

Article

Soil Water Potential Control of the Relationship between Moisture and Greenhouse Gas Fluxes in Corn-Soybean Field

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Academic Editors: Nir Y. Krakauer, Tarendra Lakhankar, Soni M. Pradhanang, Vishnu Pandey and Madan Lall Shrestha

Received: 11 March 2015 / Accepted: 11 August 2015 / Published: 19 August 2015

Abstract: Soil water potential (Ψ) controls the dynamics of water in soils and can therefore affect greenhouse gas fluxes. We examined the relationship between soil moisture content (θ) at five different levels of water potential ($\Psi = 0, -0.05, -0.1, -0.33$ and -15 bar) and greenhouse gas (carbon dioxide, CO_2 ; nitrous oxide, N_2O and methane, CH_4) fluxes. The study was conducted in 2011 in a silt loam soil at Freeman farm of Lincoln University. Soil samples were collected at two depths: 0–10 and 10–20 cm and their bulk densities were measured. Samples were later saturated then brought into a pressure plate for measurements of Ψ and θ . Soil air samples for greenhouse gas flux analyses were collected using static and vented chambers, 30 cm in height and 20 cm in diameter. Determination of CO_2 , CH_4 and N_2O concentrations from soil air samples were done using a Shimadzu Gas Chromatograph (GC-14). Results showed that there were significant correlations between greenhouse gas fluxes and θ held at various Ψ in the 0–10 cm depth of soil group. For instance, θ at $\Psi = 0$ positively correlated with measured CO_2 ($p = 0.0043$, $r = 0.49$), N_2O ($p = 0.0020$, $r = 0.64$) and negatively correlated with CH_4 ($p = 0.0125$, $r = -0.44$) fluxes. Regression analysis showed that 24%, 41% and 19% of changes in CO_2 , N_2O and CH_4 fluxes, respectively, were due to θ at $\Psi = 0$ ($p < 0.05$). This study stresses the need to monitor soil water potential when monitoring greenhouse gas fluxes.

Keywords: soil water potential; soil moisture; greenhouse gas fluxes; corn; soybean

1. Introduction

Agriculture is a significant source of carbon dioxide (CO₂), nitrous oxide (N₂O) and methane (CH₄) and the contribution to the emissions of these gases mainly depend on agricultural management practices (e.g., fertilizer applications, methods of irrigation, tillage, manure applications, crop cultivation, burning crop residues, *etc.*) [1–3]. Agricultural soils can constitute either as a net source or sink of these greenhouse gases (GHG) [4,5]. In fact, the production and emissions of CO₂, CH₄ and N₂O are all affected by soil temperature and moisture, which in turn are influenced by soil and crop management practices [6–10]. The water status in soils is characterized by the amount of water present, known as soil water content (SWC, θ) and as a function of its energy state, called as soil water potential (SWP, Ψ) [11]. Several authors have found significant correlation between soil water and GHG fluxes [12,13]. Other authors have suggested that GHG fluxes are greater at certain levels of water in the soil and decline as water content declines [12,14]. Unfortunately, there are only few studies relating soil water content and its energy state (water potential) to GHG fluxes [15]. The objective of this study was, therefore, to assess the relationship between soil moisture (θ) held at five different levels of water potential ($\Psi = 0, -0.05, -0.1, -0.33$ and -15 bar) and CO₂, N₂O and CH₄ fluxes.

2. Experimental Section

2.1. Experimental Field

The experiment was conducted in 2011 at the Freeman farm at Lincoln University, Jefferson City, Missouri, USA. The coordinates of the experimental site are 38°34'55.8"N and 92°06'26.9"W. The soil of experimental site is a Waldron silt loam (Fine, smectitic, calcareous, mesic Aeric Fluvaquents) with an average slope of 2%. The average annual precipitation for the previous 20 years was 1037 mm and the average two-year temperatures during the growing season of May, June, July, August, and September were 19.2 °C, 24.5 °C, 29 °C, 25.4 °C, 19 °C and 13.7 °C, respectively. Forty-eight plots, 21.34 m in length by 12.19 m in width each were established in a 4.05 ha field planted with corn (*Zea mays*) and soybean (*Glycine max*). Plots were arranged in a three-factor factorial design with three replications. The three factors (treatments) were tillage at two levels (no-tillage *vs.* conventional tillage), cover crop at two levels (no-rye *vs.* rye) and rotation at four levels (continuous corn, continuous soybean, corn-soybean and soybean-corn rotations). Corn and soybean were planted in May 2011 and harvested in late October 2011. Rye (*Secale cereale*) was planted in 12 plots of both corn and soybean, immediately after harvest. Since Rye was planted in October 2011 and harvested in May 2012, its effects could be studied only in the growing of 2012, as was therefore not part of this study. In addition, although described above, in this multi-year investigation (2011–2015), the corn to soybean and soybean to corn rotation treatments only started in 2012, and are therefore not reported in this paper. All corn and soybean plots received 26 kg N, 67 kg P₂O₅, and 67 kg K₂O/ha. However, the corn plots received an additional 202 kg N/ha from urea.

2.2. Soil Air Sampling and CO₂, CH₄ and N₂O Measurements

Soil samples were collected at two depths (0–10 and 10–20 cm) at three locations (replicates) near each gas-sampling chamber (described below) in each of the 48 plots. A core sampler of 10 cm in diameter and 4.9 cm in height was used, giving a sampling volume of 384.65 cm³. A total of 288 samples (3 locations per plot × 2 depths × 48 plots). Soil samples were collected after planting and full emergence of the seeds. After collection, the fresh weights of two replicates of soil samples were recorded, then samples were put in an oven to be dried at 105 °C for 72 h. After drying, soil physical properties, such as volumetric water content, bulk density and total pore space, were determined. The relationship between these properties and field management factors was previously examined [16]. The other replicate of soil samples was saturated and then subjected to measurements of moisture (θ) at various matric potential (Ψ) using a pressure plate apparatus as described in [17]. Soil moisture was measured at the following matric potentials: 0, −0.05, −0.1, −0.33 and −15 bar.

Soil air samples for analysis of CO₂, CH₄ and N₂O were collected on the same day while collecting soil samples. Static and vented chambers, 30 cm in height and 20 cm in diameter made of polyvinyl (PVC) were installed in each of the plot for a total of 48 chambers. The apparatus for measuring these gases and the conversion of gas concentrations to fluxes was described in [18].

2.3. Statistical Analysis

Statistix 9.0 statistical software was used to generate a summary of simple statistics, as well as correlation and regression analyses.

3. Results and Discussion

3.1. Summary Statistics for Soil Moisture at Different Matric Potentials

The matric potential has been a useful way to describe the availability of soil water and the ability of plants to extract it. The magnitude of matric potential depends on soil water content, the size of soil pores, the surface properties of soil particles, and the surface tension of soil water [19].

Table 1 shows soil moisture content determined at five different matric potentials ($\Psi_m = 0, -0.05, -0.1, -0.33$ and -15 bar). The values of matric potential range from zero, when the soil is saturated, to increasingly negative values, as the soil becomes drier [20]. In magnitude, a large difference was found in soil moisture content between matric potentials 0 and -0.05 bar, as showed by soil moisture content levels of 0.33 and 0.21 m³m^{−3}, respectively.

3.2. Summary Statistics for Measured Soil GHG Fluxes

Table 2 shows that CO₂ flux from experimental plots ranged from 318.05 to 764.78 mg C-CO₂ m^{−2} h^{−1} during the study period. The mean was 477.83 with a median of 462.37 mg C-CO₂ m^{−2} h^{−1}. The closeness between the mean and median values suggests that CO₂ distribution approached normality. Nitrous oxide (N₂O) flux ranged from -108.49 to 285.81 µg N-N₂O m^{−2} h^{−1}. CH₄ flux ranged from -315.26 to 751.47 µg C-CH₄ m^{−2} h^{−1}. Similarly to N₂O, the flux data from individual plots show

both uptake and emission of CH₄ during different sampling periods. However, the average flux was very low, 16.82 µg C-CH₄ m⁻² h⁻¹.

Table 1. Descriptive statistics for soil moisture (θ , m³m⁻³) at five different matric potentials.

Statistics	$\Psi_m = 0$	$\Psi_m = -0.05$	$\Psi_m = -0.1$	$\Psi_m = -0.33$	$\Psi_m = -15$
Mean	0.33	0.21	0.13	0.12	0.09
SD	0.07	0.04	0.01	0.01	0.02
C.V.	21.86	21.61	9.25	8.61	18.47
Minimum	0.18	0.11	0.10	0.09	0.06
Median	0.34	0.21	0.13	0.12	0.09
Maximum	0.45	0.31	0.16	0.14	0.12
Skew	-0.33	-0.12	-0.09	0.39	0.07
Kurtosis	-1.09	0.71	-0.39	0.30	-1.40

Table 2. Descriptive statistics for CO₂, N₂O and CH₄ fluxes in 2011.

Statistics	CO ₂ (mg C-CO ₂ m ⁻² h ⁻¹)	N ₂ O (µg N-N ₂ O m ⁻² h ⁻¹)	CH ₄ (µg C-CH ₄ m ⁻² h ⁻¹)
Mean	477.83	21.02	16.82
SD	125.67	100.87	292.21
C.V.	26.30	479.85	1737.10
Minimum	318.05	-108.49	-315.27
Median	462.37	-15.65	-110.04
Maximum	764.78	285.82	751.47
Skew	0.94	1.04	1.07
Kurtosis	0.03	0.45	0.20

The negative values of N₂O suggest that there was an uptake or consumption of N₂O flux during this investigation. Net N₂O consumption has been measured under various conditions, from the tropics to temperate areas, and in natural and agricultural systems. Low mineral N and large moisture contents have sometimes been found to favor N₂O consumption. This fits in with denitrification as the responsible process, reducing N₂O to N₂. However, it has also been reported that nitrifiers consume N₂O in nitrifier denitrification. A combination of various processes can explain the wide range of conditions found to allow N₂O consumption, ranging from low to high temperatures, wet to dry soils, and fertilized to unfertilized plots. Generally, conditions interfering with N₂O diffusion in the soil seem to enhance N₂O consumption [21]. However, the factors regulating N₂O consumption are not yet well understood and merit further study.

3.3. Relation between Soil Moisture and GHG Fluxes

Results showed that when the matric potential (Ψ) was close to 0 bar, *i.e.*, saturated conditions at the 0–10 cm depth, soil moisture was positively correlated with CO₂ ($p = 0.0043$, $r = 0.49$) and N₂O ($p = 0.0020$, $r = 0.64$) fluxes, but negatively correlated with CH₄ ($p = 0.0125$, $r = -0.44$) fluxes. Similarly, we found that there was a significant correlation between CO₂ fluxes and $\Psi = -0.05$ bar ($p = 0.05$, $r = 0.47$). The relationship between soil moisture held at matric potential close to zero and

GHG fluxes was more apparent for N₂O, as demonstrated in Figure 1, which shows a positive correlation between N₂O fluxes and θ at $\Psi_m = 0$ bar ($p = 0.0020$, $r = 0.64$).

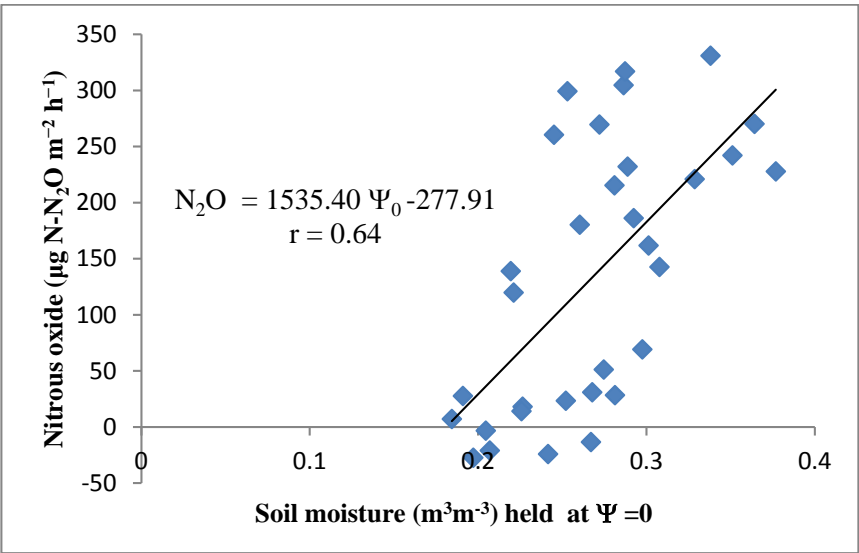


Figure 1. Correlation between soil moisture held at $\Psi = 0$ and N₂O fluxes.

The figure suggests that when soil moisture content is higher, it accelerates soil microbial activity and root respiratory activity [22] resulting in more N₂O emissions. Similarly, the greater the soil moisture content, the greater the N₂O emissions will be, because both the nitrification and denitrification processes are influenced by moisture [23]. Methane (CH₄) flux also varied from uptake to emissions. In fact, CH₄ is formed in soils by the microbial breakdown of organic compounds in strictly anaerobic conditions, at a very low redox potential [24]. However, there is also some evidence that nitrifiers can also oxidize CH₄ [25] and, hence, NH₄⁺ competes at the enzyme’s active site, inhibiting CH₄ emissions.

Table 3. Linear regression analysis ($Y = a + b x$) between soil moisture held at five different levels of matric potential and greenhouse gases fluxes.

Y	X	A	B	F	<i>p</i>	R ²
CO ₂	$\Psi_m = 0$	95.719	1800.780	9.530	0.004	0.241
	$\Psi_m = -0.05$	316.975	1323.160	7.420	0.011	0.230
	$\Psi_m = -0.1$	660.242	−1446.240	0.570	0.455	0.019
	$\Psi_m = -0.03$	692.787	−1891.690	0.420	0.520	0.014
	$\Psi_m = -15$	754.336	−2589.960	0.550	0.463	0.050
N ₂ O	$\Psi_m = 0$	−277.910	1535.410	20.810	0.000	0.410
	$\Psi_m = -0.05$	−462.235	2259.790	1.280	0.267	0.041
	$\Psi_m = -0.1$	106.962	−681.353	0.200	0.662	0.007
	$\Psi_m = -0.33$	90.396	−610.499	0.070	0.796	0.245
	$\Psi_m = -15$	24.162	−29.411	0.000	0.992	0.000
CH ₄	$\Psi_m = 0$	2391.670	−7649.010	7.050	0.013	0.190
	$\Psi_m = -0.05$	90.330	−370.831	0.180	0.672	0.071
	$\Psi_m = -0.1$	−810.305	6557.660	2.300	0.140	0.071
	$\Psi_m = -0.33$	−669.196	6037.050	0.810	0.375	0.026
	$\Psi_m = -15$	−1247.560	11842.900	2.260	0.143	0.070

Table 3 shows the results of a linear regression analysis between GHG fluxes and soil moisture held at 5 different matric potentials. The results suggest that CO₂ emissions were controlled by soil moisture when it was held at $\Psi = 0$ and $\Psi = -0.05$. Twenty-four percent of changes in CO₂ emissions were due to soil moisture being held at $\Psi = 0$ while 23% of changes in CO₂ emissions were due to soil moisture being held at $\Psi = -0.05$. For N₂O and CH₄, however, 41% and 19% of changes in these two gas fluxes were due to soil moisture being held at $\Psi = 0$.

4. Conclusions

The study indicates that soils that had higher water content near saturation (matric potentials close to zero) had higher measured CO₂ and N₂O emissions and higher CH₄ uptake, whereas water content under dry conditions (low matric potentials) was less variable and did not show significant correlations with GHG emissions. Since soil moisture availability is controlled by the matric potential at which this water is held, this study stresses the need to monitor soil water potential when monitoring greenhouse gases fluxes.

Acknowledgments

This research is part of a regional collaborative project supported by the USDA-NIFA, Award No. 2011-68002-30190, “Cropping Systems Coordinated Agricultural Project: Climate Change, Mitigation, and Adaptation in Corn-based Cropping Systems.” Project Web site: <http://sustainablecorn.org>

Author Contributions

Panday carried out the main part of writing, and coauthor contributed for data analysis and important intellectual content; author and coauthor approved the final manuscript for publication.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Horowitz, J.; Gottlieb, J. The Role of Agriculture in Reducing Greenhouse Gas Emissions. Available online: http://www.ers.usda.gov/media/140711/eb15_1_.pdf (accessed on 07 February 2015).
2. Satterthwaite, W. Cities’ contribution to global warming: Notes on the allocation of greenhouse gas emissions. *Environ. Urban.* **2008**, *20*, 539–549.
3. Tubiello, F.N.; Salvatore, M.; Rossi, S.; Ferrara, A.; Fitton, N.; Smith, P. The FAOSTAT database of greenhouse gas emissions from agriculture. *Environ. Res. Lett.* **2013**, *8*, doi:10.1088/1748-9326/8/1/015009.
4. Gregorich, E.G.; Rochette, P.; VandenBygaart, A.J.; Angers, D.A. Greenhouse gas contributions of agricultural soils and potential mitigation practices in Eastern Canada. *Soil Tillage Res.* **2005**, *94*, 262–263.
5. Mosier, A.R.; Halvorson, A.D.; Reule, C.A.; Liu, X.J. Net global warming potential and greenhouse gas intensity in irrigated cropping systems in Northeastern Colorado. *J. Environ. Qual.* **2006**, *35*, 1584–1598.

6. Kuzyakov, Y. Sources of CO₂ Efflux from soil and review of partitioning methods. *Soil Biol. Biochem.* **2006**, *38*, 425–448.
7. Firestone, M.K.; Davidson, E.A. Microbiological basis of NO and N₂O production and consumption in soil. In *Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere*; Andraea, M.O., Schimel, D.S., Eds.; John Wiley & Sons: New York, NY, USA, 1989; pp. 7–21.
8. Laughlin, R.J.; Stevens, R.J. Evidence for fungal dominance of denitrification and Codenitrification in a grassland soil. *Soil Sci. Am. J.* **2002**, *66*, 1540–1548.
9. Davidson, E.A.; Janssens, I.A. Temperature sensitivity of soil carbon decomposition and Feedbacks to climate change. *Nature* **2006**, *440*, 165–173.
10. Conrad, R. Control of methane production in terrestrial ecosystems. In *Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere*; Andraea, M.O., Schimel, D.S., Eds.; John Wiley & Sons: New York, NY, USA, 1989; pp. 39–58.
11. Campbell, G.S.; Gee, G.W. Water potential: Miscellaneous methods. In *Methods of Soil Analysis*; Klute, A., Ed.; ASA and SSSA: Madison, WI, USA, 1986; Volume 9, pp. 619–633.
12. Linn, D.M.; Doran, J.W. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. *Soil Sci. Soc. Am. J.* **1984**, *48*, 1267–1272.
13. Davidson, E.A.; Louis, V.V.; Cattanio, J.H.; Ackerman, I.L.; Carvalho, J.E.M. Effects of soil water content on soil respiration in forests and cattle pastures of Eastern Amazonia. *Biogeochemistry* **1998**, *48*, 53–69.
14. Orchard, V.A.; Cook, F. Relationship between soil respiration and soil moisture. *Soil Biol. Biochem.* **1983**, *15*, 447–453.
15. Gun-Yeob, K.; Jeong, H.; Sonn, Y.; Kim, S.; Lee, J.; Kim, P.J. Effect of soil water potential on methane and nitrous oxide emissions in upland soil during red pepper cultivation. *J. Korean Soc. Appl. Biol. Chem.* **2014**, *57*, 15–22.
16. Haruna, S.; Nkongolo, N.V. Effects of tillage, cover crop and corn-soybean rotation on the Chemical and physical properties of a silt-loam soil. Master Thesis, Lincoln University of Missouri, Jefferson, MO, USA, May 2013.
17. Caruso, M.; Jommi, C. Enhancement of a commercial pressure plate apparatus for soil water retention curves. *Unsaturated Soils: Res. Appl.* **2012**, doi:10.1007/978-3-642-31116-1_9.
18. Nkongolo, N.V.; Johnson, S.; Eivazi, F.; Schmidt, K. Greenhouse gases fluxes and soil thermal properties in a pasture in Central Missouri. *J. Environ. Sci.* **2010**, *22*, 1029–1039.
19. Whalley, W.R.; Ober, E.S.; Jenkins, M. Measurement of the matric potential of soil water in the Rhizosphere. *J. Exp. Bot.* **2013**, *64*, 3951–3963.
20. Cassel, D.K.; Klute, A. Water potential: Tensiometry. In *Methods of Soil Analysis: Part 1. Physical and Mineralogical Methods*, 9, 2nd ed.; Klute, A., Ed.; American Society of Agronomy—Soil Science Society of America: Madison, WI, USA, 1986; pp. 563–596.
21. Lydie, C.L.; Wrage, N.; Metay, A.; Chotte, J.; Bernoux, M. Soils, a sink for N₂O? A review. *Glob. Change Biol.* **2007**, *13*, 1–17.
22. Edwards, N.T. Root and soil respiration responses to ozone in *Pinus taeda* L. seedlings. *New Phytol.* **1991**, *118*, 315–322.

23. Davidson, E.A.; Swank, W.T. Environmental parameters regulating Gaseous-N losses from two forested ecosystems *via* nitrification and denitrification. *Appl. Environ. Microbiol.* **1986**, *52*, 1287–1292.
24. Ponnamperna, F.N. The chemistry of submerged soils. *Adv. Agron.* **1972**, *24*, 29–96.
25. Silvia, D.M. *Principles and Applications of Soil Microbiology*, 2nd ed.; Pearson Prentice Hall: Upper Saddle River, NJ, USA, 2005.

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