Agricultural diversification and soil carbon dynamics in southeastern Michigan

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Abstract

Agricultural diversification is often proposed as a way to rebuild soil organic carbon (SOC) in intensively managed row-crop landscapes, but less is known about how land use and management affect functionally-distinct SOC pools across the soil profile. Particulate organic carbon (POC) is generally associated with recent plant inputs and relatively rapid turnover, whereas mineral-associated organic carbon (MAOC) reflects carbon that has been microbially processed and stabilized on mineral surfaces. In the Western Lake Erie Basin (WLEB), shallow soil degradation and nutrient loss are major environmental concerns, yet it remains unclear how agricultural soils compare with nearby forest reference systems in these distinct carbon pools and in whole-profile carbon storage.

This thesis used a paired crop-field and forest design across southeastern Michigan to evaluate soil C dynamics in 9 site pairs sampled to 60 cm depth (0–10, 10–20, and 20–60 cm). Four cores were collected per plot, and soils were analyzed for bulk density, total organic C, POC, MAOC, and surface microbial biomass carbon (MBC). Mixed-effects models with farm as a random effect were used to test land use × depth patterns and to evaluate whether surface MBC explained variation in surface POC and MAOC. Crop soils had greater bulk density than adjacent forest soils at 0–10 and 10–20 cm, but not at 20–60 cm. Forest soils contained more total C than crop soils at 0–10 and 10–20 cm, with the sharpest surface separation observed for POC at 0–10 cm. MAOC remained higher in forests through 0–20 cm, and clay significantly explained variation in MAOC and total C. Across the full 0–60 cm profile, forests stored more carbon than crop fields ($p = 0.0291$), and most of that difference was concentrated in the upper two depth increments. Surface MBC tended to be higher in forests and was positively associated with surface MAOC (p

= 0.0014), surface POC (p = 0.0098), and surface total C (p = 0.0013). Together, these results indicate that the main crop–forest C contrast in this working landscape is concentrated in the upper profile and reflects differences in both fresh organic inputs and microbial–mineral stabilization. Forest reference systems therefore provide a useful benchmark for understanding C loss and recovery potential in agricultural soils, while within-crop variation suggests that management history also influences surface carbon outcomes.

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Introduction

The Western Lake Erie Basin (WLEB) is one of the most intensively farmed regions in the Great Lakes basin. It is also a major source of nutrient loading to Lake Erie. Phosphorus, nitrogen, and sediment losses from row-crop agriculture have contributed to harmful algal blooms and ongoing water-quality problems, which has increased interest in management strategies that can improve soil structure, retain nutrients, and rebuild long-term soil function (Baker et al., 2014). In this context, soil carbon matters for two reasons. It reflects past soil degradation, and it also supports resilience in working agricultural landscapes.

Restoration of soil organic carbon (SOC) is especially important because it drives several core soil functions. It contributes to aggregation, water and nutrient retention, nutrient supply, and overall soil resilience. Still, total SOC changes slowly and may not be the best metric to assess the impacts of changing agricultural management practices. Furthermore, two soils can contain similar amounts of carbon while differing in how that carbon cycles and how long it persists. For that reason, recent research on soil carbon accrual often separates two functionally-distinct fractions of SOC: particulate organic carbon (POC) and mineral-associated organic carbon (MAOC). POC is more closely tied to recent plant inputs and usually turns over more quickly (e.g., years to decades). MAOC, by contrast, tends to reflect C that has been processed by microbes and is stabilized on mineral surfaces (Lavallee et al., 2020; Poeplau et al., 2018). Assessing these fractions of SOC can better determine fresh-input pathways, more stable C pools, or both.

Depth also shapes how soil C is processed and stabilized. Soil C is not distributed evenly through the profile because vegetation, rooting patterns, and litter inputs all vary with depth. A

substantial share of soil C can lie below the shallow topsoil emphasized in many agricultural studies (Jobbágy & Jackson, 2000; Hicks Pries et al., 2023). Yet management effects are still often inferred from only the upper 20 or 30 cm. That leaves an important gap because the processes that control C accumulation and persistence do not remain constant with depth. Near the surface, fresh biological inputs from plant residues, roots, and microbial products tend to dominate. Deeper in the profile, where those inputs decline, mineral controls often become a more important driver of C retention and stabilization (Doetterl et al., 2018; Hicks Pries et al., 2023).

These depth-dependent controls are especially relevant when considering agricultural diversification as a strategy to rebuild SOC. Rotations that include perennial crops, legumes, and reduced soil disturbance can increase both the amount and continuity of C inputs to soil, while also improving nutrient retention and biological cycling relative to simplified annual systems (King & Blesh, 2018; Blesh, 2019). Perennial crops can contribute greater root biomass and longer periods of active growth, while legumes can alter residue quality and support biological N cycling. Together, these changes to crop rotations may influence both how much C enters the soil and how that C is processed and retained. Earlier work has shown that more complex rotations can strengthen soil N cycling and other microbial functions, pointing to a plausible link among diversification, soil biological activity, and SOC formation (Blesh, 2018; Bowles et al., 2022; Breza et al., 2023).

Against this background, it remains less clear how diversified crop fields compare with nearby reference forests when C is separated into POC and MAOC across the full 0–60 cm profile. Adjacent forest plots provide a useful benchmark for SOC storage because they experience less physical disturbance, receive continuous perennial inputs, and accumulate more litter than annual

row-crop fields. In this thesis, I used a paired crop–forest design across southeastern Michigan to address three questions: 1) how do crop and forest soils differ in total organic C, POC, and MAOC across depth? 2) How does surface microbial biomass relate to POC and MAOC? And, 3) Do management factors within crop fields, including tillage, legume cover, and crop rotation complexity, help explain C distribution across depth? I expected the strongest crop–forest differences to appear in the upper profile, where the effects of recent C inputs and soil disturbance are most pronounced. I also expected POC to differ most between land uses at the soil surface, while MAOC would remain responsive through 0–20 cm. Because microbial processing is thought to contribute to MAOC formation, I further expected higher surface microbial biomass to be associated with greater MAOC accumulation.

Methods

Study design and soil sampling

This study was conducted within a broader study in the Western Lake Erie Basin (WLEB) that examined relationships among agricultural management, soil health, and environmental outcomes. From this larger dataset, I selected paired crop and forest plots to compare soils under contrasting land uses within similar local site conditions. Crop fields varied in recent crop rotation diversity, nutrient sources, and tillage intensity, while adjacent forest plots served as nearby reference systems on the same soil types.

At each of the 20 original plots, four soil cores were collected to 60 cm depth using a gas-powered corer fitted with 5.1-cm split-core attachments. Each core was divided into three depth increments: 0–10 cm, 10–20 cm, and 20–60 cm. Collecting four cores per plot was intended to

capture within-site spatial heterogeneity (Stanley et al., 2023), which can strongly influence soil carbon estimates in both cropland and forest soils. Sampling across multiple topsoil increments and extending measurements to 60 cm also improves characterization of vertical carbon distribution and reduces bias associated with bulk density differences when calculating soil C stocks.

Soils from the same plot and depth interval were composited for laboratory analysis. One paired site, MH, was excluded from the final dataset because the crop and forest plots differed in parent material. The forest plot appeared to be influenced by lacustrine deposits over glacial till, whereas the paired crop field did not share the same geologic setting. Because this violated the assumptions of the paired design, the MH pair was removed from analysis, leaving 9 paired sites in the final dataset.

Soil carbon measurements and fractionation

To quantify particulate organic matter (POM) and mineral-associated organic matter (MAOM), dried soil was fractionated using a size-based method informed by Poeplau et al. (2018). Representative subsamples were dispersed in sodium hexametaphosphate solution and shaken for 18 hours to promote aggregate dispersion. The slurry was then sieved at 53 μm to separate coarse and fine fractions. Material retained on the sieve was operationally defined as the POM fraction, whereas material passing through the sieve was considered the MAOM fraction. Both fractions were dried, weighed, ground to a fine powder, and analyzed for carbon concentration by dry combustion. POC and MAOC content (g C kg dry soil^{-1}) was calculated as the product of fraction mass and carbon concentration.

Total SOC and total N in bulk soil, and in separated organic matter fractions, were measured across all depth increments to 60 cm by dry combustion on an Elementar UNICUBE elemental analyzer. Samples were also screened for the presence of inorganic C (carbonates), and no evidence of carbonates was detected; therefore, total C was interpreted as organic C throughout this study. These measurements were used to compare both whole-profile carbon content and the distribution of carbon among operationally defined soil organic matter pools.

Microbial biomass carbon

Microbial biomass carbon (MBC) was measured on fresh 0–10 cm soil using a modified chloroform-fumigation extraction method based on Vance et al. (1987) and Fierer and Schimel (2003). For each composite sample, 10 g of fresh soil was weighed into four replicate tubes containing 40 mL of 0.5 M K_2SO_4. Two tubes received 0.5 mL chloroform as the fumigation treatment, while the remaining two tubes served as non-fumigated controls. Following fumigation, samples were shaken for 4 hours, centrifuged, and filtered. Dissolved organic carbon in the extracts was measured on a Shimadzu TOC-TN analyzer. Microbial biomass carbon was then calculated as the difference between fumigated and non-fumigated extracts using an extraction coefficient of 0.33 (Vance et al., 1987; Fierer & Schimel, 2003).

Carbon stock calculations

Bulk density data collected during field sampling were used to convert concentration-based measurements into carbon stocks. Because stock estimates are sensitive to both sampling depth and soil mass, depth-resolved bulk density information was retained for each increment. Bulk-soil C stocks were calculated on an equivalent soil mass basis to improve comparability across

sites with different bulk density values. Depth-specific stocks were then summed to calculate whole-profile 0–60 cm carbon stock for each plot.

Statistical analysis

All statistical analyses were conducted in R. For the main paired crop–forest comparisons, I used linear mixed-effects models with farm included as a random intercept to account for the paired site structure. Response variables included bulk density, total C concentration, POC, MAOC, the POC:MAOC ratio, and fraction C:N metrics. Fixed effects in the main profile models included land use, depth, land use × depth, and clay percentage as a covariate. Depth was grouped into 0–10, 10–20, and 20–60 cm.

To test microbial relationships in surface soil, I fit additional mixed-effects models using 0–10 cm samples. MBC was modeled as a function of land use and clay. I also modeled 0–10 cm POC and MAOC as functions of MBC, land use, and clay. Whole-profile 0–60 cm carbon stocks were analyzed by summing depth-specific stocks within each plot and fitting mixed-effects models with farm as a random effect.

I also conducted crop-only exploratory analyses to test whether management variables were associated with total C, POC, MAOC, and the POC:MAOC ratio across depth. Management variables were derived from recent (five year) field management histories and included rotation complexity index (RCI), tillage intensity, legume cover, and crop diversity. Each predictor was evaluated in a separate model with depth, the predictor × depth interaction, and clay percentage as fixed effects, with farm again retained as a random intercept. Pairwise crop–forest contrasts within depth were evaluated using estimated marginal means with Tukey-adjusted comparisons.

Model assumptions were assessed with residual diagnostics and graphical checks of fitted values and normality.

Results

Paired crop–forest differences

Bulk density differed between crop and forest soils, and that contrast was strongly depth dependent (land use × depth, $p < 0.0001$; Figure 1). Tukey-adjusted post-hoc comparisons showed that crop soils were 0.417 g cm^{-3} denser than adjacent forest soils at 0–10 cm ($p < 0.0001$) and 0.264 g cm^{-3} denser at 10–20 cm ($p < 0.0001$), whereas the two land uses did not differ at 20–60 cm ($p = 0.8147$). This pattern indicates that the structural imprint of cropping was concentrated in the upper profile, where disturbance and compaction effects would be expected to be strongest.

Total organic C showed a parallel land-use-by-depth pattern (land use × depth, $p < 0.0001$; Figure 2). Forest soils contained 26.32 g C kg^{-1} more total C than crop soils at 0–10 cm ($p < 0.0001$) and 9.62 g C kg^{-1} more total C at 10–20 cm ($p = 0.0026$), whereas the crop–forest contrast disappeared at 20–60 cm ($p = 0.6519$). Clay was also significant in the mixed model for total C ($p = 0.0078$), indicating that mineral context helped explain variation in C retention alongside land use. Together, the bulk density and total C results show that the upper 20 cm was the zone where crop and forest soils diverged most strongly.

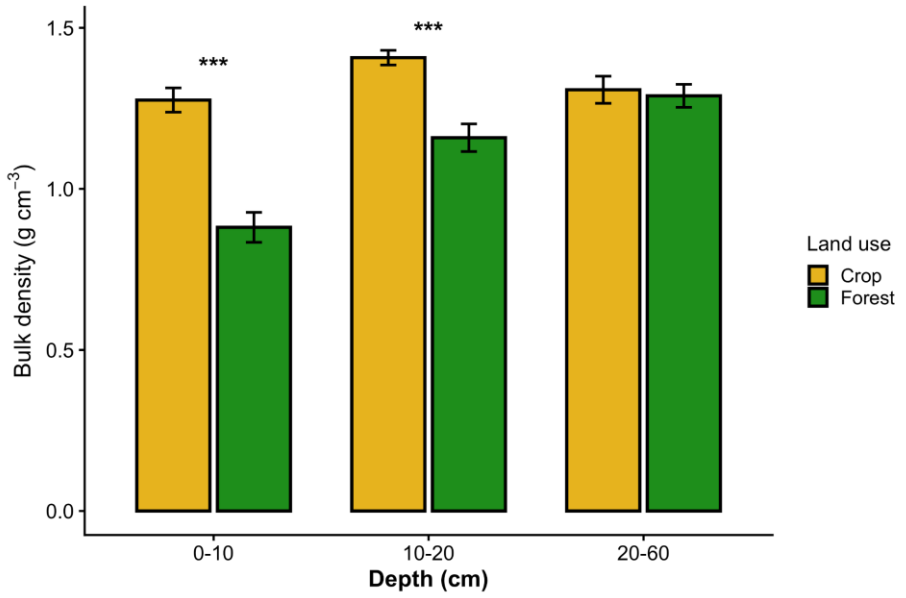


Figure 1. Bulk density by land use and depth. Crop soils had higher bulk density than adjacent forest soils at 0–10 and 10–20 cm, but not at 20–60 cm. Asterisks indicate Tukey-adjusted post-hoc crop–forest contrasts within depth (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

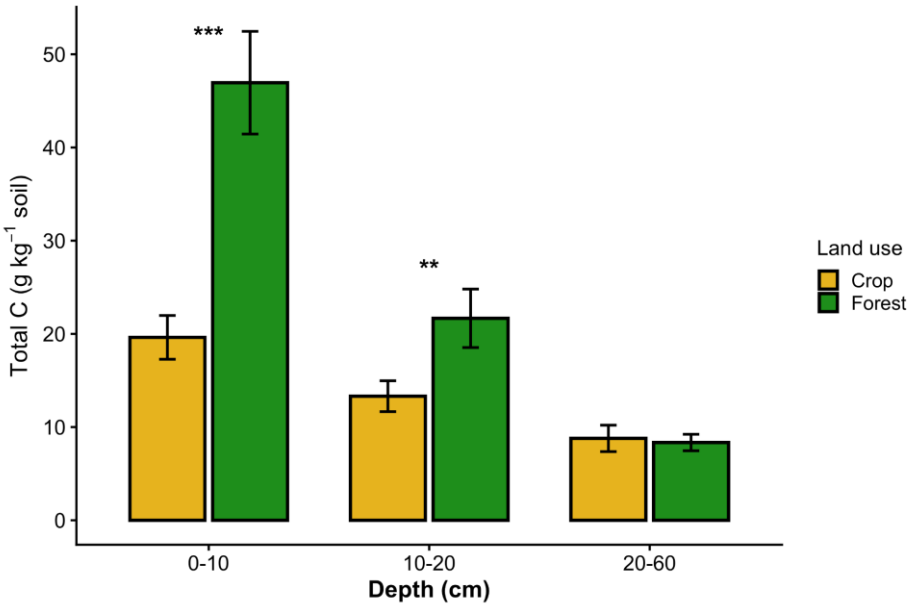


Figure 2. Total organic C concentration by land use and depth. Forest soils contained more total C than crop soils at 0–10 cm (46.9 vs. 19.6 g C kg^{-1} soil; Tukey-adjusted $p < 0.0001$) and 10–20 cm (21.7 vs. 13.3 g C kg^{-1}

soil; $p = 0.0026$), but not at 20–60 cm ($p = 0.6519$). Asterisks indicate Tukey-adjusted post-hoc crop–forest contrasts within depth (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

POC and MAOC show distinct depth patterns

POC showed the clearest response to surface C inputs in the dataset (Figure 3). The largest crop–forest difference occurred at 0–10 cm, where forest soils contained 6.82 g C kg^{-1} more particulate C than crop soils ($p < 0.0001$). At 10–20 and 20–60 cm, the land uses were lower and much more similar, and the crop–forest contrasts were not significant ($p = 0.0579$ and $p = 0.8153$, respectively), indicating that the strongest POC separation was restricted to the surface layer.

MAOC showed a related pattern (Figure 4). Unlike POC, MAOC remained higher in forests at both 0–10 and 10–20 cm before converging with crop soils at 20–60 cm. Forest soils contained 19.56 g C kg^{-1} more MAOC than crop soils at 0–10 cm ($p < 0.0001$) and 7.97 g C kg^{-1} more MAOC at 10–20 cm ($p = 0.0019$), whereas the land uses did not differ at 20–60 cm ($p = 0.6150$). Clay was significant in the MAOC model ($p = 0.0035$), consistent with the expectation that mineral surfaces help explain variation in stabilized C. The paired profile models therefore distinguished two kinds of upper-profile separation: POC, which is associated with fresh organic inputs, captured the strongest surface difference, whereas MAOC preserved a broader 0–20 cm contrast consistent with more processed and stabilized C.

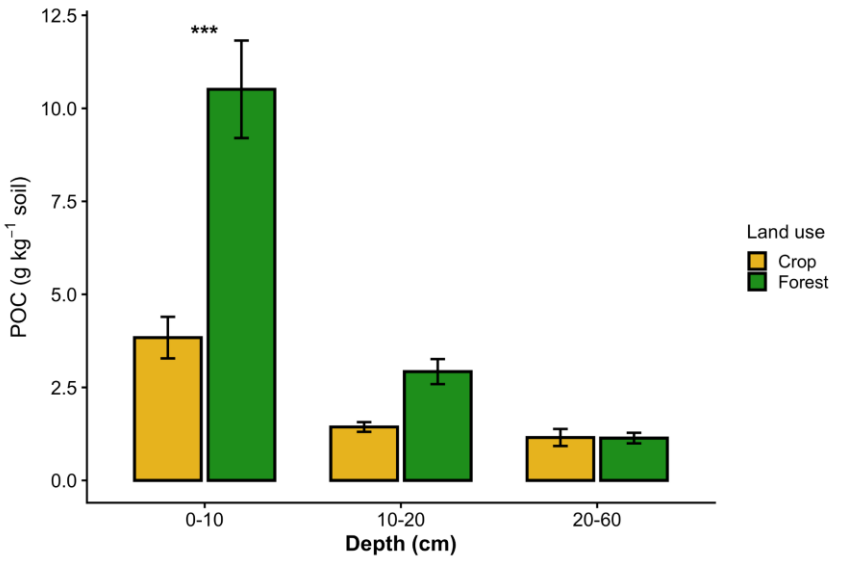


Figure 3. Particulate organic carbon (POC) by land use and depth. The strongest crop–forest separation occurred at 0–10 cm (difference = 6.82 g C kg⁻¹ soil; Tukey-adjusted $p < 0.0001$); differences at 10–20 cm and 20–60 cm were not significant. Asterisks indicate Tukey-adjusted post-hoc crop–forest contrasts within depth (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

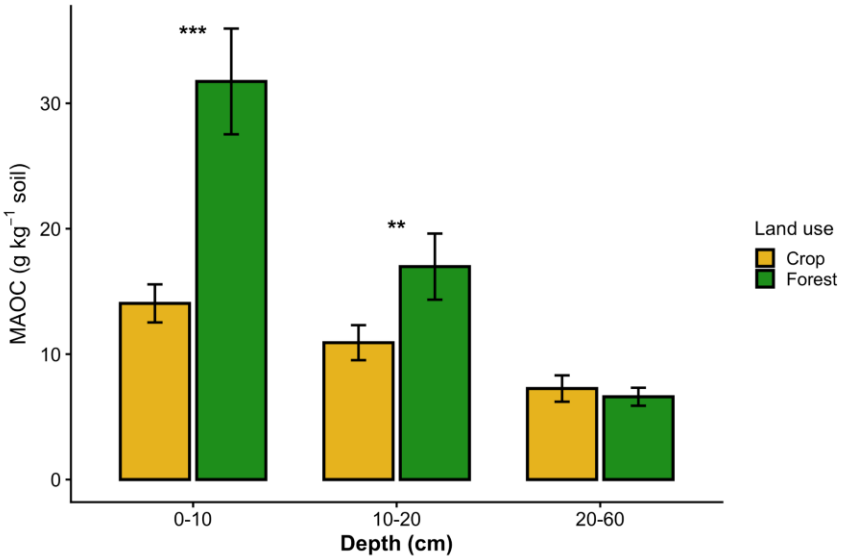


Figure 4. Mineral-associated organic carbon (MAOC) by land use and depth. Forest soils contained more MAOC than crop soils through 0–20 cm (0–10 cm difference = 19.56 g C kg⁻¹ soil, $p < 0.0001$; 10–20 cm difference = 7.97 g C kg⁻¹ soil, $p = 0.0019$), with convergence at 20–60 cm. Clay was significant in the paired

MAOC model ($p = 0.0035$). Asterisks indicate Tukey-adjusted post-hoc crop–forest contrasts within depth (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Table 1. Summary of the main paired crop–forest mixed-model results.

Response	Significant fixed effects	Depth-specific crop–forest contrasts	Interpretation
Bulk density	Land use, Depth, Land use × Depth	0–10 ***, 10–20 ***, 20–60 ns	Crop soils are more compacted than forests near the surface; the difference weakens with depth.
Total C	Land use, Depth, Clay, Land use × Depth	0–10 ***, 10–20 **, 20–60 ns	Forest soils contain more total C in the upper profile; contrasts shrink by 20–60 cm.
POC	Land use, Depth, Land use × Depth	0–10 ***, 10–20 ns, 20–60 ns	The strongest POC separation occurs at the surface.
MAOC	Land use, Depth, Clay, Land use × Depth	0–10 ***, 10–20 **, 20–60 ns	MAOC remains higher in forest soils through 0–20 cm and also tracks clay.

Whole-profile carbon storage and surface microbial associations

Concentration differences in the upper profile scaled up to the whole 0–60 cm profile (Figures 5 and 6). Forest soils stored more total C than crop soils across the full profile ($p = 0.0291$; Figure 5), with mean whole-profile stocks of 105.900 Mg ha^{-1} in forests and 87.816 Mg ha^{-1} in crop soils, a difference of 18.085 Mg ha^{-1}. The stacked stock profile showed that most of this crop–

forest separation was concentrated in the 0–10 and 10–20 cm layers (Figure 6). Mean depth-specific stocks were 39.334 vs. 24.157 Mg ha^{-1} at 0–10 cm and 23.821 vs. 18.403 Mg ha^{-1} at 10–20 cm for forest and crop soils, respectively. By contrast, the 20–60 cm layer was more similar between land uses (42.745 vs. 45.255 Mg ha^{-1} for forest and crop soils, respectively).

Surface microbial biomass results helped connect these patterns. Forest soils tended to have higher mean 0–10 cm MBC, although the paired land-use effect was marginal (p = 0.0593). More importantly, surface MBC was positively associated with surface MAOC (p = 0.0014) and surface POC (p = 0.0098). Table 2 shows that the surface models explained a substantial share of the observed variation, with marginal R^2 values of 0.379 for MBC, 0.778 for surface MAOC, and 0.639 for surface POC. For whole-profile stocks, marginal R^2 values ranged from 0.364 to 0.692, while conditional R^2 values ranged from 0.668 to 0.953, indicating that both fixed effects and between-farm variation contributed to stock patterns across sites.

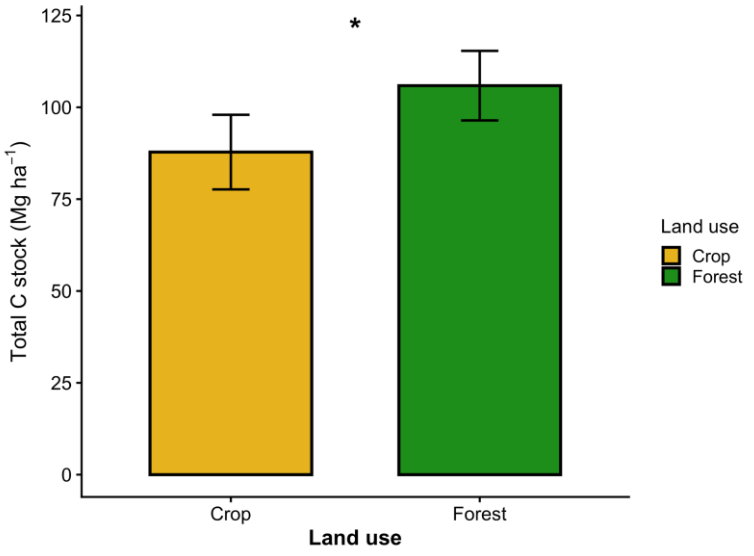


Figure 5. Total 0–60 cm carbon stock by land use. Forest soils stored more total carbon than crop soils across the full profile ($p = 0.0291$), with mean whole-profile stocks of 105.900 Mg ha^{-1} in forests and 87.816 Mg ha^{-1} in crop soils.

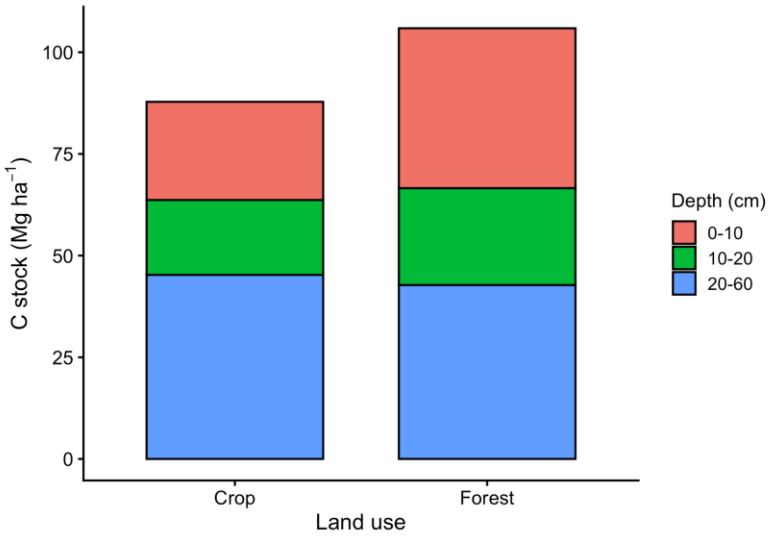


Figure 6. Depth distribution of total carbon stock by land use. Most of the whole-profile crop–forest separation was concentrated in the upper two depth increments. Mean stocks were 39.334 vs. 24.157 Mg ha^{-1} at 0–10 cm and 23.821 vs. 18.403 Mg ha^{-1} at 10–20 cm for forest and crop soils, respectively, whereas the 20–60 cm layer was similar between land uses (42.745 vs. 45.255 Mg ha^{-1}).

Table 2. Summary of surface microbial biomass and whole-profile C stock models.

Model	Main statistical pattern	Marginal R^2	Conditional R^2	Interpretation
MBC (0–10 cm) ~ Land use + Clay	Land use marginal (*p* = 0.0593); Clay marginal (*p* = 0.0815)	0.379	0.379	Forest soils tended to have higher surface MBC.

MAOC (0–10 cm) ~ MBC + Land use + Clay	MBC $p = 0.0014$; Land use $p = 0.0287$; Clay $p = 0.0663$	0.778	0.778	Within surface soil, MBC helped explain MAOC while land use remained important.
POC (0–10 cm) ~ MBC + Land use + Clay	MBC $p = 0.0098$; Land use $p = 0.0218$; Clay not significant ($p = 0.3113$)	0.639	0.641	Surface MBC was also positively associated with POC.
Total 0–60 cm stock ~ MBC + Land use + Clay	Land use $p = 0.0484$; Clay $p = 0.0029$; MBC marginal ($p = 0.0562$)	0.659	0.953	Across the full profile, differences in total C stock were mainly associated with land use and clay, with weaker evidence for a microbial relationship.
POC 0–60 cm stock ~ MBC + Land use + Clay	Land use $p = 0.0170$; MBC not significant ($p = 0.2254$); Clay not significant ($p = 0.3056$)	0.364	0.668	POC stock differed by land use, not by MBC or clay.
MAOC 0–60 cm stock ~ MBC + Land use + Clay	Clay $p = 0.0024$; MBC not significant ($p = 0.0977$); Land	0.692	0.950	MAOC stock was primarily structured by clay.

	use not significant (*p* = 0.2986)			

Crop-only patterns

Crop fields were not a uniform category. Recent crop histories differed substantially among the nine crop fields, ranging from continuous alfalfa to continuous soy and annual row crop rotations, reflecting meaningful heterogeneity in vegetation history and disturbance. This variation was also reflected in surface soil C. Surface total C concentration differed noticeably among crop fields, with fields under stronger perennial or alfalfa influence generally ranking higher than fields dominated by simpler annual soy-corn histories. In contrast, the continuous soy field had the lowest surface total C concentration. These descriptive patterns suggest that crop-system history likely contributed to within-crop variability in surface C, even though the crop-only mixed models detected only weak statistical support for most management predictors due to a small sample size. Among the variables tested, tillage showed the strongest evidence of a depth-dependent relationship with MAOC, although this pattern was only marginally significant ($p = 0.0576$), and within-depth till versus no-till contrasts were not significant. Taken together, these crop-only results are interpreted as contextual rather than definitive: they suggest that management history likely contributed to heterogeneity among crop fields, but these effects were much weaker than the main paired crop–forest contrast.

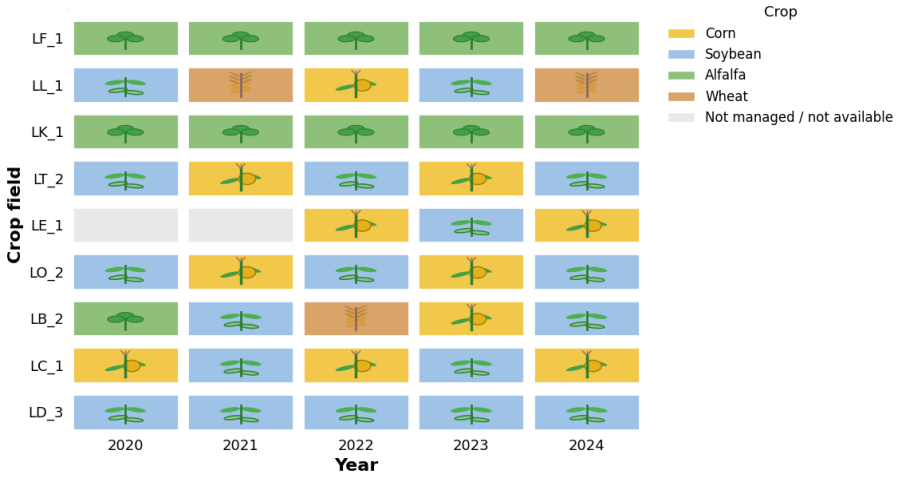


Figure 7. Recent crop rotation history (2020–2024) for the nine crop fields included in the paired dataset.

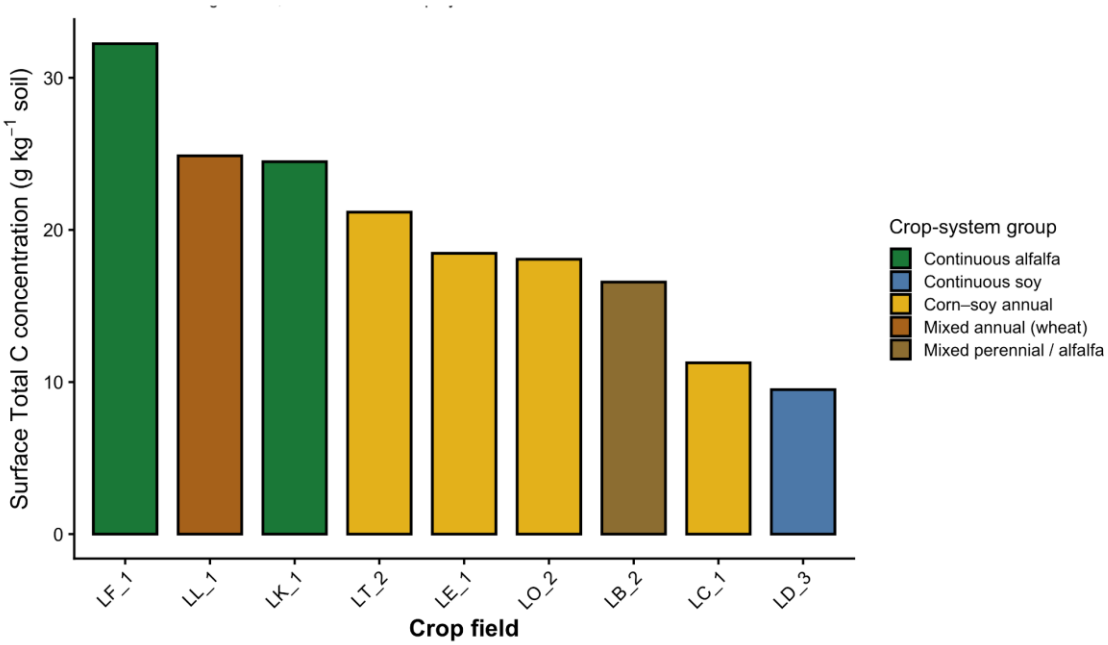


Figure 8. Surface total C concentration across crop fields. Fields with stronger perennial or alfalfa influence generally ranked higher, whereas the continuous soy field ranked lowest.

Discussion

In the Western Lake Erie Basin (WLEB), rebuilding soil carbon matters not only for long-term climate mitigation, but also for nutrient retention, soil structure, and resilience in intensively managed row-crop systems (Baker et al., 2014; Hicks Pries et al., 2023). Within that context, this thesis addressed three linked questions: how crop and forest soils differ in total carbon, POC, and MAOC across depth; how surface microbial biomass relates to those pools; and whether management differences among crop fields help explain within-crop variation. The first hypothesis, that crop–forest differences would be strongest in the upper profile, was supported. The second hypothesis, that POC would show the strongest land-use separation at the soil surface while MAOC would remain differentiated through 0–20 cm, was also supported. The third hypothesis, that higher surface microbial biomass would align with greater MAOC accumulation, was only partially supported. Crop-only analyses suggested that management history likely contributed to heterogeneity among crop fields, but those effects were weak relative to the stronger influences of land use, depth, and clay.

Across the paired crop–forest comparison, the clearest pattern was that land-use effects on soil C were concentrated in the upper 20 cm. Crop soils were denser than forest soils at 0–10 and 10–20 cm, and those same layers also showed the largest reductions in total organic C relative to paired forest reference plots. This pattern is consistent with earlier work showing that land-use effects on soil C are often strongest near the surface, where litter accumulation, fine-root turnover, disturbance, and aggregation are most concentrated (Jobbágy & Jackson, 2000; King & Blesh, 2018; Hicks Pries et al., 2023). Although the 20–60 cm increment still contained a substantial amount of carbon, it contributed less to the crop–forest contrast than the upper profile. In other

words, deeper soil remained important for total profile storage, but it did not drive the main land-use separation observed here.

Differences in POC and MAOC across depth help explain why the upper profile mattered most. POC showed clear crop–forest separation only at 0–10 cm, which is consistent with the broader understanding that particulate C is especially sensitive to recent organic matter inputs, residue retention, and physical disturbance (Lavallee et al., 2020; Poeplau et al., 2018; Jobbágy & Jackson, 2000). In this study, forests maintained a much larger surface POC pool than crop fields, whereas the POC contrast weakened rapidly with depth. Because this study did not directly measure litterfall or root-derived C inputs, that pattern should be interpreted cautiously. Even so, it is consistent with the lower disturbance, continuous litter accumulation, and perennial root activity expected in adjacent forest systems relative to annually harvested row-crop fields (Jobbágy & Jackson, 2000; King & Blesh, 2018). In that sense, POC appears to have captured the near-surface organic matter dynamics that were most responsive to land use in this working landscape.

MAOC showed a similar but not identical pattern. Forest soils contained more MAOC than crop soils through 0–20 cm, and clay explained a significant share of MAOC variation. This suggests that mineral-associated carbon reflected not only overall differences in organic matter availability, but also differences in the capacity of soils to retain processed C on mineral surfaces (Doetterl et al., 2018; Lavallee et al., 2020). More broadly, current soil C frameworks suggest that labile plant inputs can be transformed by microbes and then stabilized on mineral surfaces, rather than assuming that only chemically recalcitrant inputs persist in soil.(Cotrufo et al., 2013; Lavallee et al., 2020). Recent syntheses further show that microbial necromass is an important component of SOC, especially within more stable pools, which provides a plausible mechanism

for the stronger MAOC response observed here, even though necromass was not measured directly in this study (Liang et al., 2019; Wang et al., 2021; Hu et al., 2023). That distinction matters because MAOC is widely recognized as a relatively persistent SOC fraction and a major contributor to longer-term soil C storage, including deeper profile C that is relevant to climate mitigation (Hicks Pries et al., 2023; Lavallee et al., 2020). In the WLEB, where intensively managed cropland contributes to nutrient export and Lake Erie water-quality impairment, reductions in both particulate and mineral-associated SOC matter for more than carbon accounting alone (Baker et al., 2014). Taken together, these results suggest that agricultural land use in this system altered both the near-surface organic matter dynamics reflected in POC and the mineral-stabilization pathways reflected in MAOC, rather than affecting only a single pathway of soil C loss.

The microbial biomass results support biological drivers of these C patterns, although the results should be interpreted with caution. Surface microbial biomass was higher on average in forest soils, although the land-use contrast in MBC was weaker than the contrast observed for POC and MAOC. More importantly, higher surface MBC was associated with higher surface MAOC, total C, and POC. The stronger association with MAOC than with POC is consistent with a closer link between microbial processing and mineral-associated C formation than with the particulate pool alone. At the same time, the positive association between MBC and POC indicates that biologically active surface soils also tended to contain more fresh, labile organic matter. These patterns are therefore most consistent with a surface-soil mechanism in which lower disturbance, greater litter accumulation, and more continuous perennial inputs in forests support greater microbial activity and, in turn, stronger formation or retention of processed C. That interpretation is consistent with studies showing that microbial physiology and necromass strongly influence

agricultural soil C accumulation and mineral-associated C formation (Kallenbach et al., 2015; Liang et al., 2019; Wang et al., 2021). It is also consistent with recent evidence that legume–grass systems can promote transfer of C from particulate to mineral-associated pools and that fungal taxa were associated with increases in both POCand MAOC (Connell et al., 2025).

That said, tthis study was observational, and microbial biomass was measured only in the 0–10 cm layer. For that reason, the results do not show a causal relationship between microbial activity and the observed MAOC differences. What they do show is that sites with greater surface biological activity had higher surface C.

Whole-profile stock calculations also showed why depth-resolved sampling was necessary. Forest soils stored more C across the full 0–60 cm profile, yet the stacked stock results showed that most of this difference still came from the upper two depth increments. That distinction matters because a deeper interval can contain a large amount of C simply by representing a thicker section of the profile, even when it contributes relatively little to the main land-use contrast. In this study, the 20–60 cm interval remained important for total C storage, but it did not drive the main crop–forest separation. This is exactly the kind of pattern that can be missed when studies focus only on shallow topsoil or, conversely, report only whole-profile totals without depth-specific interpretation (Fowler et al., 2023; Raffeld et al., 2024). In a region like the WLEB, where both nutrient retention and long-term resilience are central concerns, that means upper-profile C losses may be especially important for understanding both soil function and the practical recovery potential of working cropland.

The crop-only analyses addressed the third research question and suggested that management history contributed to heterogeneity among crop fields, although those effects were weaker than the broader influences of depth and clay. Crop fields were not a uniform category. Recent crop

histories ranged from continuous alfalfa to continuous soy and mixed annual systems, and surface total C varied substantially among fields. Fields with stronger perennial or alfalfa influence generally ranked higher in surface total C, whereas the continuous soy field ranked lowest. That pattern is ecologically plausible and consistent with the idea that perennial phases, lower disturbance, and more continuous cover can support greater soil C retention (King & Blesh, 2018; Blesh, 2019). It is also consistent with recent evidence that legume–grass systems can promote transfer of C from particulate to mineral-associated pools (Connell et al., 2025). Even so, most management predictors were weak relative to depth and clay, and the clearest crop-only statistical signal was only a marginal tillage × depth pattern for MAOC. In practical terms, this suggests that management history likely contributed to within-crop heterogeneity, but it did not override the broader crop–forest result. Even crop fields with more conservation-oriented histories did not approach the C status of adjacent forest reference plots in the upper profile.

That weak crop-only signal is not especially surprising. The number of crop fields was limited, several management variables likely overlapped, and real field histories do not separate neatly into independent effects. A field with greater perennial influence may also differ in tillage, residue dynamics, and nutrient inputs. Under those conditions, the paired crop–forest design was better suited to detecting an integrated land-use signal than the crop-only models were to isolating subtler practice-level effects. The crop-only results are therefore most useful as exploratory context rather than firm evidence. They show that cropped fields were heterogeneous, but they also confirm that within-crop management effects were weaker than the broader contrast between annual cropland and adjacent forest reference systems.

Several limitations should remain explicit. This was an observational study, so land-use differences cannot be assigned to any single management practice. One paired site had to be excluded because of mismatched parent material, highlighting the sensitivity of comparative soil studies to geologic context. The fractionation method also defined POC and MAOC operationally through a standardized laboratory procedure, which was appropriate for comparison across sites but does not imply perfect separation of natural pools (Poeplau et al., 2018; Lavallee et al., 2020). Microbial biomass was measured only in the surface layer, so the biological interpretation is strongest for 0–10 cm soil. Finally, the crop-only models were exploratory and based on a limited number of fields, so weak effects should not be taken to mean that management history is unimportant.

Even with these limitations, the results provide a useful benchmark for soil C dynamics in southeastern Michigan and, more specifically, in the WLEB. In a region where nutrient retention, soil health, and resilience are tightly linked, the paired forest reference plots show not only that soil C is lower in cropped systems, but also where in the profile those losses are concentrated and which fractions drive them (Baker et al., 2014). More broadly, this thesis suggests that soil C loss and recovery in this working landscape should not be understood through total SOC alone. They are better understood through the combined roles of depth, disturbance, organic matter supply, biological processing, and mineral stabilization (Doetterl et al., 2018; Lavallee et al., 2020; Hicks Pries et al., 2023; Liang et al., 2019; Wang et al., 2021). Separating total C into POC and MAOC across the full 0–60 cm profile made those interacting controls more visible.

Conclusion

This thesis showed that paired crop and forest soils in southeastern Michigan differed most strongly in the upper profile. Forest soils contained more total organic C, POC, and MAOC than crop soils in the upper 20 cm, whereas crop–forest differences were much smaller at 20–60 cm. Among the two fractions, POC showed the clearest surface-restricted response, while MAOC remained higher in forest soils through 0–20 cm and was also related to clay, consistent with mineral stabilization. Across the full 0–60 cm profile, forests stored more C overall, although most of that stock difference still came from the upper profile.

Together, results from this study suggest that soil C loss and recovery in this working WLEB landscape depend on the interaction of land use, soil depth, biological activity, and soil mineralogy. Forest reference systems therefore provide a useful benchmark for judging the extent of soil C depletion in cropland and for identifying where recovery is most needed. In this system, the upper profile appears to be the most sensitive zone for detecting land-use effects and the most likely zone where management-driven improvements in soil function would first become visible.

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Appendix

A. Crop-field context

Table A1. *Crop-only management screening table.*

Predictor	Response	Predictor p	Depth p	Clay p	Predictor × Depth p	result
RCI	Total C	0.4513	<0.0001	0.0440	0.1430	Depth + clay significant; RCI not significant.
Tillage	Total C	0.5104	<0.0001	0.0784	0.1099	Mostly a depth story.
Legume cover	Total C	0.8838	0.0005	0.0415	0.5786	Depth + clay significant; legumes not significant.
Crop diversity	Total C	0.3522	<0.0001	0.0387	0.1003	Depth + clay significant; diversity weak.
RCI	POC	0.7344	0.0011	0.8219	0.2486	Depth significant; RCI not significant.
Tillage	POC	0.8270	0.0024	0.8190	0.7013	Depth significant; tillage not significant.
Legume cover	POC	0.3371	0.0020	0.5003	0.7298	Depth significant; legumes not significant.
Crop diversity	POC	0.6184	0.0009	0.8105	0.1894	Depth significant; diversity not significant.
RCI	MAOC	0.3724	0.0002	0.0172	0.1572	Depth + clay significant; RCI not significant.
Tillage	MAOC	0.3584	<0.0001	0.0390	0.0281	Best crop-only signal: tillage × depth significant.
Legume cover	MAOC	0.6011	0.0004	0.0253	0.5344	Depth + clay significant; legumes not significant.
Crop diversity	MAOC	0.2856	<0.0001	0.0147	0.1102	Depth + clay significant; diversity weak.
RCI	POC:MAOC ratio	0.8202	0.0874	0.0172	0.6611	Mostly a clay story.
Tillage	POC:MAOC ratio	0.1856	0.0839	0.0211	0.6610	Mostly a clay story.
Legume cover	POC:MAOC ratio	0.1139	0.0952	0.0315	0.8163	Mostly a clay story.
Crop diversity	POC:MAOC ratio	0.8858	0.0891	0.0177	0.6540	Mostly a clay story.

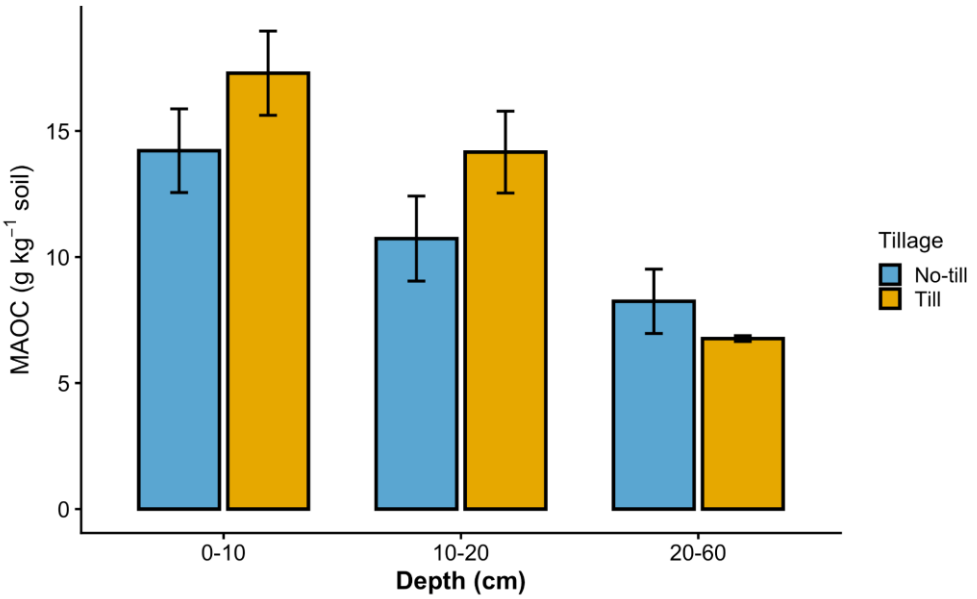


Figure A1. Relationship between tillage category and MAOC across depth in crop fields. The tillage-by-depth pattern was interpreted as marginal ($p = 0.0576$), with no significant within-depth contrasts.