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Organic residue and agricultural lime interactions on CO_2 emissions from two contrasting soils: implications for carbon management in acid soils

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Abstract

Purpose Agricultural lime (aglime) has been recognised to promote the production of CO_2 from acid soils. However, the role of organic residues in controlling the magnitude of these emissions is poorly understood. This study, therefore, investigated the interactive effects of aglime and organic residues on inorganic- and organic-derived CO_2 emissions from two contrasting acid soils.

Materials and methods The experiment was carried out as a completely randomised $2 \times 2 \times 4$ factorial design where two contrasting acid soils (Nariva clay series, Mollic Fluvaquents and Piarco loam series, Typic Kanhaplaquults) were amended with varying rates of ^{13}C-enriched aglime (0% w/w and 0.230% w/w $Ca^{13}CO_3$, ^{13}C 5.99% atom abundance) and organic residues (0% w/w and 1% w/w corn stover, poultry litter, or glucose) to give a total of 16 treatment combinations. These treatments were triplicated, resulting in 48 experimental units that were incubated for 103 days in 1-L media bottles.

Results and discussion The mineralisation of carbon (C) in the Piarco soil increased by 27% with aglime addition relative to the no-organic residue control but decreased (by as much as 13.2%) when applied to the organic residue-amended soils. This interaction was, however, not evident in the Nariva soil, which may be attributed to the fact that aglime-induced priming effects were negligible in this soil. Results also show that the rate of aglime-CO_2 emissions decreased with the application of poultry litter and corn stover, and increased with the application of glucose. This effect was particularly evident in the Piarco soil and is likely related to the organic residue-induced changes in the soil pH.

Conclusions Overall, our results highlight the importance of considering organic residue addition when assessing the global warming effect associated with aglime use. In addition to crop nutrition benefits, our results further emphasise the need to optimise liming and organic residue management practices to enhance C sequestration in acid soils.

Keywords Soil acidity · Calcium carbonate dissolution · Inorganic- and organic-derived CO_2 · Priming effects · Carbon sequestration · Emission factor

1 Introduction

Liming is a long-standing agricultural practice that has greatly benefited the productivity of acid soils (Caires et al. 2008; da

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Costa et al. 2016). However, while much is known about the influence of this practice on soil fertility and crop productivity, its effects on soil C dynamics remain largely uncertain (Bramble et al. 2019). In fact, the Intergovernmental Panel on Climate Change (IPCC) originally assumed in their 1996 guidelines that 100% of the C that is stored in aglime (calcitic and dolomitic limestone) is ultimately released into the atmosphere as CO_2. However, it is now recognised that this may not always be the case and countries are allowed to report on their own emission factors (De Klein et al. 2006). This amendment to the IPCC's guidelines is supported by biogeochemical theory, which suggests that aglime dissolved by weak acids, such as H_2CO_3, whose production is enhanced by root and

microbial respiration, results in the formation of HCO_3^- instead of CO_2 (West and McBride 2005; Hamilton et al. 2007). In keeping with this theory, Hamilton et al. (2007) suggest that soils can sequester as much as 50% of the C from aglime, which were based on indirect assessments of the quality of drainage waters in a watershed and not on direct measurements of CO_2 emissions. Therefore, more studies directly quantifying the proportion of aglime-C released as CO_2 under various soil conditions are warranted to verify these claims (Biasi et al. 2008).

As CO_2 emitted from limed soils can originate from numerous sources, stable isotope techniques are necessary to distinguish emissions from aglime as opposed to other sources. While these techniques have been utilised in a number of studies over the past decade to trace aglime-CO_2 emissions (Bertrand et al. 2007; Biasi et al. 2008; Dumale et al. 2011; Ahmad et al. 2014; Grover et al. 2017; Cho et al. 2019; Bramble 2020), the mechanisms/factors controlling these emissions from acid soils remain elusive. For example, some researchers suggest that organic residues, which are commonly applied to enhance soil fertility and C sequestration, may play a pivotal role in regulating the dynamics of aglime-C in acid soils by (i) enhancing the release of CO_2 from aglime by reducing soil pH and enhancing the rate of aglime dissolution (Bertrand et al. 2007), (ii) reducing the release of CO_2 from aglime by increasing the soil pH and reducing aglime dissolution (Ahmad et al. 2014), and (iii) reducing the release of CO_2 from aglime by stimulating microbial respiration and the production of weak carbonic acid, which in turn reacts with the aglime to form HCO_3^- instead of CO_2 (Bramble et al. 2019). Studies utilising isotopic techniques are, however, still yet to provide empirical evidence to support these hypotheses. For example, Ahmad et al. (2014) and Bertrand et al. (2007) were not able to separate aglime-CO_2 emissions from emissions originating from other sources using the natural abundance isotope technique in treatments with organic residues. In the case of Bramble et al. (2019), the sources of emissions were not determined; however, the release of CO_2 following the combined application of aglime and poultry litter was lower than expected. The authors suggested that this could have been attributed to a reduction in aglime-CO_2 release but acknowledged that stable isotope techniques would be required to confirm this claim. Given the complications that arose with the use of natural abundance aglime in the studies that were conducted by Bertrand et al. (2007) and Ahmad et al. (2014), it seemed imperative that ^{13}C-enriched aglime be used in future studies investigating the effects of organic residues on aglime-CO_2 emissions.

Apart from the direct release of CO_2 from aglime upon dissolution, aglime can also affect soil C dynamics by inducing priming effects on soil organic C (SOC) decomposition (Wachendorf 2015; Grover et al. 2017; Bramble et al. 2020). However, these effects are not currently considered in the IPCC's greenhouse gas inventories (De Klein et al. 2006). This may lead to inaccuracies in the calculated CO_2 emission factor for liming since the magnitude of priming can be quite substantial in comparison with the amount of inorganic substance added (Kuzyakov et al. 2000; Dumale et al. 2011; Li et al. 2018; Xiao et al. 2018). Aglime-induced loss of SOC may also negatively affect soil fertility since organic C is a major component of soil organic matter, which serves as an important source of nutrients for soil microorganisms and plants (Brady and Weil 2008; Oldfield et al. 2019).

The magnitude of the aglime-induced priming effects is also likely to be greater when organic residues are applied (Ahmad et al. 2014), which itself can induce priming effects that could also be exacerbated by liming. Furthermore, liming can also affect the decomposition of the residue itself, with Aye et al. (2017) reporting on a linear increase in residue decomposition with initial soil pH. They also found that priming of native SOC increased with initial soil pH up to 6.5, especially when wheat or field pea residues were applied suggesting that liming can encourage soil-C loss. Wachendorf (2015), however, reported on lower total C mineralisation from soils amended with both aglime and poplar residue compared with those that only received residue. They attributed this effect to soil structure and the SOC stabilisation effect of the Ca^{2+} in aglime. This mechanism of C stabilisation was also previously demonstrated by Muneer and Oades (1989a, b). These conflicting reports of aglime effects on SOC levels may be attributed to the fact that the soil used by Aye et al. (2017) was pre-treated with lime for an extended period prior to the addition of the residues. As such, the stabilisation effect of the aglime would not have been as apparent. In addition, differences in the quality of the applied residue and the properties of the soils used (e.g. initial C content) could also explain the conflicting findings. Intuitively, studies evaluating the interactive effects of soil type, type of organic residue, and liming on C mineralisation in acid soils are warranted. However, previous studies have only used one soil type (Aye et al. 2017; Wachendorf 2015; Ahmad et al. 2014) or one residue type (Wachendorf 2015; Ahmad et al. 2014).

In the current study, ^{13}C-enriched $CaCO_3$—referred to herein as aglime—and organic residues of varying quality were used to assess their interactive effects on inorganic- and organic-derived CO_2 emissions from two acid soils that differed in texture, initial C content, and buffering capacity. This study also compared the estimates of the aglime-CO_2 emission factors calculated using isotopic and non-isotopic techniques. It was hypothesised that (i) the effect of aglime on increasing C mineralisation would be greatest when the most labile organic residue is applied to the coarse-textured soil with the lower initial C content, (ii) aglime-CO_2 emissions would be regulated by the synergistic effects of organic residue, decreasing with increasing mineralisation of C, and (iii) there would be a significant difference in the

emission factors estimated using the isotopic and non-isotopic techniques.

2 Materials and methods

2.1 Soil and organic residue collection, preparation, and characterisation

Soil samples from two Trinidad soils (Nariva series: very-fine, mixed, semiactive, isohyperthermic Mollic Fluvaquents; and Piarco series: clayey, kaolinitic, isohyperthermic Typic Kanhaplaquults) were collected from the top 15-cm layer at 10° 27′ 19″ N, 61° 19′ 26″ W and 10° 36′ 37″ N, 61° 19′ 26″ W, respectively. The collection sites for these soil series were previously under vegetable crop production. The soils were air-dried, sieved through a 5-mm mesh, and stored in sealed polyethylene buckets before being shipped to the Department of Soil Science, University of Saskatchewan, Saskatoon, Canada, where the experiment was performed. The poultry litter, which was collected from a poultry farm in Trinidad, and the corn stover, collected from The University of the West Indies Field Station (10° 38′ 17.21″ N, 61° 25′ 44.87″ W), were also air-dried before being passed through a 2-mm mesh, and then transferred into polyethylene bags before shipping in polyethylene buckets. Subsamples from the transported bulk soils were further ground and sieved to obtain the 'fine earth fraction' (< 2 mm) for experimentation and characterisation purposes. The poultry litter and corn stover were finely ground (< 250 μm) using a ball mill after being dried in an oven at 65 °C for 48 h.

The water holding capacity of the soils was determined using the procedure described in Wuddivira et al. (2013). The percentage of water stable aggregates in the soils was determined using a single sieve wet sieving apparatus (Eijkelkamp Agrisearch Equipment, Giesbeek, NL) following a procedure described in Francis et al. (2019). Soil particle size analysis was carried out using the hydrometer method (Gee and Or 2002). Soil pH and electrical conductivity were determined on 1:2.5 soil:water slurries after a 1-h equilibration period (Henershot et al. 2008) using a pre-calibrated Mettler Toledo S975 pH/ORP/Ion/Conductivity/DO meter. The pH and electrical conductivity of the organic residues were, however, measured in a 1:10 ratio. The soil lime requirement to pH 6.5 was determined according to Hardy and Lewis (1929). Soil cation exchange capacity was estimated using the ammonium acetate buffered method (Rhoades 1982) where the exchangeable cation sites were first saturated with NH_4^+ using a 1 M NH_4-acetate solution. One molar KCl solution was then used to displace the NH_4^+ from the exchangeable cation sites after the sample was washed three times with 95% ethanol and the concentration of the displaced NH_4^+ in the final phase was determined by steam distillation on a Labconco II Rapidstill.

The extract from the NH_4-acetate saturation phase was also used to determine the exchangeable Ca^{2+} and Mg^{2+} concentration on an Agilent Technologies 200 series Atomic Absorption Spectrometer. Available nitrogen (N) forms (i.e. NH_4^+ and NO_3^-) from the soils and organic residues were extracted using 2 M KCl in a 1:10 material:extract volume (Maynard et al. 2008) and the concentration of these ions was then determined by colorimetry on a Technicon Auto-Analyser (Tamir et al. 2013).

Samples for total C, total N, $CaCO_3$, and $\delta^{13}C$ analyses were oven-dried and finely grounded (< 250 μm) using a ball mill. The total C and total N content of the samples were determined simultaneously on a Costech Elemental Analyser, while their $\delta^{13}C$ was characterised on a Delta V Advantage Mass Spectrometer (IRMS) (Thermo Fisher 192 Scientific, Inc.). Inorganic C in the poultry litter was first removed by treating with 12 M HCl vapour for 48 h prior to characterising the $\delta^{13}C$ of its organic C fraction (Harris et al. 2001). The quantity of inorganic C in the poultry litter was determined on a Bruker 450 gas chromatograph using the procedure described in Bramble et al. (2019) and this value was used to estimate the $CaCO_3$ content of the sample (Bramble et al. 2019). The $\delta^{13}C$ of this inorganic C fraction was determined using the same procedure on a Picarro G1101-i isotopic CO_2 analyser. The properties above for the soils and organic residues are presented in Table 1.

2.2 Laboratory incubation and experimental design

The experiment investigated three factors [soil type (2), organic residue (4), and liming (2)] in a $2 \times 4 \times 2$ factorial study. Each of the two soils was amended with varying combinations of aglime [0% and 0.23% w/w = 4.6 Mg ha^{-1} Ca^{13}CO$_3$ (5.99% ^{13}C atom abundance)] and organic residue [0% and 1% w/w = 20 Mg ha^{-1} corn stover, poultry litter, or glucose; the latter serving as a positive control] to give a total of 16 treatment combinations. All treatments were triplicated and the experimental units were arranged in a completely randomised design. Each experimental unit consisted of 150-g samples of soil (on an oven-dry basis) incubated in 1-L media bottles (Fisher Scientific, Inc.) whose lids were fitted with a sampling port that was sealed with a butyl-rubber septum. It is important to note that the bottles were only kept closed for CO_2 measurement. These units were incubated at 25 ± 1 °C in a large capacity incubator (VWR International Ltd) for 103 days. The length of this incubation period followed that of similar medium-term studies conducted by Ahmad et al. (2014) and Aye et al. (2017). An additional set of replicates ($n = 3$) were also included for soil sampling at 3 days after incubation (DAI). The moisture content of all soil treatments was adjusted to 100% water holding capacity at the start of the experiment and maintained by adding distilled water every 1 to 3 days. This moisture regime was selected to

Table 1 Properties of the soils and organic residues used in the experiment

Parameter	Nariva	Piarco	Corn stover	P.Litter	Glucose
pH (water)	4.76^1	4.82^1	5.85^2	8.53^2	5.55^2
Electrical conductivity (dS m^{-1})	0.753^3	0.197^3	3.60^4	6.67^4	0.003^4
Lime requirement (Mg ha^{-1})^5	7.94	1.36	na	na	na
Clay (%)	49.0	13.7	na	na	na
Sand (%)	20.0	40.0	na	na	na
Silt (%)	31.0	46.3	na	na	na
Water stable aggregates (%)	74.7	41.1	na	na	na
Cation exchange capacity (cmol$^+$ kg^{-1})	35.4	5.50	nd	nd	nd
Ca^{2+} (cmol$^+$ kg^{-1})	17.7	2.04	nd	nd	nd
Mg^{2+} (cmol$^+$ kg^{-1})	4.74	0.636	nd	nd	nd
Water holding capacity (g g^{-1})	0.607	0.283	nd	nd	nd
Total C (%)	5.80	1.31	43.0	21.5	39.9
Inorganic C (%)	---	---	---	1.10	---
δ^{13}C total C (‰)	− 26.08	− 23.21	− 12.73	− 19.51	− 10.67
δ^{13}C inorganic C (‰)	---	---	---	− 2.649	---
δ^{13}C organic C (‰)	nd	nd	nd	− 20.86	nd
Total N (%)	0.62	0.131	1.14	3.58	---
NH$_4$-N (mg kg^{-1})	129	27.5	199	135	---
NO$_3$-N (mg kg^{-1})	25.3	41.3	21.0	1387	---
C:N^6	9.35	10.0	37.7	6.01	---
CaCO$_3$ (%)	---	---	---	9.18	---

[1] pH in a 1:2.5 ratio; [2] pH in a 1:10 ratio; [3] Electrical conductivity in a 1:2.5 ratio; [4] Electrical conductivity in a 1:10 ratio; [5] Lime requirement to pH 6.5; [6] Carbon:nitrogen ratio (calculated using total C and total N.); *P.Litter*, poultry litter; *na*, not applicable; *nd*, not determined; '---' indicates not detected

enhance the rate of aglime dissolution. The ^{13}C enrichment of the aglime (5.99% ^{13}C atom abundance) was achieved by mixing Ca^{13}CO$_3$ (99% ^{13}C atom abundance) (Sigma-Aldrich, Inc.) with non-labelled Ca^{12}CO$_3$ (δ^{13}C of − 34.99‰) (Fisher Scientific, Inc.) following the procedure described in Bramble et al. (2020). Subsamples from this mixture ($n = 5$) were within 2.08% (coefficient of variation), thereby validating its homogeneity.

2.3 Sampling and analysis

2.3.1 Gas sampling

Gas samples were collected at 0.167, 1, 2, 3, 4, 5, 7, 11, 16, 24, 32, 43, 56, 82, and 103 DAI following the procedure described in Bramble et al. (2020). The incubation vessels were first flushed with ultra-zero air for 1 min to expel CO$_2$ from the headspace and then completely sealed for 1.67 to 24 h depending on the anticipated rate of CO$_2$ emissions at the time of sampling. Two blank vessels were also included to correct for any CO$_2$ that remained in the headspace after flushing. The concentration of CO$_2$ that remained in the vessels after flushing was on average 17.2 μL L^{-1} over the 103-day

incubation, indicating that the flushing was effective. Sixty millilitres of ultra-zero air was injected into the vessel to increase the internal gas volume at the actual time of gas sampling (Biasi et al. 2008). Thirty-and 20-mL gas samples were then taken using a 30-mL and 20-mL polyethylene syringe. These samples were injected into pre-evacuated, N$_2$-flushed 22-mL and 12-mL vials, respectively, which were then analysed for ^{13}CO$_2$ and ^{12}CO$_2$ concentration on a Picarro G1101-i isotopic CO$_2$ analyser and total CO$_2$ concentration on a Bruker 450 gas chromatograph, respectively. Repeated analysis of a laboratory-working enriched ($n = 8$) and natural abundance ($n = 7$) gas standard showed that the isotopic measurements were within 0.618% and 0.784% (coefficient of variation), respectively. Measurements for total CO$_2$ ($n = 10$) were within 1.87% (coefficient of variation).

2.3.2 Soil sampling

Soil samples of approximately 150 g were collected at 3 DAI and 103 DAI. These samples were oven-dried at 60 °C for 12 h (equivalent to air-drying) and analysed for pH as previously described.

2.4 Stable isotope and cumulative CO_2 calculations

The quantity of CO_2 emitted from aglime (aglime-CO_2 emissions) was calculated from the ^{13}C atom% excess values—to correct for any $^{13}CO_2$ that may have originated from soil organic matter and/or residue decomposition—using Eqs. 1 to 4 below:

$$^{13}C \text{ atom}\% = \left[\text{number of}^{13}C \text{ atoms/number of } (^{12}C + ^{13}C \text{ atoms})\right] \times 100 \quad (1)$$

$$^{13}C_{EN} \text{ atom\%excess} = {}^{13}C_{EN} \text{ atom\%} - {}^{13}C_{NA} \text{ atom\%} \quad (2)$$

$$^{13}C_{Lime} \text{ atom\%excess}$$
$$= \left(^{13}C_{Lime} \text{ atom\%} - {}^{13}C_{NA} \text{ atom\%}\right) \quad (3)$$

$$\text{Aglime}-CO_2-C \text{ emissions}$$
$$= \left(^{13}C_{EN} \text{ atom\%excess} / {}^{13}C_{Lime} \text{ atom\%excess}\right)$$
$$\times CO_2-C_{total} \quad (4)$$

where $^{13}C_{EN}$ atom% is the ^{13}C atom% value of the CO_2 in the sample amended with ^{13}C-enriched aglime; $^{13}C_{NA}$ atom% is the ^{13}C atom% value of the CO_2 in the corresponding non-limed sample; $^{13}C_{Lime}$ atom% is the ^{13}C atom% of the ^{13}C-enriched aglime; and CO_2 total is the total CO_2 in the sample amended with ^{13}C-enriched aglime. Similar calculations were performed by Shahbaz et al. (2018) and Bramble et al. (2020).

The emission factor associated with liming was calculated using the isotopic method and difference method as outlined below:

Isotopic method

$$= [\text{Cumulative aglime}-CO_2-C/\text{Quantity of aglime}-C]$$
$$\times 100 \quad (5)$$

$$\text{Difference method} = [(\text{Cumulative total } CO_2-C \text{ emitted from limed soil} - \text{Cumulative total } CO_2-C \text{ emitted from non-limed soil})/\text{Quantity of aglime}-C] \times 100 \quad (6)$$

Cumulative CO_2 emissions were estimated by linear interpolation of measured CO_2 effluxes (Miao et al. 2017). All CO_2 calculations were based on an oven-dried soil weight.

The aglime-induced relative change in C mineralisation (AIRCICM) was calculated using the following equation:

$$\text{AIRCICM (\%)} = [(\text{Organic}-\text{derived } CO_2-C \text{ emitted from limed soil} - \text{Organic}-\text{derived } CO_2-C \text{ emitted from non-limed soil})/ \quad (7)$$
$$\text{Organic}-\text{derived } CO_2-C \text{ emitted from non-limed soil}] \times 100$$

This value indicates the magnitude of the aglime-induced priming effect in the no-organic residue-amended soil treatment. Unfortunately, the aglime-induced priming effect could not be quantified when organic residue was applied as it was not possible to separate residue-derived CO_2 emissions from soil-derived CO_2 emissions in these treatments.

2.5 Statistical analyses

All data were tested for normality using the Shapiro-Wilk test prior to statistical analyses. The CO_2 emission rates and the flux in cumulative AIRCICM with incubation time were analysed by repeated measures analysis. A general linear model (GLM) ANOVA was used to analyse cumulative AIRCICM at the end of the 103-day incubation, soil pH at the two soil sampling times, and cumulative CO_2 and the emission factor data at the end of the study. These analyses were performed in SPSS 20 statistical package (IBM, Inc.). In

each case, differences between means were assessed using Tukey's honest significant difference test at $p < 0.05$. In some cases, the inclusion of soil as a factor resulted in differences between treatments not being observed and so the results of GLM-ANOVAs, where the two soils were analysed separately, were also reported. A similar case was previously reported by Butterly et al. (2019). Only the sources of variation that were statistically significant and related to the objectives of the study are presented.

Regression analyses were performed using zunzun.com to model the effects of the soil treatments on the change in cumulative total, organic-derived (organic), and aglime-CO_2 emissions with incubation time. In the case of each CO_2 parameter, all treatments were pooled to identify a model that sufficiently fitted the treatments. In cases where the global fit did not sufficiently explain the variation in cumulative CO_2 emissions with time for a particular treatment, a separate model was applied. The variation in these emissions with incubation time was either best explained by (i) a quadratic

logarithmic model [$y_i = a + b \times \ln(x_i) + c \times \ln(x_i)^2$], where y_i is the cumulative quantity of CO_2-C released at day^i; a is the y-intercept (i.e. the value of y when $x = 0$); b is the slope of the curve at the y-intercept (i.e. when $x = 0$); c describes the direction and slope of the curvature; and x_i is the incubation time in days; (ii) a simple linear model [$y_i = a + bx_i$], where y_i is the cumulative quantity of CO_2-C released at day^i; a is the y-intercept; b is the slope of the line; and x_i is the incubation time in days; or (iii) a double exponential model [$y_i = a \times exp(bx_i) + c \times exp(dx_i)$] where y_i is the cumulative quantity of CO_2-C released at day^i; a is the y-intercept of the first component of the equation; b is the slope of the first component of the equation; c is the y-intercept of the second component of the equation; d is the slope of the second component of the equation; and x_i is the incubation time in days. Differences between coefficients generated for the various soil treatments were assessed using 95% confidence intervals.

3 Results

3.1 Total and organic-CO_2 emissions

Total CO_2 emission rates were as low as 0.080 mg CO_2-C kg^{-1} h^{-1} (Piarco-control + aglime) and as high as 36.2 mg CO_2-C kg^{-1} h^{-1} (Nariva-poultry litter + aglime) during the 103-day incubation (Fig. 1). For organic-derived (organic)-CO_2 emissions, the rates were in the range of 0.090 to 35.9 mg CO_2-C kg^{-1} h^{-1} (Fig. 1). The peak in these emissions across all 16 treatments was achieved between 0.167 and 2

Fig. 1 Total and organic-CO_2 emission rates for the Nariva and Piarco soil treatments. 0% aglime (− aglime); 0.23% aglime (+ aglime). The closed square symbol with the solid line represents total CO_2 emissions in the aglime-amended soil treatment, while the open square symbol with the broken line represents organic-CO_2 emissions in the aglime-amended soil treatment. The double slash on the x-axis indicates a change in the scale. The error bars represent one standard error for the means of the samples for each treatment at specific times. The bars are hidden when they are smaller than the symbol
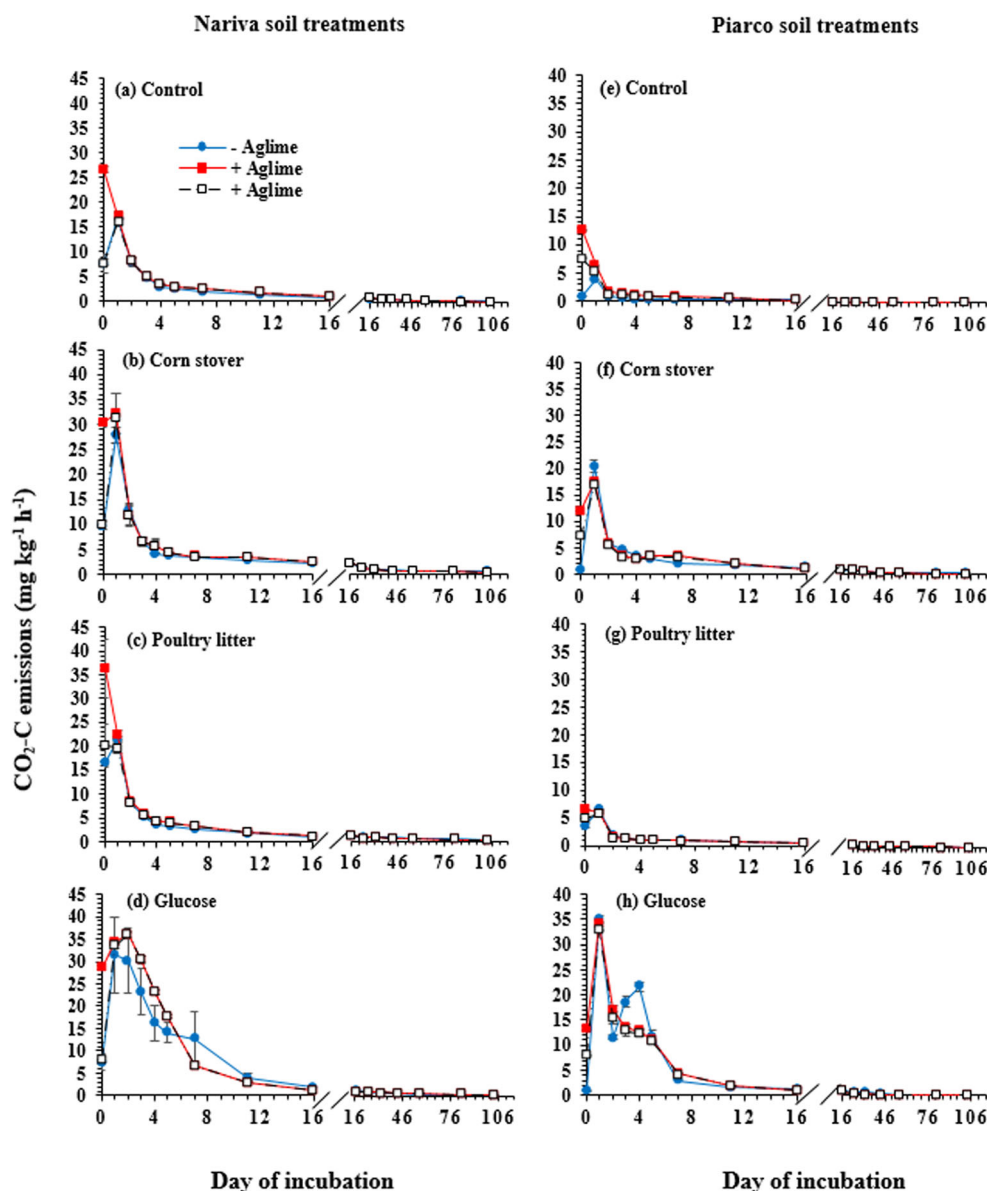
DAI. Thereafter, the rates of emissions progressively declined in all treatments except Piarco-glucose (Fig. 1h) where there was a notable increase at 3 DAI. The rates of both total and organic-CO_2 emissions were generally highest from this and other treatments that received glucose up to 16 DAI. However, thereafter, the highest emission rates were recorded from the corn stover-amended treatments (Fig. 1b and h).

The interaction between soil, organic residue, and aglime on both total and organic-CO_2 emission rates was also evident during the incubation (Fig. 1). Relative to the no-aglime control, the increases in total and organic-CO_2 emission rates within the first sampling time (0.167 DAI) ranged from 74.8% (control + aglime) to 1400 (corn stover + aglime) and 33.7% (poultry litter + aglime) to 800% (corn stover + aglime), respectively for the Piarco soil. This represents a relative change in total and organic-CO_2 emission rates, respectively that was on average ~9 and 36 times greater than that observed for the Nariva soil (Fig. 1). This distinctly significant effect of liming in the Piarco soil, however, became progressively less significant with time, and by the second sampling time (1 DAI), the relative change in total and organic-CO_2 emission rates with aglime addition had already declined to much lower ranges with values from 2.63% (Piarco-glucose + aglime) to 63.4% (Piarco-control + aglime), and from 6.69% (Piarco-glucose + aglime) to 33% (Piarco-control + aglime) for total and organic-CO_2, respectively (Fig. 1). Furthermore, by this time, the rates observed were also lower from the limed treatments, especially when organic residue was applied.

At the end of the incubation, both cumulative total and organic-CO_2 emissions ranged from 553 mg CO_2-C kg^{-1} (control) to 3793 mg CO_2-C kg^{-1} (glucose) for the Piarco soil (Fig. 2). For the Nariva soil, these emissions ranged from 2435 mg CO_2-C kg^{-1} (control) to 6098 mg CO_2-C kg^{-1} (glucose + aglime) and 2435 mg CO_2-C kg^{-1} (control) to 5802 mg CO_2-C kg^{-1} (glucose), respectively (Fig. 2). These cumulative emissions were significantly affected by the three-way interaction between soil, organic residue, and aglime (Fig. 2). While there was no significant change in emissions with aglime application to the Nariva soil treatments, the responses were variable among the Piarco soil treatments. Specifically, by the end of the study, total CO_2 were 59% higher with aglime addition to the no-organic residue-amended soil, 8.34% lower for the glucose-amended soils, but were unaffected by liming in the corn stover and poultry litter-amended soils. Organic-CO_2 emissions significantly declined by 15.2% and 7.81%, respectively when aglime was applied to the glucose and corn stover-amended soils. No effect of aglime was, however, observed for the poultry litter and no-organic residue treatments (Fig. 2). All other sources of variation in the GLM-ANOVA, with the exception of the main effect of aglime on organic-CO_2 emissions, were also found to be statistically significant.

Further statistical analysis of this data by curve fitting showed that a quadratic logarithmic model best explained the relationship between cumulative total and organic-CO_2 emissions with incubation time. The coefficients from this model were significantly affected by the soil treatments (Table 2).

3.2 Aglime-induced relative change in C mineralisation

The cumulative AIRCICM was greatest at the first sampling time (0.167 DAI) in all Piarco soil treatments, where values ranged from 34.6% (poultry litter) to 721% (glucose) (Fig. 3e–h). The AIRCICM also peaked at 0.167 DAI in the Nariva-poultry litter treatment (Fig. 3c). However, maximum AIRCICM occurred later in the incubation in the other Nariva soil treatments, where the peaks in the glucose, corn stover, and control treatments were recorded at 5, 16, and 24 DAI, respectively (Fig. 3a, b, and d). The AIRCICM subsequently declined in all treatments with the exception of Nariva-poultry litter, Piarco-corn stover, and Piarco-glucose where increases at 7, 11, and 11 DAI, respectively were observed (Fig. 3).

A repeated measures analysis found organic residues to have no effect on the cumulative AIRCICM in the Nariva soil throughout the 103-day incubation. This was, however, not the case for the Piarco soil, and at times, differences were observed between the organic residues themselves (Fig. 3). This soil × organic residue interaction was also found to be significant at the end of the incubation, where the AIRCICM means were in the order of control > corn stover = poultry litter = glucose for the Piarco soil, while no significant differences were observed between the Nariva soil means (Fig. 3). The main effect of organic residue was also found to be significant at this time.

3.3 Aglime-CO_2 emissions

The emission rate of CO_2 originating from aglime (aglime-CO_2) for all treatments was greatest at the first sampling time (0.167 DAI) (Fig. 4a, b), with emissions by that time ranging from 23.5% (Piarco-poultry litter) to 72% (Nariva-glucose) of total CO_2 emissions (Fig. 4c, d). The emission rates for the Nariva soil at this time ranged from 16.0 mg CO_2-C kg^{-1} h^{-1} (poultry litter) to 20.6 mg CO_2-C kg^{-1} h^{-1} (glucose; Fig. 4a). For the Piarco soil, the rates were significantly lower, being lowest with poultry litter (1.55 mg CO_2-C kg^{-1} h^{-1}) and highest with glucose (5.33 mg CO_2-C kg^{-1} h^{-1}; Fig. 4b). The emission rates, thereafter, progressively declined in all treatments with the exception of the Piarco-poultry litter treatment where there was a 0.077 mg CO_2-C kg^{-1} h^{-1} (335%) increase between 32 and 43 DAI (Fig. 4b). After 11 days of incubation, these emissions stabilised in all the Nariva

Fig. 2 Total and organic-CO_2 cumulative emission for the Nariva and Piarco soil treatments. 0% aglime (− aglime); 0.23% aglime (+ aglime). The closed square symbol with the solid trend line represents total CO_2 emissions in the aglime-amended soil treatment, while the open square symbol with the broken trend line represents organic-CO_2 emissions in the aglime-amended soil treatment. The error bars represent one standard error for the means of the samples for each treatment at specific times. The bars are hidden when they are smaller than the symbol. The data points are the observed values with a trend line
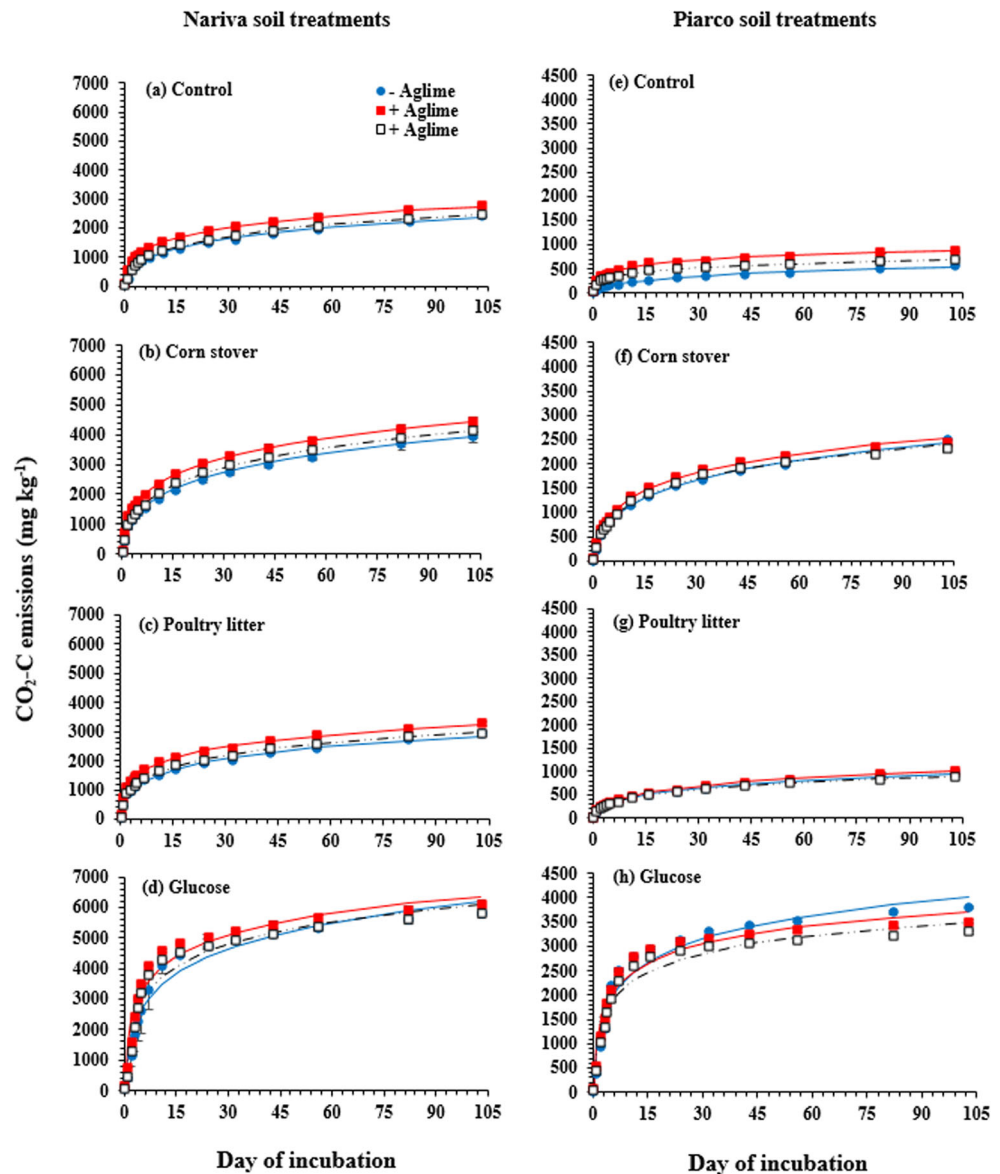
treatments. However, emissions were still detectable from the Piarco soil treatments even at the end of the incubation (103 DAI), where it accounted for as much as 5.77% of total CO_2 emission rates (Fig. 4d). The contribution of aglime-CO_2 to total CO_2 also fluctuated to a greater extent in the Piarco soil treatments (Fig. 4d).

The effect of organic residue on the aglime-CO_2 emission rates was very apparent in the Piarco soil (Fig. 4b). This source of variation significantly affected the emission rates from this soil for all sampling times except at 56, 82, and 103 DAI. In contrast, the effect of organic residue on the emission rates from the Nariva soil was only statistically significant between days 1 and 11 of incubation, where rates from the poultry litter treatment were significantly greater than that from all other treatments (Fig. 4a). On average, the emission rates from the Nariva soil ranged from 1.31 mg CO_2-C kg^{-1} h^{-1} (poultry

litter) to 1.44 mg CO_2-C kg^{-1} h^{-1} (glucose) with no significant differences being observed between organic residue means. The average emission rates in the Piarco soil, however, ranged from 0.150 to 0.639 mg CO_2-C kg^{-1} h^{-1} over the entire incubation in the order of glucose > control > corn stover > poultry litter (Fig. 4).

At the end of the incubation, cumulative aglime-CO_2 emissions ranged from 107 mg CO_2-C kg^{-1} (Piarco-poultry litter) to 205 mg CO_2-C kg^{-1} (Piarco-glucose) and 298 mg CO_2-C kg^{-1} (Nariva-control) to 309 mg CO_2-C kg^{-1} (Nariva-corn stover) for the Piarco and Nariva soil treatments, respectively (Fig. 5). These emissions did not differ across the organic residue treatments in the Nariva soil but the poultry litter treatment was significantly lower than all other organic treatments (where glucose = control = corn stover > poultry litter) for the Piarco soil (Fig. 5). The main effect of soil was also significant.

Table 2 $R^2_{adjusted}$ values and regression coefficients of quadratic logarithmic models relating cumulative total and organic-CO_2 emissions with incubation time

Treatments				Regression coefficients		
Soil	Organic residue	Aglime	R^2_{adj}	a	b	c
Nariva	Control	–	0.995	350[de]	247[g]	40.2[b]
Nariva[1]	Control	+	0.999	585[c]	319[ef]	31.1[c]
Nariva[2]	Control	+	0.998	350[de]	263[g]	41.5[b]
Nariva	Corn stover	–	0.998	523[c]	400[d]	71.6[a]
Nariva[1]	Corn stover	+	0.999	817[b]	498[bc]	60.8[a]
Nariva[2]	Corn stover	+	0.998	566[c]	440[c]	71.7[a]
Nariva	Poultry litter	–	0.996	521[c]	321[ef]	39.0b[c]
Nariva[1]	Poultry litter	+	0.999	779[b]	405[d]	27.1[cd]
Nariva[2]	Poultry litter	+	0.999	568[c]	346[de]	37.2[bc]
Nariva	Glucose	–	0.953	1060[ab]	919[ab]	39.6[b]
Nariva[1]	Glucose	+	0.947	1537[a]	1069[a]	− 6.52[h]
Nariva[2]	Glucose	+	0.940	1294[a]	1012[ab]	3.99[g]
Piarco	Control	–	0.991	50.1[i]	41.7[j]	13.2[f]
Piarco[1]	Control	+	0.999	241[f]	114[h]	4.66[g]
Piarco[2]	Control	+	0.998	164[g]	86.2[i]	6.02[g]
Piarco	Corn stover	–	0.997	294[e]	247[g]	45.8[b]
Piarco[1]	Corn stover	+	0.996	388[d]	281[fg]	39.5[bc]
Piarco[2]	Corn stover	+	0.996	327[de]	260[fg]	40.3[bc]
Piarco	Poultry litter	–	0.998	119[h]	87.8[i]	20.0[e]
Piarco[1]	Poultry litter	+	0.996	139[gh]	90.5[i]	20.7[de]
Piarco[2]	Poultry litter	+	0.999	128[h]	87.4[i]	17.0[ef]
Piarco	Glucose	–	0.952	863[ab]	671[ab]	1.37[g]
Piarco[1]	Glucose	+	0.949	996[ab]	663[ab]	− 17.7[h]
Piarco[2]	Glucose	+	0.945	890[ab]	622[ab]	− 13.2[h]

[1] Measurement represents total CO_2 emissions in aglime-amended soil treatments; [2] represents organic-CO_2 emissions in aglime-amended soil treatments; 0% aglime (−); 0.23% aglime (+). Coefficients of treatments within the same column that are followed by different letters are significantly ($p < 0.05$) different

There were also significant treatment effects on the pattern of increase in cumulative aglime-CO_2 emissions with incubation time (Fig. 5 and Table 3). The results of the curve-fitting analyses showed that a double exponential model best explained the relationship between these two parameters in the Nariva soil treatments. This was in divergence to the Piarco soil treatments where a quadratic logarithmic model was able to explain this relationship in all treatments except for Piarco-poultry litter (Fig. 5 and Table 3). Significant treatment effects were also observed on the coefficients generated from these models (Table 3).

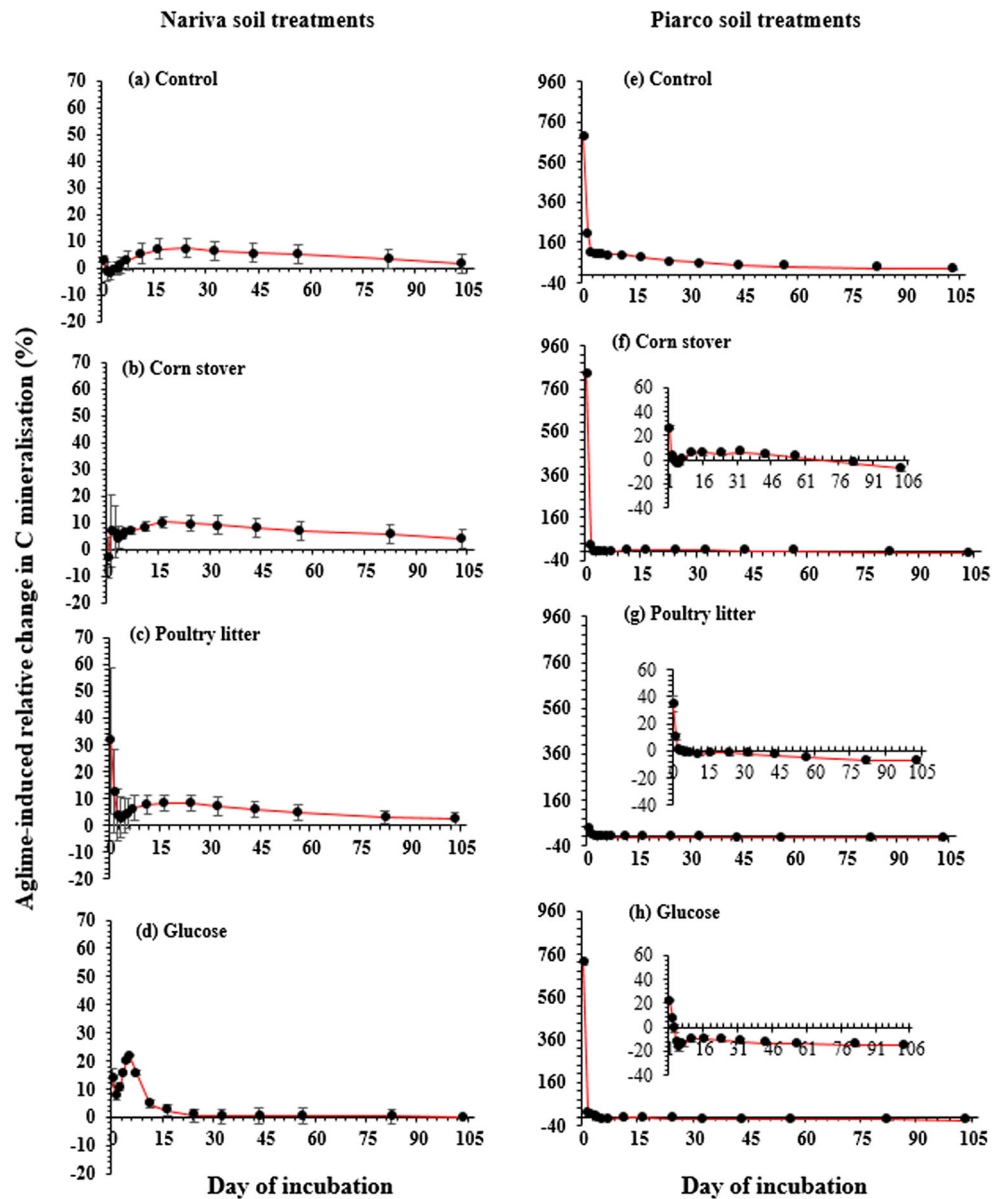### 3.4 Aglime emission factors

The aglime emission factor values were significantly affected by the interaction between soil, organic residue, and estimation method. The means of this interaction are presented in Table 4, which shows that the effect of the method of estimation on the emission factor values was dependent on the organic residue treatment for the Piarco soil but not the Nariva soil.

For the former soil, the greatest disparity in the emission factor values between the two methods of estimation was observed when glucose was applied, while the least was when poultry litter was applied (Table 4). These emission factor values were also significantly affected by all other sources of variation except for the main effect of estimation method (Table 4).

3.5 Soil pH

There were significant differences among soil treatments in the pH measured at 3 and 103 DAI, with the greatest change of 0.83 units being recorded in the Piarco-glucose treatment and the least (0.03) in the Nariva-control treatment (Table 5). At both times, soil pH was found to be significantly affected by the three-way interaction between soil, organic residue, and aglime (Table 5). While the pH of both soils increased significantly with liming, the magnitude of increase for the Piarco soil largely depended on the organic residue treatment (Table 5). The range in pH increase with liming in this soil was as much as 1.95 units at 3 DAI, which is almost 28 times

Fig. 3 Cumulative aglime-induced relative change in carbon mineralisation (AIRCICM) for the Nariva and Piarco soil treatments. The error bars represent one standard error for the means of the samples for each treatment at specific times. The bars are hidden when they are smaller than the symbol. f and h are magnified to more clearly display the trend in AIRCICM from 1 to 103 days after incubation (DAI) in treatments Piarco-corn stover and Piarco-glucose, respectively. g is magnified to more clearly display the trend in AIRCICM from 0.167 to 103 DAI in the Piarco-poultry litter treatment

4 Discussion

4.1 Organic residue and aglime effects on total and organic-CO_2 emissions

Cumulative total and organic-CO_2 emissions at the end of the incubation, averaged across organic residue, followed

greater than the range that was observed for the Nariva soil treatments (Table 5). This range in the change in pH was smallest when poultry litter was applied, and largest when no-organic residue was applied to this Piarco soil (Table 5). The effect of all other sources of variation was also statistically significant (Table 5).

the order glucose > corn stover > poultry litter > control for both soils, which is likely explained by the differences in the quantity and lability of C in the residues (Aye et al. 2017; Hossain et al. 2017). Glucose, being a monomer, is readily available to soil microorganisms and a flush in microbial respiration is always observed following its application (Shahbaz et al. 2017; Aye et al. 2018; Shahbaz et al. 2018). Respiration, however, quickly diminishes as this labile C source is depleted (Aye et al. 2018; Fig. 1; Table 2). Conversely, respiration is more sustained when substrates with more diverse C groups, such as corn stover, are applied (Aye et al. 2018), which accounts for the emissions in the latter stages of the incubation being greatest from soils amended with this residue (Fig. 1; Table 2).

Fig. 4 Aglime-CO_2 emission rates (a and b) and aglime-CO_2 contribution to total emission rates (c and d) for the Nariva and Piarco soil treatments. The double slash on the *x*-axis indicates a change in the scale. The error bars represent one standard error for the means of the samples for each treatment at specific times. The bars are hidden when they are smaller than the symbol
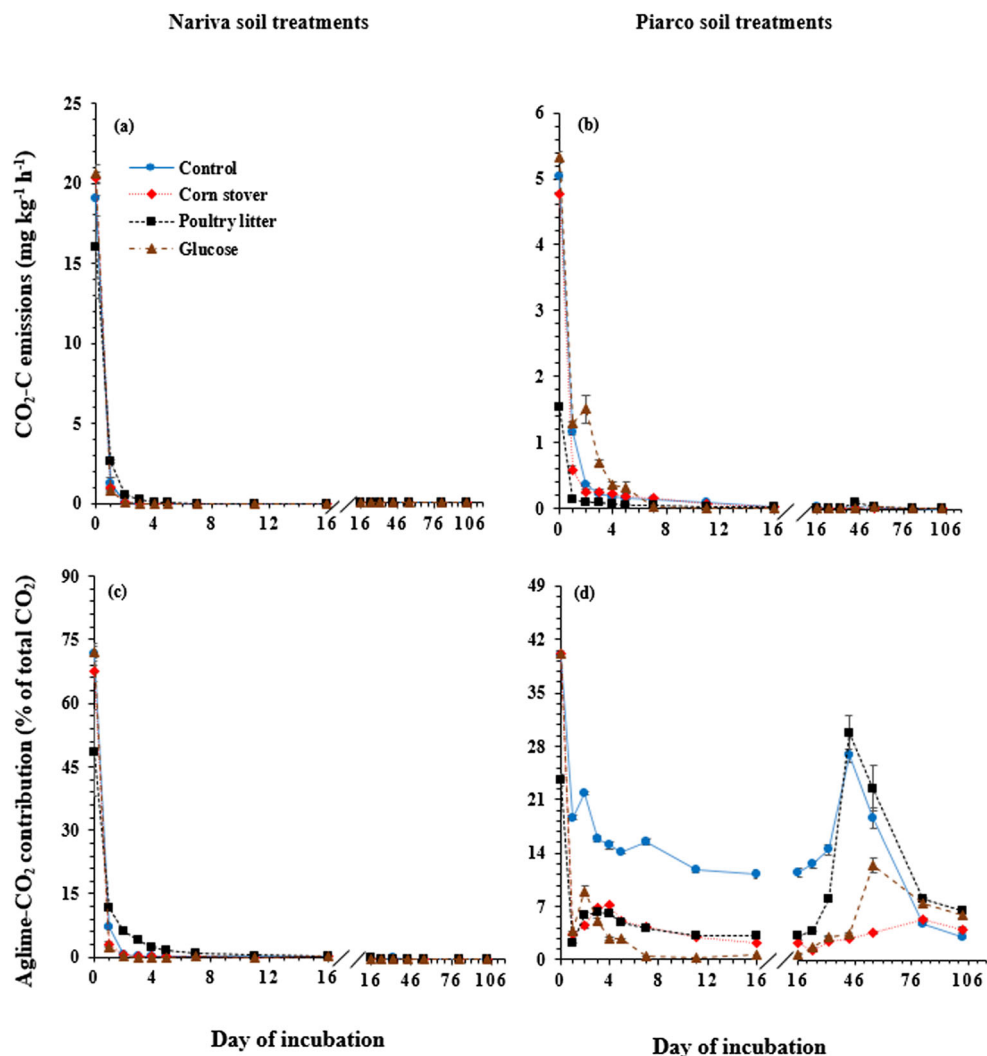
In agreement with our hypothesis, the magnitude of the aglime-induced priming effect on SOC decomposition in the no-organic residue-amended treatments was ~ 17 times greater in the coarse-textured Piarco soil compared with the fine-textured Nariva soil (Fig. 3). This can be explained by a greater capacity of the Nariva-clay soil to physically protect C (Badagliacca et al. 2017; Grover et al. 2017; Xu et al. 2019; Bramble et al. 2020) and shield decomposer microorganisms in the soil microsites against pH changes that may occur in the bulk soil solution (Grover et al. 2017; Bramble et al. 2020). In contrast, the hypothesis that the magnitude of the aglime-induced increase in mineralisation of C would be greatest when the most labile C substrate is applied was not supported. By the end of the 103-day incubation, the cumulative AIRCICM in the Nariva soil ranged from − 1.04 to 4.03% with no significant treatment effect being observed (Fig. 3). This further highlights the negligible influence of changes in soil pH on the mineralisation of C in this soil. Moreover, while organic residue addition influenced the magnitude of change in C mineralisation in the Piarco soil (Fig. 3), the direction of

this change was not congruent with our hypothesis. Our results showed that in contrast to the no-organic residue-amended Piarco soil, where there was a 27% increase in the AIRCICM with this soil, C mineralisation in the organic residue-amended soils decreased with the application of aglime (Fig. 3). This trend contrasts with recent observations by Aye et al. (2017) for which there are two plausible reasons. Firstly, the Ca^{2+} in the aglime could have helped to stabilise residue-C, thereby rendering it less accessible to the decomposer microorganisms (Muneer and Oades 1989a; Wachendorf 2015; Rowley et al. 2018). This mechanism of C stabilisation is more important in sandy soils with low aggregate stability such as Piarco (Wachendorf 2015). Secondly, soil microorganisms could have preferentially utilised residue-C instead of SOC (Blagodatskaya and Kuzyakov 2008; Blagodatskaya et al. 2011; Xu et al. 2019). This, when coupled with the possible increase in the microbial C-use efficiency in the limed soils (Pal et al. 2007; Grover et al. 2017), would have led to the overall reduction in C mineralisation. These hypotheses need to be validated in future experiments,

Fig. 5 Aglime-CO_2 cumulative emission for the Nariva and Piarco soil treatments. The error bars represent one standard error for the means of the samples for each treatment at specific times. The bars are hidden when they are smaller than the symbol. The data points are the observed values with a trend line
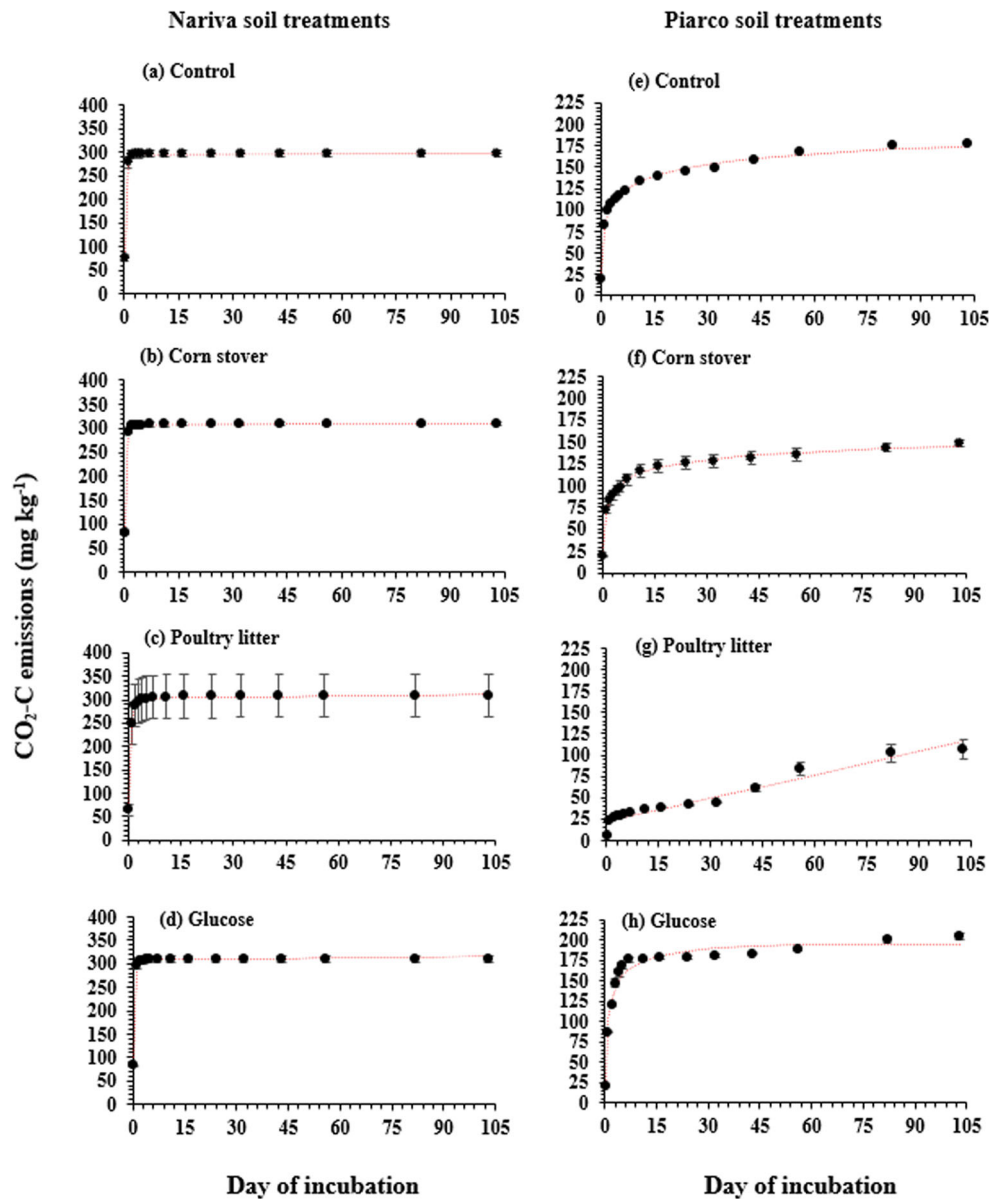
which would benefit from utilising both labelled and natural abundance aglime and organic residue so that the sources of CO_2 can be fully distinguished in treatments receiving these materials simultaneously. It will also be important to monitor changes in the soil microbial biomass C, as well as changes in the ^{13}C signature in the soil aggregates and the microbial biomass.

It is important to note that although the AIRCICM did not vary significantly across the glucose, corn stover, and poultry litter-amended Piarco soils by the end of the 103-day incubation (Fig. 3), it cannot be concluded that residue type will not affect the entire process. This is because in contrast to the glucose and poultry litter-amended soils, the AIRCICM values in the corn stover-amended treatment were generally positive over the incubation, which were at times significantly higher than that of the former treatments (Fig. 3).

4.2 Soil and organic residue effects on aglime-CO_2 emissions

The rate of aglime dissolution, as indicated by the release of CO_2 from aglime, was greater in the Nariva soil (Table 3; Figs. 4 and 5). This is likely explained by (1) the higher water holding capacity of the Nariva soil, as higher moisture content has been shown to increase carbonate solubility (Dumale et al. 2011; Dong et al. 2014; Lardner et al. 2015), and (2) the greater buffering capacity of this soil (Table 1).

For both soils, there was a dramatic decline in the contribution of aglime-CO_2 to total CO_2 emission rates after the first sampling time (Fig. 4c, d), which could have been due to a reduction in CO_2 originating from aglime and/or an increase in the contribution of CO_2 from organic C mineralisation. However, as aglime-CO_2 emission rates progressively

Table 3 $R^2_{adjusted}$ values and regression coefficients of double exponential, quadratic logarithmic, and simple linear models relating cumulative aglime-CO_2 emissions with incubation time

Treatments				Regression coefficients			
Soil	Organic residue	Model	R^2_{adj}	a	b	c	d
Nariva	Control	Double exponential	0.999	-366^b	-3.05^b	297^b	7.32×10^{-5a}
Nariva	Corn stover	Double exponential	0.999	-396^{bc}	-3.35^{bc}	308^a	6.03×10^{-5a}
Nariva	Poultry litter	Double exponential	0.998	-318^a	-1.73^a	303^a	2.56×10^{-4a}
Nariva	Glucose	Double exponential	0.999	-410^c	-3.57^c	308^a	6.59×10^{-5a}
Piarco	Control	Quadratic logarithmic	0.989	76.9^b	27.0^b	-1.29^a	na
Piarco	Corn stover	Quadratic logarithmic	0.993	66.7^c	23.0^c	-1.31^a	na
Piarco	Poultry litter	Simple linear	0.945	22.7	0.9	na	na
Piarco	Glucose	Quadratic logarithmic	0.962	103^a	40.0^a	-4.34^c	na

na, not applicable. Coefficients of treatments of the same model within the same column that are followed by different letters are significantly ($p < 0.05$) different

declined after the first sampling time in all treatments with the exception of Piarco-poultry litter, where there was a 335% increase between 32 and 43 DAI (Fig. 4b), the notable increases in the contribution of aglime-CO_2 emissions to total CO_2 emission rates that were observed in the Piarco soil treatments at 32–56 DAI (Fig. 4d) would have likely been mainly

because of a reduction in the quantity of CO_2 originating from organic C mineralisation.

There was strong evidence in the Piarco soil to support the hypothesis that aglime-CO_2 emissions are regulated by the synergistic effects of organic residue (Fig. 5). However, while cumulative organic-CO_2 emissions at the end of the 103-day

Table 4 Aglime emission factor values as affected the interaction between soil, organic residue, and estimation method

Treatments		Estimation method	
Soil	Organic residue	Isotopic (%)	Difference (%)
Nariva	Control	$108^{a\ AB}$	$121^{a\ AB}$
Nariva	Corn stover	$112^{a\ AB}$	$172^{a\ A}$
Nariva	Poultry litter	$112^{a\ AB}$	$129^{a\ AB}$
Nariva	Glucose	$112^{a\ AB}$	$107^{a\ AB}$
Piarco	Control	$64.2^{b\ ABC}$	$118^{a\ AB}$
Piarco	Corn stover	$53.9^{bc\ BC}$	$-12.0^{d\ CD}$
Piarco	Poultry litter	$38.7^{bc\ BC}$	$17.5^{cd\ BC}$
Piarco	Glucose	$74.4^{ab\ ABC}$	$-106^{e\ D}$
Significance			
Soil (S)		***	
Organic residue (OR)		*	
Estimation method (M)		ns	
S × OR		**	
S × M		**	
OR × M		**	
S × OR × M		**	

'*,' '**,' and '***' indicate significance at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively; *ns*, not significant ($p > 0.05$). Lowercase letters are used to compare means from the OR × M interactions for each soil when they were analysed by separate ANOVAs (i.e. when soil type was excluded as a factor). Means of the same soil that are followed by different lowercase letters are significantly ($p < 0.05$) different. Uppercase letters are used to compare means from the highest order (S × OR × M) interaction when soil type was included as a factor in the ANOVA. Means that are followed by different uppercase letters are significantly ($p < 0.05$) different

Table 5 Soil pH at 3 and 103 days after incubation as affected by the interaction between soil, organic residue, and aglime

Treatments		3 days after incubation		103 days after incubation	
		Aglime			
Soil	Organic residue	−	+	−	+
Nariva	Control	5.07[h]	5.62[f]	5.16[fg]	5.65[de]
Nariva	Corn stover	5.07[h]	5.66[f]	5.16[fg]	5.60[e]
Nariva	Poultry litter	5.59[f]	6.07[e]	5.7[de]	6.11[c]
Nariva	Glucose	4.82[i]	5.37[g]	5.11[g]	5.58[e]
Piarco	Control	5.16[h]	7.39[a]	5.27[f]	6.50[b]
Piarco	Corn stover	5.49[fg]	7.12[b]	5.61[e]	6.76[a]
Piarco	Poultry litter	6.74[c]	7.02[b]	5.75[d]	6.44[b]
Piarco	Glucose	4.87[i]	6.26[d]	5.70[de]	6.70[a]
Significance					
Soil (S)		***		***	
Organic residue (OR)		***		***	
Aglime (L)		***		***	
S × OR		***		***	
S × L		***		***	
OR × L		***		***	
S × OR ×L		***		***	

0% aglime (−); 0.23% aglime (+). '***' indicates significance at $p < 0.001$. Means of the same day that are followed by different letters are significantly ($p < 0.05$) different

incubation were in the order of Piarco-glucose + aglime > Piarco-corns stover + aglime > Piarco poultry litter + aglime > Piarco-control + aglime, cumulative aglime-CO_2 emissions were in the order of Piarco-glucose = Piarco-control = Piarco-corn stover > Piarco-poultry litter (Figs. 2 and 5, respectively). Therefore, the other hypothesis—that the magnitude of aglime-CO_2 emissions would decrease as more organic C is mineralised—was not supported. Our results further showed that the rate of aglime-CO_2 emissions decreased with the application of poultry litter and corn stover but increased with the application of glucose to the Piarco soil (Fig. 4b; Table 3). There are two alternative hypotheses that can explain these results. Firstly, organic residues can reduce the soil pH, in turn leading to an increase in aglime dissolution and the release of aglime-CO_2 emissions (Bertrand et al. 2007). Secondly, some organic residues can instead increase the soil pH, in turn leading to a decrease in aglime dissolution and the reduction in aglime-CO_2 emissions (Ahmad et al. 2014). Our results provide some support for both of these hypotheses as the pattern of aglime-CO_2 emissions seemed to be related to the organic residue-induced changes in soil pH, especially at the earlier stage of incubation where aglime dissolution was greatest (Table 5 and Fig. 4b, respectively). It is, however, acknowledged that monitoring the temporal changes in soil pH would help to establish a better relationship between soil pH and these emissions. Moreover, accounting for soil processes that generate alkalinity and acidity would also be paramount to

elucidating these effects, since pH alone can be misleading. In fact, our own pH data emphasise this point (Table 5), where pH in the non-limed Piarco soil treatments were in the order of poultry litter > corn stover > control > glucose at 3 DAI, while those of the limed soils followed the order control > corn stover = poultry litter > glucose. This is suggestive of a competing effect between the organic residues and the aglime for H^+, which should be considered when these amendments are applied in combination.

Cumulative aglime-CO_2 emissions at the end of the incubation did not significantly differ among organic residue treatments in the Nariva soil (Fig. 5). Nevertheless, the emission rates and regression models demonstrated a significant effect of the poultry litter and glucose in this soil (Fig. 4a and Table 3). The initial slope in the double exponential model was negative for all organic residue treatments, which indicates that aglime-CO_2 emissions increased at a diminishing rate (Table 3). The rate of reduction was, however, significantly faster in the glucose treatment and slower in the poultry litter treatment in comparison with the control. This implies that the rate of aglime dissolution was enhanced by glucose addition but slowed when poultry litter was applied (Table 3). These results are likely attributed to the reasons aforementioned, although they were not as apparent in this soil because of a more rapid solubilisation of the aglime compared with the Piarco soil.

4.3 Comparison of emission factor values

The emission factor values for the Nariva soil treatments were generally significantly greater than those of the Piarco soil for both methods of estimation (Table 4). The higher emission factor values in the Nariva may be partly due to the fact that all of the aglime-C was estimated to be released as CO_2 in these treatments over the course of the incubation, while there was still evidence of aglime emissions from the Piarco soil treatments—whose emissions were much lower than the Nariva treatments during the early stages of the incubation—even at 103 DAI (Figs. 5 and 4, respectively). These are conservative estimates of direct emissions from aglime since the brief incubation times—particularly in the initial stages of the incubation—may increase the degree of uncertainty of our estimates by linear interpolation. This would have likely been the case with the Nariva soil, where aglime-CO_2 emissions were immediate and short-lived, and could explain why the emission factor values that were generated using the isotopic method were above 100% (Table 4). Indeed, keeping the incubation vessels closed for longer periods would help to reduce this uncertainty. However, analytical error must also be considered given that Ahmad et al. (2014) also reported an emission factor value slightly above 100% although the mason jars in their study were kept closed with alkali traps for the majority of the 96-day incubation. Note, however, that this limitation does not negate the comparisons that can be made between the treatments in the current study, which is core to meeting our objectives.

As predicted, the emission factor values differed between the two estimation methods for each soil treatment, but while this was statistically significant for most of the organic residue treatments in the Piarco soil, the differences in the Nariva soil were not (Table 4), which is likely attributed to the relatively large variability between the replicates of the difference method treatments of the latter soil. Nevertheless, there was a greater disparity in the emission factor values between the two estimation methods for the Piarco soil (Table 4), which could be explained by a greater influence of the interactive effects of aglime and organic residues on aglime-CO_2 emissions and C mineralisation in this soil compared with the Nariva soil. The methodology that is currently used by the IPCC to calculate CO_2 emission factors for liming does not consider aglime-induced changes in C mineralisation (De Klein et al. 2006), which may contribute to inaccuracies in these estimates (Lochon et al. 2018). Our results suggest that current inventory approaches can significantly overestimate- or under-estimate the global warming effect associated with liming if aglime-induced changes in C mineralisation are not considered. These effects should, therefore, be further investigated on a wider range of soil types and climatic conditions so that a more robust methodology can be developed.

5 Conclusions

Our study demonstrated a significant interactive effect of organic residue and aglime on the mineralisation of C in the low fertility and low C Piarco soil, but not in the high fertility and high C Nariva soil due to negligible aglime-induced priming effects in the latter. The mineralisation of C in the Piarco soil increased by 27% with aglime addition to the no-organic residue treatment but decreased by as much as 13.2% when applied to soils amended with organic residues, alluding to an enhanced stabilisation of C when organic residue and aglime are simultaneously applied. These findings, therefore, emphasise the need to consider organic residue management practices when assessing the global warming effect associated with the usage of aglime.

Our study also showed—possibly for the first time—that direct CO_2 emissions from aglime are regulated by organic residues. The application of these residues either increased or decreased the rate at which CO_2 was released from aglime, particularly in the low buffering Piarco soil. This effect was likely related to the organic residue-induced changes in soil pH. Hence, further work should explore the mechanism(s) underlying these pH changes to ascertain a better understanding of the key processes controlling the dynamics of aglime-C in acid soils.

Compliance with ethical standards

The authors declare that they have no conflict of interest. The research did not involve human participants and/or animals.

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