s imagery would make an impact on the total percent water and wetlands. Should the methodology of this study be repeated, two different avenues could be taken to remedy this challenge. If the scope of future studies remained the same, woody wetlands could instead be included under the category of forested land for the NLCD 2016 data, because the distinction is so difficult to make via greyscale aerial imagery. The resulting data from the historic imagery would be more comparable to the NLCD data, and there would likely be a larger increase in forested area observed between the historic and modern imagery. If the distinction of woody wetlands as water and wetlands is important to future work and LiDAR is available over the study area, there is a potential alternative methodology that could be used to circumvent the challenges of the greyscale imagery. The imagery could be used only to distinguish whether or not an area is forested, and the LiDAR data could be used to distinguish areas of lower-lying wetlands (Figures 11c and 12c).

Despite this challenge, however, it is evident that the area has experienced a general trend of reforestation of land altered for human use since the 1950s. This phenomenon of reforestation is not isolated to the study area, and can be observed across many areas of New England over the past half-century (Foster et al. 2008; Barton et al. 2012). Developing future studies that follow similar veins to this one would contribute towards a greater understanding of how the history of colonial land clearance to modern reclamation of forested land impacts the sedimentation patterns and watershed dynamics in New England, as there is potential for the legacy effects of cleared land to impact sediment delivery to watersheds that are currently undergoing a period of reforestation. However, with at least a 5.38% and 2.39% increase in forest cover and -12.23% and - 12.03% decrease in non-forested land in Sennebec and Medomak watersheds (respectively) over the past ~50 years, it is reasonable to expect soil rates from agricultural lands to be decreasing (Table 5). Furthermore, figures 7 and 8 appear to show a general trend in magnetic susceptibility, %LOI, ρ_{db}, $MAR_{clastic}$ and SSY back towards pre-industrial levels, suggesting that the effects of reforestation indicated in the results of the GIS analysis may already be implicated in the sediment records of these watersheds.

A different story is told in the mountainous regions of Maine, as evidenced in Little Kennebago Lake (LKL) watershed (Cook et al., 2020). EuroAmerican land use in the region was primarily road construction and timber harvest, which did not begin until later in the 19^{th} century. This is reflected in the later acceleration of $MAR_{clastic}$ and SSY values at LKL around the turn of the 20^{th} century, nearly 100 years after a similar pattern is seen in the watersheds included in this study (Cook et al. 2020, Fig. 5). The signal of land clearance that is demonstrated in the $MAR_{clastic}$, SSY, and magnetic susceptibility data from LKL is much more pronounced than in Sennebec or Medomak. A number of factors could contribute to the different magnitude of $MAR_{clastic}$. SSY, and magnetic susceptibility acceleration between LKL and the lakes of the lower lying coastal region examined in this study. The 666 m relief of LKL is approximately 2x that of Sennebec, and nearly 3x that of Medomak (Table 1). With an average slope of 11 degrees (19 percent), LKL is approximately 2.8x steeper on average than both Sennebec and Medomak (Table 1). A steeper, higher relief watershed would contribute to more erosion off of the landscape and quicker delivery of sediment to the lake, which would contribute to the clastic-rich event layers observed in the LKL records. Furthermore, the LKL watershed contains 6.0% water and wetlands, compared to 17.05% in Sennebec and 19.42% in Medomak (Table 5). Both coastal watersheds have a higher percentage of water and wetlands than LKL, demonstrating higher sediment trapping potential that would slow the delivery of sediment to the watershed and potentially mute or lessen the signal of accelerated $MAR_{clastic}$ and SSY in the sediment record.

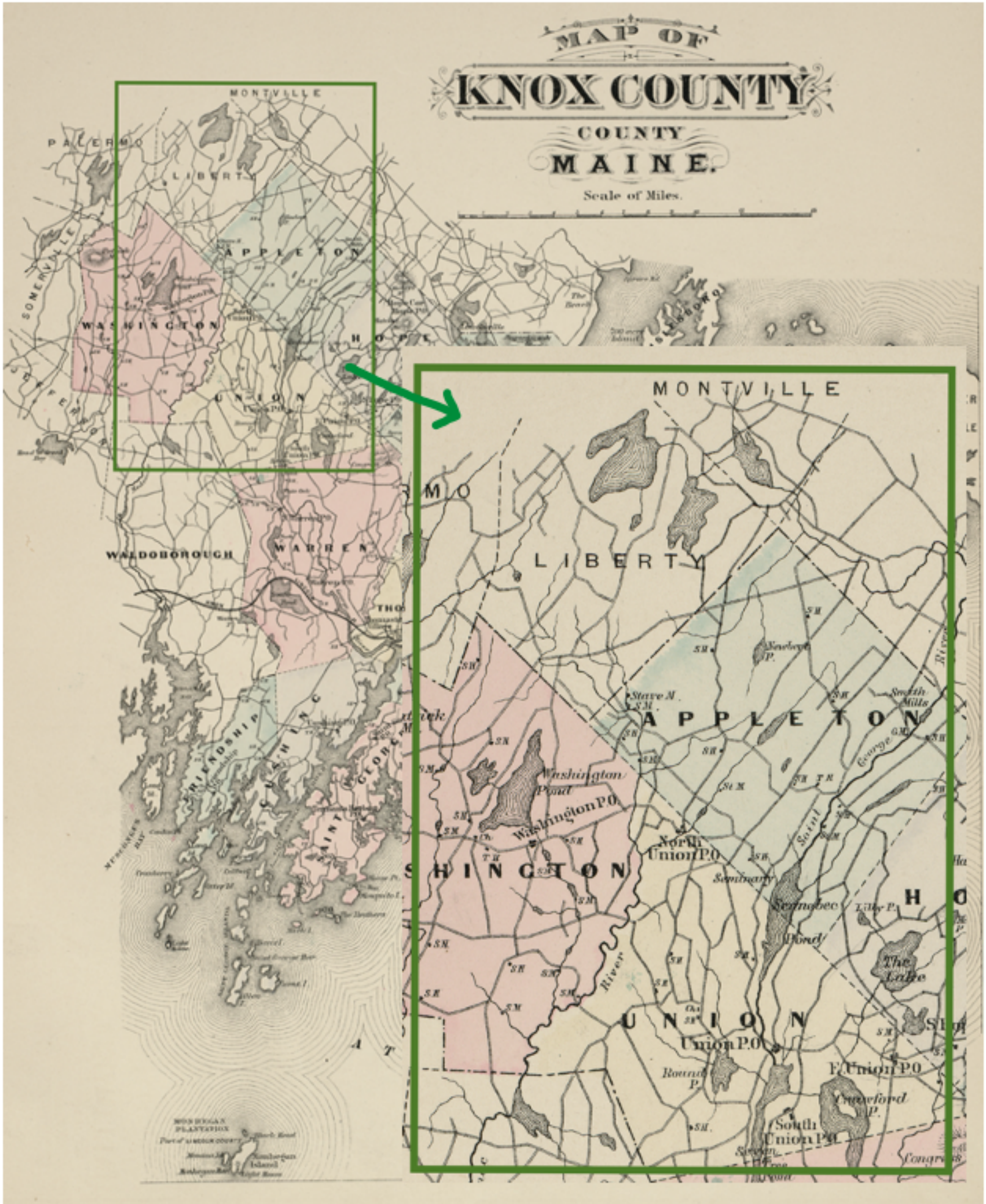

Figure 13. An 1884 map of Knox County, with school houses indicated with a S.H and sawmills indicated with a S.M. The zoomed insert is included for legibility of symbols, and the green rectangle represents the general area included in the study.

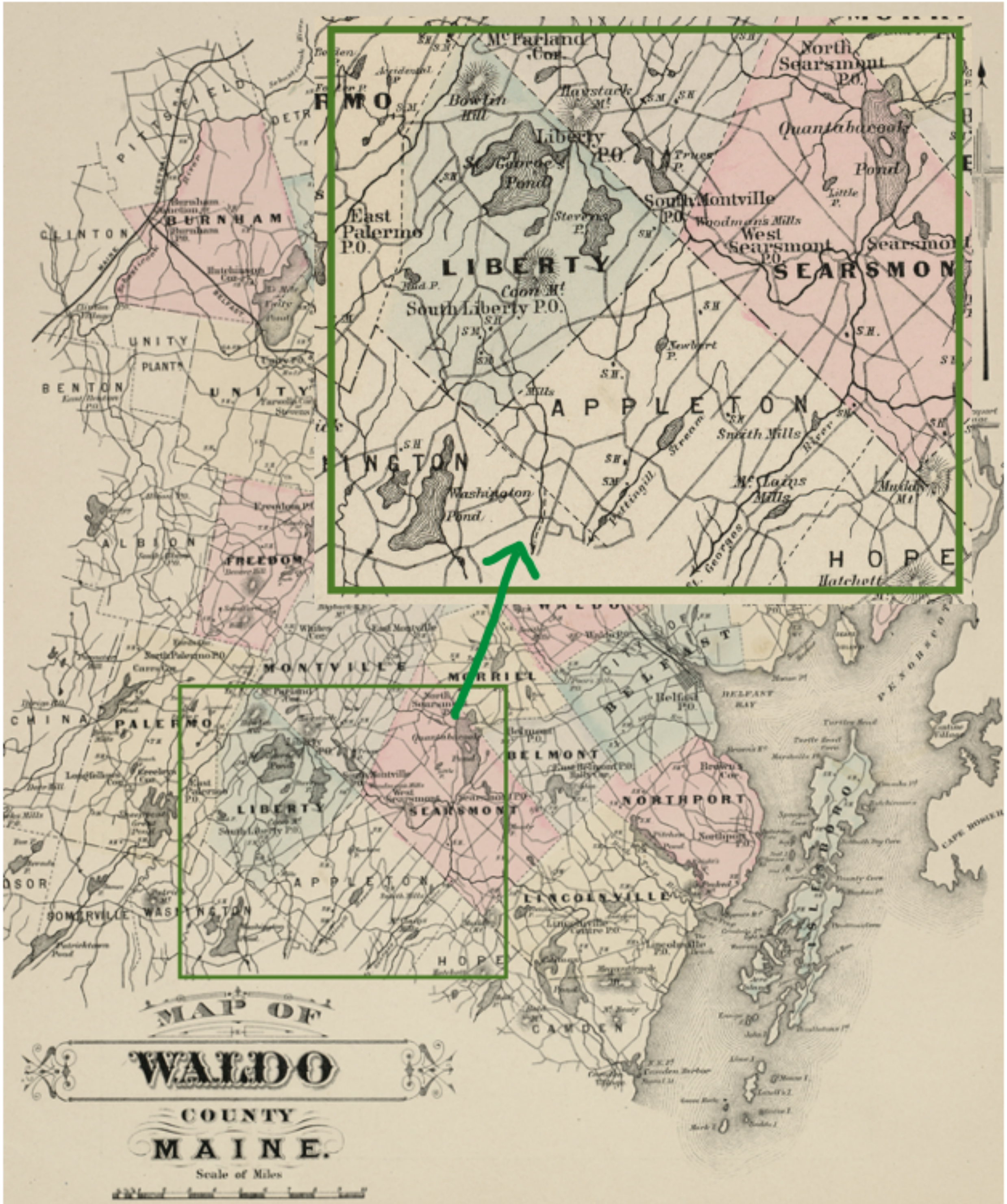

Figure 14. An 1884 map of Waldo County, with school houses indicated with a S.H and sawmills indicated with a S.M. The zoomed insert is included for legibility of symbols, and the green rectangle represents the general area included in the study.

5. CONCLUSION

This study quantified land use change in two coastal Maine watersheds through a combination of lake core and GIS analysis to understand the impact of anthropogenic land clearance on watershed dynamics. Lake core sampling and age-depth modeling provided sediment records of ~880 years (Sennebec) and ~1620 years (Medomak). Magnetic susceptibility, %LOI, and ρ_{db} measurements were collected and plotted against time. $MAR_{clastic}$ and SSY were then calculated and plotted against time to further our understanding of sedimentation patterns across each watershed's history. Results demonstrated that accelerated patterns of sediment delivery to both Sennebec and Medomak ponds corresponded with a period of accelerated land clearance by EuroAmerican settlers around the turn of the 19^{th} century.

Likely due to differences in watershed and lake characteristics, as well as the impact of age-depth model limitations on $MAR_{clastic}$ and SSY calculations, the signal of this land clearance in the sediment record was notably muted in the Medomak Pond record. However, the persistence of the pattern in Medomak Pond further demonstrates the impact of land clearance on sediment yield despite watershed characteristics, older age-control points, and a conservative age-depth model.

GIS analysis of aerial imagery revealed recent trends of reforestation over the past half-century. A general increase in forested land and decrease in anthropogenically altered land was evident from comparison of land cover analysis from the 1950s against land cover data from 2016. This follows similar trends exhibited in many parts of New England, as historically cleared land from the era of EuroAmerican settlement is generally being converted back to forested land. Furthermore, this study provides comparative data to that of Cook et al. (2020) in the mountainous watershed of Little Kennebago Lake, which experienced a different land use history than other regions of New England. Different watershed characteristics, such as mean slope, relief, and percent water and wetlands, potentially contributed to the different magnitudes of the results seen at LKL compared with Sennebec and Medomak. However, overall trends were similar between the two studies, as $MAR_{clastic}$ and SSY values increased around the time of accelerated EuroAmerican land-use change in each watershed.

As humans wrestle with the ecological and societal trajectory of the Anthropocene, it becomes increasingly important to understand how we have been impacting our ecosystems and environment for generations. By developing a comprehensive analysis of the impact of land cover change on watershed dynamics in coastal Maine, this study furthers the critical pursuit to understand how changes in anthropogenic activity across time are reflected in ecosystems and environmental processes.

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