Water regime affects soil N_2O emission and tomato yield grown under different types of fertilisers

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Abstract

Tomato plants were subjected to three fertilisation treatments (M: mineral fertiliser; DMPP: mineral fertiliser + 3,4-dimethylpyrazole phosphate; OM: NKP + organic animal manure) in combination with two water regimes (100% and 50% evapotranspiration). Plant biomass, fruit production, nitrogen use efficiency (NUE) and N uptake, maximal PSII photochemical efficiency, F_v/F_m and cumulative soil N_2O emission were determined. Well-watered OM plants showed higher values of biomass, fruit production, NUE and N uptake than M and DMPP plants; cumulative N_2O fluxes were lower in DMPP plots than in M and OM plots. The reduced water supply determined a drop in crop biomass, fruit production, NUE and N uptake, and cumulative N_2O fluxes in M and OM treatments that were higher in OM plots, whereas it determined a significant rise in cumulative N_2O fluxes in DMPP plots that was lower in absolute term compared to M and OM plots recorded under well-water irrigation. It can be concluded that DMPP added-fertiliser has a good performance in semi-arid environment resulting a better nitrogen source compared to conventional and organo-mineral fertilisers under reduced water supply, able to preserve crop yield and to determine soil N_2O emissions (as expressed in CO_2 eq) not dangerous for global environment.

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Introduction

Crop production is very sensitive to climatic change, as modified rainfall and air temperature patterns can seriously affect plant physiology with negative impact on productivity and yield (Gornall *et al.,* 2010). On the other hand, agriculture contributes to global change with the emission in atmosphere of greenhouse gases (GHG_s).

Agricultural soil management practices can contribute for about 60% of the total nitrous oxide (N_2O) emissions from the agricultural sector (Smith *et al.,* 2007). The increase of nitrogen fertilisation to satisfy the demand of high nitrogen consuming crops has enhanced the biogenic N_2O emissions due to nitrification and denitrification processes, driven by temperature, nitrogen availability and soil moisture, this latter influenced by irrigation.

In this scenario, it is essential to define sustainable management practices to minimise the impact of cropping systems on the global environment while maintaining the yield. In this frame, several different approaches have been proposed in terms of appropriate management of irrigation (Vallejo *et al.,* 2014; Meijjde *et al.,* 2016; Wolff *et al.,* 2016) as well as of fertilisation, such as the use of fertilisers added with nitrification inhibitors (NI_s) (Vitale *et al.,* 2013; Abalos *et al.,* 2016; Hube *et al.,* 2016; Huérfano *et al.,* 2016; Vitale *et al.,* 2017) and organo or organo-mineral fertilisers (Ball *et al.,* 2004; Guardia *et al.,* 2016; Vitale *et al.,* 2017). The latter release nitrogen (N) more gradually over the course of season, compared to conventional mineral fertilisers, thus improving synchrony between soil N availability and crop N demand and potentially increasing overall efficiency of fertiliser use. NI_s delay nitrate production by depressing the activity of *Nitrosomonas* bacteria, thus allowing nitrogen to accumulate in the soil, making it available for plant growth in longer time period. Organo and organo-mineral fertilisers also release nutrients progressively throughout the late stages of the crop development, due to the slow process of mineralisation of the organic matter.

Both fertilisation types thus potentially improve crop growth and yield but have different effects on N_2O production in the soil. The use of NI_s mitigates soil N_2O emission by suppressing microbial activity for a period of time depending on soil type moisture and temperature (Soares *et al.,* 2015). On the contrary, the application of organic manure or sludge to soil has been showed to enhance N_2O emission as a consequence of the increased soil moisture and the degradable labile carbon addition. These soil conditions might favour microbial growth and metabolism, thus resulting in N_2O production (Kaiser and Ruser, 2000; Sánchez-Martín *et al.,* 2008; Yao *et al.,* 2015).

Among factors involved in crop management, irrigation regime also deserves considerable attention, as it has been shown to foster GHG emissions (Tost *et al.,* 2013). In particular, water supply can also increase N_2O emissions favoring conditions for nitrification and denitrification (Maris *et al.,* 2015), while a rational management of irrigation can enhance crop yield and mitigate the impact of cropping systems on environment and global climate by favoring Carbon sequestration and reducing GHGs emission. Most of the studies on the effects of NI_s and organic and organo-mineral fertilisers on crop production and N_2O emission has been carried out under optimal irrigation conditions (Vitale *et al.,* 2013; Guardia *et al.,* 2016; Huérfano *et al.,* 2016; Vitale *et al.,* 2017), while little information is available for open field crops under reduced water supply (Albalos *et al.,* 2016).

The main objective of this study was to investigate the efficiency of three fertiliser types on crop growth and soil N_2O emission under optimal and reduced water supply. In particular, we tested a mineral fertiliser added with 3,4-dimethylpyrazole phosphate (DMPP) - a new generation nitrification inhibitor, and an organo-mineral fertiliser. Our study moves from the consideration that organic matter mineralisation and the resulting release of nutrients in the soil requires adequate soil moisture conditions, so that its decomposition could be limited under low soil water content affecting crop growth and N_2O emissions. On the other hand, laboratory studies have shown that DMPP is efficient to mitigate NH_4^+ oxidation also under reduced soil water potential (Barth *et al.,* 2008). This should benefit plant growth and yield while mitigating nitrous oxide production also under reduced soil moisture.

Materials and methods

Experimental site, crop management and experimental set-up

The field trial was carried out in Ponticelli (province of Naples, southern Italy, at 50 m a.s.l.; 40°86'N, 14°33'E), a location characterised by Mediterranean climate conditions with warm dry summer and mild wet winter (Figure 1).

The soil has a sandy-loam texture and relative content for the 0.0-0.9 m soil layer are: sand 80%, silt 12%, clay 8%, bulk density 1.37 g cm^{-3}; Chemical characteristics for the layer 0.0-0.1 m are: 2.54% organic matter content, total carbonate absent, 0.149 dS m^{-1} electrical conductivity, pH 7.08 and 1.86 g kg^{-1} nitrogen. The experimental site is equipped with a meteorological station that allowed estimating the reference evapotranspiration (ET) according to the Hargreaves equation that was locally calibrated, tested and validated.

Tomato seedlings (*Solanum lycopersicum* L.) were transplanted on May 3rd 2012 in 12 m^2 plots at a spacing of 1.0x0.3 m. A total of 18 plots were arranged in a split plot experimental design with two water regimes (factor A) and three fertilisation treatments (factor B). Three different fertilisation treatments were applied as follows: ammonium nitrate (Control, M plots), ammonium sulfate nitrate added with nitrification inhibitor (3,4 dimethylpyrazole phosphate, Entec 26) (DMPP plots), and organo-mineral fertilisation using dried pellets (NPK + animal waste, Olivas) (OM plots). Different fertiliser amounts were supplied, to allow for balancing N amount among treatments. A total 120 Kg N ha^{-1} was applied to all plots, split in two times: 50% at transplanting and 50% 30 days later. Phosphate and potash supplies were also balanced by supplying supplemental inputs of superphosphate and potassium-sulphate fertilisers to treatments M and OM, one week after the initial N fertilisation event.

The experimental area was watered by drip irrigation. One meter spaced 4 L h^{-1} drip lines were installed, with drippers spaced 0.30 m. All plots were well watered until 13 June (41 Days After Transplanting, DAT) receiving a water volume of 176 m^3 ha^{-1}. Thereafter, 9 plots were well watered by replenishing the 100% of ETc (100% ET), with total water supply of 1083 m^3 ha^{-1}, whereas the other plots received only the 50% of ETc (50% ET), with a total water supply of 541.5 m^3 ha^{-1}. Kc coefficients used to calculate ETc were 0.8, 1.2, and 0.9, respectively for initial, middle and end season (Rinaldi and Rana, 2004).

Fruits were periodically hand-picked, as they reached maturity, and final harvest took place on July 27 (82 DAT).

Biometrical and physiological measurements

Plant biomass and leaf area were determined at 82 DAT, by sampling three plants *per* plot. Due to the sandy texture of the soil, it was possible to recover most of the root system when pulling up. Plants were therefore partitioned in root, leaf, stem, and fruits. All plant parts were transferred in an oven at 60°C up to constant weight. Green leaf area was determined by means of an area mater (Li-3000, Licor Inc. Lincoln, NE, USA). Nitrogen (N) content was determined in stems and leaves on three plants *per* plot. Samples were grounded into a fine powder by an agate mortar and pestle (Fritsch pulverisette). N concentration was measured by gas chromatography (CNS analyser - Thermo Finning).

Nitrogen use efficiency (NUE) was estimated as the ratio between crop yield and applied N, whereas N uptake was estimated by multiplying total biomass weight by N tissue content. Maximal photochemical efficiency of photosystem 2, *i.e.* F_v/F_m, related to functionality of photosystem 2 (Maxwell and Johnson, 2000), was determined on 30 min darkened leaves by using a fluorometer (Junior PAM, Walz GmbH, Effeltrich, Germany).

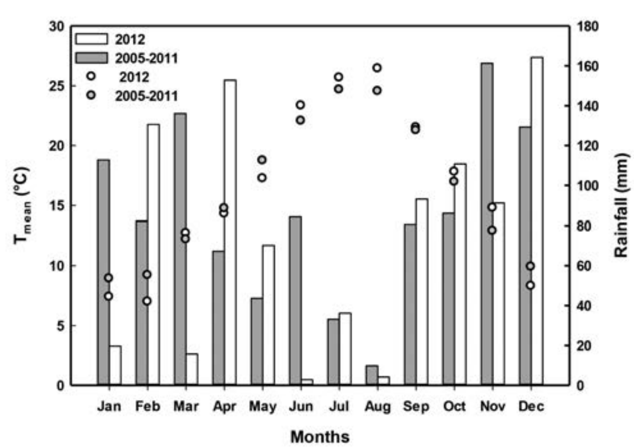

Figure 1. Monthly air temperature (circles) and rainfall (bars). Gray: mean 2005-2011 values; white: 2012 values.

Cumulative soil N_2O emissions

N_2O emissions were measured by means of the static chamber technique; 20 cm diameter and 10 cm heigh chambers were placed on collars previously inserted 3 cm into the soil the previous day or before, to minimise disturbance. Air samples, collected before and three times following chambers closure in a time window of 30 min, were picked up by means of a polypropylene syringe, and stored in 20 mL vials. Gas samples were then analysed by gas chromatography (SRI 8610C, Gas Chromatograph, Torrance, USA) using a ^{63}Ni electron-capture detector. Gas fluxes were calculated by linear regression of gas concentrations over time. Only curves where the regression slope did not change sign over the observation period, *i.e.* $dC/dt|_{t=0}$ / $dC/dt|_{t=30} > 0$ (Stolk *et al.,* 2009), were considered in results. Cumulative fluxes were calculated by summing the products of the average of two neighboring measurement fluxes by their interval time (Maucieri *et al.,* 2016).

Statistical analysis

Statistical analysis of data was performed by means of the Sigma-Plot package (Sigma-Plot 12.2). Differences among fertilisation treatments and water regimes were checked by two-way ANOVA followed by the Duncan's test. Spearman's correlations were performed to assess the soil-related independent variables on soil gas emissions.

Results and discussion

Plant growth and yield

In Table 1 are summarised the ANOVA results. Shoot biomass of well-watered (100% ET) plants treated with organo-mineral (OM) fertiliser was greater (P<0.05) compared to plants fertilised with mineral (M and DMPP) fertiliser (Figure 2A). No significant differences in root dry matter production was observed (Figure 2B). The higher carbon gain in OM plants under well-watered conditions is likely due to the higher (P<0.01) total leaf area, which increased light interception (Figure 2D) as previously reported by Vitale *et al.* (2017) on tomato gown upon same conditions, rather than to an enhanced unit photosynthesis rate or to higher photosynthetic pigments and/or proteins content. In fact, the leaf-nitrogen content (Table 2), also related to Rubisco content (Makino, 2003) and F_v/F_m values (Table 3), related to functionality of photosystem 2 (Maxwell and Johnson, 2000), were comparable among treatments, thus suggesting that the unit photosynthetic rate was the same for all treatments.

At 50% ET, M and OM plants showed a reduction (P<0.01) in shoot biomass, that was more pronounced in OM (Figure 2A). On the contrary, shoot biomass was not affected by limited water supply under DMPP fertilisation while a significant (P<0.05) increase in root biomass was detected (Figure 2B). As a consequence, the shoot/root ratio (SRR) decreased in M and OM plants but was unaffected in DMPP plants (Figure 2C). SRR offers an estimation of the distribution of dry matter among the different plant organs. The reduction in SRR in M and OM plants indicates that the proportion of dry matter allocated to shoots was lower compared to those diverted to roots. Reduced shoot-root ratio is a common adaptive reaction of plants to withstand water stress (Boutraa *et al.,* 2010), and is aimed at reducing water loss by transpiration while exploring deeper layers of the substrate in search of water. A reduction (P<0.01) in leaf area in both M and OM plants was observed, particularly evident in OM plants (Figure 2D), that represents an effective mean to control water loss by transpiration under limited water supply. On the other hand, the reduced leaf area in response to water shortage also explains the reduced carbon gain (*i.e.* the lower dry matter production) in M and OM plants as a consequence of a reduced light interception.

Water shortage is known to determine also a reduced nutrient uptake by roots; it is well known that the capacity of roots to absorb nutrient declines in water stressed plants, due to either a decrease in transpiration rate (passive uptake) and/or to an impairment of the transport and root membrane permeability (active uptake) (Alam, 1999). A reduction in passive nutrient uptake by roots, likely as a consequence of reduced plant transpiration rates (Youssef *et al.,* 2012) due to a reduced total leaf area, may be assumed for M and OM plants, as indicated by the lower N content

Table 1. Levels of significance (P values) from the two-way ANOVA for comparison of fertilisers and water regime. Pairwise Multiple Comparison Procedures by Duncan's' test.

Variables	Fertiliser	Water regime	Fertiliser x water regime
Shoot	<0.05	<0.05	<0.05
Root	0.43	0.23	<0.05
Shoot/root	0.86	<0.05	0.11
Leaf Area	0.44	0.08	<0.05
Fruit yield	0.32	<0.05	<0.05

Table 2. Nitrogen content in leaves and stems determined at 65 DAT (days after transplanting). Data are mean (n=9) ± SE.

	Fertilisation treatments					
	$M_{100\%ET}$	$M_{50\%ET}$	$DMPP_{100\%ET}$	$DMPP_{50\%ET}$	$OM_{100\%ET}$	$OM_{50\%ET}$
Leaves	6.4±1.9[a]	4.3±0.3[b]	6.4±1.9	5.1±0.7	6.6±2.0	6.2±1.9
Stems	2.2±0.1	2.1±0.1	2.2±0.3	2.7±0.5	2.7±0.5[a]	2.0±0.1[b]

M: NH_4N_{O3} + KP; DMPP: Entec 26 + KP; OM: NPK+ animal manure. Different letters indicate significant differences.

Table 3. Maximal PSII photochemical efficiency (F_v/F_m). Data are mean (n=9) ± SE.

	Fertilisation treatments					
	$M_{100\%ET}$	$M_{50\%ET}$	$DMPP_{100\%ET}$	$DMPP_{50\%ET}$	$OM_{100\%ET}$	$OM_{50\%ET}$
54 DAT	0.78±0.01	0.79±0.01	0.79±0.01	0.78±0.01	0.77±0.01	0.77±0.02
76 DAT	0.79±0.01	0.76±0.02	0.78±0.01	0.75±0.03	0.76±0.01	0.75±0.03

M: NH_4N_{O3} + KP; DMPP: Entec 26 + KP; OM: NPK+ animal manure.

in water stressed plants compared to well-watered plant (Table 3), leading to a reduction in fruit yield (Figure 2E). Instead, the high efficacy of DMPP in mitigate NH_4^+ oxidation during the fast growth of plants, when wheatear conditions were unfavorable for a fast degradation of 3,4-dimethylpyrazole phosphate molecular (soil temperature below 20°C, data not shown), allowed to maintain a good plant growth under limited water supply. Barth *et al.* (2008) reported, also on a sandy soil, as DMPP efficiently inhibits nitrification under limited soil water content, thus allowing high NH_4^+ accumulation in the soil that will be readily available for plant growth (Peet *et al.,* 1985). As a consequence, DMPP plants enhanced crop N uptake (*i.e.* total biomass weight multiplied by N tissue content) and NEU (*i.e.* the ratio between crop yield and applied N) leading, under water shortage, to a higher fruit yield compared to M and OM plants (Figure 2E).

Cumulative N_2O fluxes

During the studied period, ranging from May to July 2012, the highest and lower cumulative N_2O fluxes (in absolute value) were found respectively in M plots and DMPP plots under well waterd

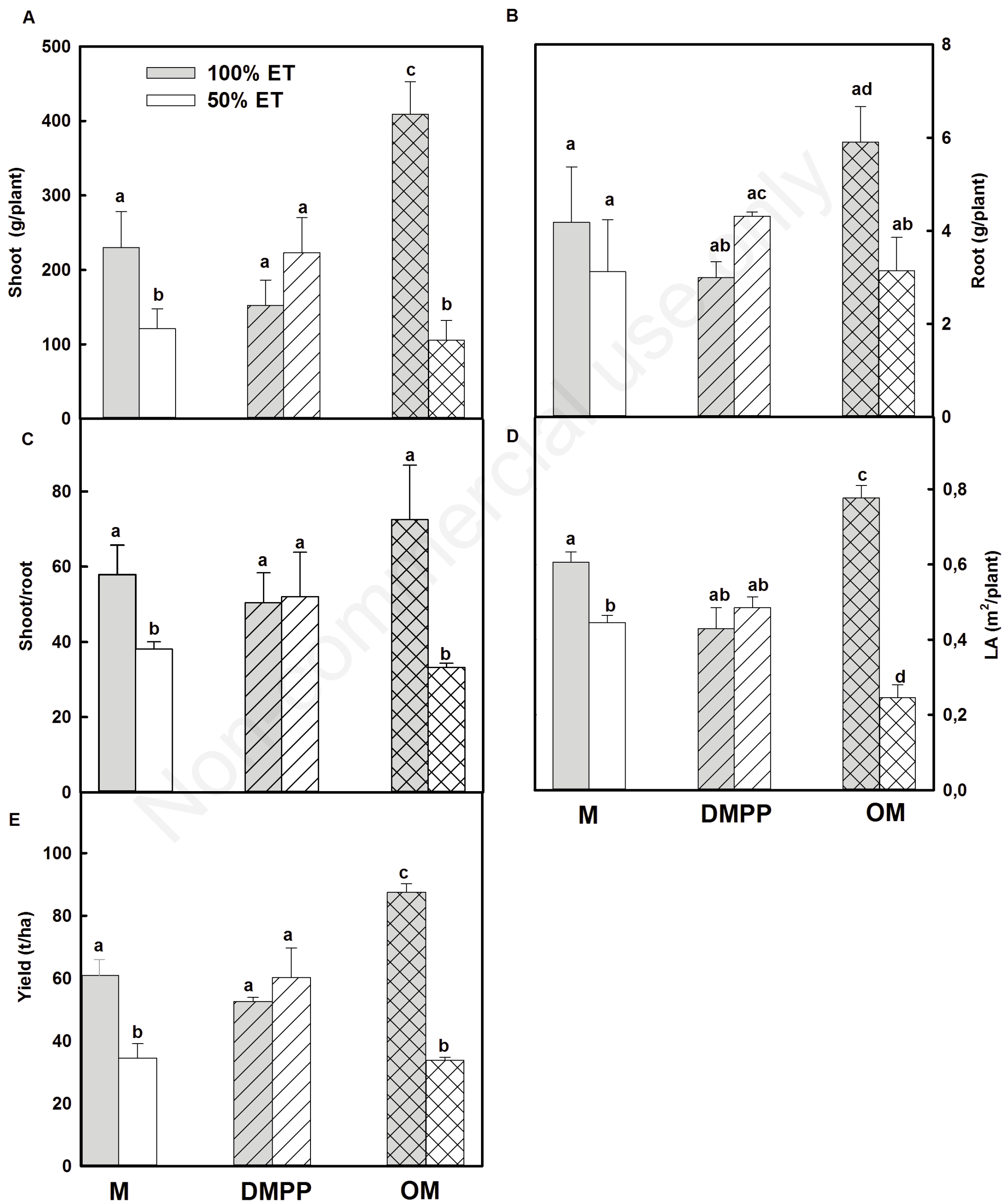

Figure 2. Above-ground biomass (A); Below-ground biomass (B); Shoot/root ratio (C); Leaf area (D); Fruit production (E). Data are mean (n=9) ± SE. M: NH_4NO_3 + KP; DMPP: Entec 26 + KP; OM: NPK + animal manure. Different letters indicate significant differences.

conditions, corresponding to about 230 kg ha^{-1} CO_2 eq and 80 kg ha^{-1} CO_2 eq. This values do not result dangerous for environment; thus it can be stated that crops managment in this study was so to derterm a low impact on global environmental.

Cumulative N_2O emission was lower ($P<0.05$) in DMPP compared to M and OM treatments under condition of adequate water supply (Figure 3), highlighting the effectiveness of DMPP in mitigating nitrification, the main process involved in N_2O production. On the other hand, N_2O fluxes were similar between M and OM plots (Figure 3). Field studies report higher N_2O emissions in response to animal manure fertilisation with respect to synthetic N fertilisers (Bouwman *et al.,* 2002). In our study, this difference could be related to the higher NEU and N uptake by plants grown under organo-mineral fertilisation compared to those grown under mineral fertilisation, as the latter could suffer from a reduced soil N availability, a critical factor for biological N_2O production.

We observed a reduction in cumulative N_2O fluxes under conditions of limited water supply in M and OM plots (Figure 3). Soil moisture is one of the main factors affecting N_2O production and a reduced water content in the soil has been reported to reduce N_2O emission, as also confirmed by the positive relationship between N_2O fluxes and Water Filled Pore Spavce (WFPS) (Table 4). The reduction of N_2O emissions under water scarsity in M and OM plots could be related to the reduced availability in the soil of N in a form readily available for biological N_2O production. On the contrary, a significant increase in cumulative N_2O fluxes was observed in DMPP plots (Figure 3) under water shortage, likely due to a reduced capacity of 3,4-dimethylpyrazole phosphate to mitigate NH_4^+ oxidation, a consequence of increased soil temperature under conditions of reduced soil moisture. It is well known that the 3,4-dimethylpyrazole phosphate (DMPP) degradation is faster under soil temperature above 20°C, as found in this study during late spring and summer (data not shown). In fact, a positive corrrelation between N_2O fluxes and soil temperature (T_{soil}) as well as a negative corrrelation between N_2O fluxes and WFPS in DMPP plots were observed (Table 3), evidencing the reduced power of DMPP in limiting NH_4^+ oxidation. Nevertheless, soil N_2O emission values measured in DMPP plots under water scarsity were lower in absolute term compared to those measured in M and OM plot recorded under well-water irrigation. As expressed in CO_2 eq they were about 180 kg ha^{-1}, not dangerous for global environment.

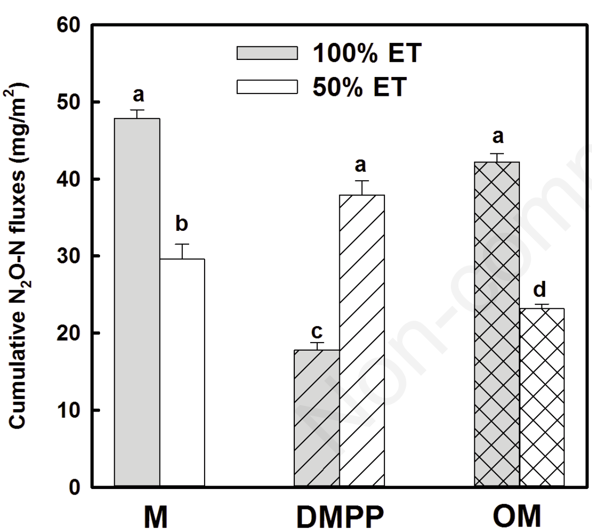

Figure 3. Cumulative N_2O fluxes. Data are mean (n=3) ± SE. M: NH_4NO_3 + KP; DMPP: Entec 26 + KP; OM: NPK + animal manure. Different letters indicate significant differences.

Table 4. Correlation coefficients of Spearman rank order correlation between soil N_2O fluxes and soil temperature (T_{soil}) and water filled pore space (WFPS) during tomato growing season.

	T_{soil}	WFPS
M	0.12	0.67*
DMPP	0.62*	–0.54*
OM	0.19	0.59*

M: NH_4NO_3 + KP; DMPP: Entec 26 + KP; OM: NPK+ animal manure. *The asterisk indicates significant correlation.

Conclusions

Crops management determined low N_2O emissions from soil resulting in a low impact on global environment as refferred to emissions expressed in CO_2 eq.

Organo-mineral fertilisation proved a more efficient nutrient source compared to mineral fertilisation, leading to a significant improvement in crop yield. It is well-known that organic colloids strongly holds mineral nutrients, that are progressively released when organic matter is degraded. This provides plants with nutrients at the later stages of the crop development. On the other hand, mineral fertilisers containing nitrates makes N readily available already during the early vegetative growth stages. However, the mineral fertiliser added with nitrification inhibitor (DMPP) reduced marcately the N_2O emission.

The reduced performance of organo-mineral fertiliser under water shortage is a likely consequence of unfavourable soil environmental conditions for the mineralisation of the organic component. The environmental conditions during the course of the experiment were such as to limit NH_4^+ oxidation by DMPP, with consequent benefits on crop N uptake and yield but not to mitigate soil N_2O emssions that, however, were lower in absolute term compared to M and OM values recorded under well-water irrigation. Thus, it can be stated that, under reduced water supply, DMPP added-fertiliser could represent a better nitrogen source compared to conventional and organo-mineral fertilisers able to preserve crop yield and to determine soil N_2O emissions (as expressed in CO_2 eq) not dangerous for global environment.

References

Abalos D, Sanz-Cobena A, Andreu G, Vallejo A, 2016. Rainfall amount and distribution regulate DMPP effects on nitrous oxide emissions under semiarid Mediterranean conditions. Agric. Ecosyst. Environ. 238:36-45.

Alam SM, 1999. Nutrient uptake by plants under stress conditions. In: M. Pessarakli (Ed.), Handbook of plant and crop stress. Second ed. rev. and exp. Marcel Dekker, New York, NY, USA, pp. 285-313.

Ball BC, McTaggart IP, Scott A, 2004. Mitigation of greenhouse gas emissions from soil under silage production by use of organic or slow-release fertilizers. Soil Use Manage. 20:287-95.

Barth G, von Tucher S, Schmidhalter U, 2008. Effectiveness of 3,4-dimethylpyrazole phosphate as nitrification inhibitor in soil as influenced by inhibitor concentration, application form, and soil matric potential. Pedosphere 18:378-85.

Boutraa T, Akhkha A, Abdulkhaliq A, Al-Shoaibi A, Alhejeli M, 2010. Effect of water stress on growth and water use efficiency (WUE) of some wheat cultivars (*Triticum durum*) grown in Saudi Arabia. J. Taibah Univ. Sci. 3:39-48.

Bouwman, AF, Boumans LJ, Betjes NH, 2002. Modelling global annual N_2O and NO emissions from fertilized fields. Global Biogeochem. Cy. 16:1080.

Gornall J, Betts R, Burke E, Clark R, Camp J, Willett K, Wiltshire A, 2010. Implications of climate change for agricultural productivity in the early twenty-first century. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 365:2973-89.

Guardia G, Cangani MT, Sanz-Cobena A, Lucas Jr J, Vallejo A, 2016. Management of pig manure to mitigate NO and yield-scaled N_2O emissions in an irrigated Mediterranean crop. Agric. Ecosyst. Environ. 238:55-66.

Hube S, Alfaro MA, Scheer C, Brunk C, Ramirez L, Rowlings D, Grace P, 2016. Effect of nitrification and urease inhibitors on nitrous oxide and methane emissions from an oat crop in a volcanic ash soil. Agric. Ecosyst. Environ. 238:46-54.

Huérfano X, Menéndez S, Bolaños-Benavides MM, González-Moro MB, Estavillo JM, González-Murua C, 2016. The nitrification inhibitor 3,4-dimethylpyrazole phosphate decreases leaf nitrate content in lettuce while maintaining yield and N_2O emissions in the Savanna of Bogotá. Plant Soil Environ. 62:533-9.

Kaiser EA, Ruser R, 2000. Nitrous oxide emissions from arable soils in Germany - An evolution of six long-term field experiments. J. Plant Nutr. Soil Sci. 163:249-60.

Makino A, 2003. Rubisco and nitrogen relationships in rice: leaf photosynthesis and plant growth. Soil Sci. Plant Nutr. 49:319-27.

Maucieri C, Barbera AC, Borin M, 2016. Effect of injection depth of digestate liquid fraction on soil carbon dioxide emission and maize biomass production. Ital. J. Agron. 11:657-67.

Maris SC, Teira-Esmatges MR, Arbonés A, Rufat J, 2015. Effect of irrigation, nitrogen application, and a nitrification inhibitor on nitrous oxide, carbon dioxide and methane emissions from an olive (Olea europaea L.) orchard. Sci. Tot. Environ. 15:966-78.

Maxwell K, Johnson GN, 2000. Chlorophyll fluorescence - a practical guide. J. Exp. Bot. 51:659-68.

Meijide A, Gruening C, Goded I, Seurert G, Cescatti A, 2016. Water management reduced greenhouse gas emissions in a Mediterranean rice paddy field. Agric. Ecosyst. Environ. 238:168-78.

Peet MM, Raper CD Jr, Tolley LC, Robarge WP, 1985. Tomato responses to ammonium and nitrate nutrition under controlled root-zone pH. J. Plant Nutr. 8:787-98.

Rinaldi M, Rana G, 2004. I fabbisogni idrici del pomodoro da industria in Capitanata. Riv. Ital. Agrometeorol. 1:31-5 [in Italian].

Sanchez-Martin L, Vallejo A, Dick J, Skiba UM, 2008. The influence of soluble carbon and fertilizer nitrose on nitric oxide and nitrous oxide emissions from two contrasting agricultural soils. Soil Biol. Biochem. 40:142-51.

Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, 2007. Agriculture. In: B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (Eds.), Climate Change 2007: Mitigation. Contribution of Working Group III to the 4th Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, pp. 497-540.

Soares JR, Cantarella H, Vargas VP, Carmo JB, Martins AA, Sousa RM, Andrade CA, 2015. Enhanced-efficiency fertilizers in nitrous oxide emissions from urea applied to sugarcane. J. Environ. Qual. 44:423-30.

Stolk PC, Jacobs CMJ, Moors EJ, Hensen A, Velthof GL, Kabat P, 2009. Significant non-linearity in nitrous oxide chamber data and its effect on calculated annual emissions. Biogeosci. Discuss. 6:115-41.

Tost B, Prochnow A, Drastig K, Meyer-Aurich A, Ellmer F, Baumecker M, 2013. Irrigation, soil organic carbon and N_2O emissions. A review. 33:733-49.

Vallejo A, Meijide A, Boeckx UGent P, Arce A, Garcia-Torres L, Aguado PL, Sanchez-Martin L, 2014. Nitrous oxide and methane emissions from a surface drip-irrigated system combined with fertilizer management. Eur. J. Soil Sci. 65:386-95.

Vitale L, Ottaiano L, Polimeno F, Maglione G, Amato U, Arena C, Di Tommasi P, Mori M, Magliulo V, 2013. Effects of 3,4-dimethylphyrazole phosphate-added nitrogen fertilizers on crop growth and N_2O emissions in Southern Italy. Plant Soil Environ. 59:517-23.

Vitale L, Polimeno F, Ottaiano L, Maglione G, Tedeschi A, Mori M, De Marco A, Di Tommasi P, Magliulo V, 2017. Fertilizer type influences tomato yield and soil N_2O emissions. Plant Soil Environ. 63:105-110.

Wolf MW, Hopmans JW, Stockert CM, Burger M, Sanden BL, Smart DR, 2016. Effects of drip fertigation frequency and N-source on soil N_2O production in almond. Agric. Ecosyst. Environ. 238:67-77.

Yao Z, Wei Y, Liu C, Zheng X, Xie B, 2015. Organically fertilized tea plantation stimulates N_2O emissions and lower NO fluxes in subtropical China. Biogeosci. 12:5915-28.

Youssef RA, Hussein MM, Abd El-Kadier A, 2012. Growth and mineral status of barley plants as affected by drought and foliar fertilization. Life Sci. J. 9:1166-73.