Using Soil Testing Data to Examine Organic Carbon Changes During the Past 27 Years in Maine Agricultural Soils

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USING SOIL TESTING DATA TO EXAMINE ORGANIC CARBON CHANGES
DURING THE PAST 27 YEARS IN MAINE AGRICULTURAL SOILS

By

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Agricultural soils may act as a source or a sink for carbon (C) in the global C cycle. With rising atmospheric CO$_2$ levels, C sequestration in soils may play an important role in climate change mitigation. Soil organic carbon (SOC) also contributes to key aspects of soil health and fertility, such as aggregation, water-holding capacity, microbial biomass, and nutrient mineralization. Although SOC may be calculated from estimates of soil organic matter (SOM) obtained by loss-on-ignition (LOI), factors such as sample clay concentration and combustion temperature introduce error into estimates of SOM. We explored the potential for an extensive collection of LOI values determined by the Maine Soil Testing Service from a variety of agricultural cropping systems over the last 27 years to provide insights into trends in SOM, and therefore SOC, between crop groups and over time. We evaluated furnace temperatures from 375 to 950 °C, to determine the temperature that provides the strongest correlation between SOM estimated by LOI and SOC measured instrumentally by a LECO CN Analyzer. Next, we
evaluated whether including a soil texture term in a regression between SOM estimated by LOI and SOC measured instrumentally by a LECO CN Analyzer improved the ability to predict SOC. Finally, we identified trends in the SOC in Maine agricultural soils over the past 27 years based on standard soil samples received by the Maine Soil Testing Service from 1995 to 2021. On a sample set of 48 representative agricultural soils, the standard LOI temperature used by the Maine Soil Testing Service, 375 °C, correlated as well with SOC measured instrumentally as each of three higher temperatures we studied. All temperatures produced a Pearson’s correlation coefficient between 0.97 and 0.99, although the estimated concentration of SOM increased with increasing furnace temperature. Including a texture term in the regressions between SOC and SOM as estimated by LOI did not significantly impact or improve the estimation of SOC, which we found to be approximately 50% of SOM among our sample set of Maine agricultural soils. Using historical data since 1995, the SOC concentration estimated by LOI for Maine agricultural soils has increased by 23% from 1995 to 2021. SOC concentration of soils for grain, hay, and small-scale conventional vegetable and organic vegetable production increased by 24%, 15%, 23%, and 18%, respectively. SOC remained steady for corn and large-scale conventional vegetable and organic vegetable production, while trends for blueberries and apples were difficult to interpret. Among crop groups, only potato soils showed a decline in SOC since 1995. These results show that LOI with a combustion temperature of 375 °C, without the need for clay correction, can reliably estimate SOC of Maine agricultural soils. Further, our results show the value of historical data archived by the Maine Soil Testing Service to examine changes in Maine’s agricultural soils over time.
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TABLE OF CONTENTS

ACKNOWLEDGEMENTS ........................................................................................................................................... i

LIST OF TABLES ..................................................................................................................................................... iv

LIST OF FIGURES .................................................................................................................................................... v

Chapter

1. INTRODUCTION ..................................................................................................................................................... 1

1.1. Literature review ............................................................................................................................................... 1

1.1.1. Carbon sequestration in agricultural soils ......................................................... 1

1.1.2. Soil organic carbon ................................................................................................. 2

1.1.3. Impacts of soil texture on soil carbon .................................................................. 4

1.1.4. Management practices and soil carbon sequestration ....................................... 5

1.1.5. Soil testing and soil organic matter monitoring .............................................. 7

1.1.6. Maine agricultural crops and management practices .................................. 8

1.1.7. Estimation of soil organic matter concentration ............................................ 11

1.1.8. Estimation of soil organic carbon concentration ......................................... 12

1.2. Research objectives ................................................................................................................................. 13

2. MATERIALS AND METHODS .......................................................................................................................... 15

2.1. Experimental sample set selection ...................................................................................... 15

2.2. Determination of organic carbon and total nitrogen .................................................. 17

2.3. Determination of soil texture ......................................................................................... 17

2.4. Estimation of soil organic matter by loss-on-ignition .............................................. 20

2.5. Data analysis ................................................................................................................................. 22
2.6. Historical soil testing data........................................................................................................23

3. RESULTS AND DISCUSSION....................................................................................................25

3.1. Characteristics of Maine agricultural soil samples...........................................................25

3.2. Effects of furnace temperature, soil texture, and air-dry moisture content of soil on estimation of soil organic carbon concentration ...........................................................................31

3.3. Soil organic carbon concentration of Maine agricultural soils over time .........................38

3.4. Conclusions.......................................................................................................................56

REFERENCES ..........................................................................................................................57

APPENDICES ...........................................................................................................................65

APPENDIX A: PRELIMINARY WORK ON REMOVAL OF EXCESS ORGANIC MATTER BY SODIUM HYDROXIDE ..........................................................................................................................65

APPENDIX B: REMOVAL OF CARBONATES, SOIL ORGANIC MATTER, AND IRON AGGREGATES FOR DETERMINATION OF SAMPLE TEXTURE .................................................................68

APPENDIX C: ADDITIONAL FIGURES ...................................................................................71

BIOGRAPHY OF THE AUTHOR ............................................................................................82
List of Tables

Table 3.1. Mean and range of soil organic carbon (SOC), total nitrogen, sand, clay, and pH of 48 soils included in Sample Set 1, by crop group ..........27

Table 3.2. Mean and range of soil organic carbon (SOC), total nitrogen, and pH of 43 soils included in Sample Set 2, by crop group .........................................28

Table 3.3. Mean of soil organic matter (SOM), soil organic carbon (SOC), and total nitrogen; ratio between SOC and SOM (SOC:SOM), and carbon to nitrogen ratio (C:N) for all soil samples from Sample Set 1 and Sample Set 2, by crop group .........................................................................29

Table 3.4. Mean and range of soil organic matter (SOM), soil organic carbon (SOC), and pH of Maine agricultural soil samples as determined by the Maine Soil Testing Service from 1995 to 2021 .................................30

Table 3.5. Regression coefficients for soil organic carbon (SOC) versus soil organic matter (SOM) estimated from four different combustion temperatures for 48 soils in Sample Set 1 .................................................................33

Table A.1. Resulting loss-on-ignition (LOI) values and supernatant soil organic matter (SOM) after each of three 2-hr sodium hydroxide (NaOH) extractions from soils with a range of initial LOI values .........................67
LIST OF FIGURES

Figure 2.1. Locations and crop groups of 91 soil samples included in Sample Set 1 and Sample Set 2.................................................................................................................................16

Figure 2.2. Positions of crucibles within the Thermolyne muffle furnace during loss-on-ignition (LOI) .................................................................................................................................21

Figure 3.1. Textural classes of 48 soils included in Sample Set 1, by crop group........26

Figure 3.2. Relationship between soil organic carbon (SOC) and soil organic matter (SOM) determined by loss-on-ignition (LOI) at four combustion temperatures for 48 soils in Sample Set 1 ...............................................................32

Figure 3.3. Relationships between sand (A), silt (B), and clay (C) and soil organic carbon (SOC) for 48 soil samples in Sample Set 1.................................35

Figure 3.4. Relationship between soil organic carbon (SOC) and air-dry moisture content for 91 soil samples in Sample Set 1 and Sample Set 2 ..........37

Figure 3.5. Relationship between soil organic carbon (SOC) and carbon to nitrogen ratio (C:N) for 91 soil samples in Sample Set 1 and Sample Set 2 .................................................................................................................................40

Figure 3.6. Relationship between soil organic carbon (SOC) and soil organic matter (SOM) as determined by the Maine Soil Testing Service for 91 soil samples in Sample Set 1 and Sample Set 2 .................................41

Figure 3.7. Relationship between soil organic carbon (SOC) and soil organic matter (SOM) as determined by the Maine Soil Testing Service for 91 soil samples in Sample Set 1 and Sample Set 2, when the
y-intercept is constrained to zero.

Figure 3.8. Three-year rolling means of soil organic carbon (SOC) across all samples from all crop groups from 1995 to 2021.

Figure 3.9. Mean soil organic carbon (SOC) of each crop group across all samples included from 1995 to 2021.

Figure 3.10. Three-year rolling means of soil organic carbon (SOC) from Grain (oats, barley, etc.) soil samples from 1995 to 2021.

Figure 3.11. Three-year rolling means of soil organic carbon (SOC) from Hay (includes grass and pasture) soil samples from 1995 to 2021.

Figure 3.12. Three-year rolling means of soil organic carbon (SOC) from Veg Con S (Conventional mixed vegetables small, <5,000 ft²) soil samples from 1995 to 2021.

Figure 3.13. Three-year rolling means of soil organic carbon (SOC) from Veg Org S (Organic mixed vegetables small, <5,000 ft²) soil samples from 1995 to 2021.

Figure 3.14. Three-year rolling means of soil organic carbon (SOC) from Corn (includes silage and excludes sweet corn) soil samples from 1995 to 2021.

Figure 3.15. Three-year rolling means of soil organic carbon (SOC) from Veg Con L (Conventional mixed vegetables large, >5,000 ft²) soil samples from 1995 to 2021.

Figure 3.16. Three-year rolling means of soil organic carbon (SOC) from Veg Org L (Organic mixed vegetables large, >5,000 ft²) soil samples.
from 1995 to 2021........................................................................................................52

Figure 3.17. Three-year rolling means of soil organic carbon (SOC) from Potato
soil samples from 1995 to 2021..................................................................................53

Figure A.1. Soil organic matter (SOM) visible in supernatant after each of three
sodium hydroxide (NaOH) extractions for 2, 4, 6, or 12 hr.................................65

Figure A.2. Soil organic matter (SOM) visible in supernatant after each of three
2-hr sodium hydroxide (NaOH) extractions from soils with a range
of initial loss-on-ignition (LOI) values......................................................................66

Figure C.1. Three-year rolling means of soil organic carbon (SOC) from Apple
soil samples from 1995 to 2021.................................................................................71

Figure C.2. Three-year rolling means of soil organic carbon (SOC) from
Blueberry soil samples from 1995 to 2021..............................................................72

Figure C.3. Yearly means of soil organic carbon (SOC) across all soil samples
for all crop groups from 1995 to 2021....................................................................73

Figure C.4. Yearly means of soil organic carbon (SOC) from Grain
(oats, barley, etc.) soil samples from 1995 to 2021................................................74

Figure C.5. Yearly means of soil organic carbon (SOC) from Hay
(includes grass and pasture) soil samples from 1995 to 2021...............................75

Figure C.6. Yearly means of soil organic carbon (SOC) from Veg Con S
(Conventional mixed vegetables small, <5,000 ft²) soil samples
from 1995 to 2021.....................................................................................................76

Figure C.7. Yearly means of soil organic carbon (SOC) from Veg Org S
(Organic mixed vegetables small, <5,000 ft²) soil samples from
Figure C.8. Yearly means of soil organic carbon (SOC) from Corn
includes silage and excludes sweet corn) soil samples from
1995 to 2021 .................................................................................................78

Figure C.9. Yearly means of soil organic carbon (SOC) from Veg Con L
(Conventional mixed vegetables large, >5,000 ft²) soil samples from
1995 to 2021 .................................................................................................79

Figure C.10. Yearly means of soil organic carbon (SOC) from Veg Org L
(Organic mixed vegetables large, >5,000 ft²) soil samples from
1995 to 2021 .................................................................................................80

Figure C.11. Yearly means of soil organic carbon (SOC) from Potato soil samples
from 1995 to 2021..........................................................................................81
CHAPTER 1
INTRODUCTION

A major component of soil is the element carbon (C), which exists in organic and inorganic forms. Organic carbon (OC) in soils comes from dead plant, animal, and microbial biomass, with contributions from living biomass. Organic compounds contain carbon-carbon bonds, with elements such as hydrogen, oxygen, nitrogen, phosphorus, and sulfur covalently bonded to C atoms. Conversely, inorganic C is found in minerals, primarily in carbonates that are produced biotically and abiotically, and as carbon dioxide (CO₂).

1.1 Literature review
1.1.1 Carbon sequestration in agricultural soils

Soils contain a large reservoir of OC, with a global mean estimated at 1520 Pg (Scharlemann et al., 2014) stored in the top 1 meter of the world’s soils, with roughly 10% of this (140 Pg) in the top 30 cm of agricultural soils (Zomer et al., 2017). OC is sequestered in the soil when biomass from plants, animals, and microbes is incorporated and stabilized as soil organic C (SOC) (Bruce et al., 1999). The soil pool of OC holds more C than global vegetation and the atmosphere combined (Scharlemann et al., 2014; Zomer et al., 2017). The capacity of soils to sequester C makes cropland soil management an important approach to mitigate greenhouse gas-induced climate change.

Because soils globally contain a major pool of C, soils may act as a significant sink or a source for C. C losses from the soil to the atmosphere happen by biological respiration and decomposition of organic matter (Schlesinger and Andrews, 2000). For example, conversion of
grasslands or forests to cropland may reduce SOC by 20 - 40%, and possibly as much as 70% (Davidson and Ackerman, 1993; Crews and Rumsey, 2017). While reviewing estimates for historic global SOC losses due to conversion of native vegetation to crop land, Lal (2003) found published estimates widely varied from 40 to 537 Pg of loss. More recently, a global loss of 133 Pg C was estimated from the top 2 meters of soil due to conversion of land to agriculture based on a model that included global SOC data, historical and modern land use, land characteristics, and climate (Sanderman et al., 2017).

Despite the losses in SOC with conversion to cropland, improvements in agricultural soil management that increase C sequestration could mitigate atmospheric CO₂ increases. For example, C sequestration models developed by Zomer et al. (2017) showed that globally croplands have the potential to sequester between 0.9 and 1.85 Pg C year⁻¹. The estimated total annual emissions of C from human activities were 10.7 Pg in 2021 (Friedlingstein et al., 2022). Sequestering between 0.9 and 1.85 Pg C year⁻¹ through cropland management could match between 8.4 - 17.3% of annual C emissions.

1.1.2 Soil organic carbon

OM in soil can be categorized conceptually by degree of decomposition and stability (Ramesh et al., 2019). Litter is the organic debris composed of the bulk, largely undecomposed remains of leaves, stems, and roots (FAO ITPS, 2015). The labile fraction includes the pool of biomass from plants and microbes that may degrade over months to several years (FAO ITPS, 2015). This fraction, which provides a consistent source of energy for microorganisms, is the source from which mineralized plant-available nutrients are released (Strosser, 2010). Also within the labile pool is particulate SOM, a sand-sized fraction that is easily decomposed and is
sensitive to management practices (Besnard et al. 1996). The intermediate fraction is a pool of SOM that has been degraded by microbes, and partially stabilized by organo-mineral complexes and by location within aggregates (FAO ITPS, 2015); it contributes to the cation exchange capacity of soils (Strosser, 2010). This fraction may remain in soils for several years to a few decades (FAO ITPS, 2015; Strosser 2010). The refractory fraction is a pool of C that is recalcitrant against decomposition, as it is protected by more fully stabilized organo-mineral complexes or by location within stable aggregates; it also includes pyrogenic C. This fraction can remain in the soil from decades to centuries (Strosser, 2010) and potentially for millennia (FAO ITPS, 2015).

Soil organic matter (SOM) is formed from plant and microbial biomass inputs. Plant-based SOM includes lignin, saccharides (cellulose and hemi-cellulose), and pectin (Cline and Zak, 2015). Lignin can make up 15 - 40% of the mass of litter (Krishna and Mohan, 2017). Lignin is made up of a series of aromatic rings and is thought to be resistant to bacterial degradation, but is decomposable by white-, brown-, and soft-rot fungi (Krishna and Mohan, 2017). In contrast to lignin, cellulose and hemicellulose are much more labile (Chen et al., 2018a). Most plant biomass is cellulose and hemicellulose, and a variety of different soil bacteria and fungi produce a large variety of cellulases and hemicellulases to degrade them (López-Mondéjar et al., 2016).

SOM provides many benefits to the health and productivity of agricultural soils. The primary physical benefit of SOM is a decrease in soil bulk density. SOM plays a role in the creation of soil aggregation (Guhra et al., 2022), a vitally important component of soil that provides structural stability and can decrease both soil bulk density and soil erosion (Torri et al., 1998). Increased aggregation due to additional SOM increases pore space of soils, increasing the
water-holding capacity, especially in sandier soils (Minasny and McBratney, 2018). Soils with high bulk density have a greater risk of reduced soil porosity through compaction, which reduces the movement of air and water, and impedes root growth (Nawaz et al., 2013). Soils that are not compacted have greater microbial activity and diversity (Ishak and Brown, 2018), which may reflect increases in suitable microbial habitat and available SOC. SOM, which can provide sites for cations that can be exchanged with the soil solution (Ramos et al., 2017), stores nutrients and can also buffer soil against changes in pH (Curtin and Trolove, 2013). SOM also provides energy to microbes, which mineralize nutrients from SOM to forms available to plants (Gan et al., 2020).

1.1.3 Impacts of soil texture on soil carbon

Soil texture, the proportion of sand, silt, and clay in a soil, is known to impact C sequestration. Recalcitrant SOM fractions like lignin and aromatic SOM, which contain no hydrolyzable bonds, tend to be associated with sand and coarse silt, because the more labile fractions are mineralized rapidly (Han et al., 2016). Additionally, lignin and aromatic SOM seem to adsorb onto coarse silt and sand fractions, as finer textured soils have lower lignin concentration as a proportion of total SOM (Han et al., 2016). Sand is associated with increased and faster decomposition of labile SOM (Marhan and Sheu, 2004), likely due to increased microbial activity in coarser soils where SOM is not protected from degradation by organo-mineral complexes and aggregation (Hassink, 1995; Franzluebbers et al., 1996). For this reason, SOM in sandier soils is more sensitive to cultivation, and SOM losses following cultivation are more pronounced (Six et al., 2002).
Clays and finer silts are associated with an increase in the physically and physio-chemically protected SOM. For example, silt and clay tend to form aggregates around particulate organic matter (POM) by adsorption that physically protect it from decomposition. Schweizer et al. (2021) found that increasing clay concentration led to a greater proportion of POM relative to mineral-associated SOM. Moreover, clay soils physio-chemically protect lower molecular-weight organic molecules, such as those leached from litter or produced by microbial processing of SOM, through formation of organo-mineral complexes into mineral-associated SOM (Lavallee et al., 2020; Lal, 2018; Schweizer et al., 2021). For this reason, microbially derived carbohydrates are more abundant in the clay and silt fraction than in the sand fraction soils (Puget et al., 1999). Soils that have a greater 2:1 clay content have a larger fraction of SOM that is associated with silt and clay than soils with more 1:1 clays (Six et al., 2002). This is because 2:1 clays, which are composed of an octahedral sheet between two tetrahedral sheets, are better able to form stable microaggregates by entrapment of SOM than 1:1 clays with one tetrahedral sheet and one octahedral sheet (Virto et al., 2008).

1.1.4 Management practices and soil carbon sequestration

Several management practices in agricultural systems are associated with decreases in soil C. For example, cultivation of fields breaks down the aggregates that protect SOM and expose it to microbial decomposition (Six et al., 2002). Although the mineral-associated SOM that is bound to silt and clay is physio-chemically protected, POM is especially prone to be lost by microbial decomposition when macroaggregates are broken down into microaggregates and microaggregates are reduced by cultivation (Six et al., 2002). In addition to C losses by cultivation, having bare soil, such as between crop plants or during fallow periods, also adds to C
losses from agricultural soils (Crews and Rumsey, 2017; Golchin and Asgari, 2008) due to lack of plant inputs and to wind or water erosion. Burning of plant residues can cause a loss of potentially mineralizable nitrogen, total nitrogen, and total C (TC), while also increasing the erosion potential of soils (Biederbeck et al., 1980). Biomass removal at harvest and growing low-residue crops limits the plant residues available to replace degraded SOM (Paustian et al., 2016). Even worse, the harvest of low-residue root crops actually removes SOM because the high-OM soil adhering to the crop is harvested along with the crop (Faraji et al., 2017).

Although many management practices reduce soil C, conservation agriculture practices can rebuild SOC using the principles of minimal soil disturbance, maximum ground cover, and crop diversification (Page et al., 2020). The use of cover cropping for increasing SOM and reducing SOM losses due to bare fallowing can rebuild SOM through the addition of plant residues (Villamil et al., 2006; Christopher et al., 2021). Rotating low-residue crops with high-residue crops can also increase the C added to the soil (Page et al., 2020). Labile C and microbial biomass C are very responsive to management and land-use changes, which makes them good indicators of recent soil changes, while total SOC may be a better indicator of long-term changes (Ramesh et al., 2019).

The addition of organic amendments, such as manures and compost directly contribute organic matter to soil by supplying labile and intermediate SOM. Application of manure has been shown to increase SOM concentration by increasing POM concentration (Mando et al., 2005), aggregation (Lin et al., 2019), and labile SOM (Yan et al., 2007). The labile fraction provides energy for microbes that in turn produces plant-available forms of nutrients like phosphate, sulfate, ammonium, and nitrate by mineralization (Jacoby et al., 2017). In addition,
Some producers use reduced-till and no-till practices to decrease the disruption of soil. Reduced or no-till farming is associated with more stable soil aggregates, more physical protection of carbon, and higher SOC than conventional tilling, at least in surface horizons (Ramesh et al., 2019; Valkama et al., 2020). In Maine, farmers have shifted toward reduced or no-till practices. From the 2012 to 2017 census, acres of cropland in no-till production increased from 9,909 to 21,676 (NASS, 2019). Similarly, the acres with other reduced tillage practices increased from 18,994 to 31,953. Intensively tilled cropland decreased from 145,558 acres to 99,167 acres from 2012 to 2017 (NASS, 2019), and cropland planted to cover crops in Maine also increased from 29,379 acres to 55,462 acres from 2012 to 2017.

1.1.5 Soil testing and soil organic matter monitoring

Soil testing gives agricultural producers invaluable information about the nutrient content, pH, and organic matter of soils sampled from their fields. In addition to providing measurements of common soil nutrients, testing laboratories typically provide recommendations for the application of fertilizer, lime, or other amendments. SOM of submitted samples is routinely measured by soil testing laboratories because of the important role of SOM in soil structure and aggregation, water holding capacity, and nutrient retention. The Maine Soil Testing Service has included SOM concentration in the standard soil test for decades and maintains an archive of SOM results dating back to 1995. This record includes submissions from the general public, as well as from diverse sectors of Maine’s agriculture economy across the state.
1.1.6 Maine agricultural crops and management practices

Maine has a diversity of agriculture crops that are grown on hundreds of thousands of acres. In the 2017 Census of Agriculture (NASS, 2019), Maine had 472,508 acres in cropland, or about 2% of the state’s area (NASS, 2019). The major agricultural regions of Maine are the northeastern portion for potatoes, the southeastern (“Downeast”) region for lowbush (wild) blueberries, and southern Maine for apples, three of Maine’s most valuable crops. Potatoes, lowbush blueberries, and apples, respectively, were worth $142,132,000 (NASS, 2022a), $80,303,000 (NASS, 2022b), and $37,610,796 (NASS, 2022b) in Maine in 2021.

Economically important crops in Maine ranked by land area include hay, grass, and pasture; potatoes; grains; lowbush blueberry; corn; apples; and vegetables. Hay, grass, and pasture accounted for a total of 270,121 acres, with 175,231 acres of hay, haylage, grass silage, and greenchop and 94,890 acres in pastureland in 2017 (NASS, 2019). Potatoes were harvested on 50,211 acres in 2017, 45,823 of those in Aroostook County in northern Maine (NASS, 2019). Grains other than corn accounted for 38,799 acres of cropland in Maine in 2017. Of these, barley was harvested from 15,115 acres (14,979 in Androscoggin County), oats from 21,294 acres (20,806 in Aroostook County), rye from 2,114 acres (1,882 in Aroostook County), and wheat from 262 acres (NASS, 2019). Lowbush blueberry growers had 38,660 acres in production in 2017, with Washington, Knox, and Hancock counties in Downeast Maine combined over 90% of production in the state (NASS, 2019). Corn was harvested from 32,581 acres, with 25,344 for silage or greenchop, and 7,237 acres for grain corn production (NASS, 2019). Apple orchards covered 2,668 acres in Maine in 2017, with most in Androscoggin, Oxford, and Penobscot counties (NASS, 2019). Vegetables other than potatoes were harvested from 2,028 acres, with the highest acres in Penobscot and Oxford counties (NASS, 2019).
Potatoes (*Solanum tuberosum*) in Maine are grown in soils that tend to be sandy, well drained, and slightly acidic. Potato cropping uses intensive cultivation, including plowing, disk ing, and harrowing prior to planting with seed potatoes (tubers) in the spring (Gallandt et al., 1998), and potato plants get hilled once or more during the growing season. In the fall, shoots are desiccated, and tubers are harvested by digging (Gallandt et al., 1998). Harvesting is done using heavy machinery, which is operated during the fall when soils tend to be wet (Saini and Grant, 1980). Potatoes in Maine are typically grown in a two-year rotation system (Gallandt et al., 1998).

Lowbush blueberry (*Vaccinium angustifolium*) is cultivated from natural populations on acidic, sandy barrens (Jensen and Yarborough, 2008; Barai et al., 2022). Most production happens in Downeast Maine, which is warming quicker than other parts of the state due to climate change (Tasnim et al., 2021). Lowbush blueberry is a rhizomatous, colony forming shrub that is managed as a patchwork of distinct clones (Barai et al., 2022). Once established, these barrens are managed on a two-year crop cycle with burning or mowing to nearly ground level, followed by a vegetative season, and then a fruiting season (Jensen and Yarborough, 2008). Management of these soils differs from most crops as there is no tillage and, subsequently, a large build-up of undecomposed plant residues.

Apples (*Malus domestica*) are grown in orchards throughout Maine and are the most valuable tree fruit in Maine (NASS, 2019). Apple varieties in the Northeast US are usually grown on dwarfing rootstocks that are planted in high density orchard rows (Autio et al., 2003). Apple orchards usually have mowed grass aisles between rows with herbicides, mulches, cultivation, or cover crops within rows for weed control (St. Laurent et al., 2008).
Corn and other grains (i.e., oats, barley, rye, and wheat), as well as hay, grass, and pasture, are grown in Maine for livestock feed. Corn (*Zea mays*) is often grown for silage in northern New England, but grain corn is also produced (NASS, 2019). Fields are tilled for sowing, which mixes in leftover plant residues and prepares fields for seeding. After harvest, corn stubble and other unused material are left in the field and later tilled into the soil, while grain stalks may be used as straw for animal bedding or left in the field to be tilled in (Larney and Angers, 2012). Grains are also often grown in crop rotations with potato. Hay is a forage made from grass, clover, alfalfa, and other plants. A hay field is typically mowed and raked at least once per year, and the hay is dried in the field, baled, and removed, whereas pastureland supports grass and other forage plants that are grazed in place.

Conventional and organic vegetable production includes numerous plant species that are grown in the state (NASS, 2019). The biggest difference between conventional and organic production is the use of synthetic fertilizers and pesticides by conventional producers (Renaud et al., 2015). Organic production uses compost and manure to introduce nutrients to soils in the form of slow-release nutrients and prohibits synthetic fertilizers and pesticides. Both conventional and organic vegetable production typically use tillage as a method to control weeds as well as prepare for seeding. However, organic vegetables often have greater weed pressure due the absence of synthetic herbicides (Renaud et al., 2015) and may be more reliant on tillage than conventional producers. Organic vegetable farmers use a variety of chemical-free weed control methods. According to a survey of northern New England organic growers, strategies used include mechanical cultivation, hoeing, hand pulling, black plastic mulch, and natural mulches of hay or leaves (Brown and Gallandt, 2020).
1.1.7 Estimation of soil organic matter concentration

SOM concentration is determined by various methods that all indirectly estimate SOM through oxidation of SOM. Walkley and Black (1934) developed the first widely used method to estimate SOM concentration. This method relies on the oxidation of SOM with potassium dichromate in the presence of sulfuric acid followed by a back titrate of unused dichromate with ferrous ammonium sulfate (Mylavarapu et al., 2014). This method has been widely used and is still a preferred method for precision measurement of SOM with soils containing less than 6% (Mylavarapu et al., 2014). However, several challenges make the Walkley-Black method problematic. Potassium dichromate is a highly toxic compound and concentrated acid is used, which requires costly disposal of this hazardous waste (Salehi et al., 2011).

Presently, loss-on-ignition (LOI) is the most common method used by soil testing laboratories to estimate SOM concentration. This method oxidizes SOM to CO₂ in a furnace at temperatures ranging from around <300 (Abella and Zimmer, 2007) to 800 °C (Salehi et al., 2011), leaving the mineral fraction behind (Ball, 1964). The difference in mass between oven-dried and ignited soil samples provides an indirect estimate of SOM on the assumption that all the mass lost from the sample is organic matter (Ball, 1964). Although several authors have suggested that LOI is best used as an imprecise estimate of SOM, its accuracy and precision have been found to be broadly comparable to the Walkley-Black method (Salehi et al., 2011). Moreover, LOI is less time-consuming and less costly than the Walkley-Black method (Salehi et al., 2011) and is readily applied to large sets of samples.

The accuracy of SOM determination is known to be affected by the presence of calcium carbonate (CaCO₃) and clay, and by combustion temperature. At high temperatures, CaCO₃ can degrade to give off CO₂ (Chatterjee et al., 2009), leading to more mass loss and a higher estimate.
of SOM in soils containing CaCO₃ compared to a similar soil with no carbonates. This can be avoided by combustion temperatures lower than 550 °C, at which 99.8% of carbonate remains intact (Hoogsteen et al., 2018) or by treating calcareous soils with hydrochloric acid (HCl) prior to weighing and combustion (Abella and Zimmer, 2007). Clays can also increase mass loss, and the estimate of SOM, during high-temperature combustion (Konen et al., 2002). At temperatures between 350 and 650 °C, silicate clay surfaces can dehydrate and release structural water, but a correction factor based on combustion temperature can be applied to account for this structural water loss (Hoogsteen et al., 2015). This structural water loss was found to be in the range of 0.56 to 2.45% by Sun et al. (2009). Higher temperatures can also cause the loss of water or hydroxyls from iron and aluminum oxides and hydroxides, leading to inflated estimates of SOM (Konare et al., 2010). Some have argued for correction factors to adjust SOC estimates depending on clay concentration, (De Vos et al., 2005) but the right correction factor is determined by combustion temperature and type of clay present and is difficult to determine unambiguously (Hoogsteen et al., 2015). Lower temperatures can lead to incomplete combustion (Hoogsteen et al., 2015), which can give low estimates of SOM. It is difficult to choose a temperature that both completely oxidizes SOM and avoids loss of water and carbonates.

1.1.8 Estimation of soil organic carbon concentration

SOC is estimated by combusting samples in the presence of pure oxygen at temperatures high enough to completely oxidize the C, such as 950 °C (Yeomans and Bremner, 1991). At these temperatures, SOC is completely oxidized, and inorganic C decomposes into CO₂, so pretreatment to remove inorganic C is essential for reliable estimation of SOC. The CO₂ produced by combustion is collected and quantified using an infrared spectrometer (Yeomans
and Bremner, 1991). This instrumental method is considered highly accurate because CO₂ evolved by complete sample combustion is quantitatively measured to determine C directly instead of indirectly (Chatterjee et al., 2009). This direct measurement of C is more accurate than the LOI method, as it relies neither on the indirect estimation of C as a fixed proportion of lost mass nor on assumptions about the composition of the oxidized fraction.

Soil OC is also estimated routinely from SOM using known or assumed relationships between SOM and SOC. Until recently, SOC was estimated as 58% of SOM by mass, but a recent review suggested that C is probably closer to 50% of SOM over a range of soils (Pribyl, 2010). Jensen et al. (2018) found that including clay in a regression model to estimate SOC from LOI improved accuracy. They also found that the percentage of C in SOM in agricultural soils ranged from 45-52, so the 58% estimate traditionally used probably overestimates SOC for many soils.

1.2 Research objectives

SOC contributes to key aspects of soil health and fertility. With rising atmospheric CO₂ levels, C sequestration in agricultural soils can also play an important role in climate change mitigation. Given the interest in C levels in soil, our goal was to explore the potential for an extensive collection of LOI values determined by the Maine Soil Testing Service from a variety of agricultural cropping systems over the last 27 years to provide insights into trends in SOM, and therefore SOC, among crop groups and over time. However, estimating SOC from SOM estimated by LOI can be challenging because factors such as clay concentration and combustion temperature may affect LOI values, and therefore affect estimates of SOM and SOC. For this reason, it is important to determine the temperature that provides the best estimation of SOC, and
to determine whether the inclusion of texture information improves the accuracy of estimates of SOM and SOC.

Our objectives were to 1) identify the furnace temperature that provides the strongest correlation between SOM estimated by LOI and SOC measured instrumentally by a LECO CN Analyzer, 2) evaluate whether including soil texture improves the correlation between SOM estimated by LOI and SOC measured instrumentally by a LECO CN Analyzer, and 3) identify trends in SOC in Maine agricultural soils over the last 27 years based on standard soil samples received by the Maine Soil Testing Service from 1995 to 2021.
2.1. Experimental sample set selection

Soil samples were selected to represent a diversity of cropping systems from those received by the Maine Soil Testing Service at the University of Maine, Orono, ME between September 2019 and September 2020. All samples were from commercial farms in the state of Maine and from one of the following crop categories: Apple; Lowbush Blueberry; Corn or Corn Silage; Hay, Grass, or Pasture; Grain; Potato; Conventionally grown Vegetables; and Organically grown Vegetables. Only samples representing sites of at least 5000 ft² were selected. For each sample for each crop group within a farm, a number was randomly assigned, and then a number within that range was randomly selected to ensure no farm was represented more than once within one crop category. Samples were further examined to ensure a range of SOM values and pH values. Samples of less than 125 g mass were excluded, with the exception of several lowbush blueberry soils; these soils tended to be low in volume and bulk density. For samples in the Corn and Hay, Grass, or Pasture categories, the farm type was considered so that both dairy and other farm types were included. This selection process resulted in an initial set of 48 samples. These samples, Sample Set 1, were analyzed for SOM by LOI at 4 different combustion temperatures, total C and N, and texture, as described below.

An additional set of 43 samples, Sample Set 2, was selected following the criteria above, but with additional samples to increase sample numbers in the Corn or Corn Silage; Hay, Grass or Pasture; and Potato categories. Locations of all 91 samples in Samples Sets 1 and 2 are shown in Fig. 2.1. All samples were stored air dry until use. All had previously received a standard
Figure 2.1. Locations and crop groups of 91 soil samples included in Sample Set 1 and Sample Set 2.
soil test analysis, including pH determined using a 1:1 ratio of soil to deionized water and SOM by LOI at a temperature of 375 °C (Hoskins, 1997). Soils in Sample Set 2 were analyzed for total C and N, but not texture or SOM at any temperature other than 375 °C, which was part of the original standard soil test. Deionized water was used for all analytical procedures.

2.2. Determination of organic carbon and total nitrogen

Organic C and total N were determined for Sample Sets 1 and 2 using a LECO Tru-Mac CN Analyzer. Samples with pH values above 7 were tested for carbonates. Samples that tested positive for carbonates were treated with concentrated HCl. Samples were then filtered in a Buchner funnel to remove the acidic solution and rinsed with water to decrease the excess acidity. Filter papers were backflushed to recapture anything caught in the filter paper, and the samples were dried at 105 °C for 24 hr before submission.

2.3. Determination of soil texture

For Sample Set 1, particle size distribution was determined in duplicate following the procedure of the Kellogg Soil Survey Laboratory Methods Manual (Soil Survey Staff, 2014) with some modifications described below. When there was a >10% difference between the two samples, a third sample was analyzed and included in the mean. Each was first homogenized by placing it into a one-pint container, inverting it 30 times, and thorough stirring. Subsamples (11-g for most; 15-g for blueberry) were placed in 50-ml test tubes, and 10 ml of water was added to each sample (20 ml for blueberry). After 10 min to allow full wetting, samples were placed in an ice bath and sonicated for 10 min at 20W.
To remove excess SOM, samples other than Lowbush Blueberry that had an LOI greater than 8% were treated with 200 ml of 1M NaOH in 250-ml polypropylene centrifuge bottles and shaken on an orbital shaker for 2 hr at 210 revolutions per min (Appendix A) to prevent finer particles from settling out. Samples were then centrifuged for 30 min at 2,800×g , and the supernatant removed by siphoning without disturbing the pelleted soil. Centrifugation speed and removal of the supernatant by siphoning were the same for all subsequent steps unless noted. Water (200 ml) was added, and samples were shaken for 15 min, centrifuged for 1 hr, and the supernatant removed. Sodium acetate adjusted to pH 5 (100 ml) and 100 ml of water were added, samples were shaken for 15 min, centrifuged, and the supernatant removed.

Lowbush blueberry soil samples, all with LOI greater than 8%, were treated with 200 ml of 1M NaOH and shaken for 2 hr on an orbital shaker. Samples were centrifuged for 30 min and the supernatant was removed without disturbing the pelleted soil. Preliminary work showed multiple NaOH treatments were needed, so the process was repeated one time for each LOI percentage greater than 8, e.g., a sample with 16% LOI received nine NaOH treatments. Following the final NaOH treatment, samples were shaken with 200 ml of water for 15 min and centrifuged for 1 hr, and the supernatant removed. Sodium acetate adjusted to pH 5 (100 ml) and water were added, samples were shaken for 15 min, centrifuged, and the supernatant removed.

Samples were then treated to remove carbonates, organic matter, and iron aggregates, according to the particle size procedure described in the Kellogg Soil Survey Laboratory Methods Manual Version 5.0 (2014). A more detailed description of this is given in Appendix B. Briefly, the procedure for organic matter removal was modified to include an initial overnight treatment of samples with 10 ml of hydrogen peroxide to digest the most reactive organic matter before heating, and the cumulative amount of hydrogen peroxide added to any sample was
limited to 150 ml. Following iron removal using sodium dithionite, samples were rinsed with water to remove excess salts until the supernatant was cloudy with deflocculated clay due to the reduction in solution electrical conductivity. The samples were then dried for 24 hr at 105 °C, dispersed with sodium hexametaphosphate solution, and poured through a #300 sieve and collected into a 1-L sedimentation cylinder. Sand collected on the sieve was dried and weighed, and the silt and clay were gravimetrically separated by the following procedure. The suspensions were thoroughly mixed initially and were held at 27.5 °C during the following procedure. A volumetric pipette was used to collect 25 ml of the suspension from a depth of 20 cm within 12 sec and another 25 ml of the suspension from a depth of 10 cm at 6.5 hr. The 25-ml aliquots were dried for 24 hr at 105 °C.

Particle size was calculated as follows:

Clay % = 100 x [(RW2 – DW) x (CF / TW)]

where:

RW2 = Residue mass (g), <2-μm fraction
DW = Dispersing agent mass (g), determined as the mass of sodium hexametaphosphate in a blank included with each sample batch
CF = 1000 mL / DV = 40
DV = Dispensed pipette volume, 25 ml
TW = Total mass (g), H2O2-treated, oven-dry sample

Silt % = 100 x [(RW1 – RW2 – DW) x (CF / TW)]

where:

RW1 = Residue mass (g), <0.05 mm fraction

Sand % = 100 x sand mass on sieve / TW
2.4. Estimation of soil organic matter by loss-on-ignition

A Thermolyne muffle furnace was used for the LOI procedure. Using bulk standard soils, we evaluated the furnace for positional bias and differences between increasing temperature in a stepwise manner for one sample set and using a separate sample set for each temperature. The furnace has 84 potential positions (12 rows of 7 positions), but the first 3 rows nearest to the door and the back 2 rows consistently gave lower values than central rows. Therefore, crucibles in these outer rows, although containing soil, were excluded from SOM determinations. Sample positions in use were labeled 1 – 49 (Fig. 2.2). Within these 49 positions, there was some variability from run to run, but no consistent bias. Because the difference between stepwise and single temperature heating was only 1 – 3% of the mean SOM value, we chose stepwise heating to conserve sample mass and reduce the time it took the furnace to achieve temperature stability between runs. For SOM data collection, samples were run in triplicate with their positions randomized for each run. Using www.random.org, positions 1 – 49 were randomly selected and this order was used to determine positions for samples 1 – 48. The 49th position held a standard, known sample. This was repeated for runs 2 and 3. If a position was repeated or an adjacent position was selected for the same sample in runs 2 or 3, another random number was selected for this sample to minimize any positional effect. Empty crucibles were dried in an oven at 105 °C for 12 hr, removed, placed in a desiccator to fully cool and then weighed. Thoroughly mixed samples (4cc) were placed into pre-weighed crucibles, which were then dried at 105 °C for 12 hr, fully cooled in a desiccator, and weighed. Crucibles were placed in the muffle furnace in the predetermined order and burned at 375 °C for a total of 3 hr (39-min time to reach temperature). After 3 hr, the furnace doors were opened and after the
Figure 2.2. Positions of crucibles within the Thermolyne muffle furnace during loss-on-ignition (LOI).
furnace cooled to 300 °C, the crucibles were removed, placed in a desiccator to fully cool and weighed. The crucibles were returned to the furnace in the same position and burned at 450 °C for 3 hr total (32-min time to reach temperature). After cooling and weighing, the samples were again returned to the furnace and burned at 550 °C for 3 hr total (47-min time to reach temperature), and again at 950 °C for 3 hr total (105-min time to reach temperature). This entire process was repeated for runs 2 and 3.

2.5. Data analysis

Data were analyzed using the Fit Model function in JMP v.16.0.0 (SAS Institute Incorporated, Cary, North Carolina, USA) to evaluate the effect of furnace temperature and soil texture on SOC estimates. For Sample Set 1, the mean SOM values were plotted against the SOC values, and Pearson’s correlation coefficients determined. To determine what effect texture had on the estimation of SOC from SOM, the soil separates sand, silt, and clay parameters were used. Each soil separates was individually added to the model of each temperature in estimating SOC with the Fit Model function and Pearson's correlation was determined. To check for interactions among all texture and temperature combinations, each combination was used in estimating SOC, and Pearson’s correlation was determined.

Using data from both Sample Sets 1 and 2, a regression equation was determined describing the relationship between SOM (determined by the Maine Soil Testing Service at LOI temperature 375 °C) and the SOC values (LECO) using the Fit Model function in JMP. This regression equation was used to convert SOM estimates to SOC estimates for historical soil testing as described in the next section. Regressions were used to compare the relationship of C:N with SOC, as well as air-dry moisture content with SOC.
2.6. Historical soil testing data

All data from samples submitted to the Maine Soil Testing Service from 1995 to 2021 were compiled and data representing samples from outside Maine were removed. Data from samples with SOM values of 20.0 or greater were also removed, as they were considered atypical for agricultural settings in Maine. For conventionally and organically grown vegetables, any sample that did not have a defined area was removed from analysis to allow comparison of small-scale and large-scale production. Data from the following types of samples were also excluded: no crop code; crop code indicating new crop establishment; high tunnel production; cranberry bogs; sunflower; and pH values below 4.0 or above 7.9. This resulted in a database comprising data from 159,945 different samples, including 1,053 from Apple; 1,140 from Lowbush Blueberry; 10,385 from Corn or Corn Silage; 4,662 from Grain; 49,941 from Hay, Grass, or Pasture; 32,729 from Potato; 20,134 from Conventionally grown Vegetables (11,656 for <5,000 ft² and 8,478 for >5,000 ft²); and 39,901 from Organically grown Vegetables (26,045 for <5,000 ft² and 13,856 for >5,000 ft²).

Using the regression equation described in the previous section, SOM estimates were converted to SOC estimates for all the remaining historical data. The SOC values were analyzed collectively and separately in the following crop categories: Apple; Lowbush Blueberry; Corn or Corn Silage; Grain; Hay, Grass, or Pasture; Potato; Conventionally grown Vegetables (<5,000 ft² and >5,000 ft²); and Organically grown Vegetables (<5,000 ft² and >5,000 ft²). The mean SOC value was calculated for each year of each category; to smooth between-year variation, a rolling three-year mean was also calculated for each year and was then visually observed for trends. For each year, the rolling mean was the average of values for the listed year and the one-year periods immediately before and after. Annual means without smoothing are presented in Appendix C.
Overall means were calculated for each crop group with 95% confidence intervals. The confidence interval was used to assess differences between means of the crop groups. ANOVA was not used because its assumption for equal variances was not met. Variances are considered roughly equal when the highest one is less than four times higher than the lowest. For our sample set, the highest variance of 4.15 (Lowbush Blueberry) is 4.32 times higher than the lowest variance (0.96, Potato). In addition, the sample size of the largest crop group (Hay, Grass, and Pasture) is almost 50 times higher than the lowest sample size (Apple), and this sample size disparity could be an issue using ANOVA. The confidence interval is an independent analysis of each mean, and a more conservative evaluation of differences.
CHAPTER 3
RESULTS AND DISCUSSION

3.1. Characteristics of Maine agricultural soil samples

Soils in Sample Set 1 had similar textures, typically silt loam, loam, or sandy loam, with one in each of sandy clay loam and clay loam (Fig. 3.1). The sandiest soils tended to be from apple orchards and lowbush blueberry barrens (Table 3.1). Soils with higher clay concentration tended to be from potato fields, conventionally managed vegetable fields, and hay fields. Because these samples were selected to represent agricultural soils of Maine, the textures are expected to be representative of the cropland in Maine. Glacial till is the most common parent material in Maine, so coarse, loamy soils are common. Soils with higher clay concentration might be expected to be more poorly drained, and therefore less suitable for agriculture without installed drainage, which is not common in Maine. Mean soil pH across all crop groups tended to be acidic (pH 6.1) with the lowest mean pH of 4.6 among blueberry barrens, and the highest mean pH of 6.7 among grain fields (Table 3.1).

Soils in Sample Set 1 had a mean SOC of 4.2%, with individual samples ranging from 1.4 - 9.7% (Table 3.1), broadly typical of Maine agricultural soils. Soils from blueberry barrens had the highest mean SOC (8.2%), and potato field soils had the lowest mean SOC (2.1%). Total N consistently averaged 0.2 - 0.4% across the crop groups (Table 3.1). Soils in Sample Set 2 were similar to those in Sample Set 1 in pH (6.1), SOC (3.4), and total N (0.3; Table 3.2). Mean characteristics by crop group for all 91 samples are shown in Table 3.3. Considering all samples in our historical database (159,945 received between 1991 and 2021) the mean SOC was 3.5% and the mean pH was 6.0 (Table 3.4).
Figure 3.1. Textural classes of 48 soils included in Sample Set 1, by crop group.
Table 3.1. Mean and range of soil organic carbon (SOC), total nitrogen, sand, clay, and pH of 48 soils included in Sample Set 1, by crop group.

<table>
<thead>
<tr>
<th>No.</th>
<th>SOC mean</th>
<th>SOC range</th>
<th>Total nitrogen mean</th>
<th>Total nitrogen range</th>
<th>Sand mean</th>
<th>Sand range</th>
<th>Clay mean</th>
<th>Clay range</th>
<th>pH mean</th>
<th>pH range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple</td>
<td>5</td>
<td>4.4</td>
<td>2.7 - 5.8</td>
<td>0.3</td>
<td>0.1 - 0.4</td>
<td>50.6</td>
<td>20.8 - 74.3</td>
<td>12.1</td>
<td>8.4 - 16.7</td>
<td>6.2</td>
</tr>
<tr>
<td>Blueberry</td>
<td>5</td>
<td>8.2</td>
<td>6.0 - 9.2</td>
<td>0.4</td>
<td>0.3 - 0.4</td>
<td>47.1</td>
<td>33.1 - 64.4</td>
<td>10.3</td>
<td>5.0 - 17.7</td>
<td>4.6</td>
</tr>
<tr>
<td>Corn</td>
<td>5</td>
<td>2.9</td>
<td>2.5 - 3.7</td>
<td>0.3</td>
<td>0.2 - 0.3</td>
<td>22.5</td>
<td>6.3 - 45.6</td>
<td>16.5</td>
<td>13.3 - 19.4</td>
<td>6.6</td>
</tr>
<tr>
<td>Grain</td>
<td>3</td>
<td>5.8</td>
<td>3.3 - 9.7</td>
<td>0.3</td>
<td>0.3 - 0.5</td>
<td>41.8</td>
<td>37.4 - 50.3</td>
<td>12.0</td>
<td>8.8 - 16.7</td>
<td>6.7</td>
</tr>
<tr>
<td>Hay</td>
<td>10</td>
<td>3.6</td>
<td>1.8 - 5.8</td>
<td>0.3</td>
<td>0.2 - 0.4</td>
<td>36.5</td>
<td>25.0 - 55.2</td>
<td>17.5</td>
<td>9.2 - 35.6</td>
<td>6.2</td>
</tr>
<tr>
<td>Potato</td>
<td>11</td>
<td>2.1</td>
<td>1.4 - 3.1</td>
<td>0.2</td>
<td>0.1 - 0.3</td>
<td>32.2</td>
<td>20.0 - 47.4</td>
<td>20.7</td>
<td>14.5 - 27.3</td>
<td>5.9</td>
</tr>
<tr>
<td>Conventional</td>
<td>2</td>
<td>2.8</td>
<td>1.7 - 3.9</td>
<td>0.2</td>
<td>0.1 - 0.3</td>
<td>20.3</td>
<td>16.8 - 23.9</td>
<td>17.8</td>
<td>11.0 - 24.7</td>
<td>6.4</td>
</tr>
<tr>
<td>Organic</td>
<td>7</td>
<td>3.6</td>
<td>1.4 - 7.1</td>
<td>0.3</td>
<td>0.1 - 0.4</td>
<td>39.2</td>
<td>26.7 - 49.4</td>
<td>16.8</td>
<td>10.5 - 25.9</td>
<td>6.4</td>
</tr>
<tr>
<td>Total</td>
<td>48</td>
<td>3.9</td>
<td>1.4 - 9.7</td>
<td>0.3</td>
<td>0.1 - 0.5</td>
<td>36.3</td>
<td>6.3 - 74.3</td>
<td>15.5</td>
<td>5.0 - 35.6</td>
<td>6.1</td>
</tr>
</tbody>
</table>

1lowbush, 2includes silage and excludes sweet corn, 3oats, barley, etc., 4includes grass and pasture, 5conventional mixed vegetables, 6organic mixed vegetables
Table 3.2. Mean and range of soil organic carbon (SOC), total nitrogen, and pH of 43 soils included in Sample Set 2, by crop group.

<table>
<thead>
<tr>
<th>No.</th>
<th>SOC mean</th>
<th>SOC range</th>
<th>Total nitrogen mean</th>
<th>Total nitrogen range</th>
<th>pH mean</th>
<th>pH range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blueberry&lt;sup&gt;1&lt;/sup&gt;</td>
<td>3</td>
<td>6.4</td>
<td>5.0 - 7.7</td>
<td>0.4</td>
<td>0.3 - 0.4</td>
<td>4.7</td>
</tr>
<tr>
<td>Corn&lt;sup&gt;2&lt;/sup&gt;</td>
<td>5</td>
<td>2.4</td>
<td>1.7 - 4.0</td>
<td>0.2</td>
<td>0.2 - 0.4</td>
<td>6.6</td>
</tr>
<tr>
<td>Hay&lt;sup&gt;3&lt;/sup&gt;</td>
<td>15</td>
<td>3.4</td>
<td>2.5 - 6.6</td>
<td>0.3</td>
<td>0.2 - 0.6</td>
<td>6.1</td>
</tr>
<tr>
<td>Potato</td>
<td>11</td>
<td>2.2</td>
<td>1.4 - 3.8</td>
<td>0.2</td>
<td>0.1 - 0.3</td>
<td>5.7</td>
</tr>
<tr>
<td>Conventional&lt;sup&gt;4&lt;/sup&gt;</td>
<td>3</td>
<td>2.1</td>
<td>1.5 - 3.1</td>
<td>0.2</td>
<td>0.2 - 0.2</td>
<td>6.3</td>
</tr>
<tr>
<td>Organic&lt;sup&gt;5&lt;/sup&gt;</td>
<td>6</td>
<td>4.2</td>
<td>2.3 - 6.4</td>
<td>0.3</td>
<td>0.2 - 0.5</td>
<td>6.3</td>
</tr>
<tr>
<td>Total</td>
<td>43</td>
<td>3.2</td>
<td>1.4 - 7.7</td>
<td>0.3</td>
<td>0.1 - 0.6</td>
<td>6</td>
</tr>
</tbody>
</table>

<sup>1</sup>lowbush, <sup>2</sup>includes silage and excludes sweet corn, <sup>3</sup>includes grass and pasture, <sup>4</sup>conventional mixed vegetables, <sup>5</sup>organic mixed vegetables
Table 3.3. Mean of soil organic matter (SOM), soil organic carbon (SOC), and total nitrogen; ratio between SOC and SOM (SOC:SOM), and carbon to nitrogen ratio (C:N) for all soil samples from Sample Set 1 and Sample Set 2, by crop group.

<table>
<thead>
<tr>
<th></th>
<th>No.</th>
<th>SOM</th>
<th>SOC</th>
<th>Total nitrogen</th>
<th>SOC:SOM</th>
<th>C:N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple</td>
<td>5</td>
<td>8.4</td>
<td>4.4</td>
<td>0.3</td>
<td>52.5</td>
<td>17.6</td>
</tr>
<tr>
<td>Blueberry</td>
<td>8</td>
<td>13.2</td>
<td>7.5</td>
<td>0.4</td>
<td>56.9</td>
<td>20.9</td>
</tr>
<tr>
<td>Corn</td>
<td>10</td>
<td>5.7</td>
<td>2.6</td>
<td>0.2</td>
<td>46.4</td>
<td>11.3</td>
</tr>
<tr>
<td>Grain</td>
<td>3</td>
<td>10.5</td>
<td>5.8</td>
<td>0.3</td>
<td>53.0</td>
<td>16.5</td>
</tr>
<tr>
<td>Hay</td>
<td>25</td>
<td>6.9</td>
<td>3.5</td>
<td>0.3</td>
<td>51.3</td>
<td>12.5</td>
</tr>
<tr>
<td>Potato</td>
<td>22</td>
<td>4.6</td>
<td>2.2</td>
<td>0.2</td>
<td>47.0</td>
<td>10.9</td>
</tr>
<tr>
<td>Conventional</td>
<td>5</td>
<td>5.2</td>
<td>2.4</td>
<td>0.2</td>
<td>44.9</td>
<td>12.1</td>
</tr>
<tr>
<td>Organic</td>
<td>13</td>
<td>7.7</td>
<td>3.9</td>
<td>0.3</td>
<td>50.4</td>
<td>13.5</td>
</tr>
<tr>
<td>Total</td>
<td>91</td>
<td>7.0</td>
<td>3.6</td>
<td>0.3</td>
<td>49.9</td>
<td>13.2</td>
</tr>
</tbody>
</table>

1 lowbush, 2 includes silage and excludes sweet corn, 3 oats, barley, etc., 4 includes grass and pasture, 5 conventional mixed vegetables, 6 organic mixed vegetables
Table 3.4. Mean and range of soil organic matter (SOM), soil organic carbon (SOC), and pH of Maine agricultural soil samples as determined by the Maine Soil Testing Service from 1995 to 2021.

<table>
<thead>
<tr>
<th>Type</th>
<th>No.</th>
<th>SOM mean</th>
<th>SOM range</th>
<th>SOC mean</th>
<th>SOC range</th>
<th>pH mean</th>
<th>pH range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple</td>
<td>1,053</td>
<td>6.8</td>
<td>0.4 - 19.9</td>
<td>3.5</td>
<td>0.0 - 11.1</td>
<td>5.8</td>
<td>4.4 - 7.8</td>
</tr>
<tr>
<td>Blueberry1</td>
<td>1,140</td>
<td>10.6</td>
<td>0.4 - 20.0</td>
<td>5.7</td>
<td>0.0 - 11.2</td>
<td>4.8</td>
<td>4.0 - 7.8</td>
</tr>
<tr>
<td>Corn2</td>
<td>10,385</td>
<td>5.9</td>
<td>0.4 - 16.7</td>
<td>2.9</td>
<td>0.0 - 9.2</td>
<td>6.4</td>
<td>4.0 - 7.9</td>
</tr>
<tr>
<td>Grain3</td>
<td>4,662</td>
<td>5.2</td>
<td>0.8 - 18.6</td>
<td>2.5</td>
<td>0.0 - 10.3</td>
<td>5.8</td>
<td>4.0 - 7.9</td>
</tr>
<tr>
<td>Hay4</td>
<td>49,937</td>
<td>6.9</td>
<td>0.2 - 20.0</td>
<td>3.5</td>
<td>0.0 - 11.2</td>
<td>6.1</td>
<td>4.0 - 7.9</td>
</tr>
<tr>
<td>Potato</td>
<td>32,729</td>
<td>4.4</td>
<td>0.2 - 17.1</td>
<td>2.1</td>
<td>0.0 - 9.5</td>
<td>5.8</td>
<td>4.0 - 7.9</td>
</tr>
<tr>
<td>Veg Con S5</td>
<td>11,656</td>
<td>7.6</td>
<td>0.2 - 19.9</td>
<td>3.9</td>
<td>0.0 - 11.1</td>
<td>6.5</td>
<td>4.0 - 7.9</td>
</tr>
<tr>
<td>Veg Con L6</td>
<td>8,476</td>
<td>6.4</td>
<td>0.5 - 19.9</td>
<td>3.2</td>
<td>0.0 - 11.1</td>
<td>6.2</td>
<td>4.0 - 7.9</td>
</tr>
<tr>
<td>Veg Org S7</td>
<td>26,045</td>
<td>8.3</td>
<td>0.2 - 20.0</td>
<td>4.3</td>
<td>0.0 - 11.2</td>
<td>6.5</td>
<td>4.0 - 7.9</td>
</tr>
<tr>
<td>Veg Org L8</td>
<td>13,855</td>
<td>7.2</td>
<td>0.2 - 20.0</td>
<td>3.7</td>
<td>0.0 - 11.2</td>
<td>6.3</td>
<td>4.0 - 7.9</td>
</tr>
<tr>
<td>Total</td>
<td>159,938</td>
<td>6.9</td>
<td>0.2 - 20.0</td>
<td>3.5</td>
<td>0.0 - 11.2</td>
<td>6.0</td>
<td>4.0 - 7.9</td>
</tr>
</tbody>
</table>

1lowbush, 2includes silage and excludes sweet corn, 3oats, barley, etc., 4includes grass and pasture, 5conventional mixed vegetables small (<5,000 ft²), 6conventional mixed vegetables large (>5,000 ft²), 7organic mixed vegetables small (<5,000 ft²), 8organic mixed vegetables large (>5,000 ft²)
3.2. Effects of furnace temperature, soil texture, and air-dry moisture content of soil on estimation of soil organic carbon concentration

An LOI temperature of 375 °C produced a significant correlation between SOM and SOC that was similar to, or better than, correlations produced using higher temperatures and was not improved by the addition of soil texture. The four LOI temperatures produced linear relationships between SOC and SOM with similar slopes (Fig. 3.2; Table 3.5). Mass loss, and thus, the mean SOM estimate, increased as LOI temperature increased, a result also found by Hoogsteen et al. (2015), Abella and Zimmer (2007), and Ball (1964). Similarly, the y-intercept increased with increasing temperature (Fig. 3.2; Table 3.5) and is supported by findings from Kamara et al. (2007) and Ball (1964). Both this study (Tables 3.1, 3.4) and that of Hoogsteen et al. (2015) found a decrease in the ratio of measured SOC to SOM with increasing temperature. The increasing mass loss and y-intercepts with increasing temperature are likely due to increasing loss of waters of hydration (Hoogsteen et al, 2015; De Vos et al, 2005) and oxidation of susceptible inorganic and organic compounds (Ball, 1964), as well as oxidation of recalcitrant SOM (Hoogsteen et al., 2015).

As LOI temperatures increased, the color of samples changed from an initial color of brown, typical of Maine soils, to an orange-brown at 375 °C to a red-orange (450 and 550 °C) to entirely red at 950 °C. This red appearance most likely indicates the presence of iron (III) oxide (Ulery and Graham, 1993), which is increasingly obvious as dark colored SOM is lost at higher temperatures. At 400 °C, some carbonates begin decomposing (Froelich, 1980) and by 950 °C, carbonates should be fully decomposed (Kazozi et al., 2009). Above 375 °C, the presence of carbonates would contribute to an overestimate of SOM.
Figure 3.2. Relationship between soil organic carbon (SOC) and soil organic matter (SOM) determined by loss-on-ignition (LOI) at four combustion temperatures for 48 soils in Sample Set 1.
Table 3.5. Regression coefficients for soil organic carbon (SOC) versus soil organic matter (SOM) estimated from four different combustion temperatures for 48 soils in Sample Set 1.

<table>
<thead>
<tr>
<th>LOI temp (°C)</th>
<th>SOM mean</th>
<th>Slope</th>
<th>Intercept</th>
<th>r*</th>
</tr>
</thead>
<tbody>
<tr>
<td>375</td>
<td>8.3</td>
<td>1.88</td>
<td>1.00</td>
<td>0.992</td>
</tr>
<tr>
<td>450</td>
<td>8.7</td>
<td>1.87</td>
<td>1.51</td>
<td>0.990</td>
</tr>
<tr>
<td>550</td>
<td>9.2</td>
<td>1.84</td>
<td>2.10</td>
<td>0.983</td>
</tr>
<tr>
<td>950</td>
<td>10.1</td>
<td>1.85</td>
<td>2.93</td>
<td>0.974</td>
</tr>
</tbody>
</table>

*Pearson’s correlation coefficient
LOI combustion at 375 °C does not completely oxidize all SOM that is present in samples and to achieve this, 550 °C is sometimes preferred (Hoogsteen et al., 2015). However, 550 °C becomes problematic as temperatures above 400 °C can cause significant structural water loss (Hoogsteen et al., 2015; Salehi et al., 2011), loss of hydroxyl groups and bound water (Leong and Tanner, 199) and the decomposition of magnesium carbonates, if present (Froelich, 1980). Water strongly held on clay, clay-organic interfaces, other soil surfaces, and volatile organic compounds is also lost between 100 and 200 °C (Kučerík et al., 2018). This is the likely reason our regressions comparing SOM and SOC had positive y-intercepts at all temperatures including a value of 1.0 at 375 °C. Similarly, Grewal (1991) found that the relationship between SOM and SOC had a non-zero intercept due to loss of water and combustion of other soil constituents. Because all LOI temperatures had similar predictive power (r values from 0.97 - 0.99), use of LOI temperatures above 375 °C is not justified. A furnace temperature of 375 °C, which eliminates risks of structural water loss and carbonate decomposition, allows more rapid throughput because it requires a shorter time to cool down than higher furnace temperatures.

SOC was not significantly correlated with percentage of sand (p=0.06; Fig. 3.3A), silt (p=0.25; Fig. 3.3B) or clay (p=0.06; Fig. 3.3C). In addition, when each soil separates was included individually as a term in the 375 °C regression model for SOC estimation, none of the terms were significant (p-values = 0.203, 0.560, and 0.095 for sand, silt, and clay, respectively). For LOI at 450 °C, 550 °C, and 950 °C, adding the percentage clay term to the regression for SOC estimation was significant (p=0.02, >0.01, and >0.01, respectively), although inclusion of the clay term did not substantially improve predictive power (r = 0.991, 0.986, and 0.979, 450 °C, 550 °C, and 950 °C, respectively), because the predictive power of the temperature-only
Figure 3.3. Relationships between sand (A), silt (B), and clay (C) and soil organic carbon (SOC) for 48 soil samples in Sample Set 1.
model was already high. There were no interactions among any other texture and temperature combinations (all p-values > 0.05).

Although it is well known that clay can protect SOM from microbial degradation (Sarkar et al., 2018; Chen et al., 2018b) and inclusion of clay concentration commonly improves SOC estimates, our results showed no value to adding a clay term to the model among the soils we evaluated. This may be because the mean clay concentration of Sample Set 1 was 15.5% with the majority being less than 20% (Table 3.1), a narrow range. Moreover, no crop group was entirely in one texture classification, further suggesting that crop management is a more important factor in determining SOC than soil texture for our sample set (Fig. 3.1).

The moisture content of the soil after air drying, as a proportion of each sample’s oven-dry weight, was strongly and positively correlated (r=0.910; p<0.0001) with SOC (Fig. 3.4). To our knowledge, no previous research has been published on the use of moisture held after air drying as an estimator of SOC. However, Jensen et al. (2018) noted a positive correlation between air-dry moisture content and SOC and suggested that a correction factor for this moisture can reduce error when estimating SOC from LOI. Our results suggest that air-dry moisture content provides information about SOM and SOC, although with a lower correlation coefficient than LOI. For LOI, oven drying prior to combustion is important to drive off hygroscopic water and avoid overestimating SOM (Hoskins, 2002). Organic matter has high surface area, surface charges, and promotes aggregation that increases pore space, all of which can increase water holding capacity. SOM can also hold up to 40 times as much water as mineral soil components on a mass basis (Wang et al., 2011). Although measurement of air-dry moisture content could provide a simple estimation of SOC, the sensitivity of such an SOM or SOC estimate to variation in ambient temperature or humidity or air-drying duration should be
Figure 3.4. Relationship between soil organic carbon (SOC) and air-dry moisture content for 91 soil samples in Sample Set 1 and Sample Set 2.
investigated. The relationship between water lost by oven drying and soil SOC could be robust to variation in air-drying conditions, or the use of a standard set of conditions might be needed to meaningfully apply the general relationship found here.

The soil C:N ratio was positively correlated ($r=0.628; p<0.0001$) with SOC (Fig. 3.5). For samples below 5% SOC, the soil C:N mostly ranged from 8 to 16, which is similar to the mean of 12:1 reported by Xu et al. (2013) for croplands globally; they also report a mean C:N for microbial biomass of global croplands of 7:1. Soils with SOC of 6 to 10% generally had higher C:N, in the range of 12:1 to 23:1, which could indicate the presence of plant residues (Khan et al., 2016). Of the eleven samples with SOC above 6%, seven were from lowbush blueberry barrens (Table 3.1, Fig. 3.5). Lowbush blueberry soils share key characteristics with forest soils, which also tend to be highly acidic, have an accumulation of undegraded plant residue, and a C:N of 20:1, which is similar to the global average for forest soils (Khan et al., 2016). This accumulation of plant residue is most likely due to lack of cultivation and aeration. Because these soils are not plowed, the organic matter is not as extensively incorporated into the soil compared to traditionally plowed soils, limiting exposure of microbes to both oxygen and available SOM. Among crop groups, the C:N ranged from a high of 20.9 for lowbush blueberry soils to a low of 10.9 for potato fields (Table 3.3).

### 3.3. Soil organic carbon concentration of Maine agricultural soils over time

The SOM values determined by the Maine Soil Testing Service for soils in Sample Sets 1 and 2 are strongly and positively correlated with SOC ($r=0.980$) (Fig. 3.6). The predictive equation derived from Fig. 3.6 and used to estimate SOC for the historical data set from SOM (estimated by the Maine Soil Testing Service by LOI at 375 °C) is:
SOC = -0.5203 + 0.5838 * SOM\textsubscript{MSTS 375C} \hspace{1cm} (1)

From both Sample Sets 1 and 2, the mean SOC was 3.6% and the mean SOM was 7.0%. The mean of the ratios of SOC to SOM for each individual sample showed that SOM contained an average of 49.9% SOC, a finding in agreement with Pribyl (2010), who indicated that SOC is closer to 50% of SOM, rather than the historically used 58%. Although the y-intercept was significant for this regression, we also performed a regression with the y-intercept constrained to zero (Fig. 3.7). The predictive equation derived from Fig. 3.7, which was not used but predicts that SOC is 52.2% of SOM, is:

SOC = 1.8912 * SOM\textsubscript{MSTS 375C} \hspace{1cm} (2)

Averaging across all samples in our historical data set, SOM, and thus SOC, increased from 1995 to 2021, suggesting a possible increase in the amount of stored C in Maine agricultural soils over this time period. Mean SOC concentration, averaged across all samples for all crops using three-year rolling means, increased from 3.0% in 1995 (mean of 1995 and 1996) to 3.7% in 2021 (mean of 2020 and 2021) (Fig. 3.8), an increase of 23%. Averaged over the entire period, the amount of SOC held in agricultural soils varied by crop group (Fig. 3.9; Table 3.4). The crop group with the highest SOC concentration, lowbush blueberry, had soil with a mean of 5.7% SOC, over two and a half times the mean SOC concentration of soils in the group with the lowest SOC concentration (potato, 2.1%). There was no overlap in the 95% confidence intervals for the mean SOC concentration for any crop groups, except for Apple and Hay which overlapped with each other (Fig. 3.9). Considering that crop groups were not associated with particular textural classes (Fig. 3.1), it is clear that soil texture is not the cause of differences between the crop groups. This would suggest that management systems play a larger role in the SOC concentration of these soils than does texture. This will be discussed in more detail later.
Figure 3.5. Relationship between soil organic carbon (SOC) and carbon to nitrogen ratio (C:N) for 91 soil samples in Sample Set 1 and Sample Set 2.
Figure 3.6. Relationship between soil organic carbon (SOC) and soil organic matter (SOM) as determined by the Maine Soil Testing Service for 91 soil samples in Sample Set 1 and Sample Set 2.
Figure 3.7. Relationship between soil organic carbon (SOC) and soil organic matter (SOM) as determined by the Maine Soil Testing Service for 91 soil samples in Sample Set 1 and Sample Set 2, when the y-intercept is constrained to zero.
Figure 3.8. Three-year rolling means of soil organic carbon (SOC) across all samples from all crop groups from 1995 to 2021.
Figure 3.9. Mean soil organic carbon (SOC) of each crop group across all samples included from 1995 to 2021. X-axis labels are Apple, Lowbush blueberry, Corn (includes silage and excludes sweet corn), Grain (oats, barley, etc.), Hay (includes grass and pasture), Potato, Conventional mixed vegetables small (<5,000 ft²), Conventional mixed vegetables large (>5,000 ft²), Organic mixed vegetables small (<5,000 ft²), Organic mixed vegetables large (>5,000 ft²). Bars represent the 95% confidence interval for each crop group.
Among the crop groups, soils from grain, hay, and small-scale vegetable production increased in SOC since 1995 (Fig. 3.10, 3.11, 3.12, 3.13). Soils from grain fields saw an increase from 2.5% to 3.1% from 1995 to 2021 (Fig. 3.10). There was little change from 1995 to 2012, but an increasing trend from 2012 to 2021 (Fig. 3.10). SOC of hay soils steadily increased from 3.3% to 3.8% from 1995 to 2021 (Fig. 3.11). Similarly, SOC of soils from small-scale vegetable production, Veg Con S and Veg Org S, steadily increased over time from 3.5% to 4.3% and 3.9% to 4.6%, respectively (Figs. 3.12, 3.13).

The SOC of soils from several crop groups did not show a clear increase or decrease from 1995 to 2021. The mean SOC concentration of corn soils had an undulating trend from 1995 to 2021, and the 2021 value of 3.0% was lower than peaks in 1999 and 2015 (Fig. 3.14). This undulating trend was also seen in Veg Con L and Veg Org L with no clear increase or decrease in the SOC concentration over the 27-year period (Figs. 3.15, 3.16). Among the crop groups, only potato soils steadily decreased in SOC from 1995 to 2021. The mean SOC of potato soils was 2.2% in 1995, but only 1.9% by 2021, a decrease of 13% (Fig. 3.17). This finding mirrors those of Saini and Grant (1980), who found that continuously cropped potato soils have a net loss of SOM, which when not replaced, results in a continued loss of SOM and soil degradation due to lack of microbiological activity. Before planting, potato fields are tilled to kill weeds and to plant seed potatoes. During harvest, the entire plant is harvested by pulling up soil beneath the plant to collect all of the tubers. The net loss of SOM since 1995 demonstrates that the minimal plant residue that is returned to the soil is insufficient to replace SOM lost by cultivation. In New Brunswick, Canada, Wilson et al. (2018) found that this frequent disturbance of potato soils breaks down aggregates and exposes SOM to microbial degradation, which in turn leads to erosion and loss of nutrients.
Figure 3.10. Three-year rolling means of soil organic carbon (SOC) from Grain (oats, barley, etc.) soil samples from 1995 to 2021.
Figure 3.11. Three-year rolling means of soil organic carbon (SOC) from Hay (includes grass and pasture) soil samples from 1995 to 2021.
Figure 3.12. Three-year rolling means of soil organic carbon (SOC) from Veg Con S (Conventional mixed vegetables small, <5,000 ft²) soil samples from 1995 to 2021.

Mean organic C (%) vs Year

Mean organic C (%) 2 3 4 5 6 7
Figure 3.13. Three-year rolling means of soil organic carbon (SOC) from Veg Org S (Organic mixed vegetables small, <5,000 ft²) soil samples from 1995 to 2021.
Figure 3.14. Three-year rolling means of soil organic carbon (SOC) from Corn (includes silage and excludes sweet corn) soil samples from 1995 to 2021.
Figure 3.15. Three-year rolling means of soil organic carbon (SOC) from Veg Con L (Conventional mixed vegetables large, >5,000 ft²) soil samples from 1995 to 2021.
Figure 3.16. Three-year rolling means of soil organic carbon (SOC) from Veg Org L (Organic mixed vegetables large, >5,000 ft²) soil samples from 1995 to 2021.
Figure 3.17. Three-year rolling means of soil organic carbon (SOC) from Potato soil samples from 1995 to 2021.
The SOC trends for apple (Fig. C.1) and lowbush blueberry (Fig. C.2) soils are difficult to interpret. Although the SOC of apple soils in 2021 averaged 3.6% versus 3.0 - 3.1% during the first three years for which data are available, values from 1998 to 2021 ranged from 3.4 - 4.0% with no obvious trends over time (Fig. C.1). Likewise, SOC of blueberry soils was between 4.8 - 6.4% without obvious trends over time between 2001 and 2021 (Fig. C.2). Both crops have a low sample size relative to the other crop groups (Table 3.4). For both crops, foliar testing is an important method of nutrient management for Maine growers. Moreover, when apple soils are analyzed, growers typically request only nutrient analyses (pH 7 Modified Morgan) and not SOM determination. Similarly, lowbush blueberry soils are not routinely tested for SOM, as growers are primarily concerned with soil pH. In addition, there is no standard soil sampling methodology for lowbush blueberry soils. Specific sampling recommendations are absent, and different growers sample different soil horizons. Lowbush blueberry soils are similar to forest soils, in that there is an organic surface layer underlain by mineral layers. Some blueberry growers submit samples of the organic horizon, and others submit samples of only the mineral horizons. These two layers in forests are often analyzed separately, but no recommendations exist for the unique soils of blueberry barrens.

Using the data on SOC concentration to estimate the mass of stored C in Maine agricultural soil was considered. However, an absence of reliable acreage information for many samples in the historical database prevented a meaningful estimate of total C storage from year to year. In addition, mean SOC values for each year and crop group were influenced by the number of producers of each crop who chose to submit samples in that year. In other words, the historical database was not collected for the purpose of estimating C storage in Maine soils over
time. Despite those limitations, we were able to estimate the trends in the mean SOC concentration of Maine agricultural soils as a whole and for individual crop groups.

The trends in SOC found in this work provide insights into the role of Maine agricultural soils as a means of C storage. The observed increases in SOC could be attributed to increased knowledge and implementation of agricultural management practices that protect and build SOC. For example, growers in Maine shifted toward reduced-till, no-till, and cover-cropping practices between 2012 and 2017 (NASS, 2019). During this period, the acres of cropland in no-till production increased by 11,767 acres, from 2.1% to 4.6% of Maine’s total cropland. Reduced tillage increased by 12,959 acres, from 4.0% to 6.8%. During this same period, cropland under intensive tillage decreased by 46,391 acres, from 30.8% to 21.0%, while that planted to cover crops increased by 26,083 acres, a change from 6.2% to 11.7% of Maine’s total cropland (NASS, 2019). Although it is not clear that these specific practices alone account for the increase in SOC in Maine agricultural soils, their increasing prevalence suggests that farmers in Maine may implement a variety of management options that protect or build SOM. Farmers in the northeastern U.S. are increasingly interested in no-till production, which may improve soil health while reducing erosion, labor, and fuel costs during the production of forage (Jemison et al., 2019). However, some challenges to wider implementation of such measures may be present. For example, Jemison et al. (2019) found that Maine farmers could not reliably identify fields with superior soil health. Providing farmers with information that increases their knowledge of, and incentives for, the implementation of conservation agriculture practices could favor continued increases in SOC of Maine agricultural soils.
3.4. Conclusions

The standard temperature used for the estimation of SOM in Maine agricultural soils by LOI, 375 °C, correlates with independently measured SOC as well as the higher temperatures investigated, while requiring less energy and time than use of higher temperature. Inclusion of soil separates did not significantly impact or improve the estimation of SOC from SOM in our sample set, which comprised a range of textures common to Maine agricultural soils. Air-dry water content as an estimator of SOC concentration was significant and could provide an estimate of SOM that is quicker, simpler, and less expensive than LOI or LECO, but requires further investigation and methods standardization before potential routine adoption.

From 1995 to 2021, estimates of SOC concentration of Maine agricultural soils have increased by 23%. Similarly, Grain, Hay, and small-scale Conventional Vegetable and Organic Vegetable production saw an increase in SOC concentration of 24%, 15%, 23%, and 18%, respectively. The only crop group that saw a loss in soil SOC was Potato, underscoring the unique challenges associated with potato soil management relative to other cropping systems in Maine.


Figure A.1. Soil organic matter (SOM) visible in supernatant after each of three sodium hydroxide (NaOH) extractions for 2, 4, 6, or 12 hr. Results show the majority of the NaOH-extractable SOM was removed with the first extraction, and extraction duration was inconsequential.
Figure A.2. Soil organic matter (SOM) visible in supernatant after each of three 2-hr sodium hydroxide (NaOH) extractions from soils with a range of initial loss-on-ignition (LOI) values. Results show that the majority of the NaOH-extractable SOM was removed with the first extraction, regardless of initial LOI value.
Table A.1. Resulting loss-on-ignition (LOI) values and supernatant soil organic matter (SOM) after each of three 2-hr sodium hydroxide (NaOH) extractions from soils with a range of initial LOI values. Following extraction of SOM, LOI was measured and SOM in solution was inferred. Results show that the majority of the NaOH-extractable SOM was removed with the first extraction, regardless of the initial LOI value.

<table>
<thead>
<tr>
<th>Initial LOI</th>
<th>First extraction</th>
<th>Second extraction</th>
<th>Third extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LOI</td>
<td>SOM in solution</td>
<td>LOI</td>
</tr>
<tr>
<td>3.5</td>
<td>2.00</td>
<td>1.50</td>
<td>1.90</td>
</tr>
<tr>
<td>4.4</td>
<td>1.52</td>
<td>2.88</td>
<td>1.42</td>
</tr>
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<td>3.20</td>
<td>2.30</td>
<td>3.07</td>
</tr>
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<td>10.3</td>
<td>6.04</td>
<td>4.26</td>
<td>5.47</td>
</tr>
</tbody>
</table>
APPENDIX B: REMOVAL OF CARBONATES, SOIL ORGANIC MATTER, AND IRON AGGREGATES FOR DETERMINATION OF SAMPLE TEXTURE

B.1. Removal of carbonates by sodium acetate

Soil samples with a pH above 7 were tested for carbonates, and positive samples were treated to remove them. One g of air-dried subsample was tested for effervescence with 1M HCl. When the one-g sample effervesced, the two 11-g subsamples were treated with 200 ml of sodium acetate adjusted to pH 5 in 250-ml polypropylene centrifuge bottles, shaken by hand, and allowed to sit overnight. Samples were heated to 90 °C in a water bath until effervescing ceased. Samples were spun in a centrifuge for 30 min and the supernatant was siphoned off. Samples were treated for additional carbonates by adding an additional 200 ml of sodium acetate and heating to 90 °C, a step that was repeated until no more effervescing occurred with additional sodium acetate. These samples were spun in a centrifuge for 30 min and the supernatant was siphoned off. Samples were shaken with 100 ml of DI water for 15 min, spun in a centrifuge for 1 hr, and the supernatant was siphoned off.

B.2. Removal of soil organic matter by hydrogen peroxide

Following treatment for carbonates, all soil samples were treated with hydrogen peroxide to oxidize organic matter. Samples were placed into 250-ml centrifuge bottles and 5 ml of 35% hydrogen peroxide was added to begin the oxidation of organic matter. If samples became too active and risked overflowing the container, they were sprayed with a small volume of ethanol. After 1 hr, 5 ml of H₂O₂ was added again and the sample was watched for vigorous activity for 1 hr and then allowed to sit overnight. Samples were then heated in a water bath to 90 °C until all
bubbling ceased. Hydrogen peroxide was added 6 times in 5-ml increments at 15-min intervals to reduce the potential for overreaction, followed by 3 additions of 10-ml aliquots at 15-min intervals. Once the highly reactive first stage of digestion was completed, two 10-ml aliquots, two 15-ml aliquots, and two 20-ml aliquots of hydrogen peroxide were added at 5-min intervals. To decompose any residual hydrogen peroxide, samples were then heated for 45 min after any bubbling had ceased.

B.3. Removal of iron aggregates by sodium dithionite

Samples were treated for potential presence of iron aggregates. 20 ml of 0.6M trisodium citrate and 5 ml of 1M sodium bicarbonate were added, the volume of the liquid was raised to 100 ml with DI if necessary, and samples were heated to 80 °C in a water bath. Once up to temperature, 1 g of sodium dithionite was added, and the bottle was capped and shaken vigorously by hand for 1 min. Samples were kept at 80 °C and vigorously shaken for 30 sec every 5 min for 15 min. The solution and soil changed from various shades of brown to gray, blue, and green. 20 ml of 6.16M NaCl was added, and samples were shaken for 15 min, spun in a centrifuge for 30 min, and the supernatant was siphoned off. The process was repeated at least once, and if the supernatant was yellow or orange in color after the second treatment, the process was repeated until the supernatant was colorless. 20 ml of 6.16M NaCl and 100 ml of DI water were added, and the samples were shaken for 15 min and spun in a centrifuge for 30 min, and the supernatant was siphoned off.
B.4. Determination of sample texture

Following the iron-removal treatment, salts were removed from the samples. 50 ml of DI water was added and swirled to resuspend the sample, which was then spun in a centrifuge for 1 hr. If the supernatant was crystal clear, the supernatant was siphoned off because it contained only dissolved salts and no clay. The process was repeated until the supernatant was cloudy, at which point it contained clay and was left in the bottle. Samples were dried for 24 hr at 105 °C. 20 ml of 2.2% sodium hexametaphosphate solution was added to the oven dried samples, which were then swirled briefly and allowed to saturate for 1 hr. 200 ml of DI were added, and the bottle was capped and shaken vigorously by hand, and then shaken for 15 hr at 210 rpm. All water and columns for the gravimetric separation of silt and clay were placed in a 27.5-°C chamber during dispersion.

Dispersed samples were poured through a #300 sieve and collected into a 1-L sedimentation cylinder, and the bottle rinsed clean. Material left on the sieve was gently rubbed to break up any material that was stuck together and was fully rinsed so that only sand-sized particles remain. Sand was collected and the volume in the cylinder was brought up to 1 L. With a stopper at the end of a glass rod, the contents at the bottom of the cylinder were agitated to break up the thick slurry, and then the contents of the entire cylinder were homogenized for 45 sec. Using a 25-ml volumetric pipette, 25 ml of the mixture was collected from a depth of 20 cm into the suspension within 12 sec. The contents were collected into a beaker and the pipet was rinsed twice and the rinsate was collected. Cylinders were placed in a 27.5-°C chamber for 6.5 hr, at which time 25 ml of the suspension was collected from a depth of 20 cm into the suspension. The contents were collected, and the pipet was rinsed twice and collected the rinsate each time. Samples were dried for 24 hr at 105 °C, after which the texture was determined.
Figure C.1. Three-year rolling means of soil organic carbon (SOC) from Apple soil samples from 1995 to 2021.
Figure C.2. Three-year rolling means of soil organic carbon (SOC) from Blueberry soil samples from 1995 to 2021.
Figure C.3. Yearly means of soil organic carbon (SOC) across all soil samples for all crop groups from 1995 to 2021.
Figure C.4. Yearly means of soil organic carbon (SOC) from Grain (oats, barley, etc.) soil samples from 1995 to 2021.
Figure C.5. Yearly means of soil organic carbon (SOC) from Hay (includes grass and pasture) soil samples from 1995 to 2021.
Figure C.6. Yearly means of soil organic carbon (SOC) from Veg Con S (Conventional mixed vegetables small, <5,000 ft²) soil samples from 1995 to 2021.
Figure C.7. Yearly means of soil organic carbon (SOC) from Veg Org S (Organic mixed vegetables small, <5,000 ft²) soil samples from 1995 to 2021.
Figure C.8. Yearly means of soil organic carbon (SOC) from Corn (includes silage and excludes sweet corn) soil samples from 1995 to 2021.
Figure C.9. Yearly means of soil organic carbon (SOC) from Veg Con L (Conventional mixed vegetables large, >5,000 ft²) soil samples from 1995 to 2021.
Figure C.10. Yearly means of soil organic carbon (SOC) from Veg Org L (Organic mixed vegetables large, >5,000 ft²) soil samples from 1995 to 2021.
Figure C.11. Yearly means of soil organic carbon (SOC) from Potato soil samples from 1995 to 2021.
BIOGRAPHY OF THE AUTHOR

Andrew J. Chase was born in Denison, Iowa on June 14, 1985. He was raised in Dunlap, Iowa and graduated from Boyer Valley High School in 2004. He attended Iowa State University and graduated in 2012 with a Bachelor’s degree in Genetics. Andrew moved with his husband, Bryan, to Maine and later began working in the Maine Soil Testing Service in Orono. He entered the Plant, Soil, and Environmental Science graduate program at The University of Maine in the spring of 2020. After receiving his degree, Andrew will continue his service to the University of Maine. Andrew is a candidate for the Master of Science degree in Plant, Soil, and Environmental Science from the University of Maine in August 2022.