



# Tracking pedogenic carbonate formation and alkalinity migration in agricultural soils amended with crushed wollastonite ore – Evidence from field trials in Southwestern Ontario



Reza Khalidy, Fatima Haque, Yi Wai Chiang, Rafael M. Santos\*

School of Engineering, University of Guelph, 50 Stone Road East, Guelph, Ontario N1G 2W1, Canada

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## ABSTRACT

Considered a well-known carbon sequestration method, terrestrial enhanced rock weathering (ERW) involves the application of crushed silicate-bearing minerals to urban and agricultural soils. Once dissolved in a soil–water system, alkaline minerals adjust the pH in a range favorable for pedogenic carbonate formation and, hence, atmospheric carbon drawdown. As a fast-weathering Ca-rich mineral, wollastonite is recognized as a primary candidate for this process. Although previous studies have demonstrated the potential of wollastonite to sequester carbon in croplands, no study has investigated the fate of wollastonite over the vertical profile of soil. Furthermore, no studies have investigated changes in the elemental composition of soils due to wollastonite amendment at the field scale. The present study presents the results of multiyear sample collection from different layers (0–15, 15–30, and 30–60 cm) of agricultural soil amended with wollastonite in Woodstock, Ontario, Canada. The impact of initial soil pH on pedogenic carbonate formation was also investigated through the inclusion of two more field trials (Thorndale and Dawn-Euphemia, Ontario). The results indicated that wollastonite addition increased the inorganic carbon pool of the soil at a rate as fast as 0.55 t CO<sub>2</sub>/(ha·month) at higher (20 t/ha) wollastonite dosages, and with efficiencies reaching up to 0.42 t CO<sub>2</sub>/t wollastonite (as CO<sub>3</sub><sup>2-</sup>). Elemental composition analyses (WDXRF) revealed increases in the Ca (0.05–0.32 %) and Mg (0.01–0.02 %) contents in the amended soils that either were inferior to the theoretical amendment change, suggesting migration of weathering products to deeper layers, or in some cases similar and thus correlating with pedogenic carbonate retention in surficial layers. The implications of composite sampling and year-over-year comparisons on the estimated uncertainty from statistical analysis (hierarchical permutation test of the Wilcoxon signed-rank test) is discussed. This study concludes that carbonate formation is not limited to surficial layers and that deeper layers also need to be taken into account when estimating carbon capture due to ERW practices.

## 1. Introduction

Induced by anthropogenic activities, fossil fuel emissions are the prime mover of the atmospheric CO<sub>2</sub> concentration to 100 ppm above the preindustrial range and global warming and climate change-related ramifications (Khalidy and Santos, 2021a; Lindsey and Dahlman, 2020; Millar et al., 2017). As an urgent response, drawing up and scaling up carbon dioxide removal (CDR) technologies are needed to decelerate this trend (Kelemen et al., 2020; Khalidy and Santos, 2021b; Rahmani-hanzaki and Hemmati, 2022). Among CDR technologies, mineral carbonation is recognized as a long-term carbon storage sink that uses feedstocks that occur naturally in Earth's terrestrial ecosystems (Li et al.,

2018; Oelkers and Cole, 2008; Wilson et al., 2014).

As the third largest pool of carbon in the world, soil is considered a vast sink for carbon (Stanberry et al., 2023; Zamanian et al., 2016). Carbon might accumulate in the form of soil organic carbon (SOC) or soil inorganic carbon (SIC) in soil (Apesteguia et al., 2018; Beerling et al., 2018; Lal, 2007; Sanderman, 2018). Carbon sequestration as SOC, which is highly dependent on practical management (Hutchinson et al., 2007; Powlson et al., 2014; Sanderman, 2018; Wang et al., 2023) and subjected to decarbonization (Jorat et al., 2022), is usually regulated through photosynthesis and the organic matter cycle (Bruce et al., 1999; Haque et al., 2019a; Smith et al., 2008). SIC, on the other hand, is recognized as a long-term pool, and its sequestration occurs through the

\* Corresponding author.

E-mail address: [santos@uoguelph.ca](mailto:santos@uoguelph.ca) (R.M. Santos).

weathering of alkaline metals (Haque et al., 2019a). As an example of this method, the application of powdered silicate minerals (such as wollastonite ( $\text{CaSiO}_3$ ), basalt (e.g., andesine ( $\text{Na,Ca}(\text{Si},\text{Al})_4\text{O}_8$ )) or dolerite, and crushed concrete is well acknowledged as a low-cost and low-energy method for stabilizing carbon such as SIC (Haque et al., 2019b; Kelland et al., 2020; Manning et al., 2013; Renforth et al., 2015).

The process of enhanced rock weathering (ERW) begins when Ca and Mg cations are transferred to the soil–water system as silicate minerals dissolve (Andrews and Taylor, 2019; Vandeginste et al., 2024). Moreover, the dissolution of  $\text{CO}_2$ , which originates from the atmosphere or soil organic matter (SOM), in percolating water contributes to the formation of carbonic acid and promotes the release of Ca and Mg from silicate minerals (through lowering the pH) (Beerling et al., 2018). The carbonic acid that forms when  $\text{CO}_2$  dissolves in water eventually dissociates to bicarbonate and protons in the soil–water mixture. Depending on the geochemistry of the native soil, these processes conclude in pedogenic carbonate formation in the soil/subsoil profile or the migration of bicarbonates into groundwater systems (Hartmann et al., 2013; Khalidy et al., 2022). Jorat et al. (2022) estimated carbon sequestration rates of 33 and 17 t/(ha·year) as pedogenic carbonate due to crushed concrete and dolerite addition in urban soils, respectively. Haque et al. (2020a) revealed that both the weathering interval and dosage of Ca-rich silicate minerals (wollastonite) are positively correlated with the SIC accumulation rate (up to 2 t/(ha·year) after three years) in the 0–15 cm layer of agricultural fields in Southwestern Ontario, Canada. Pedogenic carbonates are also known to form in arid soils from the conversion of calcium sulfate into carbonate over time (Peng et al., 2024), which can also potentially be a degassing mechanism of bicarbonate alkalinity within aquifers (Burgess et al., 2023).

From an agronomic viewpoint, the cobeneficial effects of ERW practices on plant growth (and vice versa) are well documented (Haque et al., 2019b; Haque et al., 2020b; Jariwala et al., 2022; Kelland et al., 2020). The secretion of organic acids such as citric acid and maleic acid from plant roots increases silicate mineral dissolution and enhances the ERW process (Haque et al., 2019b). Furthermore, Haque et al. (2020b) demonstrated that increases in wollastonite application rates up to 100 and 50 t/ha increased the root biomass of alfalfa and soybean, respectively; however, higher dosages had the opposite effect on these plants. In another study, Jariwala et al. (2022) reported consistent outcomes where wollastonite treatment supplied more available Si for plants in the soil than in nonamended soils.

As a conventional agricultural practice, liming aims to adjust the pH of acidic soil to a neutral zone through the addition of Ca-rich materials such as limestone ( $\text{CaCO}_3$ ) and dolomite ( $\text{MgCa}(\text{CO}_3)_2$ ) (Sanderman, 2018). The liming process improves plant productivity (through ameliorating nutrient availability and abiotic activities) and soil aggregation (Ameyu, 2019; Ferreira et al., 2019; Holland et al., 2017; Pang et al., 2019). However, an imminent drawback of liming is the emission of  $\text{CO}_2$  into the atmosphere, which can exceed 200 Mt. C annually and is regarded as the second practice with the highest  $\text{CO}_2$  efflux just after soil acidification (Ahmad et al., 2015; Sanderman, 2018; Zamanian et al., 2021). Therefore, ERW is considered a substitute for liming, which is capable of buffering the soil pH and delivering coequal benefits to agricultural and agronomy systems while turning over carbon efflux into stabilizing carbon in soil and contributing to climate change mitigation (Haque et al., 2020a; Haque et al., 2019b).

The procedure involving amending agricultural soil with wollastonite (e.g., determining the amount of wollastonite to apply per hectare and the method to spread it over the soil) was described by Haque et al. (2020a). However, the analysis of these studies was limited to a very surficial layer of soil (0–15 cm). Since weathering products (especially the finer fraction) are exposed to downward migration (Isometric Standard, 2024), we aimed to investigate the impact of wollastonite amendment on the deeper horizons of agricultural fields in Southwestern Ontario. Two of these field trials were part of a lime replacement project, where the objective was to determine how wollastonite

enhances soil properties (particularly pH). This paper presents the results of carbonate formation alongside additional amendments due to silicate mineral powder addition to soil. For the first time, in a field-scale study, our experiment aims to observe evidence of downward migration and reprecipitation of weathering products across the vertical profile of the soil over time in an ERW experimental field setting.

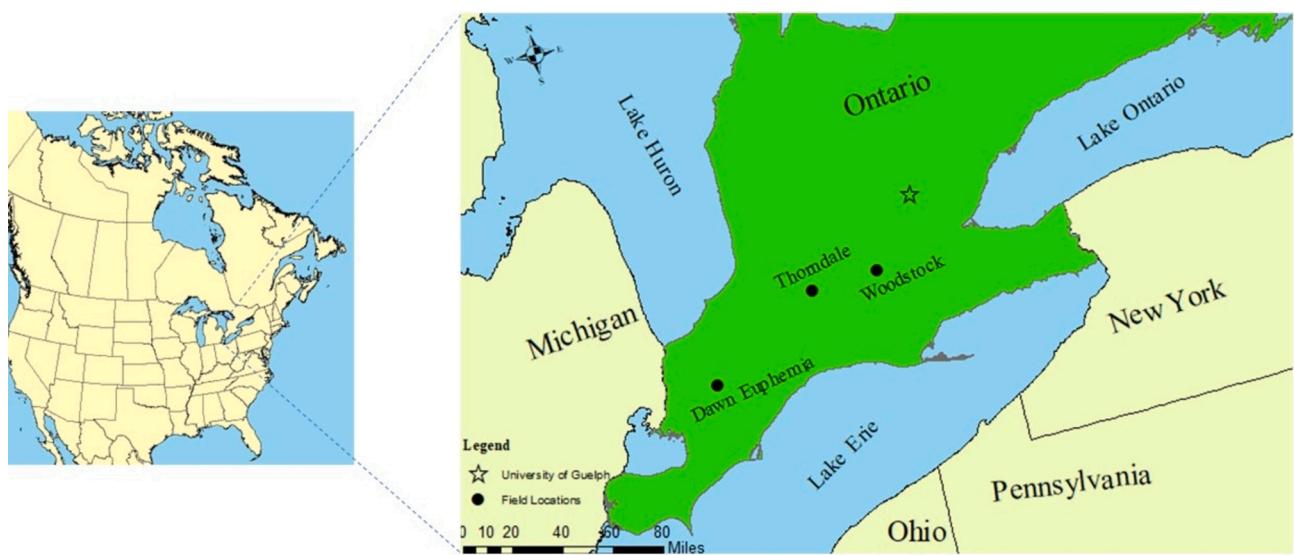
## 2. Methods

### 2.1. Site description

This study comprises three field experimental trials in Southwestern Ontario (Fig. 1). Southwestern Ontario, influenced by the Great Lakes, has a mild climate with hot and humid summers, providing a long growing season for agriculture. The region is known for its high frequency of thunderstorms, leading to varied rainfall patterns that are crucial for crop irrigation and maintaining soil moisture levels. These rainfall patterns and subsequent drying periods are particularly important for pedogenic carbonate formation. The peninsulas in Lake Erie and Lake Huron, however, experience cooler and less humid summers, which may influence the rate of this soil process. While winters, characterized by significant lake-effect snow, are less relevant to the crop season, they can impact early and late-season agricultural activities. According to the Köppen climate classification, the area of the current study experiences a humid continental climate, more specifically, a warm-summer Dfb climate. Quartz and albite are the primary mineral phases detected in the soils of southwestern Ontario, with smaller amounts of illite, microcline, goethite, Fe-chlorite, and amphibole (Schonenberger et al., 2012). The topsoil in this area is deficient in carbonates (e.g., calcite and dolomite), making it an ideal location for tracking the accumulation of newly formed carbonates in shallow layers.

The first experiment was conducted on an agricultural microplot (soil type: sandy loam, N  $43^{\circ}14'$  W  $80^{\circ}62'$ , area: 0.004 ha) harvested with rye from Woodstock, Ontario (ON) (Fig. 2a). The soil in this area is categorized as an Alfisol on the basis of the USDA soil taxonomy classification (Soil Survey Staff, 1999). According to historical soil surveys of the area (Mozuraitis and Hagarty, 1996), the soil is classified as orthic melanic brunisol. The soils in this region, which are formed on glacial till (Webber and Hoffman, 1967), are characterized by rapid drainage and high water conductivity and are nonstony, sandy, mixed, and mildly alkaline. This area is predominantly underlain by Paleozoic limestone formations, resulting in parent materials that are rich in carbonates and generally exhibit neutral to alkaline pH levels (Saurette et al., 2021). The objective of this fieldwork was to monitor pedogenic carbonate formation and migration across the vertical profile of the soil (e.g., 0–15, 15–30, and 30–60 cm layers). A dosage of 15 t/ha of powdered wollastonite was applied to this field in October 2019. The soil samples were collected at different depths yearly to track changes in the pedogenic carbonate pool in the soil. The first and second sample collections (after wollastonite application) were concluded in October 2020 and October 2021, respectively. To track carbonate changes in deeper horizons of this field, we extended the measurement and collection (with two different samplers: Dakota and Auger) down to 100 cm. A Dakota (tubular T-Style handle) sampler was used to collect samples from the 15–30 and 30–60 cm layers of the field. Furthermore, an auger sampler was used to collect core samples from two locations in this field down to 100 cm.

Two other field trials aimed to investigate the impact of wollastonite on plant growth and soil health (liming replacement). One of the fields, located in Dawn-Euphemia, Ontario (soil type: silt clay, N  $42^{\circ}42'$  W  $82^{\circ}03'$ ) (Fig. 2d), was harvested with soybean, wheat, and corn in 2021, 2022, and 2023, respectively. Wollastonite at a rate of 10 t/ha was applied to this field in May 2021. This field is 58 ha and characterized by three discrete zones of acidic or low pH (LpH,  $\text{pH} = 4.85 \pm 0.06$ ), mildly acidic or neutral pH (NpH,  $\text{pH} = 5.97 \pm 0.03$ ), and high pH or circumneutral (HpH,  $\text{pH} = 7.22 \pm 0.02$ ) areas. The sampling (after wollastonite



**Fig. 1.** Mapped locations of the fields (Dawn-Euphemia, Thorndale, and Woodstock) in Southwestern Ontario.



**Fig. 2.** (a) Experimental field located in Woodstock; (b) Wollastonite application to the experimental field in Summer 2019 using a lime spreader; (c) First phase of field sampling conducted in September 2020; Experimental fields located in (d) Dawn-Euphemia and (e) Thorndale.

application) from this field was conducted in April 2022. The soil in this area is classified as zonal on the basis of taxonomic classification (Matthews et al., 1957) and is characterized as “Gleysolic order”, poorly to improperly drained, with gray–brown podzolic soil found at drained sites (Matthews et al., 1957; Webber and Hoffman, 1967). According to the USDA soil taxonomy classification, the soil in this region is

categorized as Inceptisols (Soil Survey Staff, 1999).

The third field is located in Thorndale, ON (soil type: silt loam, N 43°07' W 81°10') (Fig. 2e), and is harvested with a three-crop rotation (wheat, corn, and soybean) system (the soil classification and characterization are the same as those of the Woodstock field). Wollastonite with an application rate of 20 t/ha was applied to this field (10 ha) in

May 2021. The first phase of sampling from this field was conducted in October 2021. In all three fields, powdered wollastonite was applied to the topsoil via a lime spreader (Fig. 2b).

## 2.2. Wollastonite characterization

The wollastonite used for the field trials was sourced from Canadian Wollastonite, Inc. (Canada), which was mined near Kingston, ON. The main characterization of the wollastonite ore from this source is shown in Table 1.

According to the elemental composition of wollastonite (Table 1), the mineral contains Mg, which could be indicative of diopside ( $\text{CaMgSi}_2\text{O}_6$ , which has been found to coexist with wollastonite). This can be corroborated by the XRD pattern of the sample, where peaks of diopside are conspicuous along with those belonging to wollastonite (Fig. 3). Albite ( $\text{NaAlSi}_3\text{O}_8$ ) and quartz ( $\text{SiO}_2$ ) are the other mineral phases detected in wollastonite ore, sourced from Canadian Wollastonite Inc., in the XRD pattern. Notably, wollastonite sourced from Ontario may contain amphiboles such as tremolite (MacKinnon, 1990), which can cause health issues if inhaled (Dichocco et al., 2018), but no amphiboles were detected in the wollastonite powder used in the present study.

## 2.3. Sample collection and soil analyses

In the Woodstock field, the samples were collected from three layers—0–15, 15–30, and 30–60 cm—of soil one year and two years after wollastonite application. Samples were collected from the surficial layer (0–15 cm) of two other fields (Thorndale and Dawn-Euphemia) before and after wollastonite application. A detailed description of the sampling scheme in each field is provided in the Supplementary Material (Fig. S1).

The methods for collecting, preparing, and analyzing the soil carbonate content were described in detail in our previous study (Khalidy et al., 2021). After being transported to the laboratory, the samples were subsequently air-dried. The carbonate content of the soil samples (soil inorganic carbon (SIC) in  $\text{gCO}_2(\text{kg-soil})^{-1}$ ) was determined via the volumetric calcimetry technique. Calcimetry is a reliable technique for determining the carbonate content across a range of soil conditions, even at low concentrations in the presence of organic or inorganic

interferences (Silva et al., 2024). This method involves adding 20 ml of ultra-purified (Milli-Q) water to the soil samples in an Erlenmeyer flask followed by the addition of 7 ml of 4 M HCl (Khalidy et al., 2021; Khalidy et al., 2023). To obtain the “ $< 50 \mu\text{m}$ ” fraction (pan fraction), the soil samples were placed in an oven at 105 °C overnight. The samples were subsequently placed on a sieve shaker consisting of different mesh sizes (710–50  $\mu\text{m}$ ) at 60 rpm for 15 min. Finally, the carbonate content of the  $< 50 \mu\text{m}$  fraction was measured and compared with that of the bulk samples. Owing to the rapid weathering of wollastonite and the dominance of carbonate precipitation to alkalinity flux during the process (Khalidy et al., 2023), as well as the complexity of pore water measurements in the field due to changes in the flow rate, this study focused on the measurement of newly formed carbonate in solid form (pedogenic carbonate), and alkalinity measurements were not included.

To determine the pH of the soil samples, a 5:1 volumetric ratio of water was added to the soil, and the formed suspension was incubated for 1 h on a shaker (Rayment and Higginson, 1992). The suspension was then kept motionless for another hour before measurement using a pH meter (Oakton pH 700 Benchtop meter). To account for the changes in the mineral phases of the soil samples due to wollastonite treatment, X-ray diffraction (XRD, Panalytical Empyrean) and wavelength dispersive X-ray fluorescence (WDXRF, Rigaku Supermini 200) analyses were employed. The multipoint Brunauer–Emmett–Teller (BET) surface area and particle size distribution of wollastonite were determined via a physisorption analyzer (Quantachrome Autosorb iQ) and laser diffraction (Malvern Mastersize SM), respectively. To determine the soil organic matter (SOM) content, samples dried overnight were combusted at 450 °C for 4 h, and the loss on ignition (LOI) of samples due to the decomposition of organic matter was calculated (Howard and Howard, 1990; Khalidy et al., 2023).

## 2.4. Data analyses

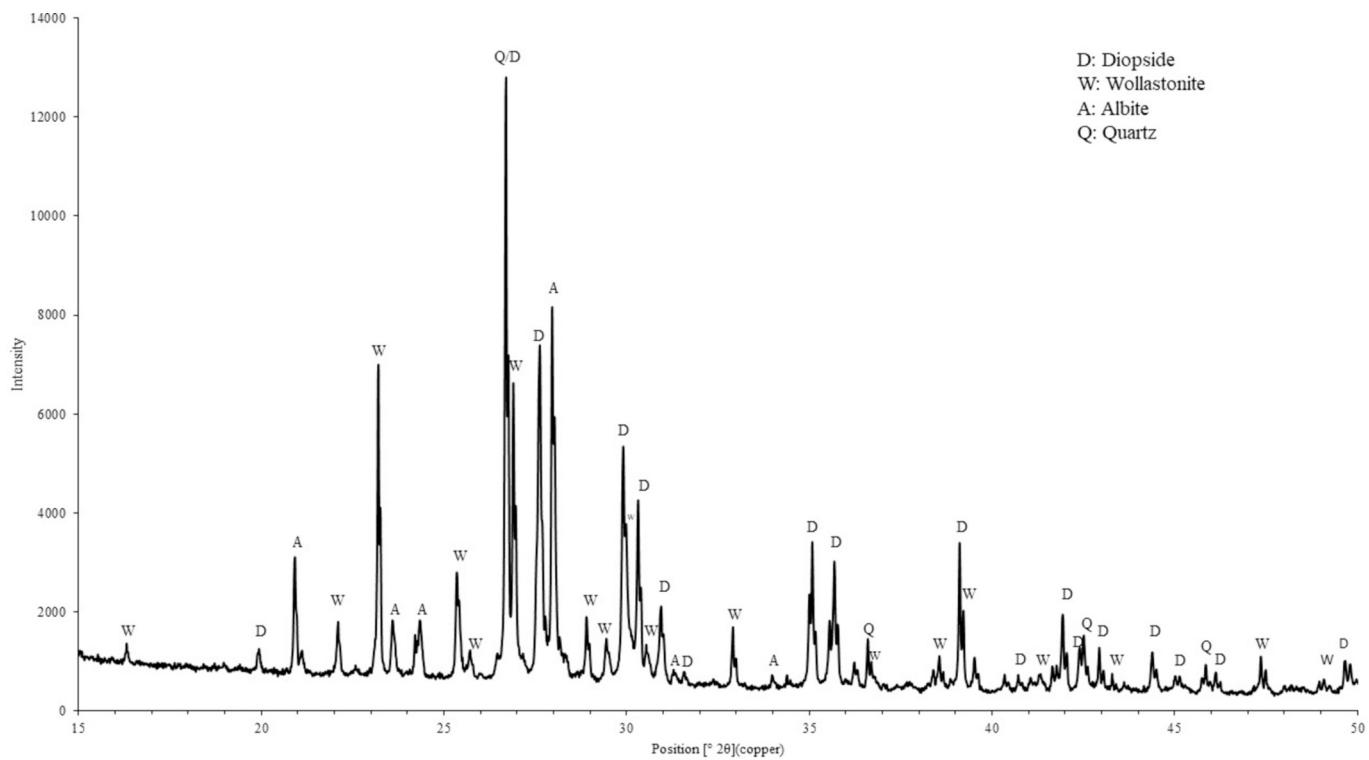
All the experimental analyses were conducted in triplicate (on triplicate subsamples split from each composite sample), and the mean results are reported along with the standard error (SE) of the population of measured subsamples. To analyze year-over-year changes in soil properties, we applied a hierarchical permutation test of the Wilcoxon signed-rank test (Python code is included in the Supplementary Material). The hierarchical permutation test was selected because of its compatibility with our data structure, which includes measurements from composite samples collected each year, with each composite comprising three subsamples. By grouping the subsamples within each composite, the test preserves the hierarchical organization of the data. Permutations were performed by shuffling these groups of three related values, maintaining their internal dependencies. This method allowed for the comparison of overall changes between years without assuming the independence of individual measurements. Statistical significance was determined by comparing the observed mean difference from the Wilcoxon signed-rank test to a distribution generated through repeated permutations, resulting in a robust *p*-value.

Additionally, the Wilcoxon signed-rank test was used in order to compare paired values between years. This nonparametric test evaluates whether the median differences between paired samples are statistically significant, making it well suited for this dataset. By combining the approaches of both the hierarchical permutation test and the Wilcoxon signed-rank test, we achieved a statistically reliable analysis of temporal changes in the measured variable.

Importantly, owing to variations in sampling schemes across fields (Fig. S1), the number of composite samples (observed variables) differed between fields. At Dawn-Euphemia, i.e., the neutral pH area and the Thorndale field, the number of composite samples collected corresponded to the number of strips; as a result, three and six composite samples per group were collected at Dawn-Euphemia, i.e., the neutral pH area, and the Thorndale field, respectively. In the Woodstock field, the plot was divided into two sections, yielding two composites per

**Table 1**  
Characterization (BET, particle size distribution, and elemental composition) of wollastonite sourced from Canadian wollastonite.

BET surface area ( $\text{m}^2/\text{g}$ )	$0.198 \pm 0.01$
Particle size (volume %):	
500–2000 $\mu\text{m}$	11.05
250–500 $\mu\text{m}$	47.21
63–250 $\mu\text{m}$	35.55
32–63 $\mu\text{m}$	2.18
< 32 $\mu\text{m}$	3.17
WDXRF (wt%)	
$\text{Na}_2\text{O}$	1.57
$\text{MgO}$	6.03
$\text{Al}_2\text{O}_3$	4.04
$\text{SiO}_2$	52.21
$\text{P}_2\text{O}_5$	0.07
$\text{SO}_3$	0.49
$\text{Cl}$	0.12
$\text{K}_2\text{O}$	1.32
$\text{CaO}$	29.80
$\text{TiO}_2$	0.24
$\text{V}_2\text{O}_5$	0.04
$\text{Cr}_2\text{O}_3$	0.02
$\text{MnO}$	0.06
$\text{Fe}_2\text{O}_3$	2.88
$\text{SrO}$	0.17
LOI	0.83



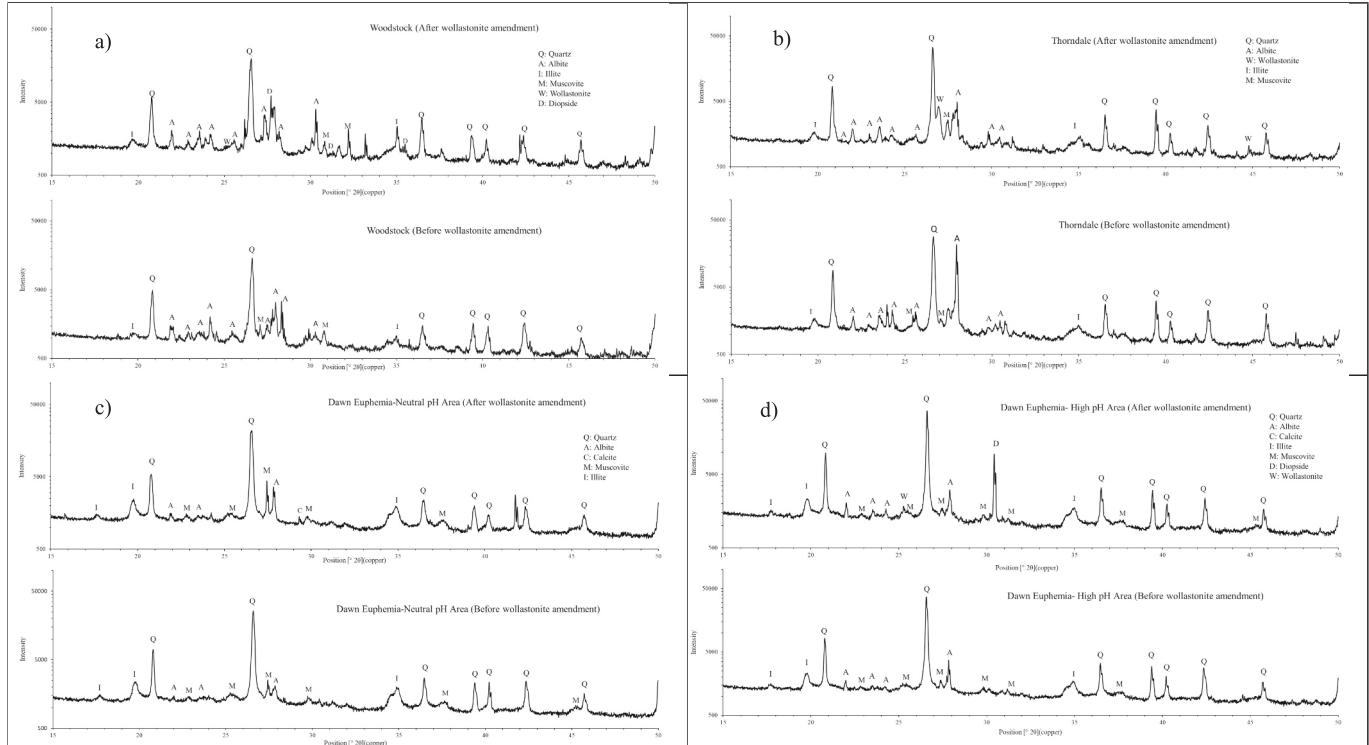
**Fig. 3.** XRD diffractogram of crushed wollastonite ore.

group. In the low-pH and high-pH areas of Dawn-Euphemia field, one composite sample was collected from each area.

### 3. Results and discussion

#### 3.1. Mineralogy and elemental composition

**Fig. 4** shows the XRD diffractograms of the soils amended with



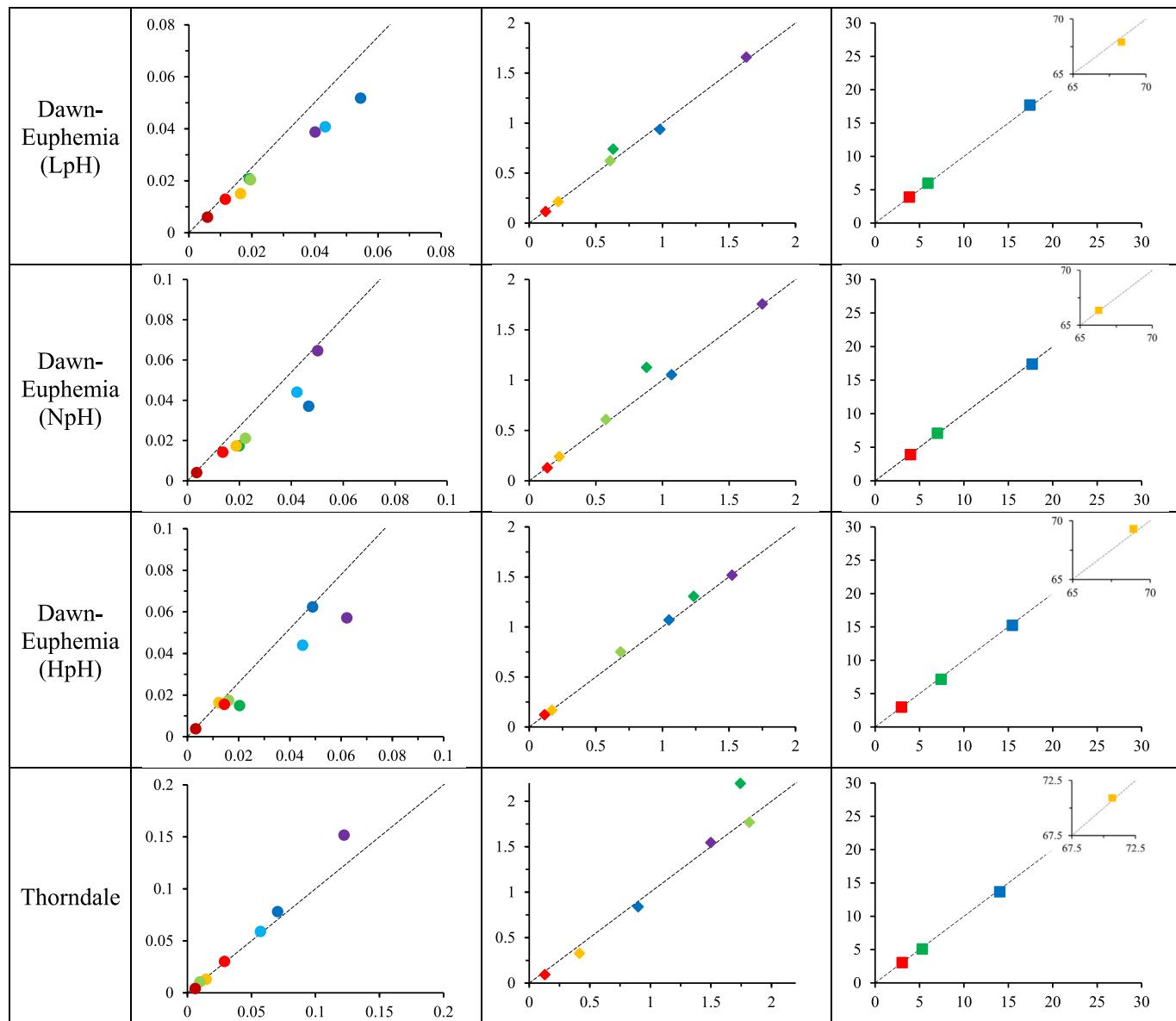
**Fig. 4.** XRD diffractograms of field soil samples (0–15 cm) before (above) and after (below) wollastonite application. a) Woodstock, b) Thorndale, c) Dawn-Euphemia (neutral pH area), and d) Dawn-Euphemia (high pH area).

wollastonite and the corresponding control soils. Owing to the complexity of soil composition, quantifying carbonate formation is challenging (Haque et al., 2020a; Singh and Agrawal, 2012); therefore, the peaks were identified qualitatively. According to Fig. 4, quartz and albite are present in samples from all locations, whereas muscovite ( $KAl_2(Si_3Al)O_{10}(OH)_2$ ) and illite ( $(K, H_3O)(Al, Mg, Fe)_2(Si, Al)_4O_{10}[(OH)_2, (H_2O)]$ ) are minor phases present in all locations, although the peaks are more visible in the Woodstock and Dawn-Euphemia soils. All of the major and minor mineral phases are prevalent in the soil compositions of Southwestern Ontario (Schonenberger et al., 2012).

With respect to weathering products, minuscule peaks of calcite are detectable in the amended sample from Dawn-Euphemia field,

suggesting the initiation of wollastonite weathering. Moreover, several wollastonite and diopside peaks are visible in Thorndale field soil, although they are absent in other fields. A comparison of the XRD results from field soil and our previous laboratory-scale column experiment (Khalidy et al., 2023) revealed that wollastonite/diopside phases are much more distinct in the latter. This is due to a higher wollastonite dosage having been applied in the column experiment (50 t/ha vs. 10–20 t/ha in the field trials), wherein it is more probable that a greater amount of the unweathered portion remains in the soil for a longer time. As discussed by Calabrese et al. (2022), ambient factors such as climate and abiotic/biotic agents could increase mineral dissolution at the field scale compared with laboratory conditions.

WDXRF analyses revealed notable changes in the elemental



**Fig. 5.** The elemental composition of the soil (0–15 cm) before (horizontal axis) and after wollastonite application (vertical axis) in different fields. The data are plotted for 18 elements (●: Y, ●: Sr, ○: Zn, ●: Rb, ●: Cr, ●: Cl, ●: Zr, ●: Mn, ●:  $SO_3$ , ●:  $P_2O_5$ , ●:  $Na_2O$ , ●: CaO, ●:  $TiO_2$ , ●: MgO, ●:  $K_2O$ , ●:  $Fe_2O_3$ , ■:  $Al_2O_3$ , □:  $SiO_2$ ) for three concentration ranges: 0–0.2 wt% (left), 0.2–2.2 wt% (left), and 2.2–30 wt% (right). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

composition of the soil following the application of wollastonite (Figs. 5 and 6); since there was no “before application” collection in the Woodstock field, this field was not included in this section. An increase in Ca content across all fields (Fig. 5, green diamonds) indicates a significant increase in calcium levels, likely due to the addition of wollastonite-rich powder. Similarly, the Mg content shows a corresponding increase in most fields, except for the HpH area at Dawn-Euphemia field, where a slight decrease is observed.

The highest variability in trace element contents after amendment (Fig. 5, leftmost subfigure column) is related to the contents of Mn, Zr, Cr, and Cl. For example, Cr slightly increased the LpH and slightly increased the NpH and HpH areas of Dawn-Euphemia fields. In contrast, the content of this element is under the detection limit for the Thorndale field both before and after wollastonite amendment. For the elemental oxides with 0.1–2 % abundance, the most apparent change was the general increase in oxides that were abundant in wollastonite skarn (CaO, MgO, and Na<sub>2</sub>O). The contents of most oxides related to mineral phases in soil (K<sub>2</sub>O, Fe<sub>2</sub>O<sub>3</sub>, and Al<sub>2</sub>O<sub>3</sub>) are stable following wollastonite application.

The consistency of elemental trends, particularly for those with an abundance exceeding 0.5 %, in consecutive samples (e.g., before vs. after wollastonite application) from a specific field site suggests that the WDXRF technique is useful for tracking changes in soil characterization following ERW practice. This consistency also reflects the effectiveness of the soil collection and preparation methods, as well as the sample preparation and execution using WDXRF equipment. Therefore, this technique shows promise for consideration within a measurement, reporting, and verification (MRV) framework for carbon credits associated with ERW implementation, although further validation is needed.

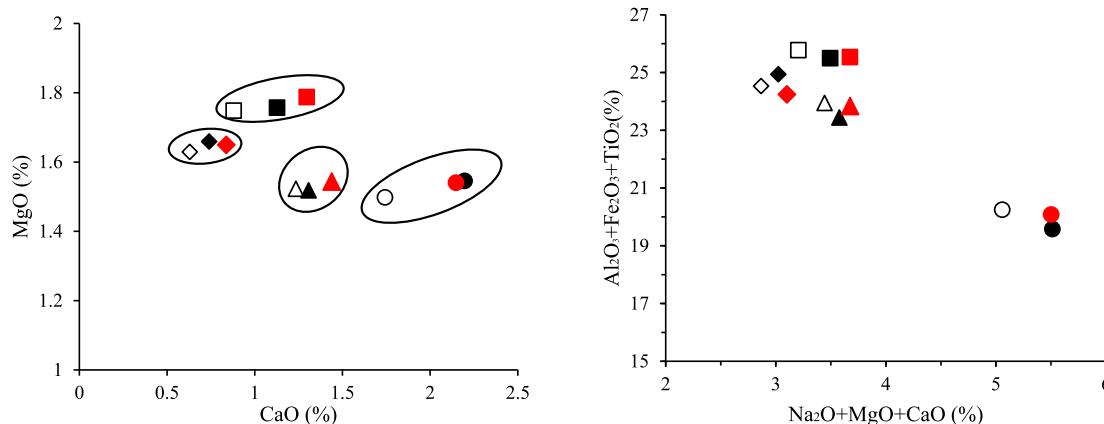
To examine the changes in weathering-related elements more closely, the correlations between CaO and MgO and the sum of mobile (CaO, MgO, and Na<sub>2</sub>O) and immobile (Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, and TiO<sub>2</sub>) elements are represented in Fig. 6. Accordingly, the most significant amendment occurred in the Thorndale field (0.45 % and 0.04 % increases in the CaO and MgO contents, respectively). A slight decrease in MgO% was observed only in the HpH field of Dawn-Euphemia. A comparison of the extent of change in CaO and MgO clearly reveals that wollastonite appears to weather faster than diopside does, which is consistent with data reported for both acidic and neutral ranges (Palandri and Kharaka, 2004). The change in immobile elements (Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, and TiO<sub>2</sub>) is minimal (with maximum changes of 2.6 %, 4.47 %, and 6.47 %, respectively) and remains relatively constant after wollastonite introduction (Fig. 6). In contrast, the change in mobile elements can be more significant, with increases of up to 28.07 %, 9.51 %, and 3.18 % for CaO,

Na<sub>2</sub>O, and MgO, respectively. To compare the observed data after wollastonite application, the theoretical change in soil composition was calculated by averaging the elemental compositions of the soil and wollastonite ore (red symbols in Fig. 6). In all three sections of Dawn-Euphemia, the increase in CaO and MgO is lower than the expected theoretical change, suggesting that the weathering of wollastonite and diopside was followed by the leaching and migration of some weathering products to deeper layers. In contrast, in the Thorndale field, the theoretical change aligns with the amended sample, which could indicate that the weathering products largely remained intact in the shallow soil layers or that pedogenic carbonates formed in the shallow layer immediately following the weathering of wollastonite and diopside.

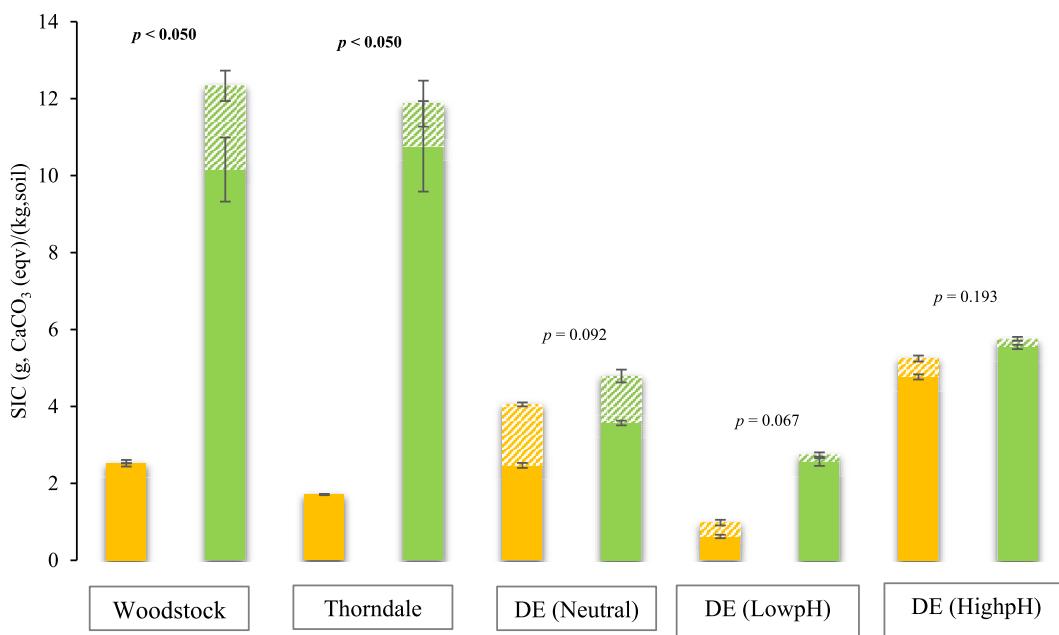
We also tracked the extent of weathering via the soil-based mass-balance approach (TiCAT) developed by Reershemius et al. (2023). The results, shown in Fig. S2 in the Supplementary Material along with more discussion, display inconsistent trends across the fields. By correlating these trends with pH and carbonate content, we concluded that the weathered fraction (F<sub>D</sub>) values serve as a better predictor of weathering within a specific pH range (e.g., weakly acidic). In contrast, calcimetry effectively detects changes in soil inorganic carbon (SIC) across broader pH ranges, particularly those that are closer to neutral and slightly alkaline.

### 3.2. Carbonate content

The carbonate mineral content in the soil samples was measured via the volumetric calcimetry technique. In this process, ultra-purified water is added to the soil samples, followed by the addition of hydrochloric acid. The carbonate contents of the field soils before and after wollastonite application are shown in Fig. 7. The SICs in the Woodstock, Thorndale, and NpH area of Dawn-Euphemia are 2.52, 1.71, and 2.46 (g, CaCO<sub>3</sub> (eqv)/(kg, soil)), respectively (in the Woodstock field, no soil collection was conducted before application, and the soil obtained from the adjacent field is regarded as the “control”). The carbonate accumulation in the Woodstock and Thorndale fields is notable, with values that are more than 4 and 6 times greater than the prior application contents, respectively. In the Dawn-Euphemia field, the SIC of field soils before wollastonite application has a negative correlation with the initial pH and is in the range of 0.62 (g, CaCO<sub>3</sub> (eqv)/(kg, soil)) (in the low-pH area of the Dawn-Euphemia field) and 4.76 (g, CaCO<sub>3</sub> (eqv)/(kg, soil)) (in the high-pH area of Dawn-Euphemia). Although the accumulation of carbonates in this field is lower than that in the other fields, the increasing trend is in agreement with the local SIC and pH of the soil. Accordingly, the estimated net carbonate accumulation in the low-pH,



**Fig. 6.** Change in the elemental composition (expressed as oxides) of the soil samples (0–15 cm) following wollastonite application in Thorndale (before: ○, after: ●, theoretical change: ●), DE NpH (before: □, after: ■, theoretical change: ■), DE LpH (before: ◇, after: ♦, theoretical change: ♦), and DE HpH (before: △, after: ▲, theoretical change: ▲) fields. The left graph correlates changes in alkaline earth metals, and the right graph correlates the sum of more mobile elements (Na, Mg, Ca) versus the sum of less mobile elements (Al, Fe, Ti). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Fig. 7.** The  $\text{CaCO}_3(\text{eqv})$  content in the soil samples (0–15 cm layer) with yellow and green bars is indicative of that before and after wollastonite application, respectively. The height of the solid and that of the solid bar plus the shaded bars are representative of the carbonate content in the bulk samples and the “< 50 µm” fraction (passed through a 50 µm sieve, pan fraction), respectively. The error bars represent SE values, and *p*-values were obtained via the permutation test.

neutral-pH, and high-pH areas is approximately 1.93, 1.10, and 0.78 (g,  $\text{CaCO}_3(\text{eqv})/(\text{kg,soil})$ ), respectively.

These findings suggest a possible relationship between initial soil pH and increased pedogenic carbonate accumulation at Dawn-Euphemia. However, previous studies have shown that increasing pH favors pedogenic carbonate formation, whereas wollastonite dissolution is promoted in low-pH soil (Haque et al., 2019b). Our previous study also demonstrated that wollastonite weathering and carbonate formation still occur at lower pH values after the soil has dried (Khalidy et al., 2023).

One possible explanation is that more carbonate formed in the high-pH area, but a portion migrated downward into sublayers over time. In contrast, in the low-pH area, the pH first stabilized within a neutral range (as discussed in Section 3.4), after which secondary carbonates formed under these neutral pH conditions. This hypothesis can be corroborated by the higher carbonate content in the 15–30 and 30–60 cm layers of the high-pH area than in the low-pH area (the results are not shown here). Another explanation could be that wollastonite dissolution slows down at higher pH values (Haque et al., 2019b; Haque et al., 2023), so it is expected that over a given period, more wollastonite will be dissolved in soils with lower pH values. In addition to the pH range, wetting–drying cycles in the field could contribute to pedogenic carbonate formation (Khalidy et al., 2022).

Although our results are in agreement with previous findings regarding the formation of carbonate due to the application of wollastonite in Southwestern Ontario (Haque et al., 2020a; Khalidy et al., 2023), it should be noted that soil conditions (e.g., range of pH) and climatic parameters are decisive parameters controlling carbonate formation. While this may hold locally (e.g., in Southwestern Ontario and Central Spain (Jiménez-Ballesta et al., 2024)), it might differ in other regions of the world, where  $\text{CO}_2$  may remain in the form of alkalinity in soil–water systems throughout the soil vertical horizon. Hence, these considerations need to be considered when developing a protocol for MRV purposes.

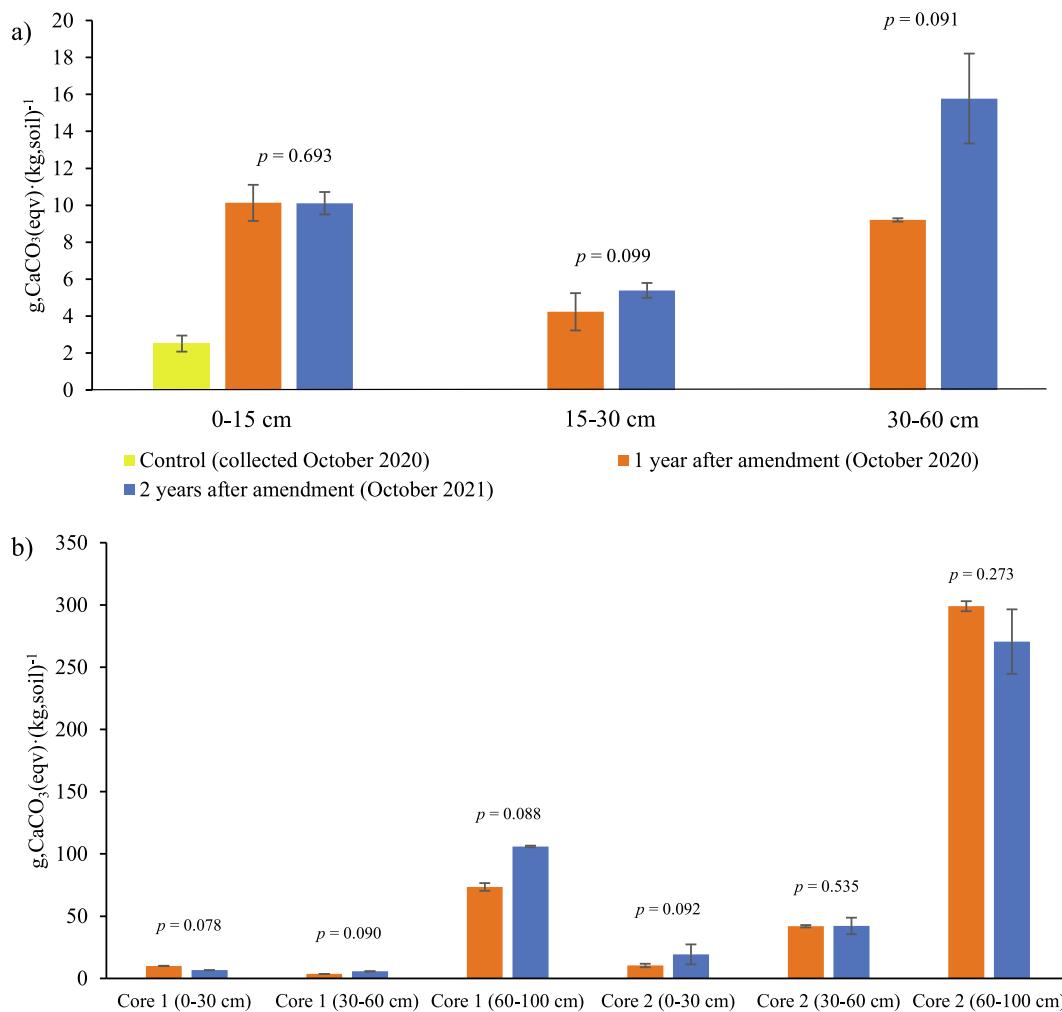
As previous studies reported carbonate content enrichment in the <50 µm fraction of soil (Dudhaiya et al., 2019), we investigated this fraction in field trials as well (Fig. 7, height to the top of the shaded bars). The carbonate content of the <50 µm fraction of soil in “year zero”

and after wollastonite application was greater than that of the bulk samples except for the Thorndale field (the control sample of Woodstock was not analyzed for the <50 µm fraction, as we did not have enough quantity of this sample). The SIC content of the <50 µm fraction followed the same trend as the accumulation of the bulk samples. However, the ratio of carbonate content in the <50 µm fraction is lower than that in the bulk samples from Dawn-Euphemia field (all three zones), whereas the trend is reversed in the Thorndale field. The timing of the Thorndale field (six months) versus Dawn-Euphemia (one year) may have contributed to the observed differences, although variability in field conditions and sampling also likely played a role.

### 3.2.1. Tracking carbonate changes in deeper layers

We assumed a uniform downward migration of weathering products in the soil profile, so the carbonate content represents an average for a given depth. However, in reality, the carbonate content may be concentrated in specific layers. The carbonate contents of the three layers from 0 to 15 cm, 15–30 cm, and 30–60 cm are shown in Fig. 8a. These samples were collected with a Dakota probe sampler, and the values are representative of the average of the whole field. These results indicate that the carbonate content of the surficial layer (0–15 cm) is barely distinct between the first and second years, whereas deeper layers (15–30 cm and 30–60 cm) tend to be more enriched in the carbonate layer in the second year. It can be inferred that the accumulation of carbonates in deeper layers (particularly 30–60 cm) may be associated with the migration of  $\text{Ca}^{2+}$  cations upon wollastonite dissolution or precipitation-dissolution-recrystallization of carbonates in deeper layers. The elemental compositions of the 30–60 cm layer of soil and the  $\text{CaO}$  (2.87 %) and  $\text{MgO}$  (1.68 %) contents of this layer are akin to the values of the surficial layer of this field reported in Fig. 5 but are far from the control field data.

An auger sampler was used to collect core samples from deeper horizons of soil (up to 100 cm) at two locations in the field for two consecutive years (Fig. 8b). In the first location (Core 1), after the soil reached 100 cm deep, the water table (or perched water table) was reached in both sample collection episodes, whereas in the second location (Core 2), a layer of rock (bedrock) was reached, and sampling became impractical at a depth of approximately 100 cm. As shown in



**Fig. 8.** Carbonate content of the Woodstock field one year and two years after wollastonite application: a) at different vertical layers collected with a Dakota sampler (averaged throughout the field), and b) in two core samples collected with an Auger sampler. The error bars represent SE values, and p-values were obtained via the permutation test.

Fig. 8b, the carbonate content is generally in the lower range (5 to 10 times) at the Core 1 location (within the same depth range) than at the Core 2 location. While the carbonate content tends to increase in year 2 in the Core 1 location (with a smaller deviation), the carbonate content at the Core 2 location depicts various shifts.

Accordingly, the increased carbonate content in shallower layers (0–30 cm and 30–60 cm) in the second year suggests a potential increase in carbonate formation processes due to wollastonite application. However, the decrease in carbonate content in the deepest layer (60–100 cm), from 299 to 271 g.CaCO<sub>3</sub> (eqv)/(kg,soil), complicates interpretation and necessitates careful consideration of the factors influencing carbonate dynamics in deep soil horizons. One possible explanation for this decline could be the dissolution of CaCO<sub>3</sub> and the migration of Ca<sup>2+</sup> to groundwater, possibly influenced by high-pressure CO<sub>2</sub> near the bedrock (Bhatt et al., 2019). Hence, investigating groundwater should be included in future works to better understand how ERW affects the deeper horizons of the soil–water system.

In Southwestern Ontario, it is common to find higher levels of carbonates in deeper soil layers, and this occurs because of a combination of natural processes such as leaching and precipitation (water moving through the soil dissolves carbonates from the upper layers and redeposits them deeper as it evaporates or continues to percolate) and soil genesis processes that form the soil from carbonate-rich parent material. The brunisolic and luvisolic soils in this region are a product of weathering of the underlying rock and the deposition of glacial sediments left

behind by the Laurentide Ice Sheet during the last glaciation; these glacial sediments provide diverse parent material that influences soil formation and leads to a well-established zone of carbonate accumulation termed Cca (Lavkulich and Arocena, 2011). This higher carbonate content in subsoil than in surficial soil layers is not unique to our region and is somewhat common globally, particularly in arid and semiarid areas where evaporation rates are high (Khalidy et al., 2022). Given the enrichment of carbonates in deeper layers (in the range of 100 to 250 times greater than newly formed carbonates) and the complexity of sampling in deep horizons (e.g., reaching the water table and encountering rocky layers), tracking and detecting an increase in pedogenic carbonate formation due to wollastonite amendment in deeper horizons even in the long term is burdensome and uncertain. These challenges highlight the logistical difficulties inherent in collecting soil samples from deeper horizons, which can impact the reliability and representativeness of the data obtained and might explain the high deviation in some layers.

### 3.3. Determination of sequestered carbon in the form of pedogenic carbonate

On the basis of the bulk density of the soil (measured at the site), depth of sampling (15 cm), and carbonate accumulation, the carbon sequestered in the soil due to amendment with wollastonite and the efficiency of CO<sub>2</sub> sequestration (defined as the ratio of tonnes of

sequestered CO<sub>2</sub>, in the form of CO<sub>3</sub><sup>2-</sup>, to tonnes of applied wollastonite) were calculated and are presented in Fig. 9. Accordingly, more than 6 t CO<sub>2</sub>/ha was stabilized in the Woodstock (0.53 t CO<sub>2</sub>/(ha·month)) and Thorndale (0.55 t CO<sub>2</sub>/(ha·month)) fields, corresponding to efficiencies (the ratio of tonnes sequestered CO<sub>2</sub> to tonnes applied wollastonite) of 0.42 and 0.33, respectively. In the Dawn-Euphemia field, the estimated sequestered CO<sub>2</sub> concentration varies between 0.52 (in the high-pH area) and 1.29 (in the low-pH area) t CO<sub>2</sub>/ha (0.04 to −0.11 t CO<sub>2</sub>/(ha·month)). The sequestration efficiency at Dawn-Euphemia (0.05 to 0.13 t CO<sub>2</sub>/t wollastonite), was much lower than that at the other two fields.

To assess the impact of the dosage of applied wollastonite on sequestered CO<sub>2</sub> and the efficiency of sequestration, the correlations among these parameters are plotted in Fig. 9b and c, respectively. These graphs show an expected increase in the sequestration amount, although the growth is not linear. Compared with a previous field study conducted in Ontario, Haque et al. (2020a) reported a lower amount of carbon sequestration (0.11 to 0.40 tCO<sub>2</sub>/ha over a few weeks to a few months) with a lower wollastonite dosage (1.25–5 t/ha). Our results indicate that higher rates of wollastonite application (e.g., 15–20 t/ha) still significantly increase the amount of stabilized carbonates. This could be related to the fact that both higher application rates and longer durations of the experiment contributed to adjusting the soil pH within a range that was favorable for carbonate precipitation in our study. Fig. 9 also shows the sequestration rate and efficiency of sequestration in a soil column study (Khalidy et al., 2023) utilizing powdered wollastonite. Accordingly, the sequestered CO<sub>2</sub> in the 0–15 cm layer of the soil column (red square in Fig. 9a) is comparable to that in the DE field, whereas the sequestered CO<sub>2</sub> in the whole column (0–60 cm, red square in Fig. 9b) is approximately 3 times greater than that in the 0–15 cm layer. This phenomenon necessitates the inclusion of downward carbonate migration and formation in deeper layers of soil and subsoil.

While several studies (e.g., Buckingham and Henderson, 2024; Kantola et al., 2023; Larkin et al., 2022) have advocated for the use of higher rates (> 50 t/ha) of silicate minerals in ERW practices, debate has been raised regarding their potential harm to plant growth (Haque et al., 2019b; Haque et al., 2020b; Swoboda et al., 2022) and mobilization of toxic elements in some cases (Dupla et al., 2023; Santos et al., 2023). Several studies have indicated that the application of a lower dosage (<10 t/ha) of wollastonite is sufficient to sequester atmospheric carbon and improve plant growth simultaneously (Wang et al., 2024). Therefore, these factors need to be considered when determining a suitable application rate for ERW candidates, as discussed by Abdalqadir et al. (2024).

#### 3.4. Soil pH

As demonstrated in Fig. 10, the mean pH of the soil appeared to increase in all fields, although the degree of change varied. In the Dawn-

Euphemia field, a larger upward shift in soil pH was observed in the low pH and neutral pH areas, with average increases of 0.97 and 0.89 units, respectively. On the other hand, the high-pH area experienced a relatively mild change (0.38-unit increment). In the Thorndale field, the pH of the soil increased to >7 (compared with pH < 5.5, before wollastonite application). In the Woodstock field, the pH was mildly greater in the amendment field (after one year of application) than in the control area; nevertheless, the increase ceased in the second year.

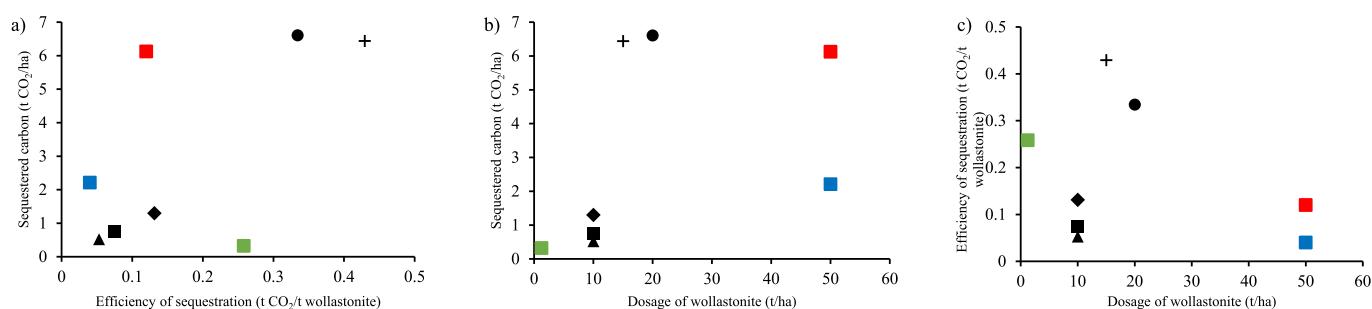
The pH measurements suggest that the response of the soil system to change is influenced by the initial pH. Accordingly, the greatest increase in pH was observed in acidic soils (the low-pH area at Dawn-Euphemia and Thorndale fields). Conversely, the pH value seems to be stable in the alkaline range (pH > 7), as is the case for the high-pH area in Dawn-Euphemia and Woodstock (Year 1 vs. Year 2) fields.

Studies reporting improvements in soil pH due to ERW practices abound in the literature (Kelland et al., 2020; Haque et al., 2020a; te Pas et al., 2023; Dietzen et al., 2018). In a field-scale experiment, Haque et al. (2020a) reported an improvement in pH in soils amended with wollastonite, while the degree of change improved over time. All of the soils investigated in the mentioned study were mildly acidic (5.9 < pH < 6.7), with a slight increase at different intervals (a few months to three years). In another field study, only a slight increase in soil pH was observed due to the introduction of glacial rock flour (enriched in Ca and Mg-bearing silicate minerals) to acidic soil (pH approximately 5) (Dietzen et al., 2018; Gunnarsen et al., 2023). It can be deduced from miscellaneous studies that pH increases because ERW practices do not follow a specific trend and are dependent on many factors, including practice management, harvested plants, and the composition of the applied mineral (te Pas et al., 2023; Dietzen et al., 2018; Jariwala et al., 2022).

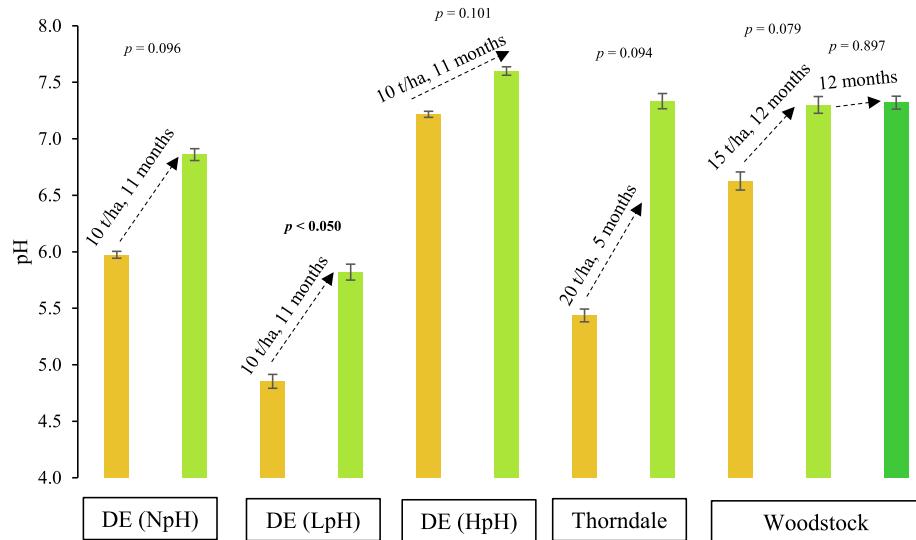
#### 3.5. Soil organic matter

The objective of LOI analysis was to determine how wollastonite addition affects SOM. Owing to the positive correlation between SOM and SOC (Ruiz Sinoga et al., 2012), it is possible to assess the impact of wollastonite on SOC. The results of the LOI analyses are represented in Fig. 11. The general trend is a reduction in SOM after wollastonite amendment, while the magnitude of alteration varies in different fields.

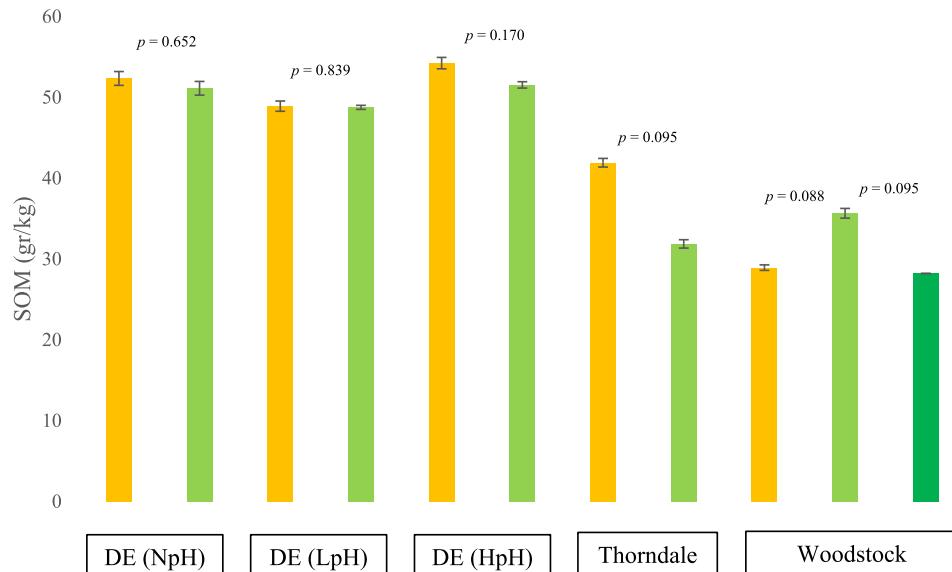
In the Dawn-Euphemia field, SOM decreases are greatest in high-pH soils and lowest in low-pH soils. The greatest depletion was observed in the Thorndale field, with an approximately 1 % reduction in the SOM content. Since there was no “Year zero” collection in the Woodstock field, the SOM of the amended field was compared to that of the neighboring area (as an indicator of background value). Accordingly, the SOC of the amended field was greater than that of the neighboring area. This could be attributed to the different harvesting/management practices performed in these two areas of the field. Interestingly, the SOM of this field in the second year of collection decreased compared



**Fig. 9.** Correlation plots: (a) amount of sequestered carbon (in terms of pedogenic carbonate formation) vs. sequestration efficiency; (b) sequestered carbon vs. dosage of applied wollastonite; and (c) sequestration efficiency vs. dosage of applied wollastonite, in field trials and previous studies. (+: Woodstock, ●: Thorndale, ▲: Dawn-Euphemia (HpH), ◆: Dawn-Euphemia (LpH), ■: Dawn-Euphemia (NpH), ■: Haque et al. (2020a), ■ and ■: Khalidy et al. (2023); 0–60 and 0–15 cm layers, respectively.) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Fig. 10.** The modification in soil pH after wollastonite application in the 0–15 cm layer of soil (yellow: before and green: after wollastonite application; the rightmost bar represents the pH of Woodstock two years after application). The error bars represent standard errors, and *p*-values were obtained via the permutation test.



**Fig. 11.** The change in soil SOM after wollastonite application in field trials (yellow: before application; green: after wollastonite application; the rightmost bar represents the SOM of Woodstock two years after application). The error bars represent SE values, and *p*-values were obtained via a permutation test.

with that in the first year (and was comparable to the value in the neighboring area).

The results for SOM are in line with the majority of observations reported in the literature, and the same trend was observed in a soil column experiment (Khalidy et al., 2023), with a significant decrease in SOM in surficial layers (e.g., 0–15 and 15–30 cm layers) of soil amended with wollastonite, whereas the SOM content of subsoil layers (30–45 and 45–60 cm) was found to be intact. Haque et al. (2019b) reported a decline in SOC in soil samples mixed with crushed wollastonite (through a pot experiment). In another study conducted by te Pas et al. (2023), the alteration of SOC due to silicate mineral introduction (including wollastonite) was found to be insignificant. However, Buss et al. (2024) recently showed that ERW (through the application of basalt and granite rock) stabilizes SOM, as micronutrients (Mn and Zn) provided by minerals contribute to the sorption of organic matter. Additionally, Bi et al. (2024) suggested that the ERW of wollastonite contributes to P solubilization and mobilization from both inorganic and organic P pools

through its effects on specific enzymes. Nonetheless, this stabilization of SOM may be partially offset by the destabilization of SOC aggregates and the weakening of organomineral interactions due to the presence of plant-derived acids (Tao and Houlton, 2024). Understanding and quantifying these interactions is crucial for assessing the net impact of ERW on atmospheric CO<sub>2</sub> levels.

### 3.6. Statistical significance of results

Examining the *p*-values obtained for different parameters, it may be inferred that most *p*-values exceed the traditional confidence threshold of 0.05. For SIC values (Fig. 7), many *p*-values are close to this threshold (i.e., less than 0.10), with two values falling within the traditional range of statistical significance ( $\leq 0.05$ ). Similarly, for pH values (Fig. 10), the trend is comparable to SIC (Fig. 7), with most *p*-values approaching the 0.05 threshold. For SIC values in deeper samples (Fig. 8), the range of *p*-values is divided into a set of smaller values ranging from 0.07 to 0.1 and

a set spanning a broader range from 0.27 to 0.69. Similarly, for SOM (Fig. 11), the *p*-values can be divided between those of  $p \leq 0.10$  and those of  $p > 0.10$ . The data thus suggests that the level of significance for the combination of sampling approach (composite samples split into replicates), number of sampling (1 to 3 composites per trial) and analysis replicates (each split replicate analyzed three times), and mathematical approach used to calculate the *p*-values conservatively (Wilcoxon signed rank test), that our study can consider is  $\leq 0.10$ . This significance level is discussed in the literature as being at times suitable or necessary, and at times part of a larger discussion on what significance means in different contexts (Wilks, 2016; Chuard et al., 2019).

It is important to note that researchers often determine the significance threshold based on their study's specific conditions (Kwak, 2023), including sample collection methods. Consequently, adjusting the significance level to alter the outcomes of statistical hypothesis tests can be considered when the analysis is rigorous and the context demands it (Kim et al., 2024). Additionally, it is essential to understand that the *p*-value does not convey the magnitude of the difference in absolute terms, but rather comparatively. That is, a study that meets the test of  $p \leq 0.05$  is not necessarily more rigorous than one that meets  $p \leq 0.10$ , as they both can be measuring a similar level of relevance, or 'secured relevance' as proposed by Stahel (2021) as an alternate statistical metric. The significance level is influenced by multiple factors, including sample size, variability of the measured outcomes, and the observed differences themselves (In and Lee, 2024).

To illustrate the above with data, a simulation can be run with seemingly significantly different datasets. Take the soil pH value in a hypothetical year 0 to have been measured, for 3 composites and 3 subsamples analyzed from each composite, as the  $3 \times 3$  array {6.0, 6.1, 6.2; 6.1, 6.2, 6.3; 6.2, 6.3, 6.4}, and in year 1 as {6.5, 6.6, 6.7; 6.6, 6.7, 6.8; 6.7, 6.8, 6.9}. Inspecting this data, we can see that all year 0 values are less than the year 1 values and that each year 1 value is 0.5 pH unit greater than the corresponding year 0 values. Hence physically speaking, we can assert that a change has happened and that such change should be reliably measured using laboratory techniques. Statistically speaking, the *p*-value for this hypothetical data, using the hierarchical permutation test of the Wilcoxon signed-rank test, is 0.079. If we now change the year 1 array to {7.5, 7.6, 7.7; 7.6, 7.7, 7.8; 7.7, 7.8, 7.9}, wherein each value is 1.5 pH units higher than in year 0, the *p*-value slightly reduces to 0.071. This further exemplifies how the *p*-value is sensitive to the sample collection method and treatment in addition to the measured effect.

Given the inherent spatial and temporal variability in cropland soils, which introduces additional noise into the data, it is mathematically challenging to achieve very small *p*-values. In this context, assuming a significance *p*-value different from 0.05 is a reasonable approach that acknowledges the natural variability and ensures that meaningful changes are not overlooked due to overly stringent criteria. This raises important questions for future work: what is an appropriate *p*-value threshold for use in ERW MRV practices, what is the tradeoff of seeking a small *p*-value versus the cost associated with intensive sampling and analysis, and given the inherent heterogeneity and uncertainties associated with soil sampling in the field, should each MRV method establish tailored statistical criteria? Developing standardized yet adaptable statistical guidelines could ensure robust and reliable analyses, particularly for ERW and other field-based studies.

#### 4. Conclusion

The results of this study add more insights to the literature concerning the potential of ERW weathering practices (via wollastonite) as a method for stabilizing atmospheric carbon in the form of pedogenic carbonate at the field scale. The highest observed amount of sequestered carbon due to wollastonite addition was equal to 6.60 t CO<sub>2</sub>/ha, corresponding to an efficiency of 0.33 (t CO<sub>2</sub>/t wollastonite). The sequestered carbon was found to be dependent on the initial soil pH and the dosage

of wollastonite applied. In line with previous studies, the carbonate content of the <50 µm fraction was greater than that of the bulk samples. The downward migration of carbonates into deeper layers of soil (e.g., up to 60 cm) was detected; however, owing to the complexity of sampling and the large deviation of primary carbonates, tracking carbonates at deeper horizons (e.g., > 60 cm) was difficult. Wollastonite amendment was found to be effective at improving the soil pH in different ranges (acidic, neutral, and alkaline), with a pronounced degree of improvement in acidic soils (e.g., from pH ≈ 5 to pH ≈ 6–7). While WDXRF analyses revealed that increases in CaO and MgO occur with wollastonite addition in most fields, XRD analyses could barely detect mineral phases associated with weathering products, particularly in soils subjected to lower dosages of wollastonite. Wollastonite amendment also reduced the SOM of field samples and had an inverse correlation with the amount of wollastonite added. Our results also present evidence of the downward movement of carbonates into subsoil layers, which is in line with our observations from our soil column experiments. Hence, the inclusion of carbonate accumulation in deep layers of carbonate and the consideration of local pH as part of the outline of carbon dioxide removal methods due to ERW practices are needed. While our findings are promising, they are based on qualitative observations and may not fully capture variability across different soil types and conditions. Further studies incorporating robust statistical analyses are necessary to confirm these trends and improve the reliability of these conclusions. Notably, the pattern of carbonate formation and downward migration demonstrated in this study might be unique to the soil characteristics and climatic conditions in Southwestern Ontario. In other soil settings, the bicarbonate flux may dominate carbonate formation. These uncertainties could address the acceptability of ERW as a reliable and enduring carbon sequestration approach to address climate change.

#### CRediT authorship contribution statement

**Reza Khalidy:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Fatima Haque:** Writing – review & editing, Investigation, Data curation. **Yi Wai Chiang:** Writing – review & editing, Resources, Funding acquisition. **Rafael M. Santos:** Writing – review & editing, Supervision, Conceptualization, Funding acquisition.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.geodrs.2025.e00918>.

#### Data availability

Data will be made available on request.

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