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Soil carbon emissions from maize under different fertilization methods in an extremely dry summer in Italy

Emissioni di carbonio dal suolo in una coltivazione di mais da insilato in condizioni di estrema siccità estiva in Italia

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Abstract. During the last decades, climate change and variability are increasingly and negatively affecting agriculture. To ensure satisfactory and stable food production, agriculture is intensifying the adoption of external input with environmental consequences such as the emission of greenhouse gases. In this experiment, we monitored CO_2 and CH_4 emission dynamics from cultivation of maize for silage grown under different fertilization treatments: (i) liquid fraction of digestate from pig slurries, (ii) urea, and (iii) no fertilization (control), in an extremely dry summer in Central Italy. Results show that the use of the liquid-organic fertilizer (digestate) significantly increased CO_2 emissions from soil (685.29 kg-C ha^{-1}) compared to the conventional fertilizer (urea) (391.60 kg-C ha^{-1}). However, CH_4 emissions were comparable between the two fertilizers and almost negligible compared to those of CO_2. In both treatments CH_4 emissions were enhanced by the only precipitation event, coupled with an increase of air temperature. Effectiveness of tested fertilizers was assessed through a yield analysis, and proved that digestate may represent a viable alternative to urea (6.97 and 6.48 t ha^{-1}). Nevertheless, considering CO_2 emissions from digestate and the numerous passes in field needed for its spreading, the use of this fertilizer in extreme dry conditions requires specific considerations.

Keywords. Carbon dioxide, Methane, Maize, Digestate, Drought.

Abstract. Il recente sviluppo del fenomeno dei cambiamenti climatici ha negativamente influenzato numerosi settori produttivi tra i quali quello agricolo. Per assicurare una produzione alimentare soddisfacente a livello globale, l'agricoltura ha dovuto incrementare il ricorso ad input esterni di sintesi con notevoli risvolti negativi a livello ambientale, come l'aumento delle emissioni di gas serra. In questo studio sono state monitorate le emissioni di CO_2 e CH_4 dal suolo in una coltivazione di mais da insilato con differenti strategie di concimazione: (i) frazione liquida del digestato da reflui suini, (ii) urea e (iii) un controllo non concimato, durante una stagione estiva (2017) estremamente siccitosa nell'Italia Centrale. Dall'analisi dei risultati è possibile affermare che l'utilizzo di un concime liquido-organico (digestato) determina un aumento significativo delle emissioni di CO_2 (685.29 kg-C ha^{-1}) rispetto all'urea (391.60 kg-C ha^{-1}). Al contrario, le emissioni di CH_4 sono risultate confrontabili fra i due trattamenti con produzioni trascurabili rispetto alla CO_2. In entrambi i trattamenti le emissioni di CH_4 sono state favorite dall'unico evento piovoso, seguito da un aumento delle temperature. L'efficacia dei due concimi è stata valutata attraverso l'analisi delle rese in termini di insilato di mais confermando che l'utilizzo del digestato rappresenta un'interessante alternativa all'urea (6.97 e 6.48 t ha^{-1}, rispettivamente). Tuttavia, alla luce dei livelli di emissioni di CO_2 e dai numerosi passaggi in campo che si richiedono in fase di distribuzione, l'utilizzo del digestato, in condizioni di estrema siccità, richiede specifiche considerazioni.

Parole chiave. Anidride carbonica, Metano, Mais, Digestato, Siccità.

1. INTRODUCTION

Climate change and extreme weather conditions are among the most important threats affecting crop production and management in agriculture (Gobin *et al.*, 2013). Extreme climatic phenomena, especially drought, determine fluctuations in crop production and affect the economic stability of farmers. In particular, as affirmed by Li *et al.* (2009), since 1960s the areas affected by drought, based on Palmer Drought Severity Index (PDSI) (Palmer, 1965), increased approximately from 5-10% to 15-25%. Comparisons between climate model simulations and observed data suggest that anthropogenic greenhouse gases emissions (GHGs) are the main driver of such trend (Burke *et al.*, 2006; IPCC, 2007; Gornall *et al.*, 2010). The combination of prolonged high temperature and absence of rainfall has a relevant impact on agricultural systems from different points of view, including soil microbiological activity, water availability, crop growth and yields. In particular, prolonged drought spells negatively affect soil microbial community that may reduce or, in extreme cases even dramatically compromise, the biological activity with a strong reduction of their metabolisms. Moreover, the effect of drought on activity of soil microorganisms results in an alteration of gas exchanges, such as CO_2 and CH_4, in the soil-atmosphere system following the modification of carbon (C) and nitrogen (N) availability in the soil (Forster *et al.*, 2007; Davidson *et al.*, 2008). As affirmed by Muñoz *et al.* (2010), Krištof *et al.* (2014), Lu *et al.* (2015) and Rutkowska *et al.* (2018) the reduction of CO_2 emissions by changes in agricultural practices is still small. This is mainly due to the complex interactions of factors affecting C emissions from soil, including agronomic practices, meteorological conditions and microbiological activity. However, technologies for their reduction are continuously under development.

One opportunity to reduce the environmental impact of human activities, including agriculture, is represented by the production of renewable energies. In this regard, biogas is one of the most interesting strategy (Alburquerque *et al.*, 2012) for reducing the negative environmental impact of current agricultural practices, and also represents an additional source of income for farmers (Carrosio, 2013).

Furthermore, digestate, which is a by-product of biogas production, represents an interesting alternative N source for crops. Although the production process ensures a lower environmental impacts of digestate compared to synthetic fertilizers, uncertainties remain regarding the direct emissions from its use in the field (Ahlgren *et al.*, 2010; Hasler *et al.*, 2015). Digestate has high level of macro and micro nutrients easily available for plants and, as an organic fertilizer, it stimulates soil microbial activities and emission dynamics from the soil. However, depending on the agricultural management, nutrients can be made available for the crops or lost through leaching or volatilization (Alburquerque *et al.*, 2012; Pezzolla *et al.*, 2012; Nkoa, 2014; Maucieri *et al.*, 2016). Therefore, beside the nutritional requirements of the crop, the environment conditions must be considered. Climate plays a key role affecting numerous soil dynamics such as water content, temperature, organic matter mineralization rate, root systems and soil microbial community development. The fluctuations in climate with extreme phenomena, such as drought or heat waves, may produce different effects based on location and agricultural systems. After a long dry period, gas exchanges between soil and atmosphere are extremely reduced by substantial modification of soil water content and soil aeration (Davidson *et al.*, 2008). In this sense, a reduced thickness in soil water films may reduce the diffusion of roots exudates with a net reduction of available soluble organic-C substrates for crops (Davidson and Janssens, 2006). However, in specific areas such as the Mediterranean and Southern Europe, a rewetting after drought through precipitation or irrigation, promotes an intense pulse of C emission flux from soil (Birch, 1964; Jarvis *et al.*, 2007; Unger *et al.*, 2010). Thereafter, organic matter decomposition, mineralization and release of inorganic N, CO_2 and CH_4 suddenly occurs. If in water-saturated soils the organic matter may accumulate producing layers of peat, in severe dry conditions an addition of organic fertilizers may produce an intense CO_2 flux from soil as consequence of microbial community stimulation (Luo *et al.*, 2001; Francaviglia *et al.*, 2018). For these reasons, the assessment of relations between drought and C emissions represents a key factor for future agricultural sector evolutions in dry climates.

The aim of this research was to evaluate CO_2 and CH_4 emission dynamics from the soil in the short period immediately after fertilization. Experimentation was carried out on a cultivation of maize for silage under different fertilization treatments: (i) liquid fraction of digestate from pig slurries, (ii) urea, and (iii) no fertilization (control), in an extreme dry summer in Central Italy.

2. MATERIALS AND METHODS

An experiment was conducted in Florence (Tuscany), Central Italy (43°47'02.3"N, 11°13'13.4"E). Twelve tanks of 1 m^3 each, equipped with a leachate collecting system to control eventual nutrient losses, were positioned in two rows on a supporting structure made by reinforced concrete poles and soil. Under the tanks a plastic mulching film was placed to reduce weed development and to favor measuring and management operations. The tanks were filled with soil from the experimental site of CREA-ABP located in Scarperia, Florence (43°58'56" N, 11°20'53" E). A silty-clay soil was used and soil layers (0 to 30; 30 to 60; 60 to 90 cm of depth) were kept divided to reproduce as much as possible the natural soil profile. Maize for silage (var. Ronaldinio) was planted on 20th June 2017 with a density of 12.000 plants/ha (13 seeds per tank). Fertilization treatments were (i) liquid fraction of digestate from pig slurries (DIG); (ii) urea (URE); (iii) no fertilization as control (CON), organized in a randomized block design, including four replicates for each treatment. All field operations were performed by hand replacing mechanical ones in field. Digestate was obtained from the biogas plant of "Marchesi de' Frescobaldi, Tenuta di Corte" farm (43°58'29" N, 11°23'21" E) from a mesophilic fermentation process of pig slurries and different kinds of agricultural by-products such as straw, olive cake and sorghum silage. Solid and liquid fractions of digestate were manually separated. Topdressing fertilization at a rate of 150 kg N ha^{-1}, was performed at the beginning of the growth stage (27 days after sowing). Based on methods adopted by local farmers, digestate was injected at a depth of 20 cm while urea was spread on soil surface. The N content of digestate was determined by a Kjeldhal analysis, and NH_4^+ and NO_3^- were determined using the method described in "Regione Piemonte Metodi di analisi del Compost Met. C.7.3 and EPA 9056A 2007". Based on fertilizers characteristics (Tab. 1), the organic C supplied was 1420.06 kg/ha and 65.22 kg/ha for DIG and URE, respectively, through the application of 150 kg N/ha of each fertilizer. GHGs emissions were monitored using a static chamber method and the portable gas analyzer XCGM 400 (Madur Sensonic). Twelve static chambers, one per each tank, were constructed as described by Verdi *et al.* (2019) following USDA-ARS GRACEnet Project Protocols (Parkin and Venterea, 2010). Chambers were made by two parts: an anchor system and the lid. The anchor system was made by a PVC cylinder of 20 cm diameter to be inserted into the soil for approximately 15 cm. The anchor ensures the support for the lid of the chamber during samplings. For the lid of the chamber a PVC cylinder of 20 cm diameter and 15 cm height, and a PVC stopper sealed with silicon glue were used. The chamber was completely covered by reflective Mylar tape to reduce the influence of solar radiation. Moreover, on the top of the chamber a hole (13.2 mm) was drilled approximately halfway between the center of the circle and the outside edge. A butyl rubber septum of 20 mm of diameter was fixed into the hole to allow sampling operations. To connect the chamber lid to the anchor system, a strip of tire tube was used (7 cm). Strip was put around the lid and fixed with silicon glue. Exceeding part of the strip (approximately 5 cm) was kept folded back on the lid of the chamber and then folded down to connect the lid to the anchor during sampling. The anchor system was placed into the soil immediately after sowing between plant rows to reduce roots disturbance. It was removed only during fertilization (digestate injection) and then reinstalled immediately at the same location. Temperature was monitored by two thermocouples placed in each chamber. In addition, an automatic meteorological station located 20 m away from the experimental field was used to monitor air temperature, atmospheric pressure and precipitations. The XCGM 400 Madur Sensonic gas analyzer uses nondispersive infrared (NDIR) sensors for the analysis of CO_2 and CH_4 concentrations in the air sample. Emission measurements lasted for three consecutive weeks after fertilization. Samplings were performed (daily in the first week and twice a week during the second and the third) by holding the sensor inside the chamber for 1 minute after chamber closing (T1) and then repeating the procedure at 1 hour interval (T2) from T1. Interpolation was used to obtain missing data from the days were measurements were not performed (eg. the weekend). Gas fluxes were calculated starting from the gas concentration into the chamber (ppm) (the difference between T2 – T1), chamber dimensions (area and volume), closing time and molecular weight of each gas. Through this calculation, it was possible to quantify C losses as kg of C emitted per hectare. As temperature had a similar trend inside each chamber (data not shown), the whole experiment was assumed to be at standard temperature and pressure (STP) conditions and the molar volume of the air was assumed as 22.4 liters. Parametric and non-parametric statistical tests were used to analyze C emissions data.

Tab. 1. Elemental characterization of fertilizers.
Tab. 1. Caratterizzazione elementare dei fertilizzanti.

	Urea	Digestate
Organic C %	20	3.02
Total N %	46	0.319
N-NH_4^+ %	-	0.284
N-NO_3^- %	-	0.035
Total P %	-	1.84
Total K %	-	6.94

3. RESULTS AND DISCUSSION

3.1 Carbon dioxide emissions

Soil under DIG treatment emitted roughly twice CO_2 than URE (685.29 and 391.60 kg C-CO_2 ha^{-1} 17 days^{-1}, respectively). Treatments comparison was performed with both a parametric (Bonferroni test) and a non-parametric (Kruskal-Wallis test) analysis (Bonferroni, 1936; Kruskal and Wallis, 1952). Both tests confirmed that DIG produced higher CO_2 emissions than URE. In addition, no significant differences were observed between URE and CON, confirming the low contribution of URE to soil CO_2 emissions compared to DIG. Highest emissions from soil mainly occurred during the first days after fertilization until the end of the first week. In particular, we observed that immediately after fertilization (AF) (24 hours) CO_2 emissions from DIG were eight times higher than those from URE (Fig. 1). This result is in accordance to Maucieri *et al.* (2016) that observed the highest soil CO_2 emissions during the first 24 hours after digestate spreading.

From the second day AF, differences among treatments were strongly reduced, and from the second week until the end of the experiment significant differences were no longer observed (Fig. 1). Nevertheless, it should be noticed that from day 3 to 5 AF average daily temperature increased by 2 °C and CO_2 emissions from soil increased also (Fig. 1 and Fig. 2). This phenomenon was defined by Luo *et al.* (2001) as "acclimatization" of soil respiration to warming, that represents a proper modification on microorganism's population to altered environmental conditions. In addition, the similarity of soil CO_2 emission trends between DIG and URE from day 2 AF until the end of the experiment suggests that after a short period (24-48h) urea decomposition occurred and soil microbial community increased its metabolic activity (Black *et al.*, 1987). As described by Xu *et al.* (1993) a positive correlation exists between the rate of urea hydrolysis and temperature. This is in accordance to our observations where soil CO_2 emission peaks were observed at days 2 and 5 AF when the highest air temperature of the first week was registered (Fig. 2).

Our observations are also in accordance to Johansen *et al.* (2013) and Verdi *et al.* (2018), affirming that the use of fertilizers with high organic C content strongly encourages a fast-growing soil microbial community with an intense oxygen demand to support microbial metabolisms (Parkin, 1987; Petersen *et al.*, 1996) and a consequent increase in soil CO_2 emissions. The high water content of digestate ensured its homogenous infiltration into the soil, thus increasing the availability of C for microorganisms. This contributed to CO_2 flux immediately after fertilization. Similar experiments performed in open fields in non-drought conditions and in soil

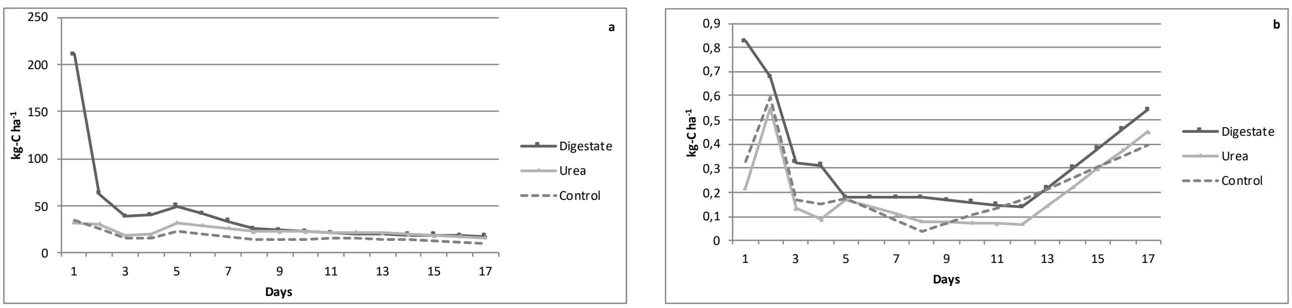

Fig. 1. CO_2 (a) and CH_4 (b) emission trends of digestate (DIG), urea (URE) and control (CON) treatments.
Fig. 1. Andamento delle emissioni di CO_2 (a) e CH_4 (b) da digestato (DIG), urea (URE) e controllo (CON).

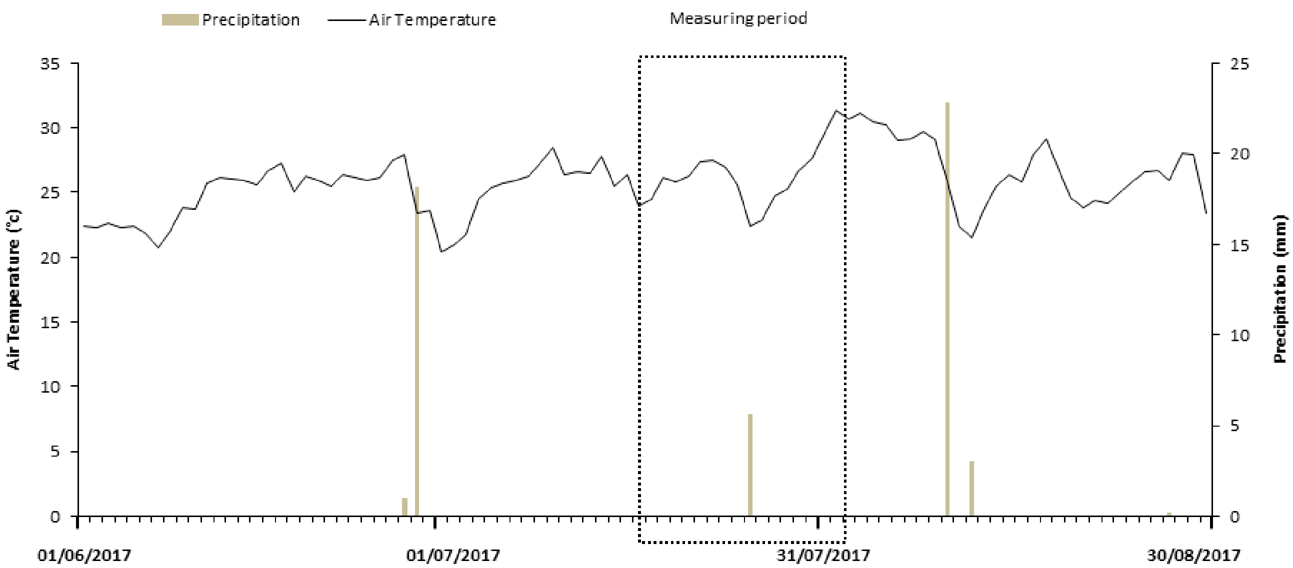

Fig. 2. Average air temperature and precipitation during the experiment (measurement period is indicated by the box).
Fig. 2. Andamento della temperatura media dell'aria e delle precipitazioni (nel riquadro è evidenziato il periodo di monitoraggio delle emissioni).

columns at field capacity (Sänger *et al.*, 2011; Severin *et al.*, 2015; Luoro *et al.*, 2016;), found 25 to 50% more soil CO_2 emissions than our study. This confirms that environmental conditions, more specifically drought, highly affect C emission dynamics. However, the emissions peak observed in the first 24-48 hours AF is confirmed by literature (Severin *et al.*, 2015; Askri *et al.*, 2016).

Despite higher soil C emissions compared to URE, DIG showed better performances in terms of fertilization potential by increasing soil organic matter (SOM). In fact, 1420.06 kg of organic C per hectare were spread with DIG in front of 690.65 kg C/ha (corresponding to about 48.6% of the distributed organic C) lost through emissions (CO_2+CH_4, Tab.2). On the contrary, URE provided only 65.22 kg of organic C/ha against 394.86 kg C/ha (CO_2+CH_4, Tab.2) lost as emissions. Probably, URE stimulated the soil microbial activity determining an increase in soil C emissions 6.05 times higher than the provided organic C. This corresponds to a depletion of soil organic carbon of about 329.64 kg/ha. This fact indicates that the use of organic fertilizers, such as DIG, contributes to an increase or at least maintenance of SOM.

3.2. Methane emissions

No significant differences in CH_4 emissions from soil were observed between treatments (Tab. 2). At day 1 AF, CH_4 emissions from DIG were significantly higher (p=0.001) compared to URE and CON also due to the intrinsic content of methanogenic bacteria of DIG. However, from day 2 AF the amount of C emitted as CH_4 from soil treated with DIG quickly decreased (Fig. 1) probably due to the fast proliferation of soil bacteria that consumed the available soil organic C for their metabolisms (Bernet *et al.*, 2000; Norberg *et al.*, 2016; Verdi *et al.*, 2018). Apparently, methanogenic population of DIG was negatively affected by the extreme dry conditions occurred during the experimentation. During the last days AF (days 12-17) soil CH_4 emissions increased in all treatments (including CON). This fact was observed, and is in accordance to Le Mer and Roger (2001), in correspondence to the warmest period of the experiment that followed the only rainy event (5.6 mm) (Fig. 2). The combined effect of increasing soil water content and atmospheric temperature encouraged soil CH_4 emissions in the last day of measurements.

3.3. Yields

Performances of the tested treatments (DIG, URE and CON) were analyzed in terms of final yields (Tab. 3). A preliminary ANOVA analysis was performed, followed by Bonferroni and Kruskal-Wallis tests. Both tests proved the effectiveness of DIG as fertilizer that provided yields comparable to those obtained under URE treatment (6.97 t ha^{-1} and 6.48 t ha^{-1}, respectively). As observed by Lotter *et al.* (2003), the use of organic fer-

Tab. 2. Measured soil CO_2 and CH_4 emissions from digestate (DIG), urea (URE) and control (CON).
Tab. 2. Emissioni cumulate di CO_2 e CH_4 da digestato (DIG), urea (URE) e controllo (CON).

	CO_2 (kg C ha^{-1} 17 $days^{-1}$)	CH_4 (kg C ha^{-1} 17 $days^{-1}$)
DIG	685.29 (± 75.49)^a	5.36 (± 1.61)^c
URE	391.60 (± 79.26)^b	3.26 (± 1.02)^c
CON	286.79 (± 32.64)^b	3.69 (± 0.52)^c

Standard deviations of the four replicates per each treatment are in brackets.
Values marked with the same letter do not differ significantly.
Deviazione standard delle quattro repliche per ogni trattamento è indicata tra parentesi.
I valori contraddistinti dalla stessa lettera non evidenziano differenze significative.

Tab. 3. Silage maize yields in digestate (DIG), urea (URE) and control (CON), DM= dry matter.
Tab. 3. Produzione di insilato di mais da digestato (DIG), urea (URE) e controllo (CON).

	Yields (t DM ha^{-1})
DIG	6.97 (± 0.56)^a
URE	6.48 (± 0.85)^a
CON	4.49 (± 0.25)^b

Standard deviations of the four replicates per each treatment are in brackets.
Values marked with the same letter do not differ significantly.
Deviazione standard delle quattro repliche per ogni trattamento è indicata tra parentesi.
I valori contraddistinti dalla stessa lettera non evidenziano differenze significative.

tilizers on maize ensures higher or similar yields compared to urea. This is due to the improvement of soil's water-holding capacity, infiltration rate and water capture efficiency of soils treated with organic fertilizers that allow to maintain more available water into the crop root zone. Furthermore, as observed by Alburquerque *et al.* (2012), DIG provides similar yields than urea due to the significant amount of ammonium N that is rapidly nitrified, becoming available for crops. During the experiment, characterized by extremely dry (5.6 mm of cumulated precipitation) and warm (average temperature of 26.55 °C) conditions, these two effects of DIG were particularly evident: on one hand, more available water was retained in the root zone, and on the other the absence of rainfall reduced the risk of N-based compounds leaching which were therefore available for crops. Nevertheless, yields obtained from this experiment were affected by drought conditions showing a strong reduction compared to national average data in well irrigated and fertilized systems (Borrelli *et al.*, 2014).

4. CONCLUSIONS

Based on the obtained results, we can conclude that C emissions from cultivated soil depend not only on the fertilizer but also on the environmental conditions. In particular, the increased CO_2 emissions from soil observed in DIG, compared to URE, were principally due to the combined effect of the high temperatures and drought that occurred during the experimentation, and the high water content of DIG. These two factors encouraged soil bacteria proliferation with a consequent increase in soil respiration. This is in accordance to Sainju *et al.* (2008) that observed an increase of 13% of soil CO_2 emissions from irrigated maize fields, compared to rainfed conditions. However, the same conditions blocked methanogenic bacteria proliferation with a sensible reduction of CH_4 production in all treatments. From a productive point of view, our analysis confirmed that DIG may represent an effective alternative to URE for maize, as similar yields were obtained. In addition, considering that digestate is a by-product of biogas, its production has a better environmental performance compared urea. Zegada-Lizarazu *et al.* (2010) reported that to produce 1 kg of urea 76-78 MJ of energy are needed, with consequent emissions from the system. Nevertheless, the use of DIG in dry summer conditions may represent a critical factor due to its higher impacts on CO_2 emissions. This aspect should be carefully considered especially under the view of global warming trends. In addition, due to its low N content, a large amount of DIG is required to satisfy the nutrient demand of crops, involving an intensive and repeated use of fossil fuel-based machinery for fertilization field operations. Thus, further experiments focused on full life cycle analysis are suggested for a more in-depth understanding of environmental impacts from DIG and URE.

AUTHOR CONTRIBUTIONS

Conceptualization, Leonardo Verdi, Simone Orlandini and Anna Dalla Marta; Data curation, Leonardo Verdi; Formal analysis, Marco Napoli; Investigation, Leonardo Verdi; Methodology, Leonardo Verdi and Marco Mancini; Project administration, Simone Orlandini; Supervision, Simone Orlandini; Writing – original draft, Leonardo Verdi; Writing – review & editing, Anna Dalla Marta.

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