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Highlights

- Topography influenced cover crop performance, CO_2 and N_2O emissions.
- The performance of rye cover was poorer at the depressions than at the slopes and summits
- The amounts of CO_2 and N_2O emissions were higher in the depressions than in the slopes and summits.
- Sensitivity of CO_2 emissions to soil temperature was higher in cover crop than no cover crop treatments.
- CO_2 emissions from the ridge tillage were higher than from the chisel tillage.
- We observed no significant effects of cover crop and tillage treatments on N_2O emissions.

Title: Cover crop and tillage systems effect on soil CO_2 and N_2O fluxes in contrasting topographic positions

Wakene Negassa[a, 1,] , Richard F. Price[a], Abdul Basir[b], Sieglinde S. Snapp[a], and Alexandra Kravchenko[a*]

[a]Plant, Soil and Microbial Sciences, Michigan State University, Plant & Soil Sciences Building, 1066 Bogue St., East Lansing, MI 48824

[b]Department of Agronomy, University of Swabi, KP, Pakistan

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[1]Present address: Institute for Advanced Sustainability Studies, Berliner St. 130, 14467, Potsdam, Germany. *Corresponding author: Alexandra Kravchenko, email: kravche1@msu.edu

Abstract

Soils are important sources of CO_2 and N_2O emissions to the atmosphere. Introducing cover crop and conservation tillage are among the strategies to improve soil organic carbon (SOC) and nitrogen (N) sequestration potentials with potential to reduce the amounts of greenhouse gases (GHG) emitted from soil. The objectives of the study were to evaluate CO_2 and N_2O emissions in rye cover crop and tillage system treatments in contrasting topographical positions. Two replicated field experiments were established in 2011 at Kellogg Biological Station and Mason Research Farm sites, located in Southwest and Central Michigan, respectively. At each site, two replications of three contrasting topographical positions, namely depression, slope and summit were used. The two studied factors were tillage system (chisel plow and ridge tillage) and winter rye cover crop (present and absent). Topographical positions significantly affected the performance of rye cover crop with above ground biomass ranged from 80 to 200 kg ha^{-1} and 120 to >500 kg ha^{-1} in depressions and summits, respectively. The presence of rye cover tended to increase CO_2 emissions across all topographical positions. However, the amount of increases in the CO_2 emissions was ~15 mg m^2 hr^{-1} and <5 mg m^2 hr^{-1} in depressions and summits, respectively, which were inversely proportional to the amount of rye biomass inputs. Ridge tillage had significantly higher CO_2 emissions than chisel tillage in depressions and showed increasing trends at the slopes and summits. Neither the effect of cover crop nor tillage system was found to be statistically significant across the whole study period on N_2O emissions. Regression analysis indicated that both CO_2 and N_2O emissions were positively associated with soil temperature. The effect of temperature on CO_2 emissions was most pronounced in management treatments with cover crops and in topographical depressions. Per a unit increase in the soil temperature was a greater increase in the CO_2 emission in the depression areas than in

other parts of the landscape. The results of the present study highlight existence of complex interactive influences among cover crop presence, tillage, and topography driven variations in soil properties on the resulting soil GHG emissions.

Keywords: greenhouse gas; rye cover crop; depression; ridge tillage; topography

1. Introduction

World soils contain as much as 2,400 Gt C from the soil surface to a depth of 2 m, which is more than four times the amount of carbon in terrestrial biota and three times of that in the atmosphere (Hillel and Rosenzweig, 2011). Conventional agricultural practices have been known to contribute to climate change through GHG including CO_2, and N_2O. Adding cover crops, crop rotation, and conservation tillage to conventional cropping systems are among the strategies to enhance SOC and N sequestration potentials to adapt and mitigate climate changes (Liebig et al., 2012). The role of cover crops in increasing SOC sequestration, improving soil and water quality by reducing nutrient losses and soil erosion is well known (e.g., Miguez and Bollero, 2005; Scholberg et al., 2010).

Farmers choose to grow and manage specific cover crop types based on their own needs and goals influenced by the biological, environmental, social, cultural and economic factors of the food systems in which they operate (Snapp et al., 2005). Winter rye has been gaining in popularity as a cover crop for row crop systems due to its winter hardiness. Rye cover takes up a high proportion of residual nitrogen (Ruffo et al., 2004; McSwiney et al., 2010), reduces soil erosion**,** enhances SOC sequestration and suppresses weeds and pests (Shipley et al. 1992; Edwards et al., 1993; Duiker and Curran, 2005). Rye is also one of the best cool-season cover crops that withstand the lowest winter temperatures, particularly in the Midwest United States (Clark, 2007). However, when rye is planted across large agricultural fields with high topographical diversity, the variations in surface topography can affect its performance and the magnitude of the environmental benefits provided by the rye cover crop.

The conventional tillage system has been practiced to destroy and disrupt pest life cycles, distribute nutrients in soil, and control weeds (Alvarez and Steinbach, 2009). At the same time, conventional tillage can enhance runoff, soil erosion and loss of associated plant nutrients and SOC depending on surface topography (e.g. Rutberg et al., 1996; West and Post, 2002; Shrestha et al 2013). An alternative is to use conservation tillage, which can reduce soil disturbance, microbial activity, and CO_2 and N_2O emissions (Sainju et al., 2012). Ridge tillage is a type of conservation tillage that can be particularly effective in providing soil and environmental benefits to row crop agricultural systems. In a course of ridge tillage, ridges are made in equal row spacing and subsequent crops are planted on top of the ridges. Crop residues are left on the slopes of the ridges and are incorporated in the soil once a year when the ridges are remade. Thus, ridge tillage affects distribution of soil moisture, bulk density and SOC (Shi et al., 2012) and mineralizable soil N (Kane et al., 2015). This type of tillage system is usually used for early planting in poorly drained soils, for reducing erosion on contour slopes, for conserving soil moisture, and for decreasing the production costs and weed infestation (Hatfield et al., 1998; Sijtsma et al., 1998; Pikul et al., 2001; Archer et al., 2002). Combinations of increased carbon inputs together with reductions in tillage intensity can potentially reduce CO_2 and N_2O emissions from agricultural soils (Dabney et al., 2001). However, little information is available on the effects of ridge tillage on soil CO_2 and N_2O emissions.

Variations in soil environmental characteristics, e.g., soil moisture and temperature, in conjunction with management effects can either hinder or enhance CO_2 and N_2O emissions in a given cropping system. Specifically, soil moisture and temperature determine microbial activities in biogeochemical processes that lead to C and N transformations and GHG production. Variations in soil CO_2 emissions were found to be associated with changes in temperature, water filled pore space, incorporated plant residues and tillage intensity, whereas N_2O emissions were associated with nitrogen fertilizer applications, temperature, soil nitrate levels, and rainfall events (Franzluebbers, 2005; Stehfest and Bouwman, 2006; Hoben et al., 2011; Abdalla et al., 2014). Seasonal weather patterns also influence soil CO_2 and N_2O emissions because of the high variability of soil moisture and temperature (Liu et al., 2008). For instance, N_2O emissions measured throughout two growing seasons showed 10 times higher emission rates in a warmer year than a colder year (Hansen et al., 2014).

Surface topography is known to greatly affect the soil characteristics related to CO_2 and N_2O emissions, including soil temperature and moisture, soil hydrologic cycle (Delin et al., 2000; Vilain et al., 2010), in situ denitrification (Pennock et al., 1992), and SOC, soil pH and available phosphorus (Dessalegn et al., 2014). Topography can also greatly affect the growth of main crops (Kravchenko and Bullock, 2000; Huang et al., 2008), and clover cover crop performance (Muñoz and Kravchenko, 2012). However, most of the experimental field work is traditionally conducted on the field sites with minimal topographical variations. This precludes analysis of the influence of the land use and management practices on GHG emissions in topographically diverse landscapes, which constitute the majority of the agricultural land in the US Midwest. We hypothesize that the effects of cover crop presence and tillage on soil CO_2 and N_2O emissions can vary depending on topography-driven variations in soil hydrology, soil characteristics, and plant growth patterns.

The objectives of the study were to examine how contrasting topography influences (i) performance of rye cover crop in maize-soybean based rotation systems under chisel and ridge tillage practices, (ii) effects of rye cover crop on CO_2 and N_2O emissions, (iii) effects of chisel and ridge tillage systems on CO_2 and N_2O, and (iv) effects of soil moisture and temperature on CO_2 and N_2O emissions.

2. Materials and methods

2.1. Description of study sites

The data for this study were collected from two experimental sites: Kellogg Biological Station (KBS) and Mason Research Farm (Mason). KBS is located in Southwest Michigan (42° 24’ N, 85° 24’ W) and has the mean annual temperature of 10°C and annual precipitation of 1027 mm with about half of the precipitation received as snow (Shcherbak and Robertson, 2014). The soils of KBS are well drained Typic Hapludalfs of the Kalamazoo (fine-loamy, mixed, mesic) and Oshtemo (coarse-loamy, mixed, mesic) series, developed on glacial outwash (Mokma and Doolittle, 1993; Crum and Collins, 1995). Mason Research Farm is located in central Michigan (42° 37’ 45.6 N and 84° 26’ 6.74 W). Its mean annual temperature is 13°C and annual precipitation is 977 mm yr^{-1}. The soils of the Mason site are Capac (fine-loamy, mixed, active, mesic Aquic Glossudalfs) and Marlette (fine-loamy, mixed, semiactive, mesic Oxyaquic Glossudalfs) series.

2.2. Experimental setup

The treatment design consisted of four studied factors: topographical position with three levels (depression, slope, and summit) (Fig. 1), phase of the main crop rotation (maize or soybean), tillage (chisel plow or ridge), and rye cover crop (present or absent). At each site, the experiment was a randomized complete block design in a multiple split-strip-plot arrangement.

Specifically, topographical position was the main plot factor. At each experimental site two whole plots were identified within each of the three topographical positions. Each whole plot was split into two sub-plots, and two phases of rotation (either maize-soybean or soybean-maize) were assigned at random to the sub-plots within each whole plot. Then the whole plots were split into two halves in an opposite direction and one of the two tillage practices was assigned at random to each half. The sub-sub-plots of each rotation-tillage combination within each whole plot were further split, and the level of the cover crop treatment (either present or absent) was assigned to each half.

((Figure 1 will be inserted here))

2.3. Soil sampling and analysis

Prior to the establishment of the research plots, soil cores were collected from each experimental plot for baseline soil measurements using a Giddings hydraulic soil probe (Giddings Machine Company, Windsor, Colorado). Three soil core samples were collected from the upper 0-10 cm and field replications were mixed and subsamples were used for analysis of selected soil properties. Soil bulk density was estimated from undisturbed soil samples taken with a core sampler (Hao et al., 2008), whereas soil particle size distribution was measured by the hydrometer method (Kroetsch and Wang, 2008). The buffered soil pH was determined by lime index method, and soil organic matter (SOM) was estimated with loss on ignition method (Jolivet et al., 1998). The available phosphorus, cation exchange capacity (CEC) and exchangeable cations were measured with Mehlich 3 (Mehlich, 1984).

2.4. Cover crop and main crop agronomy

Starting from 2011, cereal rye (*Secale cereale*) var. Aroostook was established after maize and soybean harvest in cover crop experimental plots. At the Mason site, rye was planted using a John Deere 445 grain drill (John Deere, Moline, Illinois) at 112 kg ha^{-1} seeds rate on 3 November 2011 and 29 October 2012. At KBS site, rye was planted using a John Deere 750 grain drill at 112 kg ha^{-1} seeds rate on 18 November 2011 and 10 November 2012. The biomass were collected from two 0.5 m x 0.5 m quadrats randomly placed within each plot before terminating the rye cover crop for planting the main crops. Rye was sampled at Mason on 27 April 2012 and 14 May 2013. At KBS, rye was sampled on 6 May 2012 and 8 May 2013. Rye was terminated with glyphosate [N-(phosphonomethyl) glycine] applied at a rate of 2.3 liters a.i. ha^{-1} while Ammonium Sulfate (sprayable, CAS #7783-20-2) applied at a rate of 11.97 g L^{-1} ha^{-1}. The harvested rye plant material was dried to a constant mass at 60 °C using a forced air oven and weighed to determine above ground biomass yield.

We chisel plowed to a depth of 20 cm after rye kill and before planting the main crops. Mason site was chisel plowed on 17 May 2012 and 21 May 2013. KBS site was chisel plowed on 14 May 2012 and 15 May 2013. Ridge tillage was completed after the main crop planting when maize plants reached the V6 stage. Ridge treatments were cultivated with a Hiniker 6003 ridge cultivator (Hiniker Company, Mankato, MN) on 3 July 2012 and 11 July 2013 at Mason and 6 July 2012 and 10 July 2013 at KBS.

The main crops of maize and soybeans were established in a 2-yr rotation at the start of the project. Channel hybrid 193-46VT3 seed maize was planted at a rate of 88,958 seeds ha^{-1} on 17 May 2012 and 5 June 2013 at Mason, and 15 May 2012 and 4 June 2013 at KBS. Channel 2305R2 RR2Y soybeans were planted at a rate of 333,592 seeds ha^{-1} on 17 May 2012 and 5 June 2013 at Mason and 18 May 2012 and 4 June 2013 at KBS. All maize plots received 168 kg ha^{-1}

N yr^{-1}: 34 kg ha^{-1} as a starter fertilizer at planting, and another 135 kg ha^{-1} at side-dress application as urea. These experiments were rain-fed and went without supplemental irrigation.

2.5. Greenhouse gas sampling

The Greenhouse gas samples were taken during 2012 and 2013 growing seasons from cover and no-cover plots with a maize main crop of both tillage treatments at all topographical positions. Rectangular aluminum static flux chambers were manufactured locally for the CO_2 and N_2O measurements following the protocols of Parkin and Venterea (2010). Each chamber consisted of two parts: a permanent anchor driven into the soil and a flux chamber cap equipped with a vent tube and a sampling port. The surface area of the anchor was 37.5 cm x 75.0 cm for chisel tillage plots and 41.0 cm x 79.5 cm for ridge tillage plots. The heights of chamber caps were 10 and 20.5 cm for chisel and ridge tillage plots, respectively. The surface area of ridge tillage flux chamber was slightly greater than that of the chisel tillage to accommodate the ridges and furrow that could create gradients in CO_2 and N_2O emissions. Similarly, the height of the chamber cap was double for the ridge tillage plots to accommodate the height of the ridge.

The CO_2 and N_2O were sampled from surface soil covered with rectangular static flux chambers with infrared Photoacoustic Spectroscopy (PAS) (1412 Photoacoustic multi-gas monitors; INNOVA Air Tech Instruments, Ballerup, Denmark). Details of the instrumentations and calibration of PAS were provided by Iqbal et al. (2013). The gas sampling was conducted from 8:00 a.m. to 12:00 p.m. weekly/biweekly from May to September during 2012 and 2013 growing seasons.

CO_2 and N_2O concentrations were measured with PAS at two minute intervals for a total of seven times per each flux determination per plot. The emissions were computed following the procedures outlined by Parkin and Venterea et al (2010):

$$F = \frac{(f * M * Atm)}{(R * T)} * \frac{Chv}{SA}$$

where *F*: CO_2-C or N_2O-N emissions (mg m^{-2}), *f*: CO_2 or N_2O measured with PAS (ppm), *M*: atomic mass of N or C, *Atm*: atmospheric pressure, *R*: universal gas constant (0.0820575 L atm/mol/K), *T*: temperature (K), *Chv*: chamber volume (m^3), *SA*: surface area of chamber (m^2). Linear regressions were fitted to the gas emissions obtained with the above equation, F (mg m^{-2}) vs time of sampling (hr.) to determine the rates of the CO_2 and N_2O emissions as outlined in the trace gas measurement protocol (Parkin and Venterea et al., 2010). The rates of CO_2-C and N_2O-N (hereafter called CO_2 and N_2O) emissions were used for further statistical analyses.

Soil temperature and moisture were measured alongside with CO_2 and N_2O emissions. Pocket thermometers (Taylor Precision Products, Oak Brook, Illinois, 60523) were used to measure soil temperature during gas measurements at two different positions near the chamber's anchor: in the row and in-between the rows, the latter corresponded to furrows in the ridge tillage. Soil moisture was measured using time domain reflectance (IMKO HD-2 IMKO GmbH, Ettlingen, Germany). Readings were made at three separate points around the anchor.

2.6. Statistical analysis

Statistical analysis of the rye biomass and rates of CO_2 and N_2O emissions were conducted using the PROC MIXED procedure in SAS (SAS Institute, 2012). Topography, tillage, rye cover crop presence and their interactions were treated as fixed effects in the statistical models, while plots, sub-plots, and sub-sub-plots nested within their respective factors were treated as random effects and used as error terms. Normality of the residuals was assessed using normal probability plots and stem-and-leaf plots using the PROC UNIVARIATE procedure. Whenever necessary the data were transformed using either square root or natural log transformation to achieve normality.

Linear regression analysis was carried out to examine the relationship between soil temperature and moisture with CO_2 and N_2O emissions at different topographical positions, cover crop and tillage systems. SAS procedure PROC REG was used for the regression analysis.

3. Results and discussion

3.1. Selected soil properties

The surface topography significantly affected a number of measured soil properties ($P<0.05$) at both KBS and Mason sites (Table 1). The soil particle size distributions were significantly different among topographical positions except for sand at KBS and clay at Mason sites. The significantly higher amount of sand at the depressions of Mason site than at the summits and slopes was unusual as lower amount of sand is typically expected at the depressions (Dessalegn et al., 2014) and could possibly be associated with its past history as an outwash. Bulk density was significantly higher at the summits of KBS and depressions of Mason sites. Consistent with other studies (Khan et al., 2013); higher values of bulk density at the depression of Mason site were associated with the higher amount of sand.

Exchangeable bases and CEC tended to be the highest at slopes while the lowest at summits of both sites. The higher values of exchangeable bases and CEC at the slope positions agreed with a similar study reported by Ebeid et al. (1995). The authors indicated that the concentration of exchangeable K, Ca and Mg, and CEC increased as the top soil was removed by erosion. Topography is one of the soils forming factors and continued soil removal from slopes hinder soil development and relatively high exchangeable bases and CEC are characteristics of young soils. The soil pH was significantly higher at the slopes than at the summits and depressions of Mason site, whereas there were no significant differences in soil pH among topographical positions at KBS site. The higher soil pH at the slopes than at the summits and depressions of the Mason site can be explained by higher amounts of exchangeable bases and CEC at the slopes.

The available P concentration was higher by three folds at the depressions of the Mason site than at the slopes and summits, and significantly lower at the slopes than at the summits and depressions of KBS site. The wider range between the depressions and the other topographical positions in concentration of available P clearly indicated that P is continually transported from the slopes and summits by erosion and deposited at the depressions. The magnitude of differences among topographical positions, soil types, prevailing weather conditions, and soil management practices are known to affect amounts of P transported and deposited at depressions (Siemens et al., 2008; Negassa and Leinweber, 2009).

Consistent with numerous previous observations (e.g., Changere and Lal, 1997; Kravchenko and Bullock, 2000; Khan et al., 2013) concentration of the SOM was the highest at the depressions followed by summits and then slopes. The highest concentration of SOM at depressions can be attributed to accumulation from the summits and slopes by erosion, greater carbon inputs from better vegetation growth at lower topographic positions, and frequent water logging at depressions, which can slow down SOM turnover rate.

((Table 1 will be inserted here))

3.2. Performance of rye cover crop

Overall rye performance in the studied sites was relatively poor and the above ground biomass of rye cover was in the range of 100 to 500 kg ha^{-1} (Fig. 2). These levels of the above ground rye cover biomass were several folds lower than the levels that were suggested as necessary for providing economic and environmental cover crop benefits (Duiker, 2014; Farsad et al., 2011).

The worst performance of rye cover crop was observed in depressions as compared with slopes and summits. In 2012, rye cover biomass of the depressions was significantly lower than in the summits at both KBS ($p<0.05$) and Mason sites ($p<0.1$). In 2013, the depressions had numerically lower rye biomass values, but the differences were not statistically significant. The poor performance of rye cover crop in depressions was associated with overall poorer growing spring conditions, i.e. cold and wet with frequent waterlogging (Table 2).

The performance of rye cover crop was significantly higher ($P<0.05$) in chisel tillage treatment than in ridge tillage at the slopes of the KBS site in both 2012 and 2013 cropping seasons (Table 3). The significantly lower performance of rye cover crop in ridge tillage treatment at the slopes of KBS site was attributed to exposure of many rocks with ridge formation that hindered the growth of rye cover crop on the ridges.

((Figure 2 will be inserted here))

((Table 2 will be inserted here))

((Table 3 will be inserted here))

3.3. Effects of topography and soil management on CO_2 and N_2O emissions

3.3.1. Topography

The overall emission of CO_2 and N_2O were significantly ($P<0.05$) higher in depression areas than at slopes and summits (Fig. 3). High levels of SOM and soil moisture (Table 1 and 2) are the most likely reasons for the higher CO_2 emission in depressions. The rate of CO_2 emissions under favorable temperature and moisture conditions has been reported to be limited by labile SOM (Parkin et al., 1996). The present finding is consistent with the result reported from the Northern Mixed Grass Prairie of Canada, where the largest CO_2 emission was recorded at the depression (Braun et al., 2013).

((Figure 3 will be inserted here))

The higher N_2O emission at depressions can be associated with higher soil moisture contents. Consistent with our results, Corre et al (1996) reported higher N_2O emissions at the depressions than at the slope positions in cropland, fallow, pasture and forest sites in Canada. Similarly, higher N_2O emissions were observed at the depressions of an agricultural plateau to the riparian buffer, grassland, and a forest site in France (Vilain et al., 2010). Furthermore, the temperature sensitivity of the N_2O emission exhibited the spatial trend of increasing with descending slope in Japanese coniferous forests and N_2O emissions at the depressions were higher than at the summits (Nishina et al., 2009). Although overall topographical positions affected N_2O emissions, the patterns varied seasonally as soil moisture, temperature and soil available nitrogen changes (Izaurralde et al., 2004).

3.3.2. Cover crop

Presence of cover crops numerically increased CO_2 emissions in all three topographic positions (Fig. 4a). Consistent with our observations, Sanz-Cobena et al. (2014) reported that barley (*Hordeum vulgare* L.) and vetch (*Vicia villosa* L) cover crops increased CO_2 emission by 21-28%. While Kallenbach et al. (2010) observed higher CO_2 emissions in treatments with a winter legume cover as compared to no cover crop. The higher CO_2 emissions with cover crop treatments can be attributed to the presence of the labile fraction of SOM derived from the cover crops.

However, it is interesting to notice that the greatest increase in the CO_2 emissions due to cover crop presence was observed in depressions ($p<0.05$), while the increase was smaller on slopes ($p<0.1$) and not statistically significant in summits (Fig. 4a). As discussed earlier, depressions have produced the lowest amounts of rye biomass as compared with slopes and summits in the two years of the study. Thus, it should be noted that it was not just the amounts of cover crop inputs that were driving the differences in CO_2 emissions. Most likely the CO_2 emission differences resulted from a combined effect of two components: the presence of the cover crop inputs/root activities and the inherent soil properties at each topographical position. This observation is consistent with our earlier results which indicated that in the presence of fresh plant residue; structure and characteristics of soil pores can have a substantial effect on soil CO_2 emission (Negassa et al., 2015). It is possible that the addition of cover crop inputs to the depression areas resulted in priming effect (Guenet et al., 2012) that enhanced decomposition of native SOC stimulated by additions of fresh plant residue inputs.

The presence of rye cover crop did not affect N_2O emissions at any topographical position (Fig 4b). Different studies reported contrasting results with regard to cover crop effects on N_2O emissions (Abdalla et al., 2012; Mitchell et al., 2013). A meta-analysis of 26 peer-reviewed articles demonstrated that 60% of the published studies reported that the presence of cover crops increased N_2O emissions, while 40% reported decreases N_2O emissions due to cover crop presence (Basche et al., 2014). The contrasting findings could be explained by variations in cover crop performances, soil characteristics, cropping systems, methods of cover crop incorporation and seasons of N_2O samplings among the studies.

((Figure 4 will be inserted here))

3.3.3. Tillage systems

The CO_2 emissions under the ridge tillage system were numerically higher than under chisel tillage at all three topographical positions, but it is at the depressions that the difference tended to be statistically significant ($p<0.1$) (Fig. 5a). The higher CO_2 emission with ridge tillage treatment can be attributed to higher levels of soil moisture in ridge tillage as compared to chisel tillage (Table 2). Hatfield et al (1998) also reported that ridge tillage changes soil moisture pattern as compared to other tillage systems. Tillage systems not only influence soil moisture, but also expose protected labile SOM fractions that can be reflected in the rate of CO_2 emissions.

There were no significant differences between chisel and ridge tillage systems in terms of N_2O emissions (Fig. 5b). Extremely high temporal and spatial variability in N_2O emission data is the most likely reason for difficulty in detecting statistically significant differences between the two tillage systems in N_2O emissions in this study (Kravchenko and Robertson, 2015). The influence of tillage systems on GHG emissions also can vary depending on soil characteristics. For instance, Rochette (2008) demonstrated that no-tillage system generally increased N_2O emissions in poorly-aerated soils, but were neutral in soils with good and medium aeration. Although soil moisture content slightly increased with ridge tillage treatment in the present study, the differences apparently were not sufficiently high to result in detectable differences in N_2O emissions in the spring and summer of 2012 and 2013.

((Figure 5 will be inserted here))

3.3.4. Variability of CO_2 and N_2O emissions

The variance of CO_2 emission data was the highest in depression areas in both growing seasons and both experimental sites (Fig. 6), whereas variances of N_2O emission data were similar across topographical positions, growing seasons and locations (data not shown). The highest variability of CO_2 emissions at depressions could be due to greater variations in soil moisture and temperature there during the sampling period (May to September). Soil CO_2 emissions can exhibit pronounced day-to-day differences arising from management effects and soil moisture and temperature variations (Parkin and Kaspar, 2004).

Surprisingly, even though tillage had no detectable effect on the mean levels of N_2O emissions (Fig. 5b), the variability of N_2O emission data was significantly higher in ridge tillage than in chisel across both sites and both studied years ($p<0.1$) (Fig. 7). The high variability in N_2O emissions in ridge tillage is primarily driven by very high N_2O flux values in the 1-2 weeks immediately after the formation of the ridges that took place in July of both years. The formation of ridges produced a substantial soil disturbance that led to short-term spikes in N_2O emissions at both sites of both years. Interestingly, there was only a minor increase in CO_2 emissions after ridge formation observed at the Mason (but not KBS) site in 2012.

((Figure 6 will be inserted here))

((Figure 7 will be inserted here))

3.3.5. Soil moisture and temperature

Average soil temperature and moisture of the two seasons differed among topographical positions, with the highest soil moisture observed at depressions and the highest temperature values at slopes (Table 2). However, tillage systems and rye cover crop presence did not significantly influence soil moisture and temperature; with only slightly numerically higher soil moisture levels observed in the ridge tillage.

Regression analysis indicated that the CO_2 emissions were significantly and positively associated with soil temperature in all topographical positions. The significant effects of soil temperature on CO_2 emission were consistent with those reported previously. For instance, regression analysis indicated that soil temperature accounted for 65%, soil moisture for 5%, and air temperature for 3% of variability in CO_2 emissions (Frank et al., 2002).

However, there was a tendency for regression slope values between CO2 emissions and temperature to vary across the landscape, with the highest and the lowest values observed in the depressions and slopes, respectively (Table 4). The differences in the regression slopes among the topographical positions were statistically significant at both sites in 2012. A similar numeric trend of higher regression slopes in the depressions was observed at both sites in 2013; although the differences were not statistically significant. The greater regression slopes indicate that per a unit increase in the soil temperature was a greater increase in the CO_2 emission in depression areas than in the slopes. The higher SOM, presumably associated with greater microbial activity in depression areas, is a likely explanation for the observed greater response of the CO_2 emission values to increase soil temperature. Another factor possibly contributing to stronger relationships between CO_2 emission and temperature at the depressions were the overall higher soil moisture levels (Table 2). For example, during hot dry periods in summer, especially pronounced in 2012, soils in slopes and summits were too dry to support substantial microbial activity and CO_2 emissions, while there might still be sufficient soil moisture in the depressions.

Across both years and both study sites, the regression slopes between CO_2 emissions and temperatures were significantly higher in the cover crop than in the no cover plots (Table 4). Greater sensitivity of CO_2 emissions to soil temperature in cover crop plots was likely reflecting greater presence of fresh cover crop plant residues and their decomposition was likely faster at optimal temperatures. To the best of our knowledge, this is the first report of differences in CO_2 relationships with temperatures due to cover crop presence under field conditions.

The regression analysis revealed a lack of significant differences between soil moisture and CO_2 emissions (data not shown). Studies conducted on different land use also observed lack of relationship between soil moisture and CO_2 emissions (Reth et al., 2005). Whereas Kallenbach et al (2010) reported a negative relationship between soil moisture and CO_2 emissions. The contribution of soil moisture is well known for SOM mineralization and CO_2 emissions (Abera et al., 2012, Srivastava et al., 2012). However, the relationship of soil moisture and temperature with CO_2 emissions can depend on labile fractions of SOC and microbial activity dynamics over time.

((Table 4 will be inserted here))

The linear regression between N_2O emissions and soil temperature was not significant in any of the topographical positions and cover crop treatments (data not shown). However, there was a tendency for higher regression slopes between soil temperature and N_2O emission in ridge tillage than in chisel tillage (Table 5). Greater regression slope values in ridge tillage than chisel tillage indicate that a unit increase in soil temperature resulted in a greater increase in N_2O emissions under ridge tillage than under the chisel. There was no significant relationship between soil moisture and N_2O in both chisel and ridge tillages. N_2O emissions were demonstrated to be positively related to soil temperature (Schindlbacher and Zechmeister-Boltenstern, 2004); and to have their optimum in the range of 70-80% water-filled pore space (Butterbach-Bahl et al., 2013). However, the relationships between N_2O and soil moisture, and N_2O and soil temperature are known to be not consistent in different growing seasons (Dyer et al., 2012). Furthermore, many soil physical, chemical and biological properties affect N_2O emissions that masked the effects of soil temperature and moisture both in the present and previous studies (Robertson, 1994). Our results indicate that topography and tillage practice can also be among the factors that influence the magnitude of the sensitivity in GHG emissions to soil temperature variations.

((Table 5 will be inserted here))

4. Conclusion

The topography influenced rye cover crop performance, soil moisture and temperatures, as well as CO_2 and N_2O emissions. The performance of rye cover crop was inferior at depression to the slope and summit areas. The greatest amounts of CO_2 and N_2O fluxes produced in topographical depressions.

Presence of rye cover crop increased CO_2 emissions across all topographical positions; however, counterintuitively, the largest increases in CO_2 emissions due to cover crop presence were observed in the depression areas where amounts of rye biomass inputs were the lowest. Both temporal variability and sensitivity of CO_2 emissions to soil temperature was substantially higher in the depressions than in the slopes and summits. Moreover, sensitivity of CO_2 emissions to variations in soil temperature was much higher in treatments with cover crops than in treatments without cover crops. CO_2 emissions from ridge tillage were higher than those in chisel across all topographical positions.

No significant effect on mean values of N_2O emissions from either cover crop presence or tillage was detected, likely resulting from extremely high variability of N_2O data. However, higher temporal variability of N_2O data in ridge tillage than chisel tillage reflected during the short period by substantial spikes in N_2O emissions immediately after the formation of the ridges. Temperature sensitivity in N_2O emissions was also higher in ridge tillage than chisel tillage management.

Our findings demonstrate that topographical variations can influence not only the overall amounts of emitted CO_2 and N_2O, but also the magnitude of the effects that different land use and management practices, such as use of cover crop and tillage, have on the GHG emissions. These influences are likely driven by topography induced variations in soil organic matter, soil temperature and soil moisture. Based on the obtained results it is suggested that the influence of topography should be considered when generating large scale estimates of the impacts of different land use and management practices on greenhouse gas emissions.

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Table 1

Selected soil physical and chemical properties at 0-10 cm depth at the three studied topographical positions of the KBS and Mason experimental sites. Means of each soil property within each site followed by the same letters are not significantly different from each other at ($P<0.05$). SOM: soil organic matter; CEC: cation exchange capacity; BpHΨ: buffered soil pH.

KBS	Sand	Clay	Silt	Bulk density	SOM	BpHΨ	P	CEC	K	Ca	Mg
Position		%		g cm^{-3}	%		ppm			$cmol_c$ kg^{-1} soil	
Summit	57.82a	8.38b	33.81a	1.57a	1.93	6.78a	20.13a	5.83b	0.13b	3.08a	1.38
Slope	64.17a	14.72a	21.11b	1.52b	1.90	6.74a	16.94b	6.82a	0.17a	3.61a	1.71
Depression	56.71a	11.20a	32.10a	1.53b	2.18	6.76a	18.13a	5.87b	0.18a	2.88a	1.31
Mason											
Summit	63.62b	13.16a	23.22a	1.53b	1.81b	5.59b	22.5b	5.69b	0.29a	2.95a	0.99a
Slope	61.59b	14.24a	24.17a	1.50b	1.64b	6.13a	19.87b	7.33a	0.35a	4.05a	1.59a
Depression	67.83a	7.77b	24.40a	1.58a	2.24a	5.39b	71.25a	6.96a	0.51a	3.39a	0.91b

Table 2

Effects of tillage systems on the average soil temperature and soil moisture contents across the two studied seasons at the three studied contrasting topographical positions. The differences between the two tillages were not statistically significant at each topographic position. Different letters indicate statistically significant differences among topographic positions across both tillages ($p<0.05$).

		Soil temperature (2012 & 2013)			Soil moisture (2012 & 2013)		
Topography	Tillage	No cover	Cover		No cover	Cover	
		°C			%		
Depression	Chisel	22.43	22.08	a	18.88	19.47	a
	Ridge	22.66	22.41		21.71	20.44	
Slope	Chisel	25.87	25.71	c	14.99	15.13	b
	Ridge	24.39	24.69		15.31	17.64	
Summit	Chisel	23.87	24.10	b	16.32	16.79	b
	Ridge	23.28	23.95		18.62	18.56	

Table 3

Effect of tillage systems on rye cover crop biomass. Different letters between chisel and ridge tillages at slopes of KBS indicate significant difference at ($P<0.05$).

		KBS		Mason	
Topography	Tillage	2012	2013	2012	2013
			Kg ha^{-1}		
Depression	Chisel	58.28	91.91	242.14	164.81
	Ridge	94.44	118.34	236.72	135.83
Slope	Chisel	179.44a	142.56a	334.88	272.04
	Ridge	86.38b	95.07b	269.01	174.27
Summit	Chisel	118.28	129.22	605.57	223.00
	Ridge	169.58	167.25	467.16	236.70

Table 4

Slopes from simple linear regression analysis between soil temperature and CO_2 emission at a) different topographical positions of the two studied sites during 2012 and 2013 growing seasons and b) at managements with and without cover crop across both sites and both studied years. #Regression slopes within the same site and the same year followed by different letters are significantly different from each other (p<0.05). ** and * indicate the linear regressions that were statistically significant at (P<0.05) and (P<0.1), respectively.

a)		
	KBS	
	2012	2013
	Slope	Slope
Depression	4.95a#**	6.47**
Slope	0.97b*	5.96**
Summit	3.13a**	7.10**
	Mason	
Depression	5.99a**	7.74**
Slope	1.90b*	5.18**
Summit	3.17ab**	6.84**

b)	
No cover	4.04a**
Cover	5.70b**

Table 5

Slopes from the simple linear regression analysis between soil temperature and N_2O emission at the two tillage systems of the two studied sites during 2012 and 2013 growing seasons.

[#]Regression slopes within the same site and the same year followed by different bold and regular letters are significantly different from each other at p<0.05 and p<0.1 levels, respectively. ** indicate the linear regressions that were statistically significant at (P<0.05)

	KBS	
	2012	2013
Tillage	Slope	Slope
Chisel	0.002**a**[#]	0.007
Ridge till	0.041**b****	-0.003
	Mason	
Chisel	0.014**a****	0.006a
Ridge till	0.035**b****	0.049b**

Fig. 1. Elevation of topographical positions and distributions of blocks at each experimental site

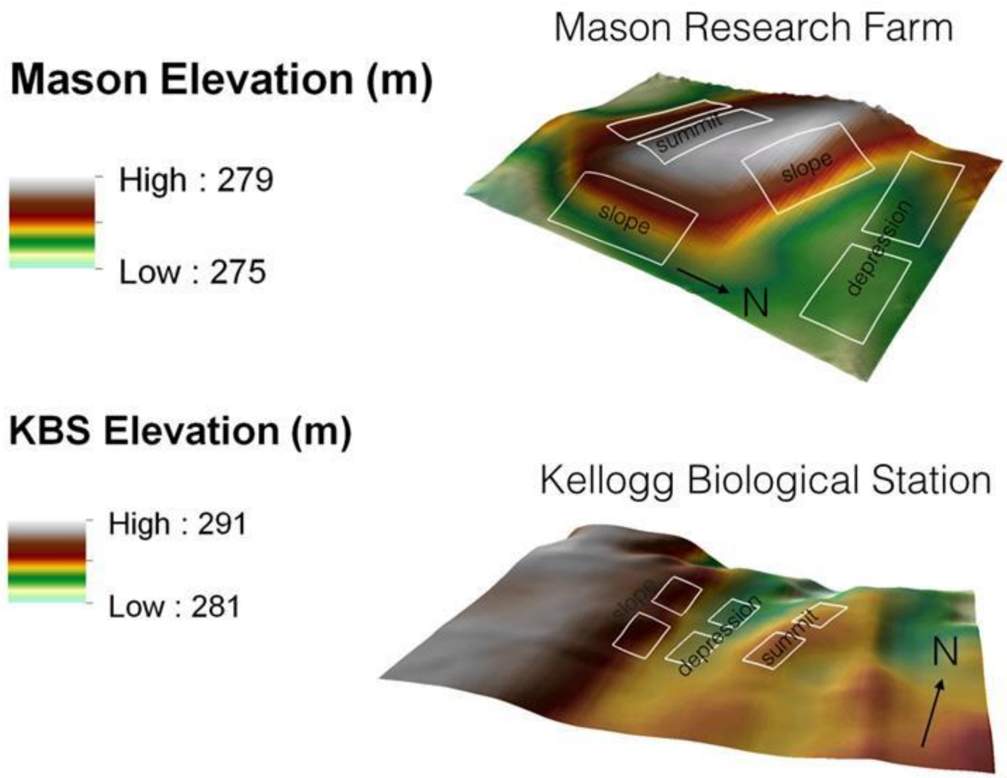

Fig. 2. Aboveground biomass of rye cover crop at the two studied experimental sites in 2012 and 2013. Different letters show significant differences among topographic positions at (P<0.05) for KBS and at (P<0.1) for Mason in 2012 cropping season. There were no statistically significant differences among topographical positions in both sites in 2013. The bars of the columns indicate standard errors of the mean.

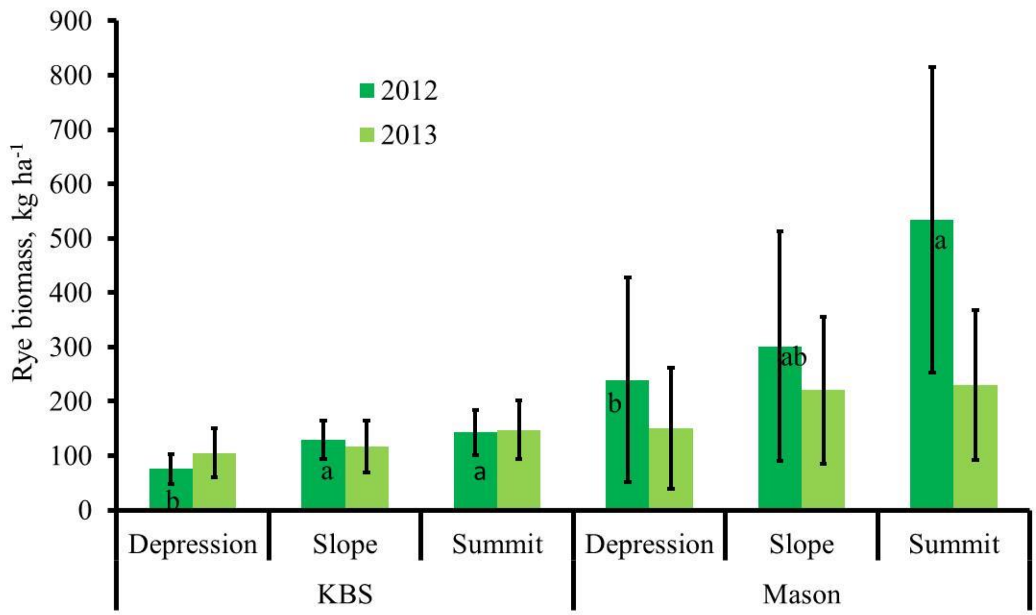

Fig. 3. Effect of topographic position on emission of CO_2 (A) and N_2O (B) across the two studied experimental sites during 2012 and 2013 growing seasons. Different letters indicate presence of significant differences among topographic positions ($p<0.05$). The bars of the columns indicate standard errors of the mean.

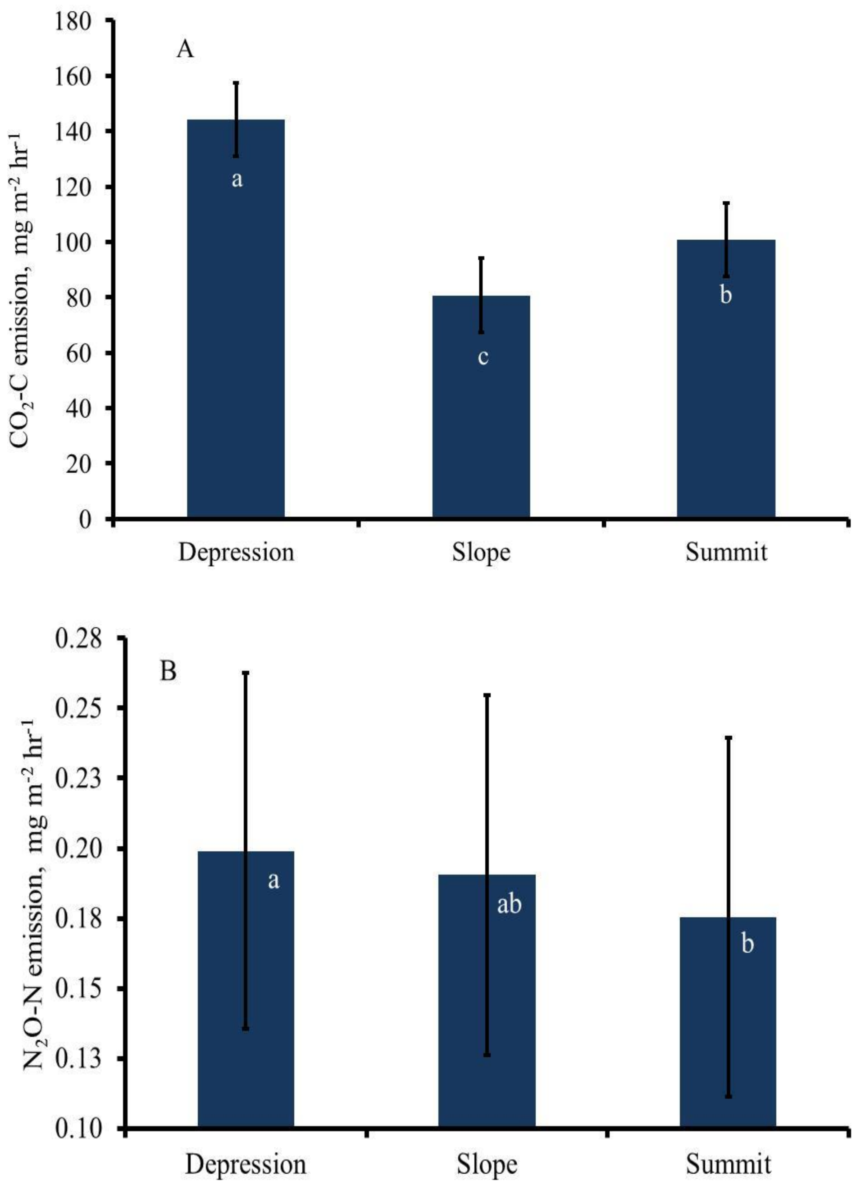

Fig. 4. Cover crop effects on CO_2 (A) and N_2O (B) emissions at different topographic positions during 2012 and 2013 growing seasons. Significant differences between managements with and without cover crops within the same topographical position are marked with ** ($p<0.05$) and * ($p<0.1$). The bars of the columns indicate standard errors of the mean.

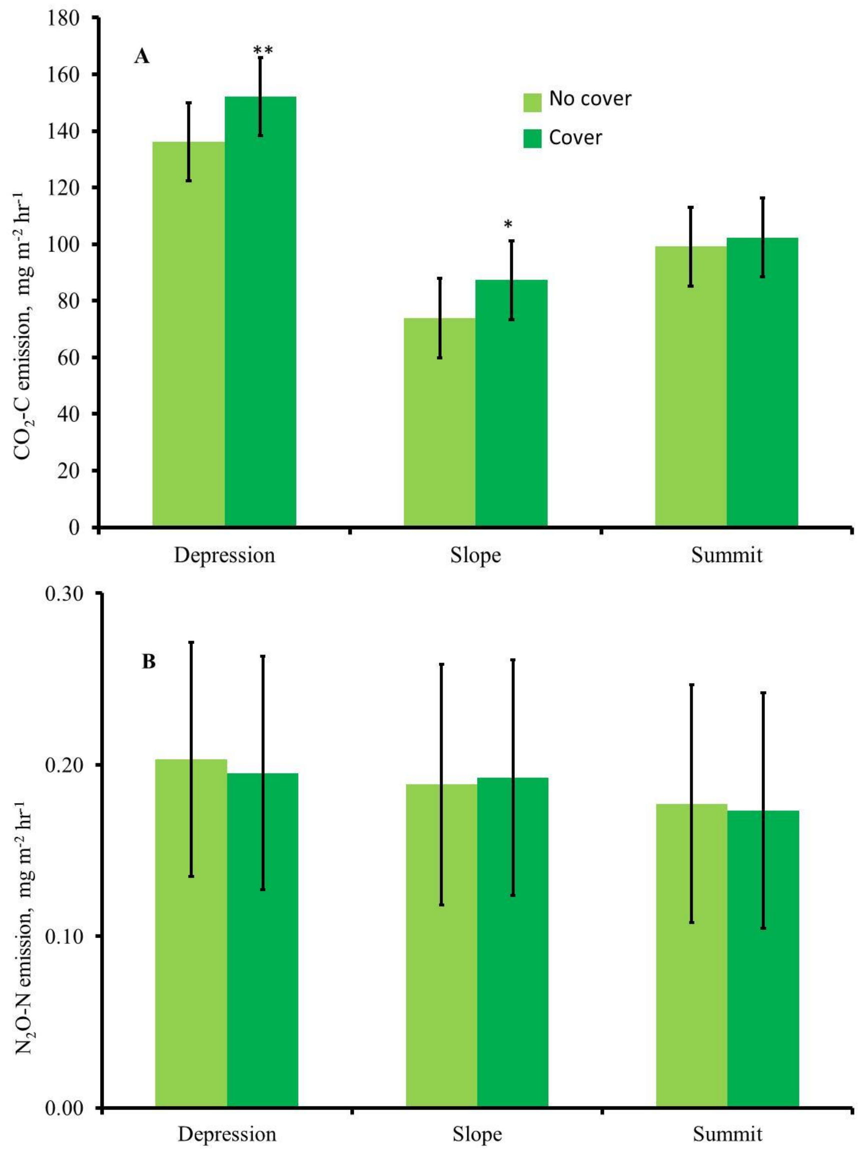

Fig. 5. Effect of tillage systems on CO_2 (A) and N_2O (B) emission at different topographic positions across 2012 and 2013 growing seasons. At the two tillages different in CO_2 emission in depressions (marked by *) (P<0.1). The bars of the columns indicate standard errors of the mean.

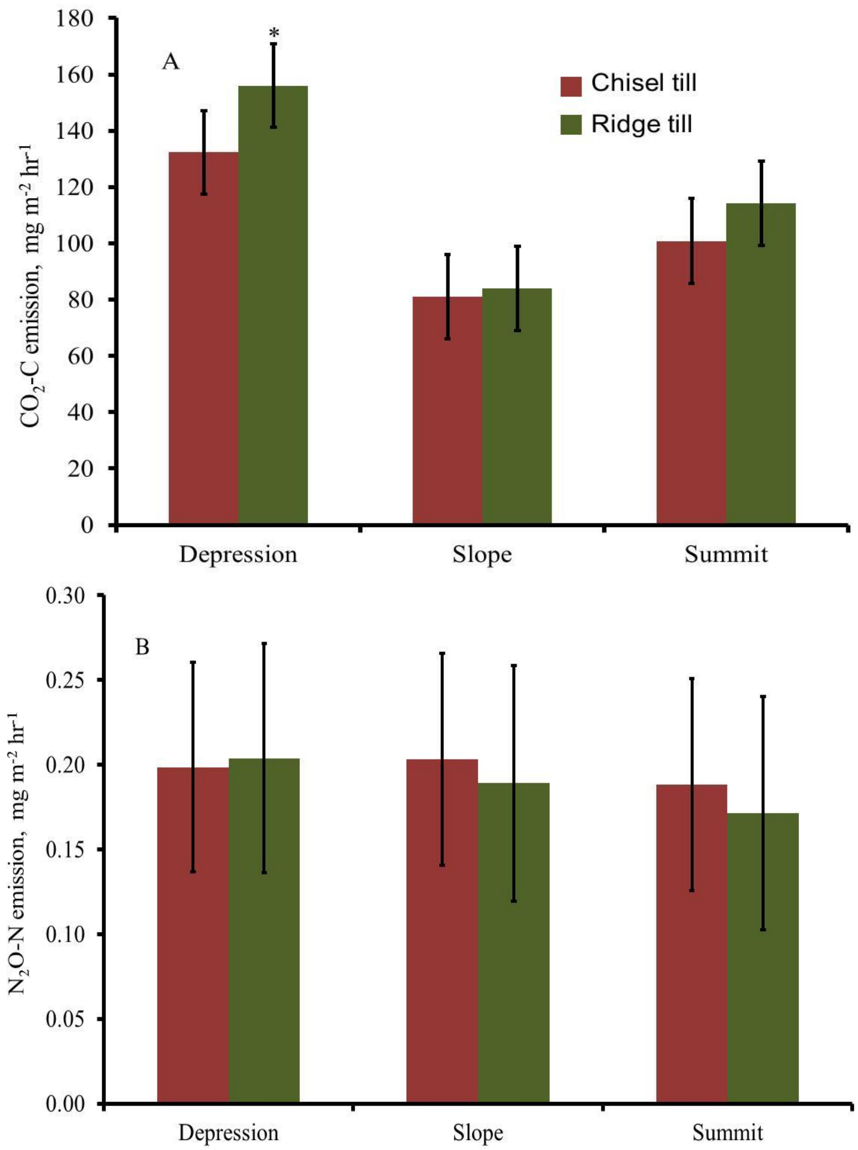

Fig. 6. Variance of CO_2 emission data at the studied topographical positions. Variance in depressions was significantly higher than that in slopes and summits in both sites of both years (p<0.05).

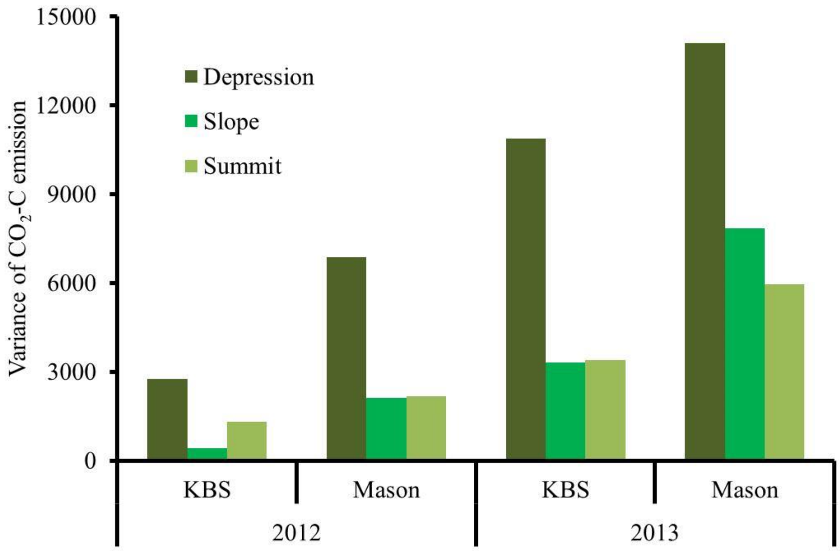

Fig. 7. Variance of N_2O emission as affected by different tillage systems. Within each year and site the tillages marked by * are significantly different from each other (p<0.1).