An assessment of factors controlling N₂O and CO₂ emissions from crop residues using different measurement approaches

Giuseppe Badagliacca¹ · Paolo Ruisi¹ · Robert M. Rees² · Sergio Saia¹,³

Abstract  Management of plant residues plays an important role in maintaining soil quality and nutrient availability for plants and microbes. However, there is considerable uncertainty regarding the factors controlling residue decomposition and their effects on greenhouse gas (GHG) emissions from the soil. This uncertainty is created both by the complexity of the processes involved and limitations in the methodologies commonly used to quantify GHG emissions. We therefore investigated the addition of two soil residues (durum wheat and faba bean) with similar C/N ratios but contrasting fibres, lignin and cellulose contents on nutrient dynamics and GHG emission from two contrasting soils: a low-soil organic carbon (SOC), high pH clay soil (Chromic Haploxerert) and a high-SOC, low pH sandy-loam soil (Eutric Cambisol). In addition, we compared the effectiveness of the use of an infrared gas analyser (IRGA) and a photoacoustic gas analyser (PGA) to measure GHG emissions with more conventional gas chromatography (GC). There was a strong correlation between the different measurement techniques which strengthens the case for the use of continuous measurement approaches involving IRGA and PGA analyses in studies of this type. The unamended Cambisol released 286% more CO₂ and 30% more N₂O than the Haploxerert. Addition of plant residues increased CO₂ emissions more in the Haploxerert than Cambisol and N₂O emission more in the Cambisol than in the Haploxerert. This may have been a consequence of the high N stabilization efficiency of the Haploxerert resulting from its high pH and the effect of the clay on mineralization of native organic matter. These results have implication management of plant residues in different soil types.

Keywords  Crop residues · Carbon dioxide · Greenhouse gas · Nitrous oxide · Residue decomposition

Introduction

Agriculture forestry and related land uses are responsible for just under 25% of global greenhouse gas emissions (IPCC 2014). Agronomic practices are recognized as key opportunities to reduce greenhouse gas (GHG) emissions (particularly for N₂O and CO₂). The addition of plant residues to the soil from crops and cover crops is of significant importance to crop management strategies to enhance soil organic C (SOC) and soil fertility and to offset agricultural GHG emissions (Lugato et al. 2014). However, decomposition of residues will also add nitrogen (N) to the soil, and with the default N₂O emission factor of 1% of the added N in the IPCC (2006) methodology, a proportional increase in estimated N₂O emissions is predicted. However, IPCC predictions have been developed around limited experimental data and recent studies indicate that default emission factors may overestimate residue N₂O emissions (Jeuffroy et al. 2013). GHG emission after crop residue amendment is related to both its decomposition and the microbial activity of soil and depends from several factors linked to the environment, soil properties and crop residue traits (Aulakh et al. 1991; Powlson et al. 2011). In particular, the GHG emission from the soil is mediated by soil porosity (Killham et al. 1993), pH (Mørkved et al. 2006), organic C
and N content (Hayakawa et al. 2009), microbial community (Graf et al. 2016), texture (Chen et al. 2013), soil temperature (Kesik et al. 2006) and moisture content, all of which regulate gas production processes and emission (Skiba and Ball 2002; Rees et al. 2013). Moreover, crop residue addition to the soil can also indirectly affect GHG emissions, providing a source of readily available C and N in the soil, stimulating microbial activity (Aulakh et al. 2001; Huang et al. 2004), promoting the decomposition of native SOC and altering soil aeration, water holding capacity, oxidation and denitrification processes in the soil (Fontaine et al. 2004; Derrien et al. 2014).

With regard to the crop residue characteristics, the most important property is its C/N ratio that determines organic N dynamics in the soil (Heal et al. 1997; Baggs et al. 2003; Al-Kaisi and Yin 2005; Garcia-Ruiz and Baggs 2007). In particular, it has been shown that higher N\textsubscript{2}O emissions occur from soil after the incorporation of residues with low C/N ratio, such as legumes, rather than after cereal straw as a result of mineralization processes (Baggs et al. 2000; Huang et al. 2004; Raiesi 2006). On the contrary, low N\textsubscript{2}O emissions were reported following the application of crop residues with high C/N ratios (Gentile et al. 2008). However, it has also been shown that the incorporation of crop residues with high C/N ratios may provide the energy for the denitrification process, and this can increase N\textsubscript{2}O emissions (Sarkodie-Addo et al. 2003). Other crop residue properties can play an important role on the decomposition process influencing microbial activity, including lignin (Palm and Rowland 1997), lignin/N ratios (Curtil et al. 1998) polyphenol (Muhammad et al. 2010), water-soluble phenolic contents (Palm and Rowland 1997), percentages of soluble C and N (Cogle et al. 1989) and neutral detergent fibre (NDF). This understanding of the multiple drivers responsible for GHG emissions from crop residues is helpful in interpreting research findings. Baggs et al. (2000) found an increase of N\textsubscript{2}O emissions after lettuce incorporation into the soil due to its low C/N ratio. However, Tanveer et al. (2014) and Zou et al. (2004) observed a reduction of N\textsubscript{2}O emission after incorporation of low C/N crop residue of corn and rice straw. This apparent contradiction may be a consequence of the interaction of multiple factors controlling emission. Shan and Yan (2013), in a meta-analysis, reported that the application of canola, bean and lettuce residues increased N\textsubscript{2}O emissions more than with other kinds of crop residues. With regard to CO\textsubscript{2} emissions, Muhammad et al. (2010) observed higher emissions in soil amended with alfalfa than with sugarcane, maize, sorghum and cotton and attributed such result to a release of more easily degradable and soluble C in alfalfa than with other crop residues. Chen et al. (2015) observed a general increase of CO\textsubscript{2} emissions from a soil amended with different types of residues but with higher cumulative emissions in peanuts, soybean and maize than in other cereals due to their higher N and lower NDF content.

An accurate quantification of CO\textsubscript{2} and N\textsubscript{2}O emission following return of crop residues to soils is required to develop efficient strategies to reduce the environmental impact of farming practices. Presently, static chamber methods coupled with gas chromatography (GC) analysis are the most widely technique used to quantify N\textsubscript{2}O losses in field and laboratory experiments. However, the method is time consuming and entails a wide series of operations from the manual sampling to the laboratory analysis, introducing errors and making difficult to implement high-resolution monitoring over time (Tirol-Padre et al. 2014). In order to obtain high-resolution temporal data, infrared gas analyser (IRGA) and photoacoustic gas analyser (PGA) have been used in agricultural GHG emission studies (Luo and Zhou 2006; Lawrence et al. 2009; Stackhouse et al. 2011). IRGA allows to measure CO\textsubscript{2} fluxes using an infrared sensor, and PGA is a photoacoustic infrared multi-gas monitoring system that allows to measure simultaneously CO\textsubscript{2}, N\textsubscript{2}O and CH\textsubscript{4}. Measurement of CO\textsubscript{2} efflux by IRGA systems is usually based on different methodologies proposed by the manufacturing companies, and there is not an internationally recognized protocol creating uncertainties in the comparison between different instruments (Mills et al. 2011). PGA has been widely used in field experiments, and several authors found a high correlation between CO\textsubscript{2} and N\textsubscript{2}O measurements made with PGA and GC (De Klein et al. 2008; Iqbal et al. 2013). Other authors reported an overestimation of emission on the data obtained with PGA than GC (Yamulki and Jarvis 1999). Furthermore, the precision of measurement may also depend from the soil type and soil cover, which can affect the assessment of emission spatial variability. The precision of the various instruments (IRGA and PGA compared to the widely used CG) in measuring GHG emission has never been measured. However, in contrast to the GC-based methodology, these systems are able to provide a continuous measurement of the GHG emission, thus allowing to better study the trend of the emission from the soil and its relationship with agronomical management techniques and environmental variability. In addition, IRGA and PGA have not been previously directly compared.

Soil GHG emissions from Cambisols which occur widely in cool temperate climates have widely studied in the past whereas the effect of soil characteristics typical of the Mediterranean such as Vertisols, with their high clay content high pH and low organic carbon content, on crop residue decomposition and gaseous emissions is less known. The aims of the present study were (i) to evaluate the short-term emissions of N\textsubscript{2}O and CO\textsubscript{2} after the addition of two crop residues with different structural fibre compositions (either faba bean and wheat), in two soils with contrasting proprieties, a Chromic Haploxerert with a high clay content and a Eutric Cambisol with a sandy-loam texture and (ii) assess the flexibility of two systems for the high temporal resolution measurements (IRGA and PGA), to measure soil GHG emissions from soils with different emission levels in controlled conditions. Experiments were undertaken in a controlled pot setup over a short period and in the absence of plants in order to
simulate the effects of crop residues between cropping cycles. These conditions avoided strong time-related variation in the emission due to the impoverishment of the ready available N pool and living plant C inputs to and mineral uptake from soil, which could have altered the emission rates.

**Materials and methods**

An experiment was established during 2014 in controlled environment conditions at Scotland’s Rural College (SRUC) Edinburgh. A complete randomized factorial design with three replicates was adopted. Treatments were soil Eutric Cambisol and Chromic Haploxerert (Vertisol) and the kinds of plant residue added were as follows: faba bean residue, durum wheat residue or unamended control. The Cambisol was collected at nine locations per plot from the top 20 cm at Bush Estate (lat, 55° 51’ N, long, 3° 12’ W; 199 m a.s.l.) near Edinburgh (Scotland); the Haploxerert (Vertisol) was collected at the Pietranera farm (37° 30’ N, 13° 31’ E; 178 m a.s.l.) in Santo Stefano Quisquina (Sicily). Both soils were sampled in early October 2014. Soil was collected from conventional tilled experimental plots at the Bush Estate in Scotland and from conventionally tilled plots at Pietranera farm in Sicily (Table 1). At both sites, the soil was collected in plots previously cultivated with cereals (wheat in Sicily and barley in Scotland). Further information regarding the soil sampling sites is available in Vinten et al. (1992) and Amato et al. (2013), respectively. Before establishing the experiment, soil was air-dried and passed through a 2-mm mesh and visible roots and organic residues were removed and then mixed thoroughly before use; water holding capacity of both soils was measured on a weight basis. Oven-dried crop biomass of wheat (cv. Simeto) and faba bean (cv. Gemini) (see Table 2 residues traits), cultivated at Pietranera farm, was ground to pass a 1-mm screen, mixed and used as crop residues. Pots were 10 cm in diameter and 25-cm height and were filled with 1.5 kg of soil to achieve a bulk density of 1.25 g cm$^{-3}$. Crop residues were mixed with the soil at a rate of 5 g crop residue per kilogram of soil. The bottom part of the pot (15–25-cm depth) was filled with sand. Then, pots were brought to 60–70% of the water holding capacity. After each sampling, an amount of water corresponding to the evaporation losses was added to each pot and the pots were randomized inside the greenhouse. During the experiment, soil temperature was recorded using a temperature data logger (EL-USB-3, Lascar Electronics, UK).

Both CO$_2$ and N$_2$O soil emissions were measured three times per week, on 22 sampling occasions, by means of two different methods: an online infrared gas analyser (IRGA, EGM-4 CO$_2$, PP system, USA) and a photoacoustic gas analyser (PGA, INNOVA 1412, LumaSense Technologies A/S, USA). Measurements were always taken between the 9:00 and the

| Soil properties           | Scotland bush estate | Sicily Pietranera               |
|--------------------------|----------------------|---------------------------------|
| Soil classification       | Eutric Cambisol      | Chromic Haploxerert (Vertisol)  |
| Soil series               | Macmerry             | Gessoso-Solfifera (sulphurous-chalky) |
| Texture                   | Sandy-loam           | Clay-loam                       |
| Coordinates               | 55.9 N, 3.2 W        | 37.3 N, 13.3 W                  |
| Altitude                  | 199                  | 178                             |
| Slope (%)                 | 6                    | 7                               |
| Clay (%)                  | 12.7                 | 52.5                            |
| Silt (%)                  | 15.7                 | 21.6                            |
| Sand (%)                  | 71.6                 | 25.9                            |
| pH                        | 6.6                  | 8.1                             |
| Field capacity (pF 2.5) (%)| 36                   | 38                              |
| Permanent wilting point (pF 4.5) (%)| 20            | 16                              |
| Organic matter (%)        | 4.3                  | 2.4                             |
| Total N (%)               | 0.21                 | 0.13                            |

---

Table 2 Composition of crop residues

| Chemical properties of crop residues | Faba bean | Durum wheat |
|-------------------------------------|-----------|-------------|
| Organic matter (%)                 | 91.8      | 92.1        |
| N content (%)                       | 1.4       | 1.3         |
| Crude protein (%)                   | 8.8       | 8.1         |
| Ether extract (%)                   | 1.1       | 1.7         |
| Acid detergent fibre (ADF) (%)      | 48.0      | 28.8        |
| Acid detergent lignin (ADL) (%)     | 10.0      | 3.5         |
| Cellulose (%)                       | 38        | 25.3        |
| Neutral detergent fibre (NDF) (%)   | 54.0      | 45.4        |
| Hemicellulose (%)                   | 6         | 16.6        |
| Ash (%)                             | 8.2       | 7.9         |
| ADL ash (%)                         | 0.4       | 3.2         |
15:00, and each time, the equipment order was reversed. The IRGA was equipped with a SRC-1 soil respiration chamber equipped with a fan, with of 10 cm of diameter and 15-cm height, sealed on top of the pot by an airtight rubber. The air from the chamber was send to the analyser at a flow rate of 0.11 min⁻¹. After 15 s of flushing, the chamber was placed above the pot, equilibrated for 15 s, then the CO₂ concentration was measured every 5 s and the flux was calculated from the concentration increase over time until a good linear fit was obtained.

The PGA was equipped with a PVC chamber with 10 cm of diameter and 10 cm height, connected to the equipment by two small rubber pipes on the chamber top, and sealed above the pot by a rubber seal. The analyser automatically pumped ~0.11 min⁻¹ of air from inside the chambers and performed the analysis with a 5-s sampling integration time and a fixed flushing time of 8 s for the chamber and 3 s for the tubing. The PGA instrument was calibrated in the lab for CO₂ and N₂O by the LumaSense technologies company, with a gas concentration of 3496.8 ppm for CO₂ and 51.32 ppm for N₂O, and its detection limits were 1.5 ppm for CO₂ and 0.03 ppm for N₂O. The equipment performed a built-in compensation for water and cross interferences. Before the flux measurements, the instrument analysed ambient air for about 30 min until readings for CO₂ and N₂O were stable. The overall time for sampling and measurement of CO₂ and N₂O concentration and dew-point temperature was approximately 70 s; each measurement was made every 2 min.

Gas flux measurement (CO₂ from both IRGA and PGA and N₂O from PGA), in two different periods during the experiment, was compared with analyses by GC in order to confirm the reliability of the instruments. CO₂ and N₂O emissions were measured using the static closed chamber technique (Hutchinson and Mosier 1981). A chamber of polyvinyl chloride (PVC) with 10 cm of diameter and 15-cm height and a lid with a gas sampling port was sealed above each pot for 60 min. Before and after this period, gas samples were collected in portable evacuated glass vials (Chadwick et al. 2014), transported to the lab and analysed by a GC (Agilent 7890a, Agilent Technologies Ltd., Stockport, UK) equipped with a thermal conductivity detector (TCD, detection limit for CO₂ of 23.9 ppm) and an electron capture detector (ECD, detection limit for N₂O of 0.074 ppm). Fluxes of CO₂ and N₂O were calculated from the increase in concentration in the chamber corrected for the chamber air temperature using the following relation (Jantalia et al. 2012):

\[
f = \frac{\Delta C}{\Delta t} \times \frac{V}{A} \times \frac{m}{V_{m}}
\]

where \(\Delta C/\Delta t\) is the gas increment during the chamber closure time, \(V\) is the volume of the chamber, \(A\) is the soil area, \(m\) is the molecular weight of the gases, and \(V_{m}\) is the gas molar volume corrected for the ambient temperature.

The total amounts of N₂O and CO₂ emissions were calculated by linear interpolation between consecutive using the following equation (Cai et al. 2012):

Cumulative emission of N₂O or CO₂

\[
F_i = \sum_{i=1}^{n} \left( \frac{F_i + F_{i+1}}{2} \times (t_{i+1} - t_i) \right) \times 24
\]

where \(F\) is the emission flow of N₂O and CO₂ at the \(i\)th measurement, \((t_{i+1} - t_i)\) is the time length between two adjacent measurements, and \(n\) is the total measurement number.

Plant dry matter (oven drying), ether extract (Method 920.39, diethyl ether, traditional Soxhlet extraction), total N (Kjeldahl) and crude protein (calculated from the total N by standard Jones factor, \(N \times 6.25\)) were analysed following methods described by AOAC (1995). NDF, acid detergent fibre (ADF), acid detergent lignin (ADL), cellulose and hemicellulose were analysed following the sequential method proposed by Van Soest et al. (1991) and using a Fibertec System M 1020 extractor (Foss, Hóganás). The soluble fraction was obtained by boiling 1 g of ground residues in deionized water (100 °C) for 30 min followed by extraction with a neutral detergent (EDTA and Na lauryl sulphate at 100 °C) for 60 min to obtain the NDF fraction. ADF extraction was performed by boiling the sample for 60 min in an acid detergent solution (cetyltrimethylammonium (CTAB) in H₂SO₄). Then, the residual detergent was removed by washing the sample with hot water. Finally, the ADF was then treated with 72% H₂SO₄ (w/w) for 3 h at ambient temperature and the final mass of the non-extractable fraction was considered as lignin (ADL). Cellulose was calculated as the difference between ADF and ADL while hemicellulose as the difference between NDF and ADF. Ash and ADL ash measurements were performed at 550 °C for 4 h. For each residue type, the analyses were performed in triplicate. Total C of biomasses and soils was analysed by an automated analyser (Flash 2000, Thermo Finnigan, Glasgow, UK).

At the end of the experiment, two soil samples from each pot were collected: one from the top to 5-cm depth and the other from 5- to 15-cm depth. Soil pH was measured in a 1:5 (v/v) suspension of soil in water. Dissolved organic C (DOC) content in the soil was determined by a total organic C analyser (DC-80, Rosemount Analytical, Inc. Dohrmann Division, USA) after the removal of inorganic C by acidifying the sample. Concentrations of NH₄⁺-N and NO₃⁻-N were determined from 10 g of soil extracted with 100 ml of 2 M KCl (1:5 ratio); then, the filtered extract NH₄⁺-N and NO₃⁻-N concentrations were measured by a continuous flow analysis autoanlyser (SAN SYSTEM, Skalar Analytical B.V., Netherlands).
Analysis of variance (ANOVA) was undertaken using a mixed model according to the statistical design in SAS environment (SAS Institute 2008). Treatment means were separated using \( p \) differences of the LSMEANS. Regressions between GC and IRGA, and GC and PGA, for \( CO_2 \), and for \( CO_2 \) and \( N_2O \), respectively, were computed. Soil \( CO_2 \) emission rate measurements from IRGA and PGA were compared on the 22 sampling occasions. Comparisons were made by a regression analysis and the index of agreement (IoAd) (SAS Institute 2008; Bennett et al. 2013).

**Results**

The temperature inside the greenhouse during the experiment ranged from a minimum of 17 °C to the maximum of 28.5 °C, with an average of 20.5 °C, while soil temperature ranged from a maximum of 27 °C to a minimum of 20 °C with a slight decreasing trend from the start to the end of the experiment (Fig. 1). The chemical composition of the plant residues used in the present study, expressed as percentages, are reported in Table 2. The N contents of faba bean and durum wheat were comparable (1.4 vs 1.3%, respectively). With regard to the other constituents, marked differences were found between the plant residues. In particular, faba bean had higher ADF (+66%), ADL (+186%), cellulose (+60%) and NDF (+19%) than wheat and a lower content of hemicellulose (−51%) (Table 2).

**Carbon and nitrogen dynamics**

The Haploxerert used in the present study had a high pH (8.1) and high clay and low total C content (1.39%), whereas the Cambisol had a near neutral (6.6), low clay and high C content (2.48%). Interaction between soil and residue type for these soil properties by the end of the experiment was strong and significant (\( p < 0.05 \)) (Table 3). As expected, the addition of organic residues mostly increased DOC in both the top and sub-soil layers of the Haploxerert (on average by 52.5% compared to unamended control), whereas there was no significant effect on the Cambisol.

The soil incubation, either with or without plant residue incorporation, decreased soil pH by 0.86 in the Cambisol and 0.33 in the Haploxerert. The effect of the addition of organic residues to the soil pH varied with both the soil and kind of biomass incorporated: in the Cambisol, addition of wheat residues significantly decreased pH in the top and sub-layers when compared with the unamended control whereas addition of faba bean residues did not influence soil pH. In the Haploxerert, no effects of the addition of organic residues on soil pH were found in both soil layers.

The concentration of \( NH_4^+ \)-N was higher in the Haploxerert than Cambisol, and this is particularly apparent in the sub-layer. The role of the addition of organic residues on soil \( NH_4^+ \)-N depended on the soil and kind of biomass added: addition of durum wheat residues increased soil ammonium-N in top layer of both soils (+40% in the Cambisol and +102% in the Haploxerert), whereas \( NH_4^+ \)-N in the soils amended with faba bean residues was similar to those of the controls. In the sub-layer of the Cambisol, the effect of the addition of the organic residues was similar to that observed in the top layer, whereas the addition of both residues strongly increased the \( NH_4^+ \)-N of Haploxerert compared to the unamended control (+133% in faba bean and +454% in wheat residues).

The concentration of \( NO_3^- \)-N in both layers was significantly higher in the Cambisol when compared with the
Haploxerert, and this occurred irrespective of the addition of organic residues. In the Cambisol, addition of faba bean residues reduced NO$_3^-$-N more than wheat residues, especially in the sub-layer, when compared with the unamended control. In the Haploxerert, NO$_3^-$-N in both layers did not vary with the addition of plant residues.

NH$_4^+$-N/NO$_3^-$-N ratio differed considerably in the different soil types: in the unamended controls, it was 6.467 in the Haploxerert and 0.006 in the Cambisol. In the latter, addition of organic residues to the soil did not influence the NH$_4^+$-N/NO$_3^-$-N of either the top or sub-layer. In the top layer of Haploxerert, the addition of organic residues reduced the NH$_4^+$-N/NO$_3^-$-N ratio, especially when faba bean residues were added. In the sub-layer, an opposite result was found, and thus, addition of organic residues increased the NH$_4^+$-N/NO$_3^-$-N ratio, especially when wheat residues were added.

### Greenhouse gas emissions

Carbon dioxide fluxes, measured with IRGA, ranged from a minimum value of 0.11 g m$^{-2}$ h$^{-1}$ to a maximum value of 3.64 g m$^{-2}$ h$^{-1}$ (Fig. 2). For almost the entire experimental period, the Cambisol had a higher CO$_2$ emission flux than the Haploxerert. At the beginning of the experiment, the two soils reached the maximum emission flux at the first and second days of measurement with fluxes of 3.58 g m$^{-2}$ h$^{-1}$ for the Cambisol and 1.42 g m$^{-2}$ h$^{-1}$ for the Haploxerert.

The highest CO$_2$ fluxes were recorded in both soils amended with wheat straw whereas the lowest in the unamended controls. The differences in emission between the two soils were strong in the first 2 weeks of measurement, where the 53.8 and 46.2% of total CO$_2$ were emitted from the Cambisol and the Haploxerert, respectively. After the first 2 weeks of measurement, the differences between the two soils reduced and the emission decreased until the end of the experimental period.

The CO$_2$ emissions measured with PGA showed a similar trend to those acquired by IRGA. However, in the first part of the experimental period, PGA emissions were slightly higher than those observed by the IRGA, especially from the Cambisol. In the second part of the experiment, no differences between the techniques were found (Fig. 3).

Total CO$_2$ emissions were 74% lower in the unamended Haploxerert (198 g CO$_2$ m$^{-2}$) compared to the Cambisol (765 g CO$_2$ m$^{-2}$). Addition of plant residues to the soil increased total emission to a different extent depending on the soil under study (interaction soil × residue type significant $p < 0.001$): in the Cambisol, addition of faba bean and wheat resulted in an increase of 24 and 88%, respectively, of the total CO$_2$ emissions. In the Haploxerert, no differences were found between the kinds of biomass incorporated, which, on average, increased total CO$_2$ emission by 171% compared to the unamended control (Fig. 4).

Emissions of N$_2$O during the experiment ranged from 0.022 to 0.348 mg m$^{-2}$ h$^{-1}$ (Fig. 5). However, there were large differences between soils with emissions of 0.024 to 0.117 mg m$^{-2}$ h$^{-1}$ and from 0.022 to 0.348 mg m$^{-2}$ h$^{-1}$ in the Haploxerert and Cambisol, respectively. The Cambisol reached a N$_2$O emission peak at 7 days after the beginning of the experiment, whereas the Haploxerert soil showed a continuous and constant reduction of the N$_2$O emission from the beginning of the experiment until the end of the trial. In addition, marked differences between amended and unamended soil were observed in Cambisol during the first half of the experiment. The highest fluxes were measured in both soils amended with wheat straw. Cumulative N$_2$O emission in the

### Table 3  Effect of the addition of two crop residues (durum wheat or faba bean, and unamended control) on dissolved organic C (DOC), pH, NH$_4^+$-N and NO$_3^-$-N content and NH$_4^+$-N/NO$_3^-$-N ratios in 0–5- and 5–15-cm soil layers of Chromic Haploxerert and Eutric Cambisol soils

| Soil Type          | Effect of residue type | pH    | DOC mg C kg$^{-1}$ soil | NH$_4^+$-N mg N kg$^{-1}$ soil | NO$_3^-$-N mg N kg$^{-1}$ soil | NH$_4^+$-N/NO$_3^-$-N | p value  |
|--------------------|------------------------|-------|------------------------|--------------------------------|--------------------------------|-----------------------|----------|
| **0–5-cm soil layer** |                        |       |                        |                                |                                |                       |          |
| Chromic Haploxerert | Faba bean              | 7.7   | 42.5                   | 1.6                              | 0.4                            | 4.3                   | <0.001   |
|                    | Durum wheat            | 7.8   | 43.2                   | 3.3                              | 2.4                            | 1.4                   | <0.001   |
|                    | No addition            | 7.8   | 33.6                   | 1.7                              | 0.3                            | 6.5                   | <0.001   |
| Eutric Cambisol    | Faba bean              | 7.8   | 73.5                   | 5.8                              | 104.6                           | 0.009                 | 0.001    |
|                    | Durum wheat            | 5.4   | 67.6                   | 1.3                              | 149.6                           | 0.008                 | 0.001    |
|                    | No addition            | 5.9   | 67.2                   | 0.9                              | 164.5                           | 0.006                 | 0.001    |
| **5–15-cm soil layer** |                        |       |                        |                                |                                |                       |          |
| Chromic Haploxerert | Faba bean              | 7.7   | 75.9                   | 13.5                             | 36.9                            | 25.7                  | <0.001   |
|                    | Durum wheat            | 7.8   | 83.0                   | 32.0                             | 43.3                            | 62.9                  | <0.001   |
|                    | No addition            | 7.8   | 48.1                   | 5.8                              | 1.5                             | 75.9                  | <0.001   |
| Eutric Cambisol    | Faba bean              | 7.9   | 86.4                   | 11.1                             | 36.9                            | 75.9                  | <0.001   |
|                    | Durum wheat            | 5.6   | 93.1                   | 1.5                              | 43.3                            | 83.0                  | <0.001   |
|                    | No addition            | 5.8   | 91.8                   | 0.9                              | 66.4                            | 48.1                  | <0.001   |

| Soil Type          | Residue type           | S × T |
|--------------------|------------------------|-------|
| Chromic Haploxerert |                        | <0.001|
| Eutric Cambisol    |                        | <0.001|
unamended controls of the Cambisol soil was 30% higher than in Haploxerert soil (85.1 and 59.9 mg N$_2$O m$^{-2}$, respectively). Crop residue addition had a different effect in each soil (interaction soil × residue type significant $p < 0.001$). In the Cambisol, N$_2$O emissions in the pots amended with wheat were 159.8 mg N$_2$O m$^{-2}$ (+88% more than the control) and that of the pots amended with faba bean was 127.0 mg N$_2$O m$^{-2}$ (+49% than the control). In the Haploxerert, faba bean-added pots emitted in total 80.8 mg N$_2$O m$^{-2}$ (+35% than the control) and that added with wheat 67.2 mg N$_2$O m$^{-2}$ (+12% than the control; Fig. 6).

Comparisons of gas measurement techniques

Few differences were found for the IRGA and PGA in CO$_2$ measurement when compared with that from the GC. The determination factor was 0.937 ($y_{GC} = 1.0534x_{IRGA} - 0.0221$ g CO$_2$m$^{-2}$ h$^{-1}$) and 0.925 ($y_{GC} = 0.9887x_{PGA} - 0.0095$ g CO$_2$m$^{-2}$ h$^{-1}$) for IRGA and PGA, respectively, and IoAd was 0.998 for both instruments.

With regard to the N$_2$O measurement, the linear regression between GC and PGA showed a relatively high relationship between the results ($R^2 = 0.90$; $y_{GC} = 0.8993x_{PGA} - 0.0063$ mg N$_2$O m$^{-2}$ h$^{-1}$)), although PGA-N$_2$O was, on average, 5.2% higher than the GC-N$_2$O measurements. However, in this case, the IoAd was also 0.998.

The comparison between CO$_2$ measurements obtained by IRGA and PGA across the entire experimental period (more than 600 measurements) showed a high correlation between the two instruments ($R^2 = 0.95$; IoAd = 0.996; $y_{IRGA} = 1.0118x_{PGA} - 0.0003$ g CO$_2$m$^{-2}$ h$^{-1}$). However, the cumulative CO$_2$ emissions measured by PGA were on average 9% higher than those measured by IRGA. Differences in CO$_2$ fluxes from the two soils were apparent from the different measurement techniques. Thus, although the overall CO$_2$ fluxes measured by PGA were 6% higher than IRGA, such differences were up to 10% greater when the comparison was limited to the Haploxerert soil, and up to 17% when only the control plots were considered. In the Cambisol, the differences between the instruments were lower at around 5%.
Fig. 3 CO₂ emission course from the Chromic Haploxerert and Eutric Cambisol soils amended with faba bean and wheat biomass, or unamended (control), measured with PGA during the experimental period. Data are means ± SE (n = 3).

Fig. 4 Total CO₂ emission from the Chromic Haploxerert and Eutric Cambisol amended with faba bean and wheat biomass, or unamended (control), measured with IRGA and PGA. Data are means ± SE (n = 3).
Fig. 5  N$_2$O emission course from the Chromic Haploxerert and Eutric Cambisol amended with faba bean and wheat biomass, or unamended (control), measured with PGA during the experimental period. Data are means ± SE ($n=3$).

Fig. 6  Total N$_2$O emission from the Chromic Haploxerert and Eutric Cambisol soils amended with faba bean and wheat biomass, or unamended (control), measured with PGA. Data are means ± SE ($n=3$).
Discussion

N₂O and CO₂ emission and soil properties

This study evaluated the effect of soil incorporation of two different plant residues on N₂O and CO₂ emissions. The characteristics of two soils were distinctly different, with the Cambisol having a low pH and high SOC, while the Haploxerert had a high pH and low SOC. Emissions and soil parameters varied according to both the kind of residue added and the soil type. The total CO₂ and N₂O emissions (measured by PGA), from the unamended Cambisol, were 249 and 40% higher than the unamended Haploxerert, respectively, suggesting large differences in biochemical and microbial activity between both soils driven by differences in soil physical and chemical properties. Moreover, the differences in CO₂ emissions between the two soils followed the differences in stable C (TOC was 78% higher in the Cambisol than in the Haploxerert) and readily available C (DOC in the Cambisol was double that in the Haploxerert). This latter form, although it may be preferentially utilized by soil microorganisms, can be protected by soil aggregates or adsorbed by mineral particles (Majumder and Kuzyakov 2010; Steinbeiss et al. 2008; Shi and Marschner 2014; Hadas et al. 2004). The higher CO₂ emissions (per unit of carbon present in the soil) from Cambisol were nevertheless a reflection of differences in the carbon pools. Such differences suggest that the Haploxerert had a relatively low respiration rate, which may have been a consequence of protection by the higher clay content in the Haploxerert of SOC pools (Baldock and Skjemstad 2000; Krull et al. 2003; Lutzow et al. 2006; Alluvione et al. 2013; Six and Paustian 2014) and coupled with relatively low soil microbial activity due to a low free substrate availability. Another important aspect related to the clay content is its mineralogy; the Haploxerert is characterized by prominent swelling-shrinkage behaviour, which suggests that a high content of montmorillonite can slow down organic matter decomposition by absorption, interacting with soil microbes and their external enzyme activity or limiting oxygen diffusion (Vogel et al. 2015). In addition, a recent highly reliable model of their external enzyme activity or limiting oxygen diffusion position by absorption, interacting with soil microbes and swelling-shrinkage behaviour, which suggests that a high capacity of this soil (35 cmol kg⁻¹) and readily available C (DOC in the Cambisol was double that in the Haploxerert) and significantly lower decomposition process up to pH 7.4. However, in our experiment, although the pH of the Haploxerert was slightly higher (7.8), the lower DOC concentration and CO₂ and N₂O fluxes in Haploxerert suggest the lower decomposition rates that can be linked to the much higher clay content (52.5%) confirming the dominant influence of clay as a key factor in determining nutrient turnover and emissions in this soil. The original pH of the soil may...
have played a role in determining the magnitude of N₂O emissions by the soil microbial community. As reported from Rousk et al. (2009), an acid pH at around 6 can stimulate fungal growth; fungi are recognized for not having the ability to synthesize nitrous oxide reductase and their denitrification end product is therefore N₂O. Other studies have reported that fungi could contribute up to 18% of potential denitrification (Herold et al. 2012). Thus, pH differences may also have contributed to differences in N₂O emissions from soils.

There was a clear correlation between CO₂ and N₂O emissions in both soils, although this was greater in the Cambisol, where oxygen depletion and CO₂ emissions could have helped create anaerobic microsites in the soil increasing denitrification and N₂O production (Gök and Ottow 1988; Aulakh et al. 1991; Begum et al. 2014; Nett et al. 2015). The mineralization rate of an organic residue added to the soil mostly depends on its C/N ratio and, to a lesser extent, to its lignin/N ratio and fibre content (Trinsoutrot et al. 2000; Nguyen and Marschner 2016; Cheng et al. 2015). However, in the present study, the difference in the C/N ratio of the residues used (38.6 in faba bean and 40.7 in wheat) does not explain the difference in soil mineral N concentration and CO₂ and N₂O emissions between the crop residues. Thus, it is more likely that mineralization rate of faba bean residues was lower than wheat residues due to the different lignin, acid detergent and NDF contents (+188, +66, +19%, respectively, in faba bean compared to wheat).

The incorporation of plant residues, either of wheat or faba bean, introduced contrasting effects on the NH₄⁺-N and NO₃⁻-N concentrations on each of the soils. The addition of plant residues increased the NH₄⁺-N concentration of the Haploxerert, but not that of the Cambisol, and such an increase was more evident when wheat residues were added. At the same time, addition of plant residues reduced the total NO₃⁻-N content of the Cambisol, but not that of the Haploxerert, and such an effect was more evident when faba bean residues were added. Such a result points to a net immobilization process in the soil due to consumption of N in order to decompose organic C (Corbeels et al. 2000; Jin et al. 2013).

In the Haploxerert, a similar quantity of total CO₂ was emitted after the addition of both crop residues, but the faba bean addition showed a slightly higher N₂O emission than wheat addition treatment coupled with lower NO₃⁻-N content at the end of the experiment. Thus, it is likely that in this soil, which was characterized by a lower soil microbial activity, the lower mineralization of faba bean residues led to a more constant availability of labile C and N, due stimulating bacterial and fungal activity along the experiment until the end and, as consequence, denitrification in soil microsites as reported from other authors (Deenik 2006; Shah et al. 2016). By contrast, wheat residues produced a rapid flush in emission in the initial phase of the experiment and have shown at the end of the experiment higher NH₄⁺-N and NO₃⁻-N concentration into the soil suggesting other limitations. This selective activity of microbes induced by the residue composition results in readily available straw C being used more rapidly while more recalcitrant and stable compounds are decomposed more slowly (Majumder and Kuzyakov 2010). In the Cambisol, both crop residues showed the same trend in gas emissions (CO₂ and N₂O), due to a direct effect of residue characteristics on decomposition and N availability. The rapid mineralization of wheat resulted lower DOC and higher NH₄⁺-N and NO₃⁻-N concentrations and a reduction in pH, as described earlier. In the case of faba bean, the higher presence of recalcitrant compounds, in particular lignin, slowed down nutrient release and decreased emissions.

**Comparison between gas flux measurement techniques**

This study has clearly demonstrated that IRGA and PGA methodologies used to measure CO₂ and N₂O emissions provided data consistent with that measured by GC. The comparison of CO₂ and N₂O emission rates measured by IRGA and PGA was very strongly correlated with GC measurements, an observation also reported by other authors (Pumpanen et al. 2004; Iqbal et al. 2013; Nicoloso et al. 2013; Tirol-Padre et al. 2014). In particular, the same trend was observed for both gas fluxes measured in the Cambisol and Haploxerert, which were characterized by different patterns of CO₂ and N₂O emissions. Similar results to those observed in the present experiment were found for N₂O fluxes by Iqbal et al. (2013), who reported slightly higher emissions with PGA than with GC (+5%). However, by contrast, we did not find any difference in CO₂ flux measurements when comparing PGA and GC. Nicoloso et al. (2013) observed an overestimation of 18.6 and 13.6% compared PGA to GC, for CO₂ and N₂O, respectively; we did not find any differences between the techniques, which may have been due to the lower gas concentrations measured during our experiment. That also defined the positive effect of the compensation against water vapour and cross interference, the two main sources of interference on measurement, during the experiments.

With regard to the accuracy of CO₂ emission data recorded by IRGA, if comparing our performance with those obtained from Pumpanen et al. (2004), the latter of which are based on CO₂ concentration measurements, we obtained better results with very similar fluxes between IRGA and GC. The quality of data obtained from EGM-4 IRGA used in the present study was also confirmed by Mills et al. (2011), who found good similarity in soil respiration flux with a different IRGA type. However, PGA was found to have some limitations in reporting CO₂ fluxes measured by IRGA in the first part of the experiment and monitoring the emissions of Haploxerert control in the later part of the experiment, showing some difficulty on measuring low and high peaks of emission producing a slight overestimation on data. At medium and low
emission rates, the instrument performances were similar and this was also confirmed by GC. Taking into account the reliability of data, together with the speed of measurement and the capacity to obtain high-resolution temporal data, this study highlights the benefits of using online IRGA and PGA measurements in studies of residue decomposition. When applied in the field experiment, the short time required from IRGA and PGA to take a measurement of emission provides an opportunity to make more measurements permitting a higher spatial and temporal resolution. In the case of the PGA, the results produced had a considerable importance due to the possibility of this instrument to measure two or more gaseous compounds simultaneously (Horsley et al. 2014).

Finally, although the chamber techniques coupled with GC are considered the reference technique for the GHG monitoring, direct measurement by these devices eliminates many of the risks resulting from sampling pitfalls and sample storage that can negatively affect the measurements (Cowan et al. 2014; Tirol-Padre et al. 2014). For the specific application to GHG studies, the initial cost and maintenance can be lower than GC systems, requiring also less specialized staff to operate. The comparison of CO2 emissions rates measured by IRGA and PGA across the entire experimental period revealed, overall, that there were small differences between both methods.

Conclusions

Soil plays a major role in controlling GHG emissions to the atmosphere and is a key determinant of emissions originating from plant residues. Our study demonstrated, when comparing two different soils, how specific properties, such as clay content and pH, can significantly alter decomposition, immobilization and gaseous emissions. These results have implications for developing low-C management practices, especially under organic farming systems where residue management could be a strategy to replace mineral fertilizers and limit C footprint. In Vertisols, which are widespread, but less well understood, CO2 and N2O emissions were strongly controlled by clay content limiting emissions, promoting C sequestration and N transfer to next crop cycle. Although many studies on the decomposition of residues have focused on C/N ratios, this study highlights the importance of fibre compounds, often referred to as secondary, on determining soil CO2 and N2O emissions and as their effect can change in relation to the soil characteristics. In particular, in soil with high organic carbon contents and microbial activity such as a Cambisol, the crop residue type determined the total emission. There was a unique trend for higher emissions of both gases (CO2 and N2O) in the presence of more decomposable wheat than with recalcitrant faba bean. In Haploxerert, by contrast, the slower decomposition of crop residues resulted in a similar CO2 release from the different residues, but slightly higher N2O emissions from faba bean.

The direct comparison between IRGA and PGA and their validation with GC confirmed that these two techniques are equivalent in providing reliable data for long-term monitoring, and this occurred under various conditions (differing soil type residue addition). This result is important when considering that GC-based methodologies need a number of sample steps from gas collection, transport, sample storage and analysis, each of which can potentially add error to the measurement. In addition, GC-based methodologies are not able to provide a continuous measurement of the GHG emissions and thus are poor at quantifying temporal variability. By contrast, the high sensitivity of IRGA and PGA, range and ease of application and number of gases analysed (including water vapour) allow a better monitoring of the radiative force of the soil while eliminating many of the risks of the GC-based methodologies.

Acknowledgments We thank John Parker and Francesca Mazza for technical advice and support and the Scottish Government’s Rural and Environment Science and Analytical Services Division, BBSRC, and MIUR—Italy PON01_01145/1 Project—ISCOCEM for financial support.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

Al-Kaisi MM, Yin X (2005) Tillage and crop residue effects on soil carbon and carbon dioxide emission in corn-soybean rotations. J Environ Qual 34:437–445. doi:10.2134/jeq2005.0437

Alluvione F, Fiorentino N, Bertora C, Zavattaro L, Fagnano M, Chiarrandà FQ, Grignani C (2013) Short-term crop and soil response to C-friendly strategies in two contrasting environments. Eur J Agron 45:114–123. doi:10.1016/j.eja.2012.09.003

Amato G, Ruisi P, Frensa AS, Di Miceli G, Saia S, Plaia A, Giambalvo D (2013) Long-term tillage and crop sequence effects on wheat grain yield and quality. Agron J 105:1317–1327. doi:10.2134/agronj2013.0019

An T, Schaeffer S, Zhuang J, Raosevich M, Li S, Li H, Wang J (2015) Dynamics and distribution of 13C-labeled straw carbon by microorganisms as affected by soil fertility levels in the black soil region of northeast China. Biol Fertil Soils 51:605–613

Association of Official Analytical Chemists (AOAC) (1995) Official methods of analysis, 16th edition. Washington, DC

Aulakh MS, Walters DT, Doran JW, Francis DD, Mosier AR (1991) Crop residue type and placement effects on denitrification and mineralization. Soil Sci Soc Am J 55:1020. doi:10.2136/sssaj1991.03615995005500040022x

Aulakh MS, Khera TS, Doran JW, Bronson KF (2001) Denitrification, NO2 and CO2 fluxes in rice-wheat cropping system as affected by crop residues, fertilizer N and legume green manure. Biol Fertil Soils 34:375–389. doi:10.1007/s003740100420
wheat residue amendment. Soil Tillage Res 67:147–157. doi:10.1016/S0167-1987(02)00058-2

Jantalia CP, dos Santos HP, Uragaia S, Boddey RM, Alves BJR (2008) Fluxes of nitrous oxide from soil under different crop rotations and tillage systems in the South of Brazil. Nutr Cycl Agroecosystems 82:161–173. doi:10.1007/s10705-008-9178-y

Jeuffroy MH, Baranger E, Carrouée B, De Chezelles E, Gosme M, Hénault C, Schneider A, Cellier P (2013) Nitrous oxide emissions from crop rotations including wheat, oilseed rape and dry peas. Biogesosciences 10:1787–1799. doi:10.5194/bg-10-1787-2013

Jin VL, Haney RL, Fay PA, Polley HW (2013) Soil type and moisture regime control microbial C and N mineralization in grassland soils more than atmospheric CO₂-induced changes in litter quality. Soil Biol Biochem 58:172–180. doi:10.1016/j.soilbio.2012.11.024

Kesis M, Blagodatsky S, Papen H, Butterbach-Bahl K (2006) Effect of pH, temperature and substrate on N₂O, NO and CO₂ production by Alcaligenes faecalis J. Appl Microbiol 101:655–667. doi:10.1111/j.1365-2672.2006.02927.x

Killham K, Amato M, Ladd JN (1993) Effect of substrate location in soil and soil pore-water regime on carbon turnover. Soil Biol Biochem 25:57–62. doi:10.1016/0038-0717(93)90241-3

Krull ES, Baldock JA, Skjemstad JO (2003) Importance of mechanisms and processes of the stabilisation of soil organic matter for modelling carbon turnover. Funct Plant Biol 30:207–222. doi:10.1071/FP02085

Lawrence AF, Grant RH, Boehm MT, Heber AJ, Wolf JM, Cortus DS, Bogan BW, Ramirez-Dortorono JC, Diehl CA (2009) Measurements of air quality around various open area sources in the U.S. Int J Civ Environ Eng 1:195–198

Lian T, Wang G, Yu Z, Li Y, Liu X, Jin J (2016) Carbon input from 13C-labelled soybean residues in particular organic carbon fractions in a Molisoll. Biol Fertil Soils 52:331–339

Lugato E, Bampa F, Panagos P, Montanarella L, Jones A (2014) Potential carbon sequestration of European arable soils estimated by modeling a comprehensive set of management practices. Glob Chang Biol 20:3557–3567. doi:10.1111/gcb.12551

Luo Y, Zhou X (2006) Soil respiration and the environment. Academic Press, Burlington, 2006, Pages ix-xi, ISBN 9780120887828, http://dx.doi.org/10.1016/B978-012088782-8.50000-0

Lutzow MV, Kogel-Knabner I, Ekschmitt K, Matzner E, Guggenberger (2006) Soil respiration and the environment. Academic Press, Burlington, 2006, Pages ix-xi, ISBN 9780120887828, http://dx.doi.org/10.1016/B978-012088782-8.50000-0

Magid J, Kjaergaard C, Gorissen A, Kuikman PJ (1999) Drying and rewetting of a loamy sand soil did not increase the turnover of native organic matter, but retarded the decomposition of added 14C-labelled plant material. Soil Biol Biochem 31:595–602. doi:10.1016/S0038-0717(98)00164-3

Majumder B, Kuzyakov Y (2010) Effect of fertilization on decomposition of 14C labelled plant residues and their incorporation into soil aggregates. Soil Till Res 109:94–102

Mills R, Glanville H, Megovern S, Emmett B, Jones DL (2011) Soil respiration across three contrasting ecosystem types: comparison of two portable IRGA systems. J Plant Nutr Soil Sci 174:532–535. doi:10.1002/jpln.201000183

Mørkved PT, Dörsch P, Henriksen TM, Bakken LR (2006) N₂O emissions and product ratios of nitrification and denitrification as affected by freezing and thawing. Soil Biol Biochem 38:3411–3420. doi:10.1016/j.soilbio.2006.05.015

Muhammad W, Vaughan SM, Dalal RC, Menzies NW (2010) Crop residues and fertilizer nitrogen influence residue decomposition and nitrous oxide emission from a vertisol. Biol Fertil Soils 47:15–23. doi:10.1007/s00374-010-0497-1

Nett L, Fuh R, Flessa H, Fink M (2015) Emissions of nitrous oxide and ammonia from a sandy soil following surface application and incorporation of cauliflower leaf residues. J Agric Sci 153:1341–1352. doi:10.1017/S0021859615000027

Nguyen TT, Marschner P (2016) Soil respiration, microbial biomass and nutrient availability in soil after repeated addition of low and high C/N plant residues. Biol Fertil Soils 52:165–176

Nicoloso RDS, Bayer C, Denega GL, De Oliveira PA V, Higashiri MM, Corrêa JC, Lopes LDS (2013) Gas chromatography and photo-acoustic spectroscopy for the assessment of soil greenhouse gases emissions. Ciência Rural 43:262–269. doi:10.1590/S0103-84782013000200012

Palm CA, Rowland AP (1997) Minimum dataset for characterization of plant quality for decomposition. Cadisch G and Giller KE (eds) Driven by nature: plant litter quality and decomposition. CAB International, UK, pp 379–392

Powolson BS, Gregory PJ, Whalley WR, Quinton JN, Hopkins DW, Whitmore AP, Hirsch PR, Goulding KWT (2011) Soil management in relation to sustainable agriculture and ecosystem services. Food Policy 36:72–87. doi:10.1016/j.foodpol.2010.11.025

Pumphen J, Kolari P, Ilvesniemi H, Minkinen K, Vesala T, Niinistö S, Lohila A, Carmola T, Morero M, Philatnie M, Janssens I, Curiel J, Grönzeig JM, Rath S, Subke J, Savage K, Kutch W, Östrem G, Ziegler W et al (2013) Comparison of different chamber techniques for measuring soil CO₂ efflux. Agric For Meteorol 123:159–176

Raisiä E (2006) Carbon and N mineralization as affected by soil cultivation and crop residue in a calcareous wetland ecosystem in central Iran. Agric Ecosyst Environ 112:13–20. doi:10.1016/j.agee.2005.07.002

Rees RM, Augustin J, Alberti G, Ball BC, Boecks P, Cantarel A, Castaldi S, Chrinda N, Chojnicki B, Giebels M, Gordon H, Grosz B, Horvath L, Juszczak R, Kasimir Klemedtsson Å, Klemedtsson L, Medinets S, Machon A, Mapanda F et al (2013) Nitrous oxide emissions from European agriculture—an analysis of variability and drivers of emissions from field experiments. Biogesosciences 10:2671–2682. doi:10.5194/bg-10-2671-2013

Rousk J, Brookes PC, Bäth E (2009) Contrasting soil pH effects on fungal and bacterial growth suggest functional redundancy in carbon mineralization. Appl Environ Microbiol 75:1589–1596

Saia S, Schillaci C, Lipani A, Fantappiè M, Märker M, Lombardo L, Matranga MG, Ferraro V, Guaitoli F, Achten M (2017) Protection of soil from the loss of organic carbon by taking into account erosion and management land use at varying soil type: indication from a model semiarid area. Proceedings of the Global Symposium On Soil Organic Carbon, Rome, Italy, 21–23 March 2017

Sarkodie-Addo J, Lee HC, Baggz EM (2003) Nitrous oxide emissions after application of inorganic fertilizer and incorporation of green manure residues. Soil Use Manag 19:331–339. doi:10.1079/SUM2003203

SAS Institute (2008) SAS/STAT® 9.2. User’s Guide. SAS Institute Inc Cary, Cary, NC, USA

Schillaci C, Lombardo L, Saia S, Fantappiè M, Märker M, Achten M (2017) Modelling the topsoil carbon stock of agricultural lands with the Stochastic Gradient Treeboost in a semi-arid Mediterranean region. Geoderma 286:35–45. doi:10.1016/j.geoderma.2016.10.008

Shah A, Lamers M, Streek T (2016) N₂O and CO₂ emissions from South German arable soil after amendment of manures and composts. Environ Earth Sci 75:427. doi:10.1007/s12665-015-5126-8

Shan J, Yan X (2013) Effects of crop residue returning on nitrous oxide emissions in agricultural soils. Atmos Environ 71:170–175. doi:10.1016/j.atmosenv.2013.02.009

Shi A, Marschner P (2014) Drying and rewetting frequency influence cumulative respiration and its distribution over time in two soils with contrasting management. Soil Biol Biochem 72:172–179

Six J, Paustian K (2014) Aggregate-associated soil organic matter as an ecosystem property and a measurement tool. Soil Biol Biochem 68:4–9. doi:10.1016/j.soilbio.2013.06.014
