Influence of conservation tillage on Greenhouse gas fluxes and crop productivity in spring-wheat agroecosystems on the Loess Plateau of China

Abdul-Rauf Malimanga Alhassan Equal first author, 1, 2, Chuangjie Yang Equal first author, 1, Weiwei Ma 1, Li Guang Corresp. 1

1 College of Forestry, Gansu Agricultural University, Lanzhou, Gansu, China
2 Department of Water Resources Development, University of Environment and Sustainable Development, Somanya, Eastern Region, Ghana

Corresponding Author: Li Guang
Email address: liguang468@yahoo.com

The effects of climate change such as dry spells, floods and erosion heavily impact agriculture especially smallholder systems on the Northwestern Loess Plateau of China. Nonetheless agriculture also contributes to global warming through the emission of greenhouse gases such as CO₂, CH₄ and N₂O. Yet this complex conundrum can be alleviated and mitigated through sound soil and water management practices. Despite considerable literature on Conservation Agriculture (CA) as a strategy to improve the resilience and mitigation capacity of agroecosystems, there is still paucity of information on the impacts of CA on crop production and environmental quality on the Plateau. In order to fill this gap this study examined the effects of no-till and straw mulch on crop productivity and greenhouse gas fluxes in agroecosystems on the Plateau where farmers’ common practice of conventional tillage (CT) was tested against 3 CA practices: conventional tillage with straw mulch (CTS), no-till (NT) and no-till with straw mulch (NTS). The results indicated that all 3 CA practices (CTS, NT and NTS) markedly increased soil water content (SWC), soil organic carbon (SOC) and soil total nitrogen (STN) but reduced soil temperature (ST). Average grain yields were 854.46±76.51, 699.30±133.52 and 908.18±38.64 kg ha⁻¹ respectively under CTS, NT and NTS indicating an increase by approximately 33%, 9% and 41% respectively compared with CT (644.61±76.98 kg ha⁻¹). There were significant (p < 0.05) reductions of Net CO₂ emissions under NT (7.37±0.89 tCO₂e ha⁻¹y⁻¹) and NTS (6.65±0.73 tCO₂e ha⁻¹y⁻¹) compared with CTS (10.65±0.18 tCO₂e ha⁻¹y⁻¹) and CT (11.14±0.58 tCO₂e ha⁻¹y⁻¹). All the treatments served as sinks of CH₄ but NTS had the highest absorption capacity (-0.27±0.024 tCO₂e ha⁻¹y⁻¹) and increased absorption significantly (p < 0.05) compared with CT (-0.21±0.017 tCO₂e ha⁻¹y⁻¹) however
CA did not reduce emissions of N₂O. These had an influence on Global warming potential (GWP) as NT and NTS resulted in significant reduction in net GWP. Grain yield was significantly correlated positively with SOC and STN ($p < 0.05$); ecosystem respiration was also significantly correlated with SWC and ST while CH₄ flux was highly correlated with ST ($p < 0.001$). Crop yield and GHG responses to CA were controlled by soil hydrothermal and nutrient changes, thus improving these conditions through adoption of sustainable soil moisture improvement practices such as no-till, straw mulch, green manuring, contour ploughing and terracing can improve crop resilience to climate change and reduce GHG emissions in arid and semi-arid regions.
Influence of conservation tillage on Greenhouse gas fluxes and crop productivity in spring-wheat agroecosystems on the Loess Plateau of China

Abdul-Rauf Malimanga Alhassan¹,², Chuangjie Yang¹, Weiwei Ma¹, Guang Li¹

¹ College of Forestry, Gansu Agricultural University, Lanzhou, Gansu province, 730070, P.R. China.
² Department of Water Resources Development, University of Environment and Sustainable Development, PMB, Somanya, Ghana.

Corresponding Author:
Guang Li¹
730070, Lanzhou, Gansu Province, 730070, China
Email address: lig@gsau.edu.cn, liguang468@yahoo.com

Abstract

The effects of climate change such as dry spells, floods and erosion heavily impact agriculture especially smallholder systems on the Northwestern Loess Plateau of China. Nonetheless agriculture also contributes to global warming through the emission of greenhouse gases such as CO₂, CH₄ and N₂O. Yet this complex conundrum can be alleviated and mitigated through sound soil and water management practices. Despite considerable literature on Conservation Agriculture (CA) as a strategy to improve the resilience and mitigation capacity of agroecosystems, there is still paucity of information on the impacts of CA on crop production and environmental quality on the Plateau. In order to fill this gap this study examined the effects of no-till and straw mulch on crop productivity and greenhouse gas fluxes in agroecosystems on the Plateau where farmers’ common practice of conventional tillage (CT) was tested against 3 CA practices: conventional tillage with straw mulch (CTS), no-till (NT) and no-till with straw mulch (NTS). The results indicated that all 3 CA practices (CTS, NT and NTS) markedly increased soil water content (SWC), soil organic carbon (SOC) and soil total nitrogen (STN) but reduced soil temperature (ST). Average grain yields were 854.46±76.51, 699.30±133.52 and 908.18±38.64 kg ha⁻¹ respectively under CTS, NT and NTS indicating an increase by approximately 33%, 9% and 41% respectively compared with CT (644.61±76.98 kg ha⁻¹). There were significant (p < 0.05) reductions of Net CO₂ emissions under NT (7.37±0.89 tCO₂e ha⁻¹y⁻¹) and NTS (6.65±0.73 tCO₂e ha⁻¹y⁻¹) compared with CTS (10.65±0.18 tCO₂e ha⁻¹y⁻¹) and CT (11.14±0.58 tCO₂e ha⁻¹y⁻¹). All the treatments served as sinks of CH₄ but NTS had the highest absorption capacity (-0.27±0.024 tCO₂e ha⁻¹y⁻¹) and increased absorption significantly (p < 0.05) compared with CT (-0.21±0.017 tCO₂e ha⁻¹y⁻¹) however CA did not reduce emissions of N₂O.
These had an influence on Global warming potential (GWP) as NT and NTS resulted in significant reduction in net GWP. Grain yield was significantly correlated positively with SOC and STN ($p < 0.05$); ecosystem respiration was also significantly correlated with SWC and ST while CH$_4$ flux was highly correlated with ST ($p < 0.001$). Crop yield and GHG responses to CA were controlled by soil hydrothermal and nutrient changes, thus improving these conditions through adoption of sustainable soil moisture improvement practices such as no-till, straw mulch, green manuring, contour ploughing and terracing can improve crop resilience to climate change and reduce GHG emissions in arid and semi-arid regions.

**Keywords:** climate-smart agriculture; sustainability; crop productivity; global warming; carbon dioxide, methane, nitrous oxide.

**Introduction**

Agricultural soils are potential sources of carbon dioxide (CO$_2$), nitrous oxide (N$_2$O) and methane (CH$_4$) (Smith et al., 2008). These gases constitute the most important greenhouse gases (GHGs) and their emissions from agriculture and land-use change account for one-third of global warming (Cole et al., 1997). Meanwhile agriculture is also one of the most affected sectors by climate change through several climate induced processes. Changes in hydrological cycle and temperature affects crop cultivation in various ways: higher temperatures may cause shortening of the crop cycle in arid and semi-arid areas, resulting in low yields (IPCC, 2007) while lower precipitation may cause moisture deficit under rainfed cultivation, which could also result in significant yield decline (Calzadilla et al., 2013). In all these complexities, agriculture still holds a potential to adapt to climate change through sound management practices and as well reduce its contribution to global warming through carbon sequestration and less GHG emissions.

Wheat is a crop with global importance (Huang et al., 2003) and is central to global food security. Its cultivation in China occupied approximately 24 million hectares (Li et al., 2019). On the Loess Plateau region of Western China wheat accounts for 35% of the region’s total production area and 40% of total crop production volumes (An et al., 2014). The Loess Plateau however is a fragile dryland area with abundant smallholder farmers whose activities are threatened by wind and water erosion. Coupled with wide adoption of rainfed agriculture and conventional tillage (CT) practices, the resilience of production systems to climate change is threatened by the intricate interaction of environmental and anthropogenic factors, increasing the risks of farmers to food insecurity and poor livelihood. Innovative soil management practices hold huge potential in alleviating the effect of climate change on production systems and vice versa.

Tillage, though an important component of crop cultivation may affect soil carbon (C) cycle. The practice of CT where mechanical means is employed in land preparation causes rapid soil organic matter decomposition and oxidation of soil C to CO$_2$ (Reicosky, 1997; Six et al., 2000). This may affect changes in soil structure which could influence soil water holding capacity, soil
fertility and GHG emissions. Under conservation tillage soil disturbance is minimal which maintains soil physico-chemical and biological properties, thereby improving soil water storage capacity. In addition, the provision of soil cover or amendments increases soil organic matter and nutrient content which may enhance crop yield. Crop yield is dependent on soil suitability and limited by soil physical properties (Indoria et al., 2016), chemical properties (Wang et al., 2008) and biological properties (Woźniak & Gos, 2014). Management practices that would facilitate meeting global food demand and conserving the already stressed environment (Lal, 2005) is key to sustainable crop production. No-till with residue retention is a key conservation agriculture (CA) practice that has been reported to improve soil condition (Li et al., 2014), increased rainfed crop yield (Pittelkow et al. 2015) and increased soil C stocks (Paustian et al., 2006). But these responses to conservation tillage is variable in literature with reports of increased yields (Fabrizzi et al. 2005), reduced yields (Taa et al., 2004) and no effect (Lampurlanés et al., 2002). Different responses are dependent on several factors such as environment, duration of implementation and types of conservation practices adopted (Zheng et al., 2014). It is not clear how the drylands of the Loess plateau will respond to conservation tillage. Furthermore, studies on GHG response to conservation tillage on the Loess Plateau are scarce and much is still unknown. This research is needed in order to provide tailor-made recommendations for sustainable and climate-smart crop production on the plateau.

Thus the objective of this study was (1) to examine the influence of no-till and straw mulching soil management practices on crop yield (2) to analyse the dynamics of CO₂, CH₄ and N₂O fluxes as affected by conservation tillage and (3) to identify the mechanisms that control the responses of yield and greenhouse gases to tillage practices in dryland areas.

Materials & Methods

Study area

This experiment was conducted for two years (2017-2018) in the Anjiapo catchment on the western Loess Plateau in Gansu province at the Soil and Water Conservation Research Institute in Dingxi (35° 34′ 53″N, 104° 38′ 30″E; 2000 m above sea level). For this study we have continuous data of forty two years (precipitation-385 mm, evaporation-1531 mm, sunshine duration-2448 h, temperature- 7.1 °C, and frost free period-153 days). The soil is formed from Loess with a sandy-loam texture, with average soil bulk density of 1.26 g cm⁻³. Average soil organic carbon (SOC) was 6.21 g kg⁻¹ while total nitrogen content was 0.61 g kg⁻¹. Precipitation, maximum and minimum temperatures for the experimental period are shown in Fig. 1.
Experimental Design

Four tillage treatments were established in a randomized complete block design. The treatments included conventional tillage (CT), conventional tillage with straw mulch (CTS), no-till (NT) and no-till with straw mulch (NTS). Sowing was conducted in spring (mid-March) in both years while crops were harvested in late July to early August. In the tilled plots, soils were tilled at two different times by manual inversion with shovels to a depth of 20 cm; first in October of the previous year and again in March just before planting. Glyphosate (30%) herbicide was applied to control weeds in the plots. Wheat straw (dry weight of 3.75 ton/ha) was spread uniformly on all straw-treated plots immediately after planting. Chemical composition of the wheat straw is shown in Table 1. Planting was done manually by the drill method in rows with row spacing of 25 cm while fertilizers were applied to all the plots using Di-ammonium phosphate (N+P₂O₅) at a rate of 146 kg/ha and urea (46%) at a rate of 63 kg/ha. Three rows per plot were harvested for determination of aboveground and below ground plant products at physiological maturity. Aboveground biomass was determined by oven drying of plants at 80 °C to constant weight (Alhassan et al. 2018), while grain yields were determined by oven-drying at 105°C for 45 minutes (Yeboah et al. 2016a).

Table 1

Sampling and Measurements

Soil Properties

Soil water content and soil temperature at 0-10 cm depth were measured using EM50 data logger and GS3 soil moisture, temperature and EC sensor (Decagon Devices, Inc., Pullman, Washington). The data was sampled every 2 minutes and subsequently downloaded onto the computer using the ECH2O software. Chamber temperature was recorded using a handheld digital thermometer (JM624, Jinming Instrument Co., Tianjing, China). Soil moisture and soil temperature data were taken concurrently with gas sampling. Soils were sampled at 0-10, 10-20 and 20-40 cm with a soil auger (4 cm diameter) for determination of soil organic carbon (SOC) and soil total nitrogen (STN). SOC was determined by the Walkley-Black dichromate oxidation method (Nelson & Sommers, 1982) while STN was determined by the Kjeldahl digestion and distillation procedure as described by Bremner & Mulvaney (1982).
Gas sampling and Flux measurements

The gas sampling procedure was conducted between September, 2017 and January, 2019. The static dark chamber and Gas chromatography (GC) method as described by Wang and Wang (2003) were used for gas sampling and flux measurements. In each plot (a total of 12 plots), a stainless steel base with a collar (50 x 50 x 10 cm) was installed to support placement of the sampling chamber (50 x 50 x 50 cm) for gas sampling. Air samples were drawn from the chambers concurrently for the 3 replicates of each treatment. Samples were drawn at 5 different times at 0, 9, 18, 27, and 36 minutes respectively using 150 ml gas-tight polypropylene syringes and released into 100 ml aluminum foil sampling bags (Shanghai Sunrise Instrument Co. Ltd, Shanghai). Gas samples were then analyzed in the laboratory with a GC system (Echrom GC A90, China) equipped with a flame ionization detector (FID) for CH$_4$ and CO$_2$ analysis and Electron capture detector (ECD) for N$_2$O analysis. The FID operates at a temperature of 250°C, and H$_2$ flow rate of 35 cm$^3$ min$^{-1}$. Peak areas of CO$_2$, CH$_4$ and N$_2$O were analyzed in Echrom-ChemLab software. Before the analyses of sample gases, calibrations were done with standard gas obtained from Shanghai Jiliang Standard Reference Gases Co., Ltd, China. Concentrations of the standard gases were 456.00 ppmv for CO$_2$, 2.00 ppmv for CH$_4$ and 0.355 ppmv for N$_2$O. The sample gas concentrations obtained for the five sampling times were plotted against time in order to obtain the change in concentration over the sampling time. CO$_2$ emissions in terms of ecosystem respiration (R$_{eco}$), CH$_4$ and N$_2$O fluxes were calculated as shown in the supplemental file 1 following equation 1(Wei et al. 2014). Further flux analysis, soil carbon input components, and global warming potential were calculated from equations 2-10 as shown in supplemental file 1 (Bolinder et al., 2007; Zhang et al., 2009; Huang et al., 2007; IPCC, 2013).

Statistical Analysis

The data was analyzed in SPSS, version 22 (IBM Corporation, Chicago, USA). One-way Anova was conducted and treatment means were separated using the Duncan’s multiple range tests (DMRT) at $p < 0.05$. Linear and non-linear regressions were used to examine the relationships between parameters crop yields, soil properties and greenhouse gas fluxes. The exponential and power equations were used to describe the relationship between ecosystem respiration, soil temperature and soil water content as shown in equations 11 and 12 respectively (supplemental file 1).
Results

Soil water content and Soil temperature

Soil water content (SWC) was higher in NTS than all other treatments while CT had the lowest SWC at almost all sampling times (Fig. 2a). Conventional tillage with straw mulch (CTS) however stored more moisture than NT and CT at most sampling times. The highest SWC values were recorded in the growing season between July and September.

Soil temperature, as shown in Fig. 2b showed peak temperatures occurring in June-August. The highest temperatures were recorded in CT in most times while NTS and NT had the least temperatures in most instances.

Soil organic carbon (SOC) and Soil Total Nitrogen (STN)

Conservation Agricultural practices increased SOC at all depths (Fig. 3 a, b, c). At the 0-10 cm and 10-20 cm depths, SOC was increased significantly ($p < 0.05$) under CTS, NT and NTS. For the 0-10 cm SOC values were 9.98±0.73, 11.97±0.5, 11.81±0.09 and 12.57±0.62 gkg⁻¹ respectively for CT, CTS, NT and NTS. Compared with CT, SOC was increased by 19.95%, 18.38% and 26.03% respectively under CTS, NT and NTS within the 0-10 cm soil depth. A similar trend was observed within the 10-20 cm profile where SOC was also increased by 12.51%, 10.76% and 14.26% respectively under CTS, NT and NTS. However in the 20-40 cm depth there was a little deviation where SOC in NTS and CTS were significantly greater than CT but NT showed no significant difference. Meanwhile SOC decreased along soil depth irrespective of treatment.

There was also significance ($p < 0.05$) in STN variations among treatments in the 0-10 cm and the 10-20 cm depths (Fig 3 d, e, f). At the 0-10 cm depth STN values were 0.29±0.04, 0.36±0.03, 0.42±0.01 and 0.49±0.03 gkg⁻¹ in CT, CTS, NT and NTS respectively. Compared with the control (CT), STN was increased significantly ($p<0.05$) by 21.59%, 43.75% and 65.91% respectively in CTS, NT and NTS. Similarly, within the 10-20 cm depth, STN was significantly ($p<0.05$) increased under CTS (0.20±0.07 gkg⁻¹), NT (0.24±0.10 gkg⁻¹) and NTS (0.31±0.01 gkg⁻¹) compared with CT (0.17±0.01 gkg⁻¹). Nonetheless there were no significant differences ($p > 0.05$) in STN within the 20-40 cm depth. However there were observed reductions of STN along soil depth in all treatments.
Grain Yield

Tillage and straw treatments influenced grain yield in both years (Table 2). Average grain yields (2017-2018) were 644.61±116.40, 854.46±76.51, 699.30±133.52 and 908.18±38.64 kg ha⁻¹ respectively for CT, CTS, NT ad NTS. This means grain yield was increased by 32.55%, 8.48% and 40.89% respectively under CTS, NT and NTS compared with CT. CTS and NTS increased grain yield significantly (p < 0.05) for the period (2017-2018) but grain yield was not significantly increased under NT. There were however slight interannual variations in yield response to treatments. Grain yields were generally higher in 2018 than in 2017. Also in 2017 NTS showed the highest grain yield but in 2018 CTS showed the highest grain yield. While only NTS significantly increased grain yield in 2017, in 2018 both NTS and CTS significantly improved grain yield.

Table 2.

Average greenhouse gas emissions

Ecosystem Respiration for all treatments are shown in figures 4a and 4b respectively. Tilled soils emitted significantly more CO₂ than non-tilled soils. In the growing season, average CO₂ emission rates were 270.475±11.03, 262.88 ±0.20, 183.83±34.05 and 190.72±19.20 mg C m⁻² h⁻¹ in CT, CTS, NT, and NTS respectively, resulting in emission reduction in CTS, NT, and NTS by 2.81%, 32.03% and 29.48% respectively. In the non-growing season, emissions were relatively lower at rates of 30.55±1.71, 45.51±3.88, 31.74±1.35 and 34.15 ± 5.71 mg C m⁻² h⁻¹ respectively in CT, CTS, NT, and NTS.

All the treatments served as minor sinks of CH₄ (Fig. 4c,d). The respective absorption rates were -0.071±0.041, -0.102±0.005, -0.106±0.009 and -0.149±0.001 mg C m⁻² h⁻¹ for CT, CTS, NT and NTS in the growing season while in the non-growing season the values were -0.081±0.064, -0.055±0.006, -0.071±0.018 and -0.055±0.004 mg C m⁻² h⁻¹ respectively. However, there were variations in their sink capacities. NTS was the largest sink in the growing season while CT was the largest sink in the non-growing season. Generally, average absorption rates were higher in the growing season than in the non-growing season in all treatments except CT.

Averagely across seasons, all treatments served as emitters of N₂O, but flux values were statistically similar under all treatments in both seasons. Also, there were higher emissions in the growing season than the non-growing season (Fig. 4 e, f). In the growing season, CTS had the highest emission of N₂O. The fluxes in the growing season were 3.09±1.96, 14.88±0.42, 11.39±6.80 and 12.61±2.76 µg N m⁻² h⁻¹ for CT, CTS, NT and NTS respectively while in the non-growing season, values of N₂O fluxes ranged between 0.21 and 2.69 µg N m⁻² h⁻¹.
Net GHG fluxes, Global warming potential (GWP) and Greenhouse Gas Intensity (GHGI)

The Net CO₂-flux, CO₂ equivalents (CO₂e) of CH₄ and N₂O, GWP and GHGI of all treatments are shown in Table 3. Grain Yield (Table 1) and Harvest index were used to estimate the carbon components of harvest i.e. grain and straw in order to obtain Gross Primary production (GPP) and Net Primary Production (NPP). Harvest index, carbon in grain and straw, GPP and NPP are shown in supplemental file 2.

Net CO₂ fluxes in NTS and NT (6.65±0.73 and 7.37±0.89 tCO₂e ha⁻¹y⁻¹ respectively) were significantly lower than those in CT and CTS (11.14±0.58 and 10.65±0.18 tCO₂e ha⁻¹y⁻¹ respectively), showing reduced net carbon exchange into the atmosphere under NTS and NT. Similarly, GWP was greater in CT than all other treatments with significant reductions in NT and NTS (p < 0.05). Compared with CT, the reduction in GWP was 2.83%, 33.40%, and 40.35% under CTS, NT and NTS respectively. The GHGI is a yield-scale quantification of GWP, thus is a factor of GWP and Grain yield. It shows the contribution of the cropping system to global warming per unit grain yield. Our results showed that CT was the highest contributor of global warming per unit grain produced compared with other treatments. Significant reductions of GHGI were found in NTS and NT (p < 0.05).

Table 3

Correlations between Soil parameters and Grain Yield

Grain yields were highly influenced by soil nutrients. There were significant positive correlations (p <0.05) of grain yield and SOC and STN (Table 4) at the 0-10 cm and 10-20 cm depths respectively (Table 4). However at deeper depths (20-40 cm), there were no significant correlations observed.

Table 4

Correlations between ST, SWC and Greenhouse gases

Greenhouse gas fluxes were generally influenced by ST and SWC as shown in Table 5. CO₂ emission in the form of ecosystem respiration (Rₑₑₑ) increased exponentially as ST increased; ST-Rₑₑₑ relationship followed an exponential function and was highly significant (p < 0.001) and positive with R² values of 0.68, 0.63, 0.80 and 0.80 respectively in CT, CTS, NT and NTS while SWC-Rₑₑₑ relationship was best described by a power function and also showed highly significant (p < 0.001) positive correlations with R² values of 0.06, 0.10, 0.14 and 0.07 respectively in CT, CTS, NT and NTS. Similarly, for CH₄ fluxes, ST-CH₄ relationship was an exponential function and highly significant as well (p < 0.001) while SWC-CH₄ relationship was
best described by a linear function, albeit not significant. Meanwhile ST and SWC did not seem
to explain variations of $N_2O$ as the correlations were not significant except in ST-$N_2O$
relationship under CTS.

Table 5

Discussion

Increased SWC and ST reduction in NTS (Fig 2) is in line with other studies where
conservation tillage improved SWC and soil water storage (Lal et al., 2012; Li et al., 2014). This
could be attributed to the effect of straw (He et al., 2011; Lal et al., 2012). Straw reduced
evaporation (Kang et al. 2004) leading to improvement in water retention (Hill et al., 1985) and
infiltration (Li et al 2011b). Straw mulch may also insulate the soil from direct impact of solar
heat leading to decline of temperature.

Other studies have also reported increased SOC stocks after adoption of conservation tillage
practices (Ogle et al., 2005; Paustian et al., 2006) which is similar to the findings of this study.
Increased SOC and STN in CA plots could be attributed to less disturbance of soil which might
reduce the risk of exposure of soil organic matter to decomposition process, thereby increasing
SOC storage (Lal, 2015; Reicosky, 1997; Six et al., 2000). Also, favorable moisture content in
CA plots (fig. 2) may foster water and nutrient uptake by plant roots and also induce substrate
movement for C fixation which may result in higher photosynthetic C input, leading to net C
sequestration. Soil moisture and residue retention in CA plots may reduce wind and water
erosion which could improve soil water storage and reduce leaching of soil nitrogen (Allmaras
and Dowdy, 1985; Lamb et al., 1985).

Higher grain yield under CA practices (Table 1) is in tandem with other studies where
conservation tillage increased grain yields (Bordovsky et al., 1998; Halvorson et al., 2000; Li et
al., 2014; Zheng et al. 2014; Yeboah et al., 2016 a,b). This could be attributed to improved soil
properties under these treatments. Higher SWC (Fig. 2) facilitated movement and uptake of
available nutrients, as shown by higher SOC and STN stocks in NTS, NT and CTS (Fig 3)
thereby leading to higher grain yields. This plausibility is increased as Pearson correlation
showed significant positive correlations between grain yield and these soil properties (Table 3).

Significant lower rates of ecosystem respiration ($p < 0.05$) in NT and NTS compared with the
tilled soils (Fig. 4) was consistent with other studies (Chaplot et al., 2012; Yeboah et al., 2016b)
where conservation tillage significantly reduced soil respiration. $CO_2$ emission rates is often
controlled by a number of factors including: gradient of concentration of $CO_2$ between the
atmosphere and the soil medium, soil water, soil temperature, wind speed and soil physical and
chemical properties (Raich & Schlessinger, 1992). Tillage influences these factors directly and
or indirectly which resultantly influences $CO_2$ emissions as well. Soil disturbance under
conventional tillage, may trigger microbial activities and increase decomposition rates (Alkaisi &
Yin, 2005), leading to higher $CO_2$ emissions. Soil disturbance may also increase soil aeration,
resulting in higher oxidation of carbon into $CO_2$ (Jackson et al., 2003). On the contrary, under
no-till, decomposition is slower due to less soil disturbance (Curtin et al., 2000). Higher soil temperature under CT (Fig 2) may exponentially increase microbial activities (Meixner, 2006) while lower soil temperature may reduce microbial activity, hence reduce emissions in the conservation tillage plots (Carbonell-Bojollo et al., 2012). This corroborates with the significant positive relationship between soil temperature and ecosystem respiration found in this study (Table 4).

All four tillage methods resulted in uptake of CH$_4$ in both growing and non-growing seasons. Other studies on the Loess Plateau obtained similar results (Wan et al., 2009; Yeboah et al., 2016b). Shen et al. (2018) indicated that agroecosystems in dry regions with minimal irrigation often act as CH$_4$ sinks due to aerobic soil conditions. This is due to oxidation of CH$_4$ under aerobic conditions (Matson et al., 2009; Schaufler et al., 2010). Lower temperatures under NTS may have played significant role in high uptake of CH$_4$ in NTS. The dominant methanogen during high temperatures (Methanosarcinaceae) utilizes H$_2$/CO$_2$ and acetate as methane producing precursors, and produces far higher methane than the methanogen at lower temperatures (Methanosaetaceae), which uses only acetate as methane producing precursor (Ding & Cai, 2003).

Average N$_2$O fluxes found in this study were in the range of fluxes reported by Ma et al. (2013) in their study of GHGs in a rice-wheat rotation under integrated crop management systems. Averagely, all treatments served as slight emitters of N$_2$O (Fig. 4). This is also consistent with the study of Yeboah et al. (2016b) on the Loess Plateau. There was significant positive correlation between soil temperature and N$_2$O emission in CTS. Higher temperatures and soil water content in the growing season where 70-80% of rainfall occurs (Fig 1) may have triggered nitrification and denitrification processes (Davidson & Swank, 1986), leading to higher N$_2$O emissions in this season. High rainfall may increase water filled pore space, which influences N$_2$O emissions in agricultural soils (Dobbie & Smith, 2003). Trujillo et al. (2008) also reported positive correlation of N$_2$O with soil temperature and soil water content. Higher emission in the growing season than in the non-growing season could also be related to fertilizer N application in the growing season and its interactive effect with wet conditions within this period on denitrification processes (Cho et al., 1997).

The GWP$_4$s (Table 2) were in the range as reported by Ma et al. (2013) but greater than those reported by Yeboah et al. (2016b). Furthermore, GHGI$_4$s in this study were far higher than those found in other studies (Qin et al., 2010; Ma et al., 2013). Higher GWPs and GHGI$_4$s in this study could be attributed to a general lower grain yield (Table 1) which is typically associated with drylands. Lower grain yield may generally result in relatively low carbon input (Supplementary file 2) which may in turn result in relatively higher net GHG emissions. However GWP being lower under NT and NTS than in CT and CTS is attributable to relatively higher carbon input from the above ground plant product coupled with lower ecosystem respiration and higher CH$_4$ uptake in these plots.
Conclusions

This study hypothesized that no-till and the application of straw improved soil chemical and physical properties, increased crop yield and reduced greenhouse gas emissions by comparing 3 conservation practices [conventional tillage with straw (CTS), No-till (NT) and no-till with straw (NTS)] to conventional tillage (CT). Our study showed that conservation tillage practices especially NTS improved soil water content and reduced soil temperature. Soil organic carbon and total nitrogen were also significantly improved under conservation practices especially within the top soil layer (0-20 cm). There was also significant improvement in average grain yield under NTS and CTS. Conservation tillage further reduced net CO$_2$ flux; increased CH$_4$ absorption but only slightly influenced N$_2$O emissions in the dryland ecosystem. NTS and NT significantly reduced GWP and yield-scale GWP. For sustainability of arid and semi-arid cropping systems and for environmental quality we recommend the adoption of conservation agricultural practices such as no-till, straw mulch, green manuring, contour ploughing and terracing on the Loess Plateau. Furthermore crop genetic and breeding techniques such as the use of drought resistant crop varieties should also be explored in order to enhance climate change resilience of crop production in dryland areas and reduce climate footprint of these areas.
References

Alhassan ARM, Ma W, Li G, Jiang Z, Wu J, Chen G. 2018. Response of soil organic carbon to vegetation degradation along a moisture gradient in a wet meadow on the Qinghai–Tibet Plateau. *Ecology & Evolution* **8**(23): 11999-12010.

Al-Kaisi MM, Yin X. 2005. Tillage and crop residue effects on soil carbon and carbon dioxide emission in corn–soybean rotations. *Journal of Environmental Quality* **34**(2): 437-445.

Allmaras RR, Dowdy RH. 1985. Conservation tillage and their adoption in the United States. *Soil Tillage Research* **5**(2): 197–222.

An P, Inoue T, Zheng M, Eneji AE, Inanaga S. 2014. Agriculture on the Loess Plateau. In Restoration and development of the degraded Loess Plateau, China, ed. Tsunekawa A, Liu G, Yamanaka N, Du S, 61–74. Japan: Springer.

Bolinder MA., Janzen HH, Gregorich EG, Angers DA, Vanden Bygaart AJ. 2007. An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. *Agriculture, Ecosystems & Environment* **118**(1-4): 29-42.

Bordovsky DG, Choudhary M, Gerard CJ. 1998. Tillage effects on grain sorghum and wheat yields in the Texas Rolling Plains. *Agronomy journal* **90**(5): 638-643.

Bouwman AF. 1996. Direct emission of nitrous oxide from agricultural soils. *Nutrient Cycling in Agroecosystems* **46**(1): 53-70.

Bremner JM, Mulvaney CS. 1982. Nitrogen-total. In A. L. Page et al., (Eds), Methods of Soil Analysis Part 2 (pp. 595-624).Madison, Wisconsin: American Society of Agronomy

Calzadilla A, Rehdzan K, Betts R, Falloon P, Wiltshire A, Tol R. S. 2013. Climate change impacts on global agriculture. Climatic change **120**(1-2): 357-374.

Carbonell-Bojollo RM, de Torres MARR, Rodríguez-Lizana A, Ordóñez-Fernández R. 2012. Influence of soil and climate conditions on CO2 emissions from agricultural soils. *Water, Air, & Soil Pollution* **223**(6): 3425-3435.

Chaplot V, Mchunu CN, Manson A, Lorentz S, Jewitt G. 2012. Water erosion-induced CO2 emissions from tilled and no-tilled soils and sediments. *Agriculture, ecosystems & environment* **159**: 62-69.

Cho C M, Burton D L, Chang C. 1997. Denitrification and fluxes of nitrogenous gases from soil under steady oxygen distribution. *Canadian Journal of Soil Science* **77**(2): 261-269.

Cole CV, Duxbury J, Freney J, Heinemeyer O, Minami K, Mosier A, Paustian K, Rosenberg N, Sampson N, Sauerbeck D, Zhao Q. 1997. Global estimates of potential mitigation of greenhouse gas emissions by agriculture. *Nutrient cycling in Agroecosystems* **49**(1-3): 221-228.

Curtin D, Wang H, Selles F, McConkey BG, Campbell CA. 2000. Tillage effects on carbon fluxes in continuous wheat and fallow–wheat rotations. *Soil Science Society of America Journal* **64**(6): 2080-2086.

Davidson EA, Swank WT. 1986. Environmental parameters regulating gaseous nitrogen losses from two forested ecosystems via nitrification and denitrification. *Applied & Environmental Microbiology* **52**(6): 1287-1292.
Ding W, Cai Z. 2003. Effect of temperature on methane production and oxidation in soils. *Ying yong sheng tai xue bao= The journal of applied ecology* **14**(4): 604-608.

Dobbie KE, Smith KA. (2003). Nitrous oxide emission factors for agricultural soils in Great Britain: the impact of soil water-filled pore space and other controlling variables. *Global change biology*, 9(2): 204-218.

Fabrizzi KP, Garcia FO, Costab JL, Picone LI. 2005. Soil water dynamics, physical properties and corn and wheat responses to reduced and no-tillage systems in the southern Pampas of Argentina. *Soil Tillage Research* **81**: 57-69.

Halvorson AD, Black AL, Krupinsky JM, Merrill SD, Wienhold BJ, Tanaka DL. 2000. Spring wheat response to tillage and nitrogen fertilization in rotation with sunflower and winter wheat. *Agronomy journal* **92**(1): 136-144.

He J, Li H, Rasaily RG, Wang Q, Cai G, Su Y, Qiao X, Liu L. 2011. Soil properties and crop yields after 11 years of no tillage farming in wheat–maize cropping system in North China Plain. *Soil and Tillage Research* **113**(1): 48-54.

Hill R L, Horton R, Cruse RM. 1985. Tillage effects on soil water retention and pore size distribution of two mollisols. *Soil Science Society of America Journal* **49**(5): 1264-1270.

Huang M, Dang T, Gallichand J, Goulet M. 2003. Effect of increased fertilizer applications to wheat crop on soil-water depletion in the Loess Plateau, China. *Agricultural Water Management* **58**(3): 267-278.

Huang Y, Zhang W, Sun W, Zheng X. 2007. Net primary production of Chinese croplands from 1950 to 1999. *Ecological Applications* **17**(3): 692-701.

Indoria AK, Sharma KL, Reddy KS, Rao CS. 2016. Role of soil physical properties in soil health management and crop productivity in rainfed systems–II. Management technologies and crop productivity. *Current Science* **110**(3): 320.

IPCC. 2007. Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC. Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Cambridge University Press, Cambridge, UK, pp. 976

Jackson LE, Calderon FJ, Steenwerth KL, Scow KM, Rolston DE. 2003. Responses of soil microbial processes and community structure to tillage events and implications for soil quality. *Geoderma* **114**(3-4): 305-317.

Kang S, Su X, Tong L, Shi P, Yang X, Abe Y, Du T, Shen Q, Zhang J. 2004. The impacts of human activities on the water–land environment of the Shiyang River basin, an arid region in northwest China/Les impacts des activités humaines sur l’environnement pédo-hydrologique du bassin de la Rivière Shiyang, une région aride du nord-ouest de la Chine. *Hydrological Sciences Journal* **49**(3).

Lal R. 2005. Climate change, soil carbon dynamics, and global food security. In Climate change and global food security (pp. 113–143). Boca Raton, FL, Taylor and Francis.

Lal R. 2015. Sequestering carbon and increasing productivity by conservation agriculture. *Journal of Soil & Water Conservation* **70**(3): 55A-62A.
Lal R, Delgado JA, Gulliford J, Nielsen D, Rice CW, Van Pelt RS. 2012. Adapting agriculture to drought and extreme events. *Journal of Soil & Water Conservation* **67**(6): 162A-166A.

Lamb JA, Peterson GA, Fenster CR. 1985. Wheat fallow tillage systems’ effect on a newly cultivated grassland soils’ nitrogen budget. *Soil Science Society of America Journal* **49**(2): 352–356.

Lampurlanés J, Angas P, Cantero-Martinez C. 2002. Tillage effects on water storage during fallow, and on barley root growth and yield in two contrasting soils of the semi-arid Segarra region in Spain. *Soil Tillage Research* **65**(2): 207-220.

Li H, Zhou Y, Xin W, Wei Y, Zhang J, Guo L. 2019. Wheat breeding in northern China: achievements and technical advances. *The Crop Journal* **7**(6): 718-729.

Li L, Huang G, Zhang R, Bill B, Guandli L, Kwong YC. 2011. Benefits of conservation agriculture on soil and water conservation and its progress in China. *Agricultural Sciences in China* **10**(6): 850-859.

Li L, Zhang R, Luo Z, Liang W, Xie J, Cai L, Bellotti B. 2014. Evolution of soil and water conservation in rain-fed areas of China. *International Soil & Water Conservation Research* **2**(1): 78-90.

Ma YC, Kong XW, Yang B, Zhang XL, Yan XY, Yang JC, Xiong ZQ. 2013. Net global warming potential and greenhouse gas intensity of annual rice–wheat rotations with integrated soil–crop system management. *Agriculture, ecosystems & environment* **164**: 209-219.

Matson A, Penock D, Bedard-Haughn A. 2009. Methane and nitrous oxide emissions from mature forest stands in the boreal forest, Saskatchewan, Canada. *Forest Ecology & Management* **258**(7): 1073-1083. Doi:10.1016/j.foreco.2009.05.034.

Meixner FX. 2006. *Biogenic emissions of nitric oxide and nitrous oxide from arid and semi-arid land*. In Dryland ecohydrology (pp. 233-255). Springer, Dordrecht.

Nelson DW, Sommers LW. 1982. *Total carbon, organic carbon and organic matter*. In: AL Page et al. (eds). Methods of soil analysis Part 2 (Second edition). Chemical and microbiological properties (pp 301–312). Wisconsin/Madison USA: American Society of Agronomy and Soil Science Society of American Journal.

Ogle SM, Breidt FJ, Paustian K. 2005. Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. *Biogeochemistry* **72**(1): 87-121.

Paustian K, Antle JM, Sheehan J, Paul EA. 2006. Agriculture’s role in greenhouse gas mitigation. Arlington (VA) Canada, *Pew Center on Global Climate Change*.

Pittelkow CM, Liang X, Linquist BA, van Groenigen KJ, Lee J, Lundy ME, Van Gestel N, Six J, Venterea RT, van Kessel C. 2015. Productivity limits and potentials of the principles of conservation agriculture. *Nature* **517**(7534): 365–368.

Qin Y, Liu S, Guo Y, Liu Q, Zou J. 2010. Methane and nitrous oxide emissions from organic and conventional rice cropping systems in Southeast China. *Biology & Fertility of Soils* **46**(8): 825-834.
Raich JW, Schlesinger WH. 1992. The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. *Tellus B* 44(2): 81-99.

Reicosky DC. 1997. Tillage-induced CO$_2$ emission from soil. *Nutrient cycling in agroecosystems* 49(1-3): 273-285.

Schaufler G, Kitzler B, Schindlbacher A, Skiba U, Sutton MA, Zechmeister-Boltenstern S. 2010. Greenhouse gas emissions from European soils under different land use: effects of soil moisture and temperature. *European Journal of Soil Science* 61(5): 683-696. doi:10.1111/j.1365-2389.2010.01277.x

Shen Y, Sui P, Huang J, Wang D, Whalen JK, Chen Y. 2018. Greenhouse gas emissions from soil under maize–soybean intercrop in the North China Plain. *Nutrient cycling in agroecosystems* 110(3): 451-465.

Six JAET, Elliott ET, Paustian K. 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. *Soil Biology & Biochemistry* 32(14): 2099-2103.

Smith P, Fang C, Dawson JJ, Moncrieff JB. 2008. Impact of global warming on soil organic carbon. *Advances in agronomy* 97: 1-43.

Taa A, Tanner D, Bennie ATP. 2004. Effects of stubble management, tillage and cropping sequence on wheat production in the south-eastern highlands of Ethiopia. *Soil Tillage Research* 76: 69-82

Trujillo-Tapia N, Mondragón CC, Vásquez-Murrieta MS, Van Cleemput O, Dendooven L. 2008. Inorganic N dynamics and N$_2$O production from tannery effluents irrigated soil under different water regimes and fertilizer application rates: A laboratory study. *Applied soil ecology* 38(3): 279-288.

Wan YF, Li YE, Gao QZ, Qin XB, Lin ED. 2009. Field managements affect yield, soil carbon, and greenhouse gases emission of winter wheat in North China Plain. *Journal of Agro-Environment Science* 12.

Wang Q, Bai Y, Gao H, He J, Chen H, Chesney RC, Kuhn NJ, Li H. 2008. Soil chemical properties and microbial biomass after 16 years of no-tillage farming on the Loess Plateau, China. *Geoderma* 144(3-4): 502-508.

Wang YS, Wang YH. 2003. Quick measurement of CH$_4$, CO$_2$ and N2O emission from a short plant ecosystem. *Advances in Atmospheric Sciences* 20: 842–844.

Wei D, Liu Y, Wang YS, Wang YH. 2014. Three-year study of CO$_2$ efflux and CH$_4$/N$_2$O fluxes at an alpine steppe site on the central Tibetan Plateau and their responses to simulated N deposition. *Geoderma* 232: 88-96.

Woźniak A, Gos M. 2014. Yield and quality of spring wheat and soil properties as affected by tillage system. *Plant, Soil and Environment* 60(4): 141-145.

Yeboah S, Zhang R, Cai L, Li L, Xie J, Luo Z, Liu J, Wu J. 2016a. Tillage effect on soil organic carbon, microbial biomass carbon and crop yield in spring wheat-field pea rotation. *Plant, Soil & Environment* 62(6): 279-285.
Yeboah S, Zhang R, Cai L, Song M, Li L, Xie J, Luo Z, Wu J, Zhang J. 2016b. Greenhouse gas emissions in a spring wheat–field pea sequence under different tillage practices in semi-arid Northwest China. *Nutrient Cycling in Agroecosystems* **106**(1): 77-91.

Zhang Y, Xu M, Chen H, Adams J. 2009. Global pattern of NPP to GPP ratio derived from MODIS data: effects of ecosystem type, geographical location and climate. *Global Ecology and Biogeography* **18**(3): 280-290.

Zheng C, Jiang Y, Chen C, Sun Y, Feng J, Deng A, Song Z, Zhang W. 2014. The impacts of conservation agriculture on crop yield in China depend on specific practices, crops and cropping regions. *The Crop Journal* **2**(5): 289-296.
Figure 1

Rainfall amounts for 2017 (a), 2018 (b) and Mean, maximum and minimum temperatures for 2017 (c) and 2018 (d) in the Anjiapo catchment in Dingxi
Figure 2

Soil water content (a) and soil temperature (b) at various sampling times (10 cm depth)
Figure 3

Soil organic carbon (SOC) and soil total nitrogen (STN) among tillage treatments within different depths.

Treatments with common letters within a depth are not statistically different at p ≤ 0.05
Figure 4

Average ecosystem respiration, CH4 and N2O fluxes across treatments in growing season (a), (c) and (e) and non-growing season (b), (d) and (f).

Error bars are standard errors, n=3 PeerJ reviewing PDF | (2019:10:42209:0:1:NEW 18 Oct 2019) Manuscript to be reviewed
Table 1 (on next page)

Properties of wheat Straw mulch
Table 1 Properties of wheat Straw mulch

| Parameter   | Content (%) |
|-------------|-------------|
| Potassium   | 0.54±0.05   |
| Carbon      | 40.19±3.2   |
| Nitrogen    | 0.81±0.1    |
| Phosphorus  | 0.09±0.01   |
**Table 2** (on next page)

Wheat grain yield response to different tillage treatments
Table 2 Wheat grain yield response to different tillage treatments

| Treatment | 2017       | 2018       | 2017-2018  |
|-----------|------------|------------|------------|
| CT        | 581.45±73.89<sup>b</sup> | 707.78±96.49<sup>b</sup> | 644.61±76.98<sup>c</sup> |
| CTS       | 587.69±35.96<sup>b</sup> | 1121.23±54.19<sup>a</sup> | 854.46±59.02<sup>ab</sup> |
| NT        | 653.36±27.25<sup>b</sup> | 745.23±134.42<sup>b</sup> | 699.30±64.88<sup>bc</sup> |
| NTS       | 854.46±25.33<sup>a</sup> | 961.90±21.61<sup>ab</sup> | 908.18±22.31<sup>a</sup> |
Table 3 (on next page)

Net GHG fluxes, Global warming potential and Greenhouse gas intensity among tillage treatments
Table 3 Net GHG fluxes, Global warming potential and Greenhouse gas intensity among tillage treatments

|          | Net CO₂-flux (tCO₂e ha⁻¹y⁻¹) | CH₄ –CO₂e (tCO₂e ha⁻¹y⁻¹) | N₂O-CO₂e (tCO₂e ha⁻¹y⁻¹) | Net GWP (tCO₂e ha⁻¹y⁻¹) | GHGI (tCO₂e t⁻¹ grain) |
|----------|--------------------------------|---------------------------|--------------------------|--------------------------|-------------------------|
| CT       | 11.14±0.58ᵃ                   | -0.21±0.017ᵇ              | 0.035±0.004ᵇ             | 10.96±0.56ᵃ              | 17.21±1.18ᵃ             |
| CTS      | 10.65±0.18ᵃ                   | -0.23±0.005ᵃᵇ            | 0.22±0.016ᵃ              | 10.65±0.19ᵃ              | 12.56±0.9ᵇ              |
| NT       | 7.37±0.89ᵇ                    | -0.25±0.011ᵃᵇ            | 0.18±0.075ᵃ              | 7.30±0.97ᵇ              | 10.37±2.34ᵇ             |
| NTS      | 6.65±0.73ᵇ                    | -0.27±0.024ᵃ              | 0.17±0.016ᵃ              | 6.55±0.70ᵇ              | 7.18±1.77ᵇ              |

Note: The sign convention adopted is positive (+) means emission whilst negative (-) means absorption.
Table 4 (on next page)

Correlation between Grain Yield and soil chemical properties

**Correlation is significant at the 0.01 level (2-tailed).**  
*Correlation is significant at the 0.05 level (2-tailed).**
1 Table 4 Correlation between Grain Yield and soil chemical properties

| Soil chemical property                  | Grain Yield |
|----------------------------------------|-------------|
| Soil Organic Carbon (SOC)              |             |
| Soil organic carbon at 10 cm           | 0.642*      |
| Soil organic carbon at 20 cm           | 0.614*      |
| Soil organic carbon at 40 cm           | 0.487       |
| Total Nitrogen (TN)                    |             |
| Total nitrogen at 10 cm                | 0.672*      |
| Total nitrogen at 20 cm                | 0.609*      |
| Total nitrogen at 40 cm                | 0.260       |

*Correlation is significant at the 0.05 level (2-tailed).

**Correlation is significant at the 0.01 level (2-tailed).
Table 5 (on next page)

Correlation between greenhouse gases, soil temperature and soil water content
Table 5. Correlation between greenhouse gases, soil temperature and soil water content

| Treatment | Soil temperature | Moisture content | Ecosystem respiration | Soil water content |
|-----------|------------------|------------------|-----------------------|--------------------|
| CT        | \( y = 33.04e^{0.07x} \) | 0.68 | \(< 0.001\) | \( y = 363.57x^{0.48} \) | 0.056 | \(< 0.01\) |
| CTS       | \( y = 32.55e^{0.075} \) | 0.63 | \(< 0.001\) | \( y = 474.18x^{0.67} \) | 0.095 | \(< 0.001\) |
| NT        | \( y = 21.58e^{0.08x} \) | 0.80 | \(< 0.001\) | \( y = 483.20x^{0.88} \) | 0.138 | \(< 0.001\) |
| NTS       | \( y = 27.79e^{0.077x} \) | 0.80 | \(< 0.001\) | \( y = 317.12x^{0.67} \) | 0.07 | \(< 0.001\) |

**CH₄ flux**

| Treatment | Equation | R²  | p-value | Equation | R²  | p-value |
|-----------|----------|-----|---------|----------|-----|---------|
| CT        | \( y = -0.063e^{-0.012x} \) | 0.019 | \( = 0.001\) | \( y = -0.07-0.05x \) | 0.03 | \( = 0.79\) |
| CTS       | \( y = -0.052e^{-0.026x} \) | 0.135 | \( < 0.001\) | \( y = -0.08-0.02x \) | 0.04 | \( = 0.87\) |
| NT        | \( y = -0.062e^{-0.022x} \) | 0.085 | \( < 0.001\) | \( y = 0.12-0.35x \) | 0.1 | \( = 0.05\) |
| NTS       | \( y = -0.068e^{-0.028x} \) | 0.174 | \( < 0.001\) | \( y = -0.04-0.31x \) | 0.04 | \( = 0.137\) |

**N₂O flux**

| Treatment | Equation | R²  | p-value | Equation | R²  | p-value |
|-----------|----------|-----|---------|----------|-----|---------|
| CT        | \( y = -0.84+0.12x \) | 0.016 | \( = 0.456\) | \( y = 2.45+26.62x \) | 0.01 | \( = 0.269\) |
| CTS       | \( y = -1.77+0.66x \) | 0.209 | \( < 0.01\) | \( y = 3.87+71.36x \) | 0.08 | \( = 0.075\) |
| NT        | \( y = 4.64+0.12x \) | 0.003 | \( = 0.65\) | \( y = -0.68+43.45x \) | 0.09 | \( = 0.055\) |
| NTS       | \( y = 2.05+0.28x \) | 0.08 | \( = 0.07\) | \( y = -3.6+48.92x \) | 0.08 | \( = 0.067\) |