

1 **Drivers of soil C quality and stability: Insights from a topsoil**  
2 **dataset at landscape scale in Ontario, Canada**

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9 **Abstract**

10 Although soil C is a critical component of soil health, studies robustly exploring the agronomic  
11 and pedoclimatic effects on soil C are limited, especially at the landscape scale. Therefore, a  
12 dataset of ~~1511~~ 1490 topsoil samples from agricultural fields across Ontario was used to evaluate  
13 the impacts of agronomic and pedoclimatic factors on eight soil C indicators including chemistry  
14 and thermal stability of soil C using the programmed pyrolysis approach. Soil C quality and  
15 stability were largely controlled by the inherent soil characteristics such as soil texture. Significant  
16 interactive effects of cropping system and tillage intensity on soil C indicators were observed;  
17 however, the number of significant effects varied among the three soil textural classes. All soil C  
18 indicators were significantly different among the cropping systems for the coarse textured soils,  
19 but the cropping system differences decreased under medium and fine textured soils. From the  
20 pyrolysis analysis, the hydrogen index (HI) and oxygen index (OI) also confirmed that the soil C  
21 chemistry was influenced by the cropping system. For instance, orchard systems had stable pools  
22 of soil C whereas vegetable systems were associated with less advanced degree of soil C  
23 decomposition. Remaining soil management variables (cover crop use, tillage intensity, and  
24 organic amendments) had ~~less-a weaker~~ influence than cropping systems and soil textural classes

25 on soil C indicators ~~in all soil textural classes~~. Principal component analysis revealed a close  
26 association of soil C indicators with the mean annual precipitation (MAP) and cropping system;  
27 suggesting that the quantity and quality of soil C inputs associated with different cropping systems  
28 and increase in precipitation had a large influence on soil C. Our results confirm the significant  
29 effects of agronomic and pedoclimatic variables on chemistry, thermal stability, and composition  
30 of soil C pools, which have long-term implications on soil C storage, mitigating global climate  
31 change, and improving soil health.

## 32 1. Introduction

33 Soil C dynamics is estimated based on the amount of C in various soil C pools and the  
34 transformation rate of C within these pools due to microbial processes (Cotrufo et al., 2013; Parton  
35 et al., 1988). Several indicators, therefore, have been proposed to assess soil C dynamics. Soil  
36 organic C (SOC) content or concentration is one of the most measured parameters of soil health  
37 (Bunemann et al., 2018) and plays a significant role in many soil functions like nutrient and water  
38 cycling and greenhouse gas emissions (Lal, 2016). Soil organic C comprises C compounds with a  
39 wide range of stabilities, and so it takes a long time (5 to 10 years) to detect changes after  
40 implementation of new land use management practices (Poeplau and Don, 2015). Total organic C  
41 includes a labile C pool, which is easily metabolized by soil microbes and has a rapid turnover  
42 time. Measurements of the labile soil C pool, by using the permanganate oxidizable C (POXC;  
43 ~~Wei-Moebius-Clune~~ et al., ~~2003~~2016), potential C mineralization and soil respiration (Haney et  
44 al., 2008) tests, are useful assessments of the quantity of C that is metabolized by the soil microbes  
45 and may offer early detection of SOC changes from land use changes. Likewise, autoclaved citrate  
46 extractable protein (ACE) may be used as a predictor of labile soil N and C (Agnihotri et al., 2022).  
47 Assessment of these soil C indicators, hence, provide direct or indirect information on the soil C

48 storage and functions across diverse soil textures, management practices, and climatic conditions  
49 (Liptzin et al., 2022). Most of the research on soil C indicators and its response to management  
50 practices is conducted in field experiments and at a small-plot scale (Chahal et al., 2021; Culman  
51 et al., 2013; Mesgar et al., 2024). In this study, we apply these techniques to samples obtained at  
52 the landscape scale from operational agricultural fields. This is important to comprehensively  
53 characterize the relationship between soil C indicators and the farm management strategies that  
54 drive soil health.

55 Thermal analysis methods, such as programmed pyrolysis, is a novel technique in soil science  
56 and is used to assess the molecular composition and the thermal stability of SOC (Gillespie et al.,  
57 2014). Programmed pyrolysis subjects soil samples to a temperature ramp under an inert  
58 atmosphere and measures the organic and inorganic C released as a function of increasing  
59 temperature (Lafargue et al., 1998; Sebag et al., 2016). The thermal stability is related to the  
60 biodegradation potential of SOC (Peltre et al., 2013; Sebag et al., 2016; Soucémariadin et al.,  
61 2018), which is inferred from the hydrogen index (HI), oxygen index (OI), and T50 (temperature  
62 at which 50% of the pyrolyzable C has been released). The HI primarily represents fresh,  
63 hydrogenated organic matter, and is related to the labile pool of soil C whereas the OI represents  
64 organic matter that has been oxidized through microbial metabolism, and is a more resistant and  
65 stable pool of soil C (Carrie et al., 2012; Mesgar et al., 2024). The T50 is inversely related to the  
66 decomposition potential, in that increasing T50 indicates lower decomposition potential and thus  
67 more biologically stable organic matter (Gillespie et al., 2014; Gregorich et al., 2015). While the  
68 HI, OI, and T50 are not direct indicators of soil health, the assessment of SOC stability and quality  
69 using these indicators (pyrolysis method) provides valuable knowledge on how to build soil C and  
70 to develop effective strategies to reduce the C loss under different land use management practices.

71 Soil C quality and stability is controlled by numerous variables such as soil texture, tillage,  
72 crops grown, cover crops, use of organic amendments, changes in temperature, precipitation, and  
73 the interactions among these factors (McDaniel and Grandy, 2016). Furthermore, these controlling  
74 variables influence the composition of SOC and can potentially alter the stable and labile pools of  
75 C (McDaniel and Grandy, 2016; Soon et al., 2007). Adding manure, for instance, to an intensively  
76 managed long-term sorghum-wheat cropping system increased the labile fraction of soil C (Datta  
77 et al., 2018). Soil C mineralization and respiration was increased by using no-tillage, cover crops,  
78 and a diverse crop rotation (Balota et al., 2004; Chahal and Van Eerd, 2020; Viaud et al., 2011).  
79 Adopting reduced tillage along with cover crops or perennial crops increased SOC content and  
80 soil microbial biomass C (Sun et al., 2023). Likewise, POXC increased with the reduction in tillage  
81 intensity and cover cropping (Liptzin et al., 2022). These studies from long-term experiments  
82 confirm that different management practices impact the SOC composition which in turn, affects  
83 the labile and stable pools of soil C. Yet, it remains uncertain which management or environmental  
84 variables exert the strongest influence on soil C stability under the complexity of agricultural  
85 fields. it is largely unknown if these effects are evident given the complexity of agricultural fields.

86 Here, we used a large dataset of mineral topsoil samples collected from agricultural fields  
87 across Ontario through the Ontario Topsoil Sampling Project (OTSP). Previously, the OTSP  
88 dataset was used to assess the soil health scoring functions (Chahal et al., 2023) and SOC:clay  
89 ratio as an indicator of soil functionality (Chahal et al., 2024). The goal of the present study was  
90 to evaluate the impact of agricultural management and environmental variables on soil C indicators  
91 (SOC, 96-h C mineralization potential ( $C_{\min-96h}$ ), POXC, Solvita CO<sub>2</sub>-burst, and ACE) and  
92 indicators of thermal stability of soil C using programmed pyrolysis (HI, OI, and T50). We also  
93 assessed the associations among these soil C indicators at the landscape scale to comprehensively

94 assess the major drivers of soil C storage and stability. The study results will contribute to making  
95 improved recommendations regarding selection of soil C indicators and help growers and  
96 researchers to adjust management practices to increase soil C storage.

## 97 **2. Materials and methods**

### 98 2.1 Soil sample collection

99 Topsoil samples (n=1511) for this study were collected as a part of the OTSP from 2019 to  
100 2022. The soil samples for this project were collected from multiple locations throughout southern  
101 Ontario. The OTSP was a collaborative project between the Ontario Ministry of Agriculture, Food,  
102 and Agribusiness (formerly known as Ontario Ministry of Agriculture, Food, and Rural Affairs)  
103 and the School of Environmental Sciences at the University of Guelph, to assess the soil physical,  
104 chemical, and biological characteristics in agricultural soils in Ontario (Chahal et al., 2023; Chahal  
105 et al., 2024). Soil samples were collected from the Ap horizon (agricultural tilled layer). To ensure  
106 all samples were restricted to this horizon depth, median depth of 25 cm), and the sampling depth  
107 was terminated at 30 cm if the Ap horizon exceeded this depth. The median thickness of the  
108 sampled Ap horizons across all the sites was 25 cm. Details about soil sample collection and the  
109 selection of the locations is explained in detail in Chahal et al. (2023). Briefly, for each site, three  
110 soil samples were collected, georeferenced, and a comprehensive land management survey with  
111 the grower was conducted to document information on the crop rotation, type of crops grown,  
112 tillage, use of cover crops, and application of organic amendments. The agricultural management  
113 factors identified in our study were consistent with the commonly adopted practices by the growers  
114 and were representative of the geographical area. Mean annual temperature (MAT) and mean  
115 annual precipitation (MAP) data were collected using the WorldClim version 2.1 from 1970 to  
116 2000 (<http://www.worldclim.org/data/worldclim21.html>). The MAP and MAT were grouped into

117 two (intermediate zone with precipitation between 800 and 1000 mm and wet zone with  
118 precipitation greater than 1000 mm) and three classes (0 to 5°C, 5.01 to 10°C, and 10.01 to 15°C),  
119 respectively. All the soil samples were classified into three soil textural classes (coarse with sand  
120 % ranging between 52 to 94%), medium (between 2 to 78% sand) , and fine (between 1 to 45%  
121 sand); Moebius-Clune et al., 2016), five cropping system (annual grain, forage, vegetable, orchard,  
122 and perennial), five tillage intensity (conventional tillage, moderate disturbance, light disturbance,  
123 no disturbance, and no-tillage), two cover crop (yes or no), and two organic amendment (yes or  
124 no) classes. For the tillage intensity classes, conventional tillage represented the moldboard plow  
125 tillage with full soil disturbance, moderate tillage represented more than 2 passes with disk or  
126 chisel plow, light disturbance represented 1 or 2 passes with disk or cultivator, no disturbance  
127 referred to the little or no soil movement as observed in pasture and perennial cropping systems,  
128 and no-tillage represented minimal or no disturbance to the soil such as slot-tillage during planting.

129 We focused on the mineral soils for this study; thus, 21 soil samples with topsoil SOC  
130 concentration more than 8.7% were removed from the dataset (Chahal et al., 2024). Therefore,  
131 total number of samples used for the soil C analysis were 1490. It is important to note that the  
132 number of observations for each soil C indicator (given in section 2.2) varied by the indicator and  
133 hence the management practices. For instance, programmed pyrolysis was restricted to 151 soil  
134 samples selected via conditioned Latin hypercube approach (Minasny and McBratney, 2006) as  
135 representative of full dataset (Chahal et al., 2023).

## 136 2.2. Laboratory analyses

137 After quality assurance and quality control (QA/QC) analysis, the database consisted of eight  
138 soil C indicators: SOC (n=1490), C<sub>min</sub>-96h (n=1017), POXC (n=1413), Solvita CO<sub>2</sub>-burst (n=768),  
139 ACE protein (n=151), HI (n=151), OI (n=151) and T50 (n=151). As described above, 151 soil

140 samples used to measure ACE protein and pyrolysis parameters were representative of the full  
141 dataset and refer to the same set of soil samples. Soil organic C concentration was calculated as  
142 the difference between total C and inorganic C. Total C was estimated using the dry combustion  
143 method (samples were combusted at 1300 °C) on LECO 828 Series CN analyzer (Skjemstad et al.,  
144 2008). Inorganic C was determined by subjecting a ground subsample of soil to combustion in a  
145 muffle furnace at 470°C to remove organic C (Krom and Berner, 1983). Soil C mineralization  
146 ( $C_{\min}$ -96h) was quantified using the KOH trap method and was determined by measuring the  
147 concentration of CO<sub>2</sub> evolved (mg CO<sub>2</sub>-C 20 g<sup>-1</sup> soil) when 7.5 mL water was added to 20 g air  
148 dried soil placed in an air-tight jar with 9 mL of 0.5 M KOH at room temperature (Schindelbeck  
149 et al., 2016). Permanganate oxidizable C (µg g<sup>-1</sup>) was measured using spectrophotometer where  
150 the colorimetric change due to the reduction of manganese in a potassium permanganate solution  
151 on air dried soil was quantified (Moebius-Clune et al., 2016). Solvita CO<sub>2</sub>-burst was quantified as  
152 per the updated protocol by the Woods End<sup>®</sup> Laboratories Inc., Mt. Vernon, ME. A 30-cc scoop  
153 (around 25 to 35 g) of oven-dried (40°C) soil was placed in a vial and was wetted using 9 to 10  
154 mL distilled water. The vials were transferred to 475 mL glass jars and Solvita CO<sub>2</sub>-burst paddles  
155 were inserted into each jar. The jars were sealed and left undisturbed for 24 h at room temperature  
156 and evolved CO<sub>2</sub> concentration (mg kg<sup>-1</sup>) was determined using a digital colorimeter reader  
157 (Brinton, 2019). Autoclaved citrate extractable protein (mg kg<sup>-1</sup>) was quantified on air-dried soils  
158 by autoclaving, centrifuging, and treating a sodium citrate soil extract with bicinchoninic acid  
159 (Schindelbeck et al., 2016). Soil particle size analysis was done using the pipette method where  
160 soil organic matter was removed by treating the soil with hydrogen peroxide (Sheldrick and Wang,  
161 1993). Consistent with soil textural grouping recommended by Moebius-Clune et al. (2016), the  
162 dataset was divided into three soil textural classes (coarse, medium, and fine).

163 The programmed pyrolysis analysis was conducted using a HAWK pyrolyzer (Wildcat  
164 Technologies, Humble, Texas, USA) at the Canadian Geological Survey in Calgary Alberta  
165 according to Gillespie et al. (2014) and Gregorich et al. (2015). The standard manufacturer  
166 recommended settings (with the helium flow rate at 100 mL/min) were followed to conduct the  
167 programmed pyrolysis. About 70 mg air-dried ground soil sample is subjected to a constant  
168 temperature of 300°C for 3 min under helium gas, to quantify free hydrocarbons using a flame  
169 ionization detector (mg HC g<sup>-1</sup>) and referred to as S1. Next, the soil sample was heated at a rate of  
170 25°C per minute until 650°C where hydrocarbons were released (i.e., cracking SOC) and  
171 quantified as S2. The concentration of CO<sub>2</sub> (mg CO<sub>2</sub> g<sup>-1</sup>) released during S1 and S2 was determined  
172 using an infrared detector and represented as S3. Hydrogen index of a soil sample represents the  
173 ratio of all hydrocarbons measured as S1+S2 divided by SOC, whereas OI refers to the ratio of  
174 CO<sub>2</sub> released (S3) divided by SOC (Lafargue et al., 1998). The stability of soil C is represented by  
175 the T50 which is the temperature at which 50% of the SOC was pyrolyzed (Gillespie et al., 2014;  
176 ~~Gregorich et al., 2015~~). It is important to note that T50 is measured under S1 and S2 only.

### 177 2.3 Data analysis

178 All soil data were analyzed using the SAS (SAS Institute version 9.4, Cary, NC, USA). A  
179 variance component analysis was conducted to test the relative importance of the agronomic and  
180 pedoclimatic variables for each soil C indicator. Prior to conducting the variance component  
181 analysis, the assumptions of normality were assessed. Given the relatively large sample sizes for  
182 most of the variables studied, variance component estimates were considered robust to minor  
183 deviations from normality. For each soil textural class, the main as well the interactive effect of  
184 the agronomic management practices (cropping system, tillage intensity, cover crops, and organic  
185 amendments) on soil C indicators were tested using PROC GLIMMIX in SAS. The relationship

186 among the soil C indicators was tested using the Pearson correlation analysis (PROC CORR). To  
187 linearize the relationships among indicators, all the indicators were log-transformed for correlation  
188 analysis. Consistent with Liptzin et al. (2022) and Mesgar et al. (2024), a principal component  
189 analysis using PRINCOMP procedure was also conducted to explore how the soil C indicators  
190 interacted with the site characteristics (i.e., agronomic management practices (cropping system,  
191 tillage, cover crop, organic amendment) and pedoclimatic conditions (sand, silt, clay, mean annual  
192 temperature and precipitation)). In addition to the site characteristics and pedoclimatic conditions,  
193 the variables included in the PCA were SOC concentration, POXC, C<sub>min</sub>-24h, Solvita CO<sub>2</sub>-burst,  
194 ACE, HI, OI, and T50. The first two PCs were selected based on scree plots and the eigenvalues  
195 of the soil C indicators were used to create the biplots to better understand the interdependence  
196 among the soil C indicators and how they interacted with the site characteristics and pedoclimatic  
197 conditions. The statistical significance of all the tests was assessed at  $P < 0.05$ .

### 198 **3. Results and discussion**

#### 199 3.1 Agronomic and pedoclimatic effects on soil C indicators

200 The results of variance partitioning revealed that soil textural classes and cropping system  
201 explained a larger percentage of variance for all soil C indicators compared to the other variables  
202 (tillage intensity, cover crop, organic amendments, MAP and MAT; Table 1). For SOC, the amount  
203 of variance explained by soil texture was higher than for cropping system (60.5% and 26.4%,  
204 respectively), and for POXC, it was 53.5% and 21.7%, respectively (Table 1). Our results of strong  
205 dependence of soil texture on SOC confirm the texture mediated soil C stabilization processes. For  
206 instance, soil C retention is higher in fine textured than coarse textured soils mainly due to mineral-  
207 organic associations and through the formation of microaggregates which physically protect the  
208 soil C from microbial decomposition. This finding also aligned with Figure 1 where fine textured

209 soils exhibited greatest T50 values (i.e. indicating greater thermal stability); thus, further  
210 highlighting the role of clay induced protection of SOC. Interestingly, the percentage of variance  
211 explained by texture was comparable or less than for cropping system in  $C_{\min}$ -96h (38.8% and  
212 36.9%), Solvita CO<sub>2</sub>-burst (37.5% and 38.7%), and ACE (4.87% and 50.7%) (Table 1). The type  
213 of main crops grown (i.e., the cropping system) was found to be a key driver of labile pools of soil  
214 C (such as  $C_{\min}$  and ACE) in a study by Amsili et al. (2021). Soil texture (~~75.2%~~) also explained a  
215 large amount of variance (75.2%) in the thermal-based parameters of soil C (Table 1). Measures  
216 of SOC stability (T50) and quality (HI and OI) were largely controlled by soil texture for T50 and  
217 cropping system for HI and OI. Unlike cropping system and soil textural classes, tillage intensity  
218 was not found to be an important predictor of any of the tested soil C indicators (Table 1). While  
219 tillage intensity was not found to be an important variable impacting soil C indicators when the  
220 bulk dataset was used, its effects were detected for some soil C indicators when the data were  
221 categorized based on soil textural classes. In particular, tillage intensity significantly influenced  
222 POXC in fine-textured soils (Table 2) suggesting that effects of tillage are more pronounced on  
223 labile soil C pools in soils with high clay content than the stable fractions of soil C. The least  
224 amount of variance in soil C indicators was explained by MAT, use of cover crops, and organic  
225 amendments (Table 1). suggesting- a minor influence of these factors on soil C variability in our  
226 study. One possible explanation for this result could be that cover crop and organic amendment  
227 effects varies with soil type, climatic conditions, and baseline fertility which might have potentially  
228 masked their overall impact on soil C indicators in our multi-site study. Therefore, consideration  
229 of soil textural class and cropping system is needed when interpreting the soil C indicators (Nunes  
230 et al., 2021).

231 It is important to note that the model R<sup>2</sup> values in our study were relatively low ranging  
232 between 0.16 to 0.37 (Table 1). This is not unexpected for agronomic studies on SOC that integrate  
233 variable land use management practices and complex biochemical processes. The unexplained  
234 variance likely reflects the additional variables which were not captured in our model such as the  
235 crop residue inputs, soil microbial community composition, and/or the historical land use intensity.  
236 Although these variables are known to influence the SOC dynamics, the data on these factors were  
237 not consistently available for all the sites studied. Incorporating these variables in the future  
238 research might improve the model R<sup>2</sup> values; however, the current results still clearly highlight the  
239 importance of soil texture as the major predictor of SOC in our study.

240 Table 2 shows the variance analysis on soil C indicators broken out by texture class and  
241 parameter, and Table 3 shows the mean values and groupings. In all soil textural classes, significant  
242 differences in SOC, C<sub>min</sub>-96h, and POXC concentration due to cropping systems were observed  
243 (Table 2). Perennial and forages when grown with annual crops exhibited greater or comparable  
244 SOC concentrations relative to the other cropping systems in all soil textural classes (Table 3). ~~The~~  
245 ~~greatest SOC concentrations were observed under perennials and when forages were grown with~~  
246 ~~annual crops in all soil textural classes (Table 3).~~ Likewise, forages and perennial systems had  
247 greater or comparable concentrations of C<sub>min</sub>-96h and POXC than the remaining systems in all soil  
248 textural classes (Table 3). Less soil disturbance due to tillage, greater diversity of crop species,  
249 continuous presence of living roots in perennial systems perhaps contributed to the greatest  
250 concentration of SOC, C<sub>min</sub>-96h, and POXC observed (Amsili et al., 2021; Congreves et al., 2015;  
251 Nunes et al., 2020). Compared to annual grain, perennial and forage systems provide a more  
252 temporally consistent (i.e., no fallow period) source of substrate quality to microbial communities  
253 mainly due to high C:N ratio, lower lignin content, and high concentration of mineralizable C

254 (Mesgar et al., 2024). For most of the soil C indicators, annual grain, orchard, and vegetable  
255 cropping systems had the lowest soil C values (Table 3). Vegetable and annual grain systems are  
256 intensively managed with high intensity of tillage and have lower soil C inputs (Norris and  
257 Congreves, 2018; Nunes et al., 2020), which negatively impact soil C. Therefore, in all soil textural  
258 classes, diversification of cropping systems and addition of organic amendments are critical  
259 components of building soil C. While our findings suggest that diversification of cropping systems  
260 results in greater soil C, we did not measure the quantity and quality of crop residue inputs, which  
261 limits our ability to confirm the exact mechanisms of soil C accumulation in our study.  
262 Nevertheless, previous studies by King and Blesh (2018), McDaniel and Grandy (2016) have  
263 reported that diversifying crop rotations with cover crops, perennials, or forages tend to increase  
264 the quantity and biochemical diversity of soil C inputs than the conventional monocultures (e.g.  
265 simple annual grain systems). Similarly, studies by Adhikari and Hartemink (2017) and Presley et  
266 al. (2004) demonstrated that adoption of conservational agricultural practices such as reduced  
267 tillage, diversified cropping systems and addition of organic amendments contributed to a build up  
268 of SOC even on coarse textured soils.

269 While T50 was not statistically different due to cropping system and tillage practices in all soil  
270 textures (Table 2), annual grain had the highest whereas forage had the lowest T50 when averaged  
271 across all soil textures (~~Table 3 and~~ Figure 1a). These results suggest that annual grain perhaps  
272 contribute to more resistant organic matter additions to soil whereas forage systems might add  
273 relatively easily decomposable residue. Usually, forage cropping systems (specifically legumes)  
274 have a higher residue quality (high biomass N and low C:N) and result in larger proportion of  
275 labile fractions of soil C. Mesgar et al. (2024) found similar results where crop rotations with  
276 forages (such as alfalfa or red clover) contributed to labile components of soil C. Furthermore, fine

277 textured soils had the highest whereas coarse and medium textured soils had the lowest T50 (Table  
278 3 and Figure 1b), confirming that the soil texture and clay content influence the thermal stability  
279 of soil organic matter. It is likely related to the greater organo-mineral associations in clay rich fine  
280 textured soils than the coarse textured soils, which contributed to the protection of soil organic  
281 matter from microbial decomposition and increase its thermal stability. Previous studies by  
282 Simkovic et al. (2025) and Stoner et al. (2023) have also confirmed a positive relationship between  
283 clay content and stabilization of soil organic matter.

284 The other thermal-based parameters of soil C characterization were the HI and OI, which  
285 represented the maturity level of soil organic matter. Typically, a high HI represents a thermally  
286 labile pool of organic matter which is enriched with hydrogen and the freshly added carbohydrates  
287 and lignin (Mesgar et al., 2024). Conversely, OI represents a more resistant pool of organic matter  
288 following the oxidation processes occurring during the soil organic matter decomposition (Carrie  
289 et al., 2012; Mesgar et al., 2024; Saenger et al., 2013). Simultaneous reduction in both the HI and  
290 OI indicates aromatization. The HI was not different among the agronomic management practices  
291 in coarse and fine textured soils, but significant differences were observed in medium textured  
292 soil. Among the cropping systems in medium textured soils, perennial (200 mg HC g<sup>-1</sup> OC) had  
293 greatest while annual grain (132 mg HC g<sup>-1</sup> OC) had the least HI (Table 3). These results confirm  
294 that the diversified cropping systems with forages and perennial crops had a higher quantity and  
295 quality of H-rich labile components of soil organic matter and represented a more labile state of  
296 organic matter decomposition than the intensively managed systems with less C inputs (Ding et  
297 al., 2006; Mesgar et al., 2024). Furthermore, differences in OI due to cropping system were  
298 detected in coarse textured soil only (Table 2). Orchard (203 mg CO<sub>2</sub> g<sup>-1</sup> OC) had greatest whereas  
299 vegetable (147 mg CO<sub>2</sub> g<sup>-1</sup> OC) had the least OI in coarse textured soils; suggesting that the orchard

300 systems represent a more advanced state of soil organic matter decomposition than the other  
301 cropping system categories.

302 A significant interaction between cropping system and tillage intensity was detected for some  
303 of soil C indicators in all soil textural classes (Table 2), but trends varied among indicators and  
304 texture. For the thermal based soil C indicators, significant interaction between cropping system  
305 and tillage intensity was observed for the HI in medium-textured soil and for OI in coarse textured  
306 soil (~~Figure-Table~~ 2, Table S1 to S4). Given that the annual grain and forage cropping systems  
307 showed the strongest contrast for these indicators with sufficient number of observations, we  
308 selected only these two cropping systems to evaluate the effects of tillage intensity (Figure 2, Table  
309 S1). In coarse-textured soils,  $C_{\min-96h}$ , POXC and Solvita  $CO_2$ -burst concentrations were  
310 significantly impacted by the intensity of tillage adopted in annual grain and forage systems, while  
311 the remaining indicators were comparable across all the tillage and cropping system combinations  
312 (Table S1). In medium-textured soils, all soil C indicators except Solvita  $CO_2$ -burst had a  
313 significant interaction between cropping system and tillage intensity (Table S1). In fine textured  
314 soils, all but ACE were significantly different among the cropping system and tillage treatment  
315 combinations (Table S1). Therefore, medium and fine textured soils had a greater number of  
316 interactions than coarse textured soils. One possible mechanism might be that fine textured soils  
317 have high clay content which stabilizes soil C via mineral adsorption and formation of  
318 microaggregates. Fine textured soils also promote and support diverse soil microbial communities  
319 which play a critical role in supporting the complex microbial mediated soil C transformation  
320 processes (Six et al., 2002). In contrast, coarse textured soils have lower surface area, lower water  
321 holding capacity, and less soil microbial activity, which perhaps contributed to lesser number of  
322 detectable interactions between the management practices on soil C indicators. Overall, the

323 significant interaction of cropping system with tillage demonstrates that the changes in soil C pools  
324 brought on by various tillage intensity treatments is dependent on the type of the crop species  
325 grown and the soil texture. Similar interactive effects of tillage and cropping system on soil health  
326 were reported by Angon et al. (2023).

327 A pseudo-Van Krevelen diagram was created by plotting HI against OI (Figure 3) to visually  
328 characterize the composition of soil organic matter across various cropping systems (Carrie et al.,  
329 2012; Mesgar et al., 2024). We found that most of the orchard systems have oxygenated products  
330 and represented the more stable pool of soil organic matter whereas for vegetable systems, the  
331 organic matter composition mainly consisted of hydrogenated products and was associated with a  
332 less advanced stage of organic matter decomposition (Figure 3). While the visual representation  
333 of HI vs OI between both systems (i.e. vegetable and orchards) may appear similar due to  
334 variability and sample size, the underlying data distribution supports our interpretation (Figure 3).  
335 Interestingly, the OI values for vegetable systems were not significantly different than the annual  
336 grain systems in coarse textured soils (Table 3), suggesting that the slow decomposition of organic  
337 matter in vegetable systems is dependent on the soil texture and agronomic management practices  
338 followed. For the remaining systems, points found closer to the origin, such as in the annual grain  
339 site data, suggests that organic matter structures are undergoing aromatization processes compared  
340 to sites with forages or with perennial crops.

341 It is important to note that the frequency count of observations within the various tillage  
342 intensity classes among the cropping system categories was not equal nor balanced (Figure 4) but  
343 are reflective of typical management practices employed within the various cropping systems. For  
344 instance, and as expected, the number of observations collected from the ‘no disturbance’ category  
345 was greatest in perennial systems (n=142, Figure 4). Vegetable (n=5) and orchard (n=4) cropping

346 systems had the least number of observations for no-tillage (Figure 4). Orchards had the least  
347 number of total observations (n=33, Figure 4), which is consistent with Ontario agriculture census  
348 data where orchards represent 7.03% of farmland (Fruit and Vegetable Survey, Statistics Canada  
349 2023). Furthermore, the frequency count of samples collected from coarse textured soils (n=308)  
350 was lower than medium (n=642) and fine textured soils (n=540, Figure 5) which is largely  
351 attributed to glacier deposits that shaped the region and the topography where more sand on top  
352 and less fine particles as they are more prone to loss due to erosion. While clearly reflective of  
353 Ontario soils and agriculture, the discrepancy in the count of observations suggests the need to be  
354 cautious in directly attributing the results to a system.

### 355 3.2 Relationships of soil C indicators with agronomic and pedoclimatic variables

356 Principal component analysis was conducted where first and second PCs explained 32% and  
357 17% of the variance in the data, respectively, ~~which is consistent with variance explained in other~~  
358 ~~studies (Liptzin et al., 2022).~~ Based on the PCA, soil C indicators and the measures of SOC quality  
359 (HI and OI) were closely associated with the cropping system, MAP, and organic amendments,  
360 and were negatively associated with MAT (Figure 6), suggesting a higher value for soil C  
361 indicators under cooler temperatures. Although precipitation and organic amendments did not  
362 explain a large amount of variance in our dataset (Table 1), the PCA demonstrated that the soil C  
363 indicators increased with an increase in precipitation (Figure 6). It is important to note that PCA  
364 and variance component analysis differ in both the statistical structure and objectives, which  
365 perhaps led to differences in the results between both approaches. For instance, variance analysis  
366 evaluates the independent effect of each predictor variable on soil C indicators, whereas PCA  
367 simultaneously assesses the covariance among the multiple soil C indicators. Climate has been a  
368 key determinant of soil C (Jenny, 1941). The interactions among the soil microbes, crop residues,

369 and plant root exudates mainly control the influence of climatic variables on soil C (Schmidt et al.,  
370 2011). Our results of high values of soil C indicators with an increase in MAP and decrease in  
371 MAT were consistent with studies conducted in North America (Burke et al., 1989; Liptzin et al.,  
372 2022) and globally (Jobbagy and Jackson, 2000). While relationships of soil C indicators with  
373 temperature and precipitation were consistent with expectations, it was surprising to see an effect  
374 given the relative minimal differences within the province. In Ontario agricultural zones, MAT  
375 varies by only 1°C, and MAP by approx. 100 mm. Given current climate change predictions, these  
376 results have powerful implications for C sequestration and soil functioning under future climate  
377 conditions.

378 Furthermore, silt and clay content were ~~grouped-clustered~~ together in PCA on one side of the  
379 second axis whereas sand content was positioned on the opposite side of the second axis (Figure  
380 6). This result was consistent with the well-established associations between soil C dynamics and  
381 soil texture where and were positively associated with the soil C indicators in the second axis,  
382 whereas sand content was negatively associated with the indicators in the second axis of the PCA  
383 (Figure 6). Typically, soils rich in clay content have higher C retention capacity than coarse  
384 textured soil (von Lutzow et al., 2006); ~~).~~ Accordingly, hence, at the positive association-loading  
385 displayed by the clay and silt rich soils on the second axis corresponds to greater values of soil C  
386 indicators observed in our study. was observed between clay content and soil C indicators in our  
387 study (Congreves et al., 2015). Although important, the relationship between soil texture and soil  
388 C indicators (particularly POXC and respiration) has not been explored enough in the literature  
389 (Nunes et al., 2020; Sinsabaugh et al., 2008).

390 Soil C indicators and HI were negatively associated with tillage intensity ~~and cover crops~~ on  
391 the first PC axis (Figure 6). Increase in tillage intensity reduces soil C (mainly the topsoil C) by

392 increasing the mineralization of soil organic matter, disrupting the soil structure, and decreasing  
393 soil microbial populations and communities (Nunes et al., 2020). Therefore, adopting reduced or  
394 minimum tillage practices might contribute to building soil C and help to mitigate the negative  
395 impacts of climate change. Numerically greater SOC concentration observed with reducing tillage  
396 intensity in our study suggests the potential of the sustainable land use management practices on  
397 sequestering C, reducing CO<sub>2</sub> emissions, and mitigating the global warming effect (Melland et al.,  
398 2017) and greenhouse gas emissions (Mangalassery et al., 2014).

399 Except POXC in fine-textured soils, we did not find a significant effect of tillage intensity on  
400 soil C indicators (Table 2 and S5). It is important to note that in our study, the participants were  
401 asked to choose one of the tillage intensity categories, which might have caused a variability in  
402 the recorded data (i.e. descriptive terms and actual disturbance on the farm) and might not be a  
403 true reflection of tillage intensity over the long-term. Moreover, the producer interpretation of the  
404 tillage intensity categories could have added uncertainty. Additionally, cover crops were negatively  
405 associated with soil C indicators (Figure 6) but explained <5% of the variance in the dataset (Table  
406 1) confirming a very small response of soil C indicators to cover crops (Table S6). It is not entirely  
407 ~~negative association of soil C indicators with cover crops and a very small response of indicators~~  
408 ~~to cover crops (Figure 6 and Table S6) is not~~ clear but might be attributed to a smaller number of  
409 observations with cover crops in our study (n=55). The cover crop effects on soil C indicators are  
410 largely dependent on the cover crop management factors such as type of cover crop species grown,  
411 frequency and duration of cover cropping, planting date, and termination time of cover crops  
412 (Blanco-Canqui et al., 2015; Peng et al., 2024). Due to the unavailability of the cover crop  
413 management factors in our study, the interpretation of cover crop effect is challenging but clearly

414 demonstrates that other management factors (cropping system and tillage system) have a greater  
415 effect on soil C indicators.

### 416 3.3. Relationships among the soil C indicators

417 To better understand associations among soil C indicators, correlation analysis was conducted  
418 on the soil C indicators and the indicators characterizing the chemical composition of soil organic  
419 matter (Table 4). Interestingly, despite having a range of soil textural classes and cropping system  
420 categories, strong positive significant relationships were observed among the soil C indicators  
421 (Table 4). Among the indicators, SOC and POXC had the strongest positive relationship ( $r=0.81$ ),  
422 which was consistent with Liptzin et al. (2022) and Culman et al. (2012). Consistent with Amsili  
423 et al. (2021) and Nunes et al. (2020), our results confirm that an increase in SOC positively impacts  
424 the soil microbial activity (as demonstrated by Solvita CO<sub>2</sub>-burst and C<sub>min</sub>-96h) and the quality of  
425 soil organic matter (as demonstrated by POXC and ACE). Significant moderate negative  
426 associations ( $r=-0.24$  to  $-0.35$ ) were observed between HI and OI, HI and T50 (Table 4). Consistent  
427 with Mesgar et al. (2024), our results suggest that the indicators representing the labile components  
428 of soil organic matter such as HI were negatively associated with OI (an indicator of resistant pool  
429 of soil organic matter) and T50. We also observed that the indicators defining the stable and labile  
430 pools of soil C via the thermal analysis had a positive relationship with the soil C indicators such  
431 as SOC and C mineralization (Table 4). The correlation analysis also confirmed that the easily  
432 decomposable component of soil C (e.g., HI) was closely related to the labile indicators of soil C  
433 such as soil respiration and ACE (Table 4). The positive association of ACE with HI confirms that  
434 H-rich aliphatic C and protein like N compounds are concomitantly present in fresh organic matter  
435 and are co-metabolized by the soil microbes during the –early stages of organic matter  
436 decomposition. Collectively, these results confirm the efficacy and applicability of the

437 programmed pyrolysis method as a valuable tool to study the biochemical composition and  
438 decomposition potential of soil C.

#### 439 **4. Conclusions**

440 This study focused on understanding the key drivers of soil C quality and stability in agricultural  
441 production systems at a landscape scale. To the best of our knowledge, this is the first study to  
442 evaluate the agronomic and pedoclimatic effects on the measures of soil C quality and C stability  
443 (particularly with the pyrolysis approach) in North America at the landscape scale. Our results  
444 revealed that soil textural classes and cropping system had a strong influence on both quality and  
445 stability of soil C indicators evaluated in this study. The cropping system differences on soil C are  
446 mainly related to the quantity and quality of residue C inputs, which in turn are primarily dependent  
447 on the cropping system, cover crops, tillage intensity, and organic amendments. Among the  
448 cropping systems, we found a greater concentration of soil C in forage and perennial cropping  
449 systems than the annual grain and vegetable systems. Likewise, forage cropping systems had a  
450 greater preservation of labile components while orchards had a more stable pool of soil C. Our  
451 results, therefore, confirmed that agricultural management-induced factors play a crucial role in  
452 understanding the chemical composition of soil organic matter. The indicators representing the  
453 labile pools of soil C (such as POXC and  $C_{\min-96h}$ ) were positively correlated with the parameters  
454 indicating readily decomposable fractions of soil C (i.e., HI).

455 Furthermore, all indicators had a positive association with precipitation and a negative  
456 relationship with temperature suggesting an increase in the indicator values at cool and wet  
457 conditions despite low differences in values. Increase in the tillage intensity also negatively  
458 impacted the soil C indicators. Overall, the management-induced differences in soil C indicators  
459 in our study imply the benefits of adopting sustainable agricultural practices on building soil C,

460 reducing CO<sub>2</sub> emissions, and mitigating the negative effects of global climate change. While the  
461 findings of our study suggest a significant impact of agronomic and pedoclimatic variables on the  
462 soil C, it is important to note that the results of this study pertain only to the topsoil. It is possible  
463 that the same trends or effects on soil C quality and stability might not be observed at the deeper  
464 soil depths; hence, suggesting a need for future research. Additionally, tillage intensity categories  
465 in our study were based on subjective producer descriptions and lacked standardized metrics such  
466 as tillage depth, number of passes which might have introduced a potential bias in the interpretation  
467 of study results. The small sample sizes of cover crops (n=55) and orchards (n=33) limit the  
468 generalizability of results for these management practices. Future studies should employ more  
469 standardized tillage measurements and ensure a more balanced sample sizes across the agronomic  
470 management categories to improve the robustness of study results.

#### 471 **Code and data availability**

472 Data will be made available upon request but is not available in an online repository to protect  
473 the privacy of the participants in this project.

#### 474 **Supplement**

475 The supplementary tables and figures related to this article are attached along with the  
476 manuscript text.

#### 477 **Author contributions**

478 IC, writing, data analysis, data interpretation and presentation, and editing the manuscript; DD,  
479 data organization and curation, reviewing and editing the manuscript; AW, funding acquisition,  
480 supervising, reviewing, and editing the manuscript; LVE, funding acquisition, supervising,  
481 reviewing, and editing the manuscript.

#### 482 **Competing interests**

483 The authors declare that they have no conflict of interest.

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631 **Table 1** Partitioning of variance of soil C indicators<sup>z</sup> in the Ontario Topsoil Sampling Project database  
 632 from 2019 to 2022 into soil and crop management, soil texture, and climatic variables.

		SOC	C <sub>min</sub> -96h	POXC	Solvita CO <sub>2</sub> -burst	ACE	T50	HI	OI
Variables	df								
Cropping system	4	<b>26.4</b>	<b>36.9</b>	<b>21.8</b>	<b>38.8</b>	<b>50.7</b>	10.0	<b>59.8</b>	<b>43.0</b>
Tillage intensity	4	4.82	18.0	6.30	11.8	<b>22.3</b>	<b>10.4</b>	11.0	10.7
Use of cover crop	1	0.23	2.61	1.07	5.07	13.3	4.21	1.02	2.14
Use of organic amendment	1	0.55	0.67	10.8	6.22	5.68	0.01	3.94	5.54
Soil textural classes	2	<b>60.5</b>	<b>38.8</b>	<b>53.5</b>	<b>37.5</b>	4.87	<b>75.2</b>	<b>24.1</b>	<b>35.6</b>
Mean annual precipitation	1	7.35	2.63	6.52	0.11	0.98	0.43	0.02	1.70
Mean annual temperature	1	0.15	0.39	0.01	0.59	1.82	0.84	0.01	1.22
Model R <sup>2</sup>		0.16	0.28	0.13	0.22	0.23	0.37	0.19	0.21

<sup>z</sup> Number of observations used were: SOC= 1490, C<sub>min</sub>-96h=1017, Solvita CO<sub>2</sub>-burst=768, and POXC=1413, whereas the number of observations for ACE and programmed pyrolysis parameters (HI, OI, and T50) were 151.

SOC=soil organic carbon; C<sub>min</sub>-96h= 96-hr carbon mineralization; POXC=permanganate oxidizable carbon; Solvita CO<sub>2</sub>-burst= 24 h soil respiration test; ACE=autoclaved citrate extractable protein index; **T50=temperature at which 50% of SOC was pyrolyzed**; HI=hydrogen index; and OI=oxygen index.

For each soil C indicator, bold font indicates the top two variables explaining the variance.

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639 **Table 2** Within each soil textural class, variance analysis (*P* values) of soil and crop management  
 640 parameters on soil C indicators<sup>z</sup> analyzed in the Ontario Topsoil Sampling Project from 2019 to 2022.

		SOC	C <sub>min</sub> -96h	POXC	Solvita CO <sub>2</sub> - burst	ACE	T50	HI	OI
		mg g <sup>-1</sup>	mg CO <sub>2</sub> - C 20 g <sup>-1</sup> soil	µg g <sup>-1</sup>	mg kg <sup>-1</sup>	mg kg <sup>-1</sup>	°C	mg HC g <sup>-1</sup> OC	mg CO <sub>2</sub> g <sup>-1</sup> OC
		<i>P</i> values							
Parameter	df	Coarse- textured							
Cropping system <sup>y</sup>	4 (3)	<b>0.0403</b>	<b>0.0003</b>	<b>0.0044</b>	<b>0.0077</b>	<b>0.0298</b>	0.8275	0.5131	<b>0.0109</b>
Tillage intensity	4	0.4035	0.6495	0.9057	0.4571	0.0505	0.7480	0.7405	0.6670
Cover crop	1	0.5625	0.2332	0.4637	0.3627	<b>0.0055</b>	<b>0.0129</b>	0.0887	0.4202
Use of organic amendment	1	0.9626	0.6656	0.1358	0.9150	0.6184	0.1869	0.3257	0.4489
Crop x Tillage	16 (12)	0.1535	<b>0.0059</b>	<b>0.0071</b>	<b>0.0144</b>	0.4207	0.4651	0.9249	<b>0.0066</b>
		Medium-textured							
Cropping system	4	<b>0.0020</b>	<b>&lt;0.0001</b>	<b>0.0003</b>	0.7583	0.3830	0.4477	<b>0.0005</b>	0.3245
Tillage intensity	4	0.7602	0.2161	0.1347	0.0674	0.6528	0.5661	0.0595	0.2743
Cover crop	1	0.9172	<b>0.0091</b>	0.8947	0.2020	0.8529	0.6813	0.1646	<b>0.0123</b>
Use of organic amendment	1	0.7148	0.0735	0.4686	0.2045	0.6543	0.5044	0.0555	0.9541
Crop x Tillage	16	<b>0.0025</b>	<b>&lt;0.0001</b>	<b>0.0025</b>	0.0610	<b>0.0298</b>	0.5861	<b>0.0105</b>	0.5871
		Fine-textured							
Cropping system <sup>y</sup>	4 (3)	<b>0.0018</b>	<b>&lt;0.0001</b>	<b>0.0485</b>	<b>&lt;0.0001</b>	0.1199	0.8067	0.2488	0.9702
Tillage intensity	4	0.7322	0.7080	<b>0.0210</b>	0.1948	0.4784	0.9968	0.5926	0.5507
Cover crop	1	0.1991	0.4240	0.0962	0.1037	0.1585	0.3945	0.8834	0.9502
Use of organic amendment	1	0.8311	0.2033	0.1543	0.5495	0.0905	0.0739	0.3373	0.3781
Crop x Tillage	16 (12)	<b>0.0006</b>	<b>&lt;0.0001</b>	<b>0.0007</b>	<b>&lt;0.0001</b>	0.2743	0.5131	0.6867	0.3253

Bold font indicates statistically significant treatment differences at *P*<0.05.

<sup>z</sup> Number of observations used were: SOC= 1490, C<sub>min</sub>-96h=1017, Solvita CO<sub>2</sub>-burst=768, and POXC=1413, whereas the number of observations for ACE and programmed pyrolysis parameters (HI, OI, and T50) were 151.

<sup>y</sup> For the coarse and fine-textured soil, number of cropping system categories analyzed for HI, OI, and T50 were 4. For instance, no soil samples were collected from the perennial cropping system in coarse-textured soil and from vegetable system in fine-textured soils. Hence, the degree of freedom for cropping system and interaction between cropping system and tillage treatments was adjusted accordingly in the statistical model.

SOC=soil organic C; C<sub>min</sub>-96h= 96-hr carbon mineralization; POXC=permanganate oxidizable carbon; Solvita CO<sub>2</sub>-burst= 24 h soil respiration test; ACE=autoclaved citrate extractable protein index; T50=temperature at which 50% of SOC was pyrolyzed; HI=hydrogen index; and OI=oxygen index.

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**Table 3** Within each soil textural class, mean (SE) values of the soil C indicators<sup>z</sup> by the cropping system category sampled in the Ontario Topsoil Sampling Project from 2019 to 2022.

Cropping system	n	SOC mg g <sup>-1</sup>	C <sub>min</sub> -96h mg CO <sub>2</sub> -C 20 g <sup>-1</sup> soil	POXC µg g <sup>-1</sup>	Solvita CO <sub>2</sub> -burst mg kg <sup>-1</sup>	ACE mg kg <sup>-1</sup>	T50 °C	HI mg HC g <sup>-1</sup> OC	OI mg CO <sub>2</sub> g <sup>-1</sup> OC
Coarse-textured									
Annual grain	183	16.9ab (0.70)	14.2bc (0.96)	473ab (16.0)	53.1b (3.35)	5.49ab (0.78)	416 (1.58)	152 (5.94)	168bc (4.26)
Forage	53	19.4a (1.20)	20.4a (1.49)	547a (25.4)	72.0a (6.39)	8.45a (1.47)	412 (4.19)	163 (15.7)	207a (11.2)
Vegetable	32	15.4ab (1.50)	10.9c (1.61)	441ab (31.6)	89.4a (12.2)	6.60ab (1.75)	415 (5.13)	162 (19.2)	147c (13.8)
Orchard	9	11.7b (2.70)	14.4abc (5.70)	342b (46.0)	51.4ab (9.23)	4.71b (1.75)	419 (5.13)	132 (19.2)	203ab (13.8)
Perennial	31	19.4ab (1.70)	18.5ab (1.78)	510ab (34.5)	53.6ab (16.1)	--	--	--	--
All	308 (29) <sup>z</sup>	17.2	15.6	478	61.4	6.80	415	154	172
Medium-textured									
Annual grain	335	20.8b (0.40)	20.1b (0.57)	591a (9.74)	68.3 (2.76)	5.55ab (0.43)	421 (1.65)	132b (5.98)	196 (5.20)
Forage	129	20.2b (0.60)	22.6ab (0.92)	584a (15.2)	74.4 (3.66)	6.72ab (0.50)	417 (2.24)	159ab (8.12)	195 (7.07)
Vegetable	54	20.0b (1.00)	19.7b (1.27)	575a (22.3)	65.4 (7.74)	4.46b (1.02)	415 (5.72)	134ab (20.7)	164 (18.0)
Orchard	20	16.6b (1.50)	17.7b (2.58)	439b (34.4)	81.4 (7.94)	7.63ab (1.32)	420 (5.72)	184ab (20.7)	180 (18.0)
Perennial	104	24.0a (0.80)	25.2a (1.03)	560a (18.7)	81.1 (6.88)	10.1a (1.38)	412 (3.61)	200a (13.1)	188 (11.4)
All	642 (46)	21.1	21.6	581	72	6.30	419	149	193
Fine-textured									
Annual grain	315	23.1b (0.50)	21.2c (0.68)	574c (10.7)	76.2c (2.20)	5.62 (0.34)	428 (1.11)	132 (4.23)	186 (3.14)
Forage	131	25.5ab (0.80)	25.3ab (1.05)	623ab (15.8)	86.9b (3.36)	5.93 (0.64)	427 (2.46)	140 (9.38)	191 (6.97)
Vegetable	15	22.5b (2.50)	21.6bc (2.38)	606b (47.9)	--	--	--	--	--
Orchard	4	25.6ab (4.20)	35.0a (3.99)	694a (80.8)	107ab (13.6)	9.02 (2.05)	426 (8.16)	161 (31.3)	195 (23.1)
Perennial	72	28.9a (1.30)	30.5a (1.56)	613ab (26.7)	108a (5.81)	7.91 (0.82)	427 (2.58)	161 (9.84)	202 (7.31)
All <sup>y</sup>	540 (76)	24.5	23.4	603	83.9	6.27	427	138	189

<sup>z</sup>The number in the parenthesis represents the number of observations for ACE and the programmed parameters (T50, HI, and OI) in each soil textural class.

<sup>y</sup>There were 3 observations within the fine-textured soils for which cropping system details were missing.

<sup>a-c</sup>Within each soil textural class and for each parameter, treatment means followed by a different letter indicate statistical significance at  $P < 0.05$

SOC=soil organic carbon; C<sub>min</sub>-96h= 96-hr carbon mineralization; POXC=permanganate oxidizable carbon; Solvita CO<sub>2</sub>-burst= 24 h soil respiration test; ACE=autoclaved citrate extractable protein index; HI=hydrogen index; and OI=oxygen index.; --=not applicable.

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**660 Table 4** Pearson correlation coefficients (r) among soil C indicators sampled in the Ontario Topsoil Sampling  
**661** Project from 2019 to 2022.

Indicators <sup>^</sup>	SOC	C <sub>min</sub> -96h	POXC	Solvita CO <sub>2</sub> -burst	ACE	HI	OI	T50
	mg g <sup>-1</sup>	mg CO <sub>2</sub> -C 20 g <sup>-1</sup> soil	μg g <sup>-1</sup>	mg CO <sub>2</sub> -C kg <sup>-1</sup>	mg kg <sup>-1</sup>	mg HC g <sup>-1</sup> OC	mg CO <sub>2</sub> g <sup>-1</sup> OC	°C
SOC	1.00							
C <sub>min</sub> -24h	0.67***	1.00						
POXC	0.81***	0.63***	1.00					
Solvita CO <sub>2</sub> -burst	0.36***	0.46***	0.34***	1.00				
ACE	0.72***	0.58***	0.66***	0.17**	1.00			
HI	0.28**	0.42***	0.24**	NS	0.59***	1.00		
OI	0.21**	0.27**	NS	NS	NS	-0.30**	1.00	
T50	NS	NS	NS	NS	NS	-0.24**	NS	1.00

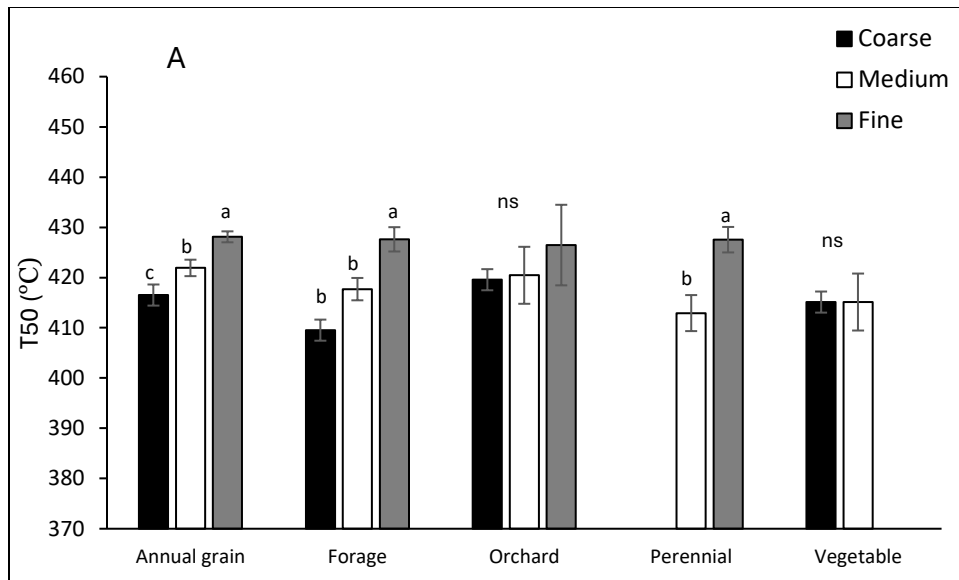
**662** SOC=soil organic carbon; C<sub>min</sub>-96h= 96-hr carbon mineralization; POXC=permanganate oxidizable carbon; Solvita CO<sub>2</sub>-burst= 24 h soil respiration test;  
**663** ACE=autoclaved citrate extractable protein index; HI=Hydrogen Index; OI=Oxygen Index; and NS=Non-significant.

**664** n=1490 for soil organic C; n=1017 for C<sub>min</sub>-96; n=1413 for POXC; n=768 for Solvita CO<sub>2</sub>-burst; n=151 for ACE, HI, OI, T50.

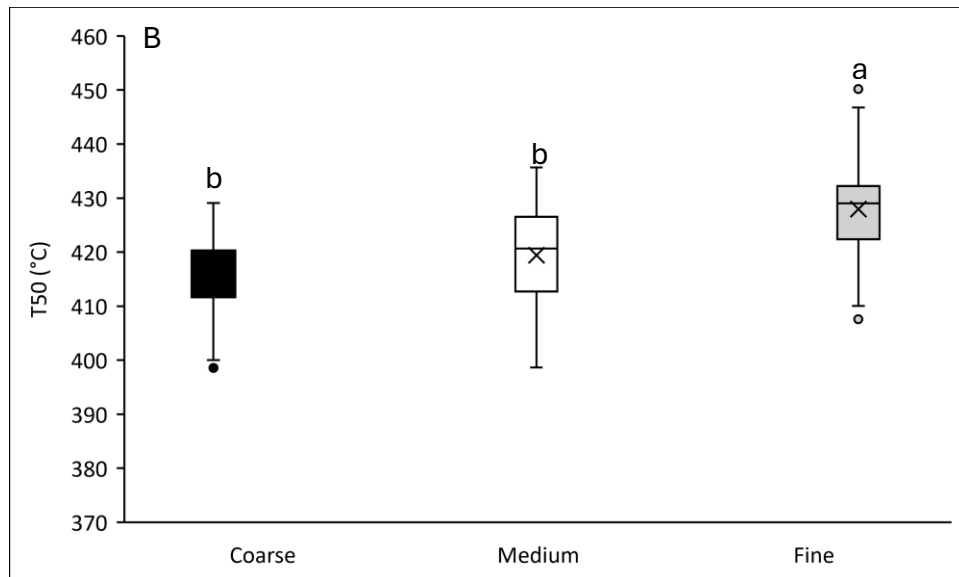
**665** \*\*,\*\*\* indicates statistical significance at P<0.05 and P<0.0001, respectively.

**666** ^All indicators were log-transformed prior to analysis.

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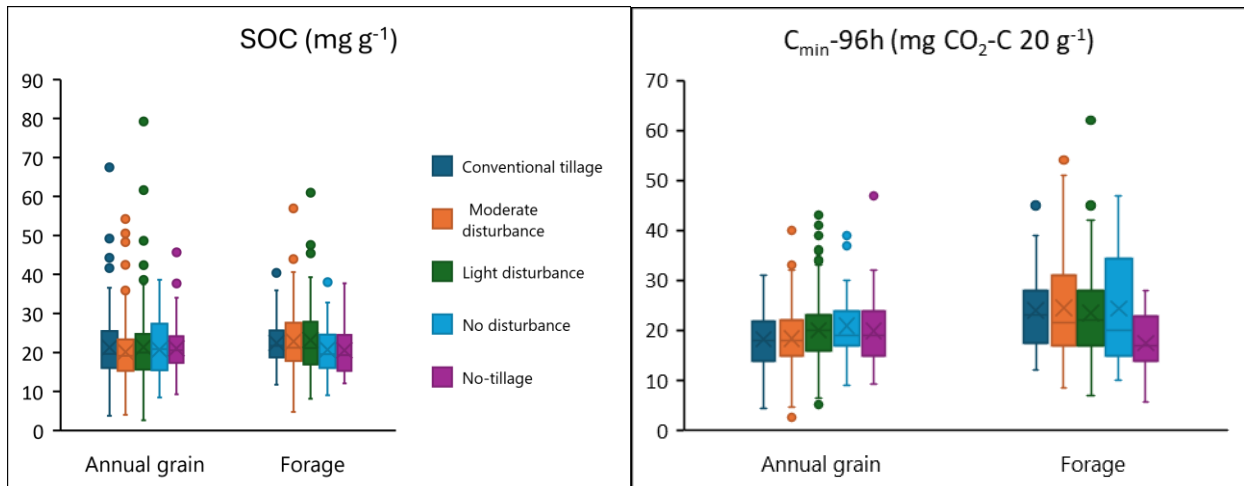
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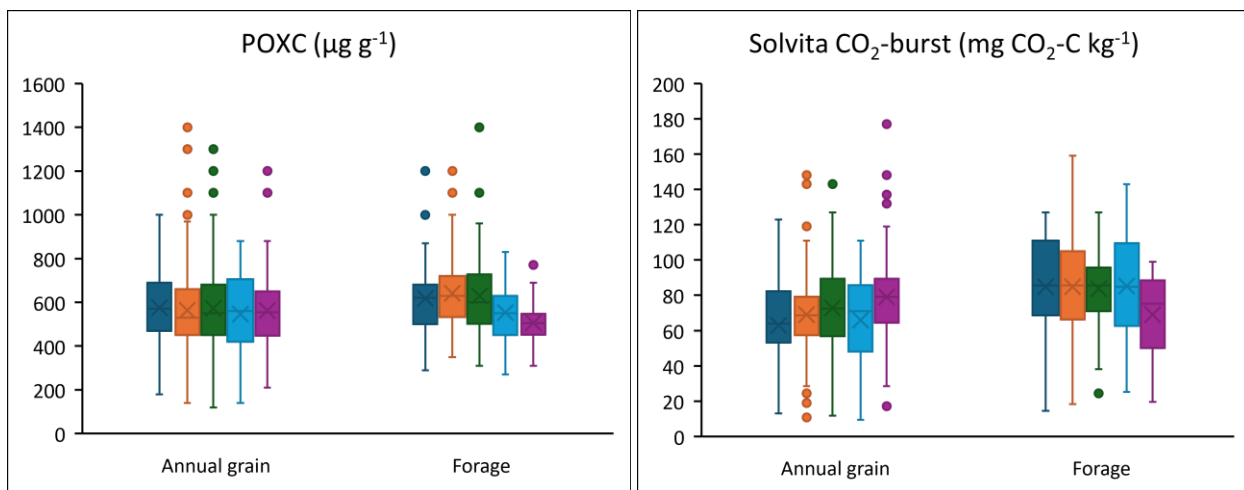
669 **Figure 1** Plots of T50 demonstrating differences due to soil textural class within each cropping system category (A)  
670 and soil textural classes (B) for the soils in the Ontario Topsoil Sampling Project in 2019 (n=151). Different letters  
671 indicate statistically significant differences at  $P < 0.05$ . ns represents non-significant statistical differences among soil  
672 textural classes within the cropping system category.

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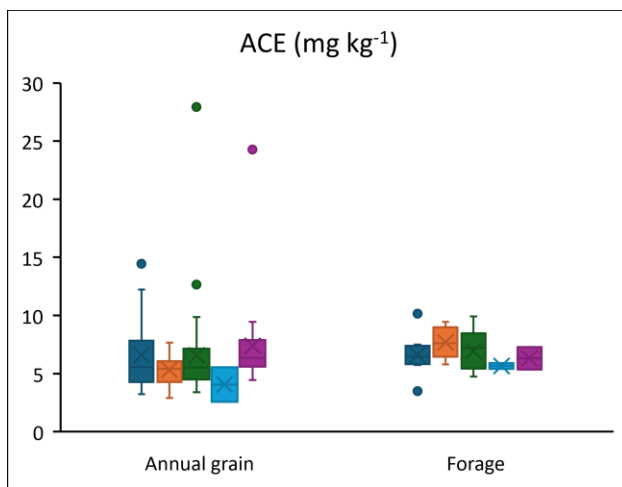
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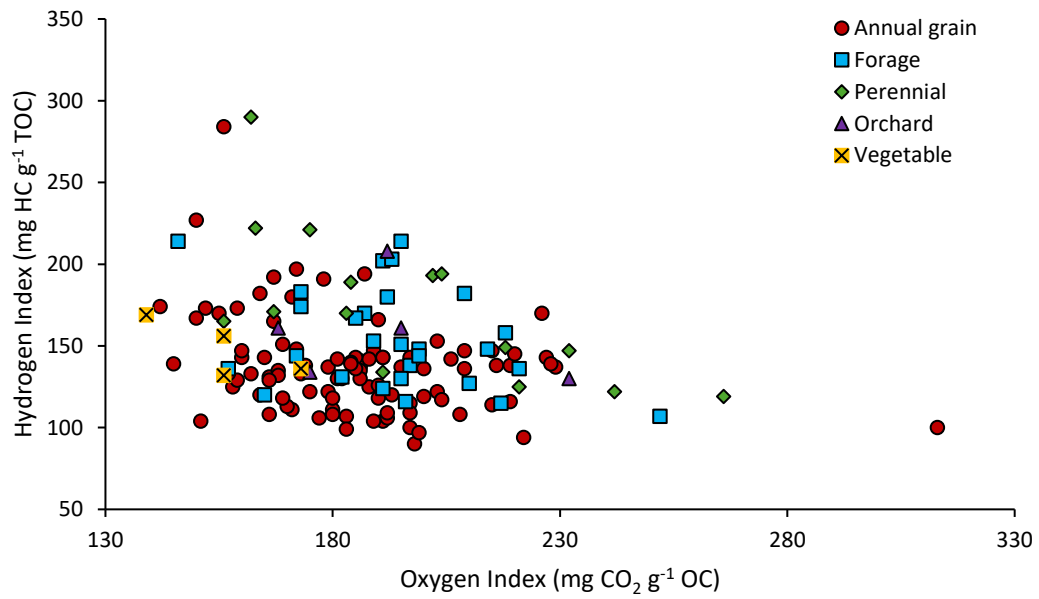
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677 **Figure 2** Box plots demonstrating the interactive effects of cropping system category and tillage intensity on soil C  
678 indicators sampled in the Ontario Topsoil Sampling Project from 2019 to 2022. SOC=soil organic carbon;  $C_{\min-96h}$ =  
679 96-hr carbon mineralization; POXC=permanganate oxidizable carbon; Solvita  $\text{CO}_2$ -burst= 24 h soil respiration test;  
680 ACE=autoclaved citrate extractable protein index. Due to insufficient number of observations, data for other  
681 cropping systems not shown.

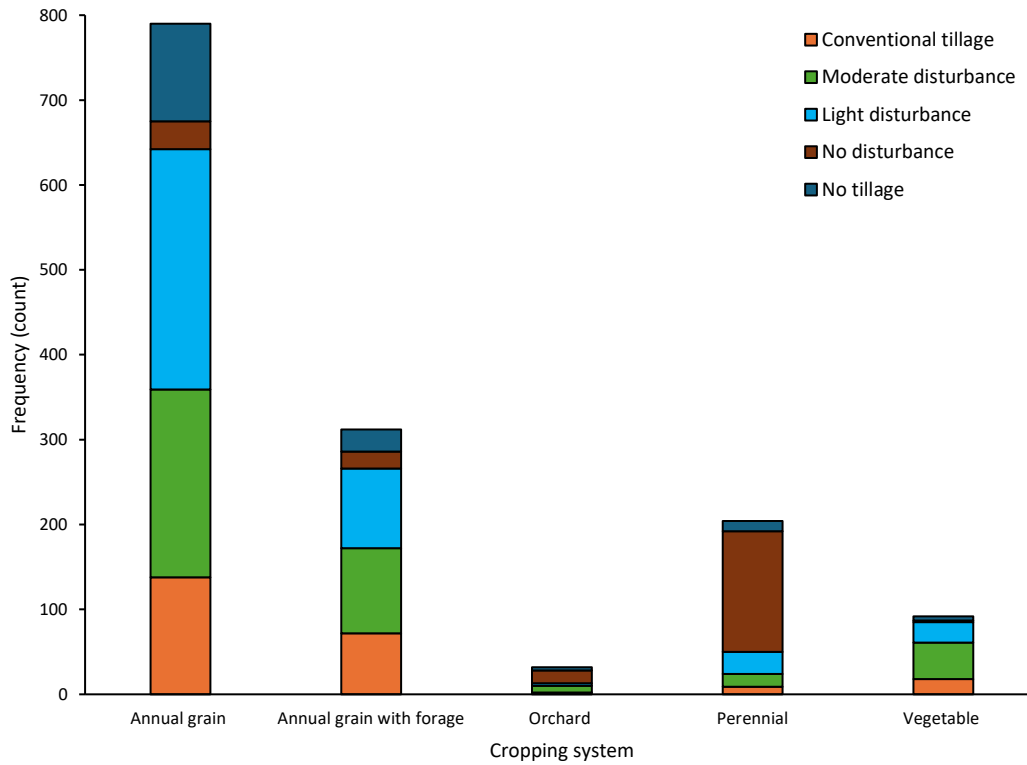


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683 **Figure 3** Pseudo van Krevelan diagram from programmed pyrolysis data for soils indicating cropping system  
 684 category sampled in the Ontario Topsoil Sampling Project in 2019 (n=151).

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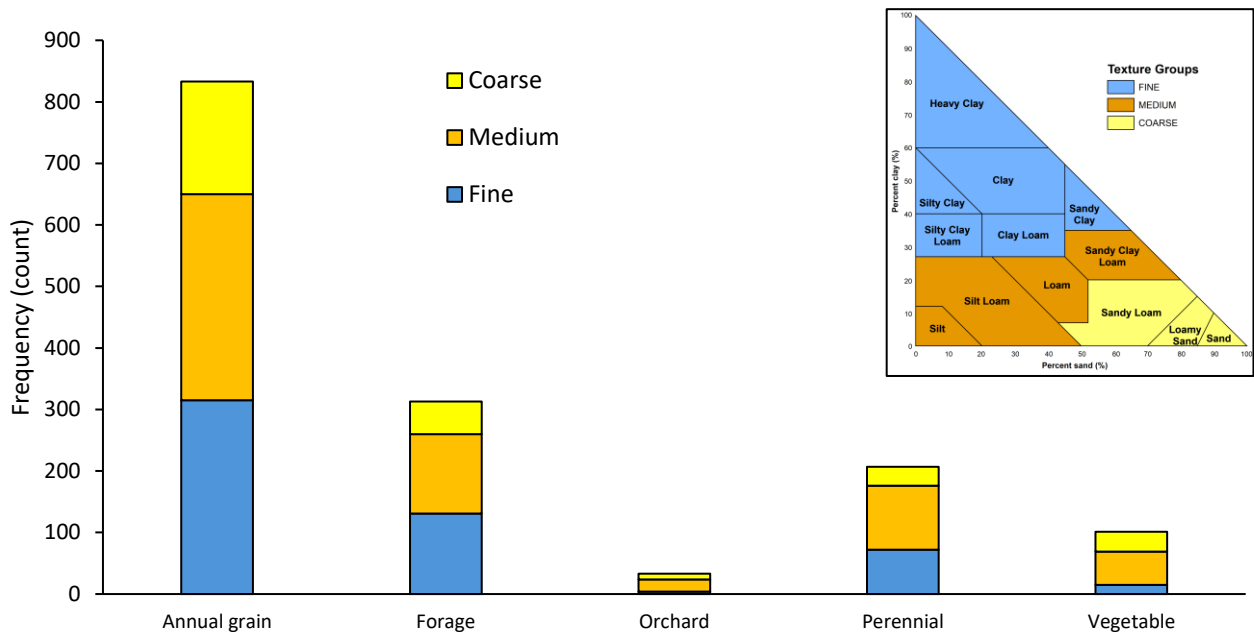


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688 **Figure 4** Frequency distribution of soils partitioned by tillage intensity within each cropping system category  
689 sampled in the Ontario Topsoil Sampling Project from 2019 to 2022. Conventional tillage represents the plow tillage  
690 in our study. No disturbance represented little to no soil movement and was associated mainly with pastures and  
691 perennial forages.

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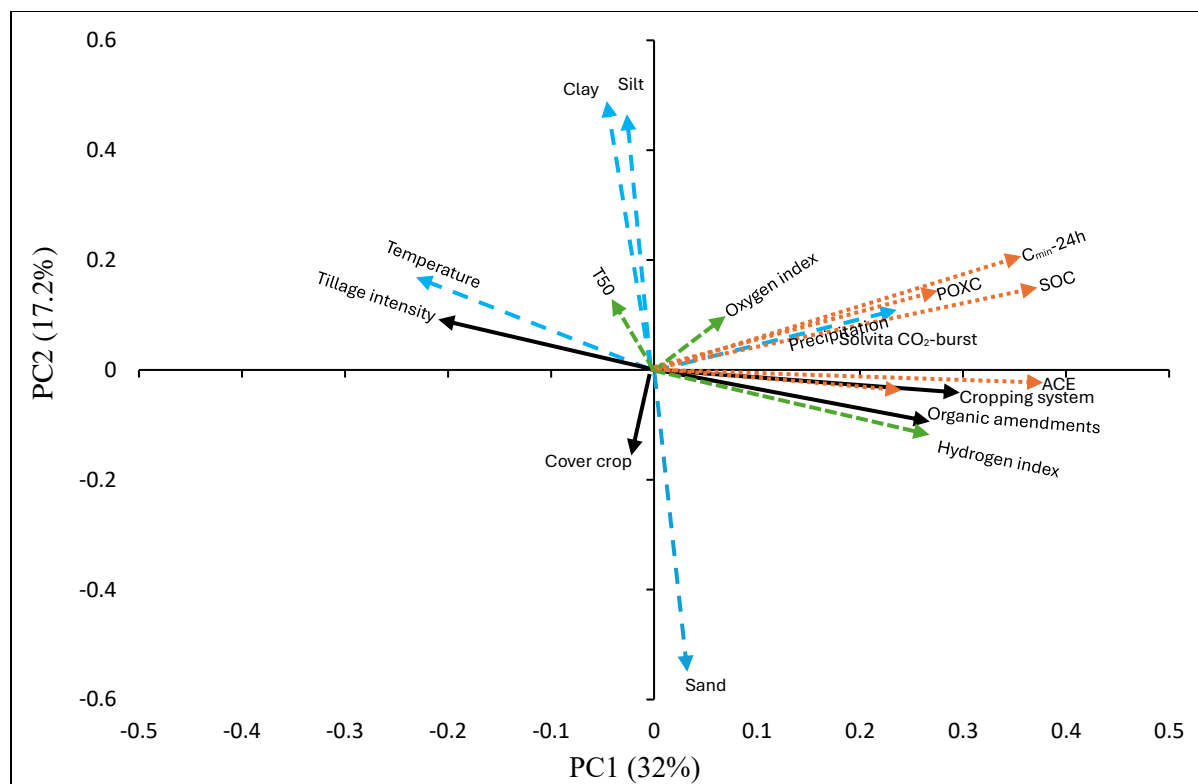
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696 **Figure 5** Frequency distribution of soils partitioned by soil textural classes within each cropping system category  
697 sampled in the Ontario Topsoil Sampling Project from 2019 to 2022.

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701 **Figure 6** Principal component analysis (PCA) demonstrating relationships between site characteristics (blue dash-line  
 702 vectors), management practices (black solid-line vectors), soil C indicators (orange dash-line vectors), and programmed  
 703 pyrolysis parameters (green dash-line vectors) sampled in the Ontario Topsoil Sampling Project from 2019 (n=151).

704 ACE=autoclaved citrate extractable protein index; C<sub>min</sub>-96h= 96-h carbon mineralization; POXC=permanganate  
 705 oxidizable carbon; SOC=soil organic carbon; and Solvita CO<sub>2</sub>-burst= 24 h soil respiration test.

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