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Annual net greenhouse gas balance in a halophyte (*Helianthus tuberosus*) bioenergy cropping system under various soil practices in southeast China

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Abstract

A full accounting of net greenhouse gas balance (NGHGB) and greenhouse gas intensity (GHGI) was examined in an annual coastal reclaimed saline Jerusalem artichoke-fallow cropping system under various soil practices including soil tillage, soil ameliorant and crop residue amendments. Seasonal fluxes of soil carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) were measured using static chamber method, and the net ecosystem exchange of CO_2 (NEE) was determined by the difference between soil heterotrophic respiration (R_H) and net primary production (NPP). Relative to no tillage, rotary tillage significantly decreased the NPP of Jerusalem artichoke while it had no significant effects on the annual R_H. Rotary tillage increased CH_4 emissions, while seasonal or annual soil N_2O emissions did not statistically differ between the two tillage treatments. Compared with the control plots, soil ameliorant or straw amendment enhanced R_H, soil CH_4 and N_2O emissions under the both tillage regimes. Annual NGHGB was negative for all the field treatments, as a consequence of net ecosystem CO_2 sequestration exceeding the CO_2-equivalents released as CH_4 and N_2O emissions, which indicates that Jerusalem artichoke-fallow cropping system served as a net sink of GHGs. The annual net NGHGB and GHGI were estimated to be

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11–21% and 4–8% lower in the NT than in RT cropping systems, respectively. Soil ameliorant and straw amendments greatly increased NPP and thus significantly decreased the negative annual net NGHGB. Overall, higher NPP but lower climatic impacts of coastal saline bioenergy production would be simultaneously achieved by Jerusalem artichoke cultivation under no tillage with improved saline soil conditions in southeast China.

Introduction

Atmospheric carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the most potent long-lived greenhouse gases (GHGs) contributing greatly to global warming. In order to combat global warming, the production of biofuels from bioenergy crop biomass has been proposed as an alternative source of renewable energy instead of fossil fuels (Pacala & Socolow, 2004; Goldemberg, 2007; FAO, 2008). The worldwide expansion of bioenergy crop is increasingly promoted, although that potential land conflicts exist between bioenergy production and food security (Kates *et al*., 2001; Fargione *et al*., 2008; Solomon, 2010). In contrast to GHGs emission associated with the burning of fossil fuels, bioenergy crop production is often a source of GHGs but with large uncertainties due to site and climate variations. However, an overall assessment of GHGs emission from bioenergy cropping systems is highly limited for the lack of field measurements, thus a complete annual accounting of GHG balance in bioenergy cropping systems is of great concern.

The development of bioenergy crop is currently advocated to meet the increasing energy demand in China. Besides traditional bioenergy crops such as sugarcane, sweet sorghum,

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and potato, China is abundant in halophyte resources, accounting for 19.3% of halophytes worldwide (Khan & Qaiser, 2006), many of which have important economic value and could be used as a source of biomass material for biofuels (Zhao *et al*., 2002). In order to avoid the conflicts between bioenergy and grain crops in farmland arable soils in China, non-cultivated coastal saline lands have been extensively exploited for bioenergy crops cultivation (Liu *et al*., 2012). Currently, China has a large tidal flat with a total area of 2.0 million hectare, of which the tidal flat for planting halophytes is rocketing at a rate of 1.3–2.0 ten thousand hectare per year in order to meet the increasing demand of large-scale industrialization for bioenergy. The state of non-agricultural coastal lands is appropriate for growth of halophytes or salt-tolerant plants while not for the traditional grain crops due to extreme salinity and other adverse effects such as drought and low soil nutrients availabilities. For example, Jerusalem artichoke (*Helianthus tuberosus* L.) is known as one of the most potential alternatives as source of biofuel, which is widely grown in coastal zones due to its high yield and growth rate, as well as its strong adaptability towards stress conditions such as soil salinity (Denoroy *et al*., 1996; Long *et al*., 2005; Guo *et al*., 2011). To our knowledge, most of the field GHG flux measurements were taken from traditional bioenergy cropping systems (e.g. sugarcane, sweet sorghum, potato, and cereal), while few studies have concentrated on the halophytes bioenergy cropping systems (Barton *et al*., 2010; Drewer *et al*., 2012; Gauder *et al*., 2012; Zona *et al*., 2013).

Numerous studies have focused on CO_2, CH_4 and N_2O emissions from Chinese grain crops under various agricultural managements, including irrigation, soil tillage, crop residue amendment and fertilizer application. (Cai et al. 1997; Zou *et al*., 2004a, 2005a; Harada *et*

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al., 2007; Jiang *et al*., 2010; Liu *et al*., 2012b). However, few field measurements were taken on CO_2, CH_4 and N_2O emissions from bioenergy cropping systems in China. While bioenergy cropping systems can serve as a GHG sink by fixing atmospheric CO_2 into biomass, it might be offset by their other GHG sources. For example, soil N_2O emissions have a strong impact on the extent to which biofuel production and consumption reduces GHG emissions as compared to fossil fuels (Adler *et al*., 2007; Crutzen *et al*., 2008). While the soil for bioenergy crop cultivation with increasing aeration often acts as pure N_2O emission source, and mostly as the greatest single source of global warming potential from cropped soils (Robertson *et al*., 2000). Soil CH_4 fluxes are also taken into account when assessing the overall GHG emissions from arable cropping systems (Robertson *et al*., 2000), as well as bioenergy crops (Adler *et al*., 2007). Therefore, an overall accounting of net greenhouse gas balance (NGHGB) and greenhouse gas intensity (GHGI) derived from soil CO_2, CH_4 and N_2O emissions is required when assessing the climatic impact of bioenergy crop production.

We presented field measurements of soil CO_2, CH_4 and N_2O fluxes as affected by soil tillage practice, soil ameliorant and crop residue amendments in a coastal saline Jerusalem artichoke-fallow cropping system over a whole annual cycle in southeast China. Soil CO_2, CH_4 and N_2O fluxes were simultaneously measured using static chamber-gas chromatograph (GC) method. The net ecosystem exchange rate of CO_2 (NEE) was determined by the difference between soil heterotrophic respiration (R_H) and net primary production (NPP). We predicted that rotary tillage relative to no tillage would increase the annual soil CO_2 and N_2O emissions due to disturbance and soil water decrease, while it would decrease soil CH_4

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emissions under saline soil conditions in the Jerusalem artichoke-fallow cropping system. Soil ameliorant amendments would facilitate soil CO_2, CH_4 and N_2O fluxes due to improved saline soil conditions benefiting the enhancement in soil microbial activities. Soil CO_2 and CH_4 emissions would be greater in straw mulched treatments than in unmulched soils for organic material input. The objectives of this study are to gain an insight into a complete accounting of NGHGB and GHGI from soil CO_2, CH_4 and N_2O emissions as affected by a range of soil practices in annual coastal saline bioenergy cropping systems, and thereby to optimize local soil practices for mitigating climatic impacts of bioenergy crop production in China.

Material and Methods

Site description

A field plot experiment was performed in the coastal saline field station of Nanjing Agricultural University located in Dafeng, Jiangsu province, China (33º 19' N, 120º 45' E), and it has an altitude of 4 m above sea level. Field plots were established in Jerusalem artichoke-fallow cropping system over the 2009-2010 annual cycle. Soil (0–15 cm) of the experimental site was classified as fluvoaquic, consisting of 67% sand, 12% silt and 21% clay. Initial pH was 8.3 (1:2.5, water/soil, w/w), electrical conductivity (EC) was 180 μS cm^{-1} (1:5, water/soil, w/w), salt content was 3.24 g kg^{-1}, an average bulk density was 1.28 g cm^{-3}, available phosphorus was 0.62 g kg^{-1}, and total N and organic C were 0.64 g kg^{-1} and 11.2 g kg^{-1}, respectively. Climate information was recorded by the local weather station (Fig. 1).

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The annual mean minimum and maximum temperatures were 15.7 ºC and 17.8 ºC over the 2009-2010 cropping rotation, respectively. Annual rainfall amounted to 1078 mm over the 2009-2010 experimental cycle, consisting of 550 mm for the Jerusalem artichoke growing season and 528 mm for the non-cropping season.

Field experiments

A field experiment was established in Jerusalem artichoke-fallow cropping systems over the period of April 28, 2009 to May 15, 2010. The site preparation was completed on April 25, 2009 and the Jerusalem artichoke (*Helianthus tuberosus* L.) was sown on April 28, 2009 with no prior cultivation, harvested on October 14, 2009. Thereafter, a fallow season was followed through October 15, 2009 to May 15, 2010, during which the fields were left overgrown with natural vegetation and no field management involved.

A split-plot experimental design with six field treatments, and each treatment with four replicates, was adopted in the present study (Table 1). The main emphasis was on soil tillage practices consisting of no tillage (NT) and rotary tillage (RT), and the rotary tillage at the soil depth of 10 cm was practiced for the RT plots on April 26, 2009. For each tillage treatment, soil amendments including saline soil ameliorant (peat and phosphogypsum, PP) and wheat straw (WS) were applied in some fields. The plots without soil amendments were set up as the control for each tillage treatment (NT-Control and RT-Control). Wheat straw was chopped at the length of 10–15 cm, and it was mulched for the NT-WS and RT-WS plots, and saline soil ameliorant was broadcast for the NT-PP and RT-PP plots on May 22, 2009. Each

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field plot was 2 m × 6 m, the row spacing was 60 cm × 40 cm and thus there were 50 individual plants in each field plot. All field plots were surrounded with pre-established isolation strips, which guaranteed the relative independence for each treatment. All the soil amendments were well-distributed both within and between the cropping rows, and the application rate of soil amendments was shown in Table 1. After the soil amendments were applied, gas flux collars were installed at inter-cropping rows within each treatment plot.

In line with the local conventional fertilizer application methods for bioenergy crop production, a compound fertilizer (N: P_2O_5: K_2O = 15%: 15%: 15%) was broadcast on the fertilized field plots and then adequately mixed with the surface soil, the seasonal N input amounted to 225 kg N ha^{-1} for all the treatments, with a split 60% as basal fertilizer on May 22, 2009, 20% at seedling stage on June 22, 2009 and 20% at blossom stage on July 30, 2009 during Jerusalem artichoke growing season (Figs. 3 and 4). The other field cropping managements were in accordance with the local Jerusalem artichoke cultivation practice.

Gas sampling and measurements

Soil gas fluxes were measured for approximately a whole year, the gas sampling initiated on May 26, 2009, was carried out once around every 10 days and terminated on May 10, 2010 (356 days, Figs. 2–4). For each field treatment, four aluminum flux collars (0.2 m diameter × 0.15 m height) within each parallel plot were permanently installed at inter-cropping rows with no crop growth enclosed to ensure reproducible placement of gas collecting chambers during successive gas flux measurements over the whole annual cycle. The top edge of the

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collar had a groove (5 cm in depth) for filling with water to seal the rim of the chamber with leveled surface. The collars were inserted into the plough pan horizon of the soil (20 cm in soil depth) at inter-cropping rows to keep Jerusalem artichoke roots and tubers outside of collars and minimize lateral gas exchange, so that the measured CO_2 effluxes can well represent soil heterotrophic respiration. The chamber was equipped with a circulating fan to ensure complete gas mixing and wrapped with a layer of sponge and aluminum foil to minimize air temperature changes inside the chamber during the period of sampling. The cross-sectional area of the chamber was 0.03 m^2 ($\pi \times 0.01$ m^2), with a height of 1.0 m. When gas sampling, the chamber was placed above the collar with the rim of chamber fitting into the groove of the collar. Gas samples were taken within 20 minutes after chamber closure starting any time between 09:00 and 11:00 local standard time on each sampling day. Gas samples from inside the chambers were collected at 0, 5, 10, 15 and 20 minutes after chamber closure using 60-mL plastic syringes fitted with three-way stopcocks (Zou *et al*. 2005a, b). Gas samples in the syringes were transported to the laboratory for analysis by GC within a few hours. In total, there were about 864 individual measurements (6 treatments × 4 replicates × 36 measuring days) for each gas type over the whole annual cycle.

Soil CO_2, CH_4 and N_2O fluxes were determined using the static chamber-GC method (Wang *et al*., 2003; Zheng *et al*., 2008a). The mixing ratios of the above three gases were analyzed with a modified gas chromatograph (Agilent 7890) equipped with a flame ionization detector (FID) and an electron capture detector (ECD) (Wang *et al*., 2003). The configuration of GC and specific procedures for simultaneously measuring CO_2, CH_4 and N_2O fluxes were detailed in our previous studies (Zou *et al*., 2005a, b). A non-linear fitting

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approach was adopted to determine the GHGs flux, as described by Kroon *et al*. (2008). Seasonal cumulative CO_2, CH_4 and N_2O emissions during the observation period were sequentially accumulated from the emissions between every two adjacent intervals of the measurements.

Determination of NEE, NGHGB and GHGI

Net ecosystem exchange of CO_2 between terrestrial ecosystems and atmosphere (NEE) depends on how much carbon lost or gained for a given ecosystem, which is equivalent to the difference between soil heterotrophic respiration (R_H) and NPP. As a typical tuber bioenergy crop with no intricate fibrous root system, the R_H was represented by soil CO_2 fluxes measured from inter-cropping rows given that Jerusalem artichoke roots and tubers were excluded by the 20-cm height wall of the gas flux collars inserted into the plough pan horizon of the soil. The NPP was determined by the harvested above- and belowground biomass and litterfall from 6 randomly selected sub-plots and each of 20 cm × 80 cm in each plot (24 of 50 individual plants in each plot). Crop litterfall was collected on each sampling day by fitting the crop growth with a special-designed mash bag over the whole Jerusalem artichoke cropping season. For the fallow season leftover with natural vegetation, the above- and belowground biomass was harvested from the same selected sub-plots for each plot. Crop biomass, litterfall and yield of tuber for each plot were determined at harvest by oven drying to a constant weight at approximately 70 ºC.

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To gain an insight of a complete annual accounting of NGHGB and GHGI from the coastal saline Jerusalem artichoke cropping systems under various soil practices, we calculated the combined NGHGB for each treatment by integrating CH_4 and N_2O emissions to NEE budgets using the IPCC GWP factors over the 100-yr time horizon based on the following equation (IPCC, 2007):

$$\text{NGHGB (t } CO_2\text{-equivalents ha}^{-1}\text{ yr}^{-1}) = \text{NEE} + 25 \times CH_4 + 298 \times N_2O$$

Further, the GHGI is calculated by dividing NGHGB by NPP:

$$\text{GHGI (t } CO_2\text{-equivalents t}^{-1}\text{ NPP yr}^{-1}) = \text{NGHGB/NPP}$$

Auxiliary measurements

The field topsoil samples (10–15 cm) were collected before Jerusalem artichoke sowing to measure soil pH, bulk density (BD), total organic carbon (TOC), total nitrogen (TN), salt content, and available phosphorus. Above soil physicochemical properties analyses were directed by the Chinese Soil Society Guidelines (Lu 2000). Soil electrical conductivity (EC) was measured at soil/water ratio of 1/2 using EC meter (Orion, Model CM-180). Soil volumetric water content at each sampling day was measured with a portable rod probe (MPM-160) and the values were further converted into water filled pore space (WFPS).

Data analyses

Differences in tuber yield, soil cumulative CO_2, CH_4 and N_2O emissions, and the net NGHGB and GHGI in Jerusalem artichoke cropping systems over the annual cycle as affected by soil

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practices including soil tillage and soil ameliorant or crop residue amendment were examined using a two-way analysis of variance (ANOVA). Before making the two-way ANOVA, the t-distribution of 864 individual flux measurements was examined for the normality of each gas type by Shapiro-Wilk test (P = 0.38, 0.26 and 0.15 for N_2O, CO_2 and CH_4, respectively). Correlation analyses were performed between soil CO_2 and soil temperature and moisture, soil CH_4 and N_2O emissions and soil WFPS across field treatments. Statistical significance was determined at the 0.05 probability level. Statistical analyses were performed using JMP version 7.0 (SAS Institute, USA, 2007).

Results

Soil R_H

Seasonal or annual dynamics of soil CO_2 fluxes were similar among the field treatments, which were independent of soil management practices (Fig. 2). Over the annual cycle, the dynamics of soil CO_2 fluxes were generally in accordance with changes in soil temperature and moisture (Figs. 1 and 2). The dependence of soil CO_2 fluxes on temperature and soil moisture were pronounced for the both NT and RT treatments, and no significant difference in the slopes of the regression lines suggested that soil respiration had a similar response to changes in soil temperature and moisture between the RT and NT cropping systems (Fig. 5a and 5b).

Seasonal total CO_2 emissions were significantly affected by soil amendments, but the effects of soil tillage and their interaction were not significant during the cropping and following

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fallow seasons (Table 2). In the Jerusalem artichoke cropping season, soil CO_2 fluxes averaged 95.0 and 110.9 mg m^{-2} h^{-1} for the control plots under NT and RT practices, respectively. Compared with the control, soil ameliorant amendment increased soil CO_2 emissions by 9–10% in the cropping season, with an average of 103.6 and 122.3 mg m^{-2} h^{-1} for the NT-PP and RT-PP plots, respectively. Soil CO_2 emissions from the cropping season averaged 111.4 and 124.5 mg m^{-2} h^{-1} for the NT-WS and RT-WS plots, which were 17% and 12% greater than those for the NT-Control and RT-Control plots, respectively.

In the following non-cropping season, soil CO_2 fluxes averaged 118.9 and 134.3 mg m^{-2} h^{-1} for the NT-Control and RT-Control plots, respectively. Relative to the control plots, soil ameliorant amendment increased soil CO_2 emissions by 13% and 8% under the NT and RT tillage practices, respectively (Table 2). Soil CO_2 fluxes from the non-cropping fallow season averaged 164.3 and 136.6 mg m^{-2} h^{-1} for the NT-WS and RT-WS plots, which were 38% and 22% greater than those for the NT-Control and RT-Control plots, respectively. Over the whole annual rotation cycle, the Jerusalem artichoke cropping season contributed about 33–38% of the annual total soil CO_2 emissions, and the other 62–67% was captured during the following non-cropping season.

NPP

The NPP of Jerusalem artichoke and natural vegetation crops were significantly affected by tillage and soil amendment, but their interaction were not significant (Table 2). Relative to the no-tillage, rotary tillage decreased the NPP Jerusalem artichoke and natural vegetation

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crops by 7–16% and 7–23% across the soil amendment treatments, respectively. In contrast, soil amendments significantly increased NPP of Jerusalem artichoke and natural vegetation crops both in the NT and RT cropping systems. Relative to the controls, soil ameliorant or straw amendment increased the NPP of Jerusalem artichoke by 37–38% or 13–25%, respectively. The NPP of natural vegetation was 53–115% and 38–61% greater in the soil ameliorant and straw amendment plots than in the control plots, respectively. Over the whole annual cycle, atmospheric CO_2 sequestrated into NPP by the Jerusalem artichoke and natural vegetation crops together were increased by 19–47% due to soil amendments, but they were decreased by 8–17% under the RT relative to NT treatments. The tuber yield of Jerusalem artichoke was significantly different among the field treatments within identical tillage cropping system ($P < 0.05$, Table 3), but no significant difference was observed between the two tillage managements. On average, soil amendments increased the tuber yield by 18–25% and 22–27% in the NT and RT cropping systems, respectively.

NEE

The negative value of NEE suggested that atmospheric CO_2 captured into biomass exceeded soil heterotrophic CO_2 effluxes, suggesting a net ecosystem CO_2 sequestration of cropping system. Obviously, the net ecosystem CO_2 sequestration was much more contributed by Jerusalem artichoke than natural vegetation crops (Table 3). During the Jerusalem artichoke cropping season, NEE was significantly affected by tillage practice and soil amendment, but independent of their interaction (Table 2). Rotary tillage relative to no-tillage decreased ecosystem CO_2 sequestration by 10–20%, while soil ameliorant amendment increased

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ecosystem CO_2 sequestration by 38–42% during the Jerusalem artichoke cropping season. Compared with the controls, soil straw amendment increased ecosystem CO_2 sequestration of the Jerusalem artichoke cropping season by 11% and 27% under the NT and RT practice regimes, respectively.

Soil CH_4 emissions

Seasonal pattern of CH_4 fluxes was not pronounced, typically varying within the small positive (indicating release) and negative (indicating uptake) fluxes in the Jerusalem artichoke-fallow cropping systems (Fig. 3). Annual CH_4 fluxes did not correlate well with soil WFPS, but higher soil CH_4 fluxes or less uptake were observed in the RT than in the NT cropping systems over the whole Jerusalem artichoke-fallow cropping cycle (Figs. 3 and 7). Mean seasonal soil CH_4 fluxes ranged from -0.04 mg m^{-2} h^{-1} for the NT-Control plots to 0.04 mg m^{-2} h^{-1} for the RT-WS plots during the cropping season, and from -0.05 mg m^{-2} h^{-1} for the NT-Control plots to 0.05 mg m^{-2} h^{-1} for the RT-WS plots during the non-cropping fallow season. Over the whole annual cycle, the seasonal total of soil CH_4 emissions was significantly distinguished by tillage practice and soil amendment, but their interaction was not significant (Table 2). Rotary tillage changed the control plots with a weak sink for CH_4 to a slight source of CH_4. Soil CH_4 emissions were increased or uptakes were weakened by soil ameliorant or straw incorporation over the annual Jerusalem artichoke-fallow cropping system (Table 2).

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Soil N_2O emissions

Similar pattern of soil N_2O fluxes was observed among treatment plots under NT or RT Jerusalem artichoke-fallow cropping systems, while it was primarily dependent on soil water content and fertilizer application during the Jerusalem artichoke cropping season (Figs. 1 and 4). Over the whole annual cycle, N_2O emissions were significantly correlated with soil moisture across the field treatments (Fig. 6). Given the identical N input for all field plots over the whole annual Jerusalem artichoke-fallow cropping rotation, seasonal total N_2O emissions were significantly affected by soil amendment, but independent of soil tillage and their interaction (Table 2). For the control plots under no-tillage regime, seasonal N_2O fluxes averaged 47.6 μg m^{-2} h^{-1} in Jerusalem artichoke cropping season and 50.9 μg m^{-2} h^{-1} in the non-cropping fallow season, 35% greater and 14% lower than those from the control plots under RT regime, respectively (Table 2). Compared with the control plots, soil ameliorant addition increased N_2O emissions by 32–43% and 27–41% during the cropping and non-cropping fallow seasons, respectively, and thus led to annual N_2O emissions increased by 34–37%. Similarly, straw mulch increased soil N_2O emissions under both tillage managements. Relative to the control plots, straw mulch increased seasonal N_2O emissions by 8–18% under NT practice and 50–59% under RT regime.

NGHGB and GHGI

Overall, the seasonal or annual NGHGB was negative for all the field treatments, indicating that net ecosystem CO_2 sequestration exceeded the seasonal or annual CO_2-equivalents

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released as CH_4 and N_2O emissions from Jerusalem artichoke-fallow cropping systems (Table 3). Rotary tillage practice relative to no-tillage significantly increased the annual net NGHGB. On average, the annual net NGHGB was 12–27% lower in NT than in RT cropping systems. Across the two soil tillage managements, the plots with soil ameliorant addition and straw mulch decreased the net NGHGB by 50–53% and 16–29% relative to the control plots, respectively (Table 3).

During the cropping season, the GHGI relating GWP to the Jerusalem artichoke and natural vegetation biomass production was not significantly affected by tillage practice, soil amendment and their interaction (Table 3). Over the whole annual cycle, the GHGI relating GWP to the Jerusalem artichoke and natural vegetation biomass production was only slightly affected by tillage practice (Table 3). Compared with no-tillage plots, the annual GHGI was increased by 4–8% when rotary tillage practiced (Table 3). Over the whole annual cycle, soil ameliorant and straw amendments had no significant effects on GHGI, although they significantly affected NGHGB. The effect of soil ameliorant and straw amendments on GHGI was pronounced only during the non-cropping fallow season.

Discussion

Effects of soil practices on NEE

The net ecosystem exchange of CO_2 (NEE) was determined by the static chamber method in present study, which refers to the C balance between outputs by soil heterotrophic oxidation of organic material and inputs by crop autotrophic fixation. Similar to the methods

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reported in previous studies on NEE estimation (Lund *et al*., 1999; Zou *et al*., 2004b; Mosier *et al*., 2006; Zheng *et al*., 2008b; Nishimura *et al*., 2008; Liu *et al*., 2012b), soil heterotrophic respiration was represented by soil CO_2 fluxes from the gas sampling collars with a 20-cm height wall inserted at inter-cropping rows in the present study. The 20-cm height wall of the gas flux collars matched the 20-cm plough pan horizon of the soil, and thus Jerusalem artichoke roots and tubers were excluded by collars wall, so that the measured CO_2 effluxes would refer to soil heterotrophic respiration. In addition, soil CO_2 fluxes were well correlated with soil temperature and moisture, but not with crop growth, suggesting soil CO_2 fluxes were derived from soil heterotrophic respiration rather than root autotrophic respiration (Fig. 5).

Evidence is amounting that the ecosystem-level CO_2 exchanges determined by the static chamber method was comparable to that estimated by the micrometeorological techniques, such as the eddy covariance flux tower (Frolking *et al*., 1998; Anthoni *et al*., 2004; Zou *et al*., 2004b; Zheng *et al*., 2008b). To our knowledge, the information on NEE estimation from bioenergy cropping systems on the same site is not yet available for extremely limited field measurements on either the seasonal or annual cropping scales. In this study, the NEE was estimated to be -10.25 to -17.52 t C ha^{-1} across the field treatments in the Jerusalem artichoke cropping season, greatly lower than those obtained using eddy covariance method in perennial willow or *miscanthus* bioenergy cropping systems, with a range of seasonal magnitude from -6.02 to -7.80 t C ha^{-1} (Drewer *et al*., 2012). Over the annual Jerusalem artichoke-fallow cropping cycle, the NEE was estimated to be -10.53 to

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-19.95 t C ha^{-1}, substantially lower than those modeled in annual switchgrass bioenergy cropping systems with less than -2.0 t C ha^{-1} (Adler *et al.*, 2007). The lower NEE with Jerusalem artichoke cultivation in this study was not due to lower soil heterotrophic respiration, rather the higher NPP arising from atmospheric CO_2 assimilation by Jerusalem artichoke as a typical bioenergy crop.

Contrary to our prediction, rotary tillage did not significantly increase soil CO_2 emissions. As rotary tillage was practiced at the soil depth of 10 cm, no significant difference in soil temperature and moisture was found between the two tillage treatments. As shown in Fig. 5, similar response of soil CO_2 emissions to changes in soil temperature and moisture might also be given for the no difference in soil CO_2 emissions between both tillage treatments. As predicted, soil CO_2 emissions were significantly increased by soil ameliorant or straw amendment, which was primarily due to improved saline soil conditions and organic substrates benefiting the enhancement in soil microbial activities. Despite an increase in soil CO_2 emissions, nevertheless, the improved saline soil conditions by soil ameliorant and crop residue amendments greatly benefited the Jerusalem artichoke crop growth.

Soil CH_4 and N_2O emissions response to tillage practice

The seasonal or annual total of soil CH_4 emissions was significantly distinguished by soil tillage practices. Relative to the NT, soil CH_4 emissions was promoted for the RT plots in the Jerusalem artichoke-fallow cropping systems. Our findings are in accordance with the

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results obtained by Ball *et al.* (1999) and Hütsch (2001) reporting that no tillage vs. conventional/reduced tillage management highly decreased soil CH_4 emissions in upland cropping soils, which allows for a porous structure that facilitates CH_4 diffusion into oxidizing zones and with high methanotrophic activity. However, it varied with soil properties (e.g. soil pH, redox potential, bulk density) and local specific climate, where sandy soil with low soil pH and bulk density in cool and wet soil conditions may generally benefit soil CH_4 oxidation (Brumme & Borken, 1999; Jiang *et al*., 2006). Instead, the Jerusalem artichoke-fallow cropping system with RT absolutely presented as a weak CH_4 emission source, despite of the difference in intensities with field management practices. This is in line with the evidence that agricultural practices (e.g. soil tillage) have adverse effects on the soil CH_4 oxidation potential (Arif *et al*., 1996; Kessavalou *et al*., 1998; Hütsch, 2001). Moreover, cultivation appears to decrease the net CH_4 consumption, as CH_4 oxidation potentials are generally lower in cultivated than in uncultivated ecosystems (Mosier *et al*., 1996).

In contrast, seasonal or annual cumulative N_2O emissions were comparable between the NT and RT managements. In general, no tillage or reduced tillage is known to facilitate soil N_2O fluxes by increasing soil water content and soil bulk density, although other changes such as decreased soil temperature and decreased N mineralization rates may induce lower N_2O emissions to varying degrees (Ball *et al*., 1999; Vinten *et al*., 2002; Six *et al*., 2002). In addition, no tillage can alter vertical distribution of microbial population and potential enzyme activities that drive soil N_2O production (Groffman, 1985). There is also evidence

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that the effect of tillage practice on soil N_2O emissions diminishes after long-term practice of no tillage (Yamulki & Jarvis, 2002; Elmi *et al*., 2003; Six *et al*., 2004). Thus, a large uncertainty existed associated with the estimates regarding the influence of the tillage alternative on soil N_2O emissions (Chatskikh & Olesen, 2007). In this study, there was no significant difference in soil N_2O emissions between no-tillage and rotary tillage practices across the field treatments under the identical seasonal N input level. Although soil moisture was slightly decreased by rotary tillage (annual average, WFPS 44.2% in NT vs. 41.0% in RT plots), most value of soil moisture was within the range of 30-70% WFPS for the both tillage treatments (Fig. 6). Presumably, the specific sandy-oriented saline soil texture, surface tillage implemented and the common climates in this study greatly narrowed the differences in soil N_2O production between the current two tillage cropping systems.

Soil CH_4 and N_2O emissions raised by soil ameliorant addition

Soil salinity is one of the important factors affecting soil microbial activities and crop productivity in most of the Asian humid and sub-humid coastal saline areas (Ismail *et al*., 2009). Soil pore water salinity can mediate the availability of soil terminal electron acceptors (e.g. NO_3^-, SO_4^{2-}) that affect organic matter mineralization and greenhouse gas emissions (Craft *et al*., 2009; Larsen *et al*., 2010). In this study, peat and phosphogypsum (a by-product from the manufacture of phosphorous fertilizers) were selected as promising soil ameliorants for desalination, which have been widely used for saline soil reclamation as a result of their being cheap, generally available, and easy to apply (Shainberg *et al*., 1989; Chi *et al*., 2012). With the identical seasonal N input, the plots with soil ameliorant

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incorporation greatly increased soil CH_4 emissions as compared to control plots under the both tillage alternatives over the annual cropping cycle. Several studies have obtained the similar evidence that increase of CH_4 emissions from soil strengthened with the decline in soil salinity under either controlled or field conditions (Denier van der Gon & Neue, 1995; Biswas *et al*., 2006; Datta *et al*., 2013). Since the higher soil salinity level progressively decreased soil microbial activities as reflected by decreased microbial biomass carbon (MBC) and low soil microbial populations (including methanogens) (Pattnaik *et al*., 2000). Likewise, a strong negative correlation between annual CH_4 flux and soil salinity was found in coastal saline marshes of the United States (Bartlett *et al*., 1987). Also, Supprattanapan *et al*. (2009) examined the effect of locally available organic amendment (used as a kind of desalter) on CH_4 emissions from saline soils but reported no significant difference in CH_4 emissions from soils amended with organic matter relative to unamended soils.

In this study, soil N_2O emissions were greatly increased with the decreased soil salinity improved by soil ameliorant addition. As reported by Craft *et al*. (2009), decreasing nitrification-denitrification (processes generating soil N_2O) rates were observed when the tidal fresh converted to salt marshes, which was known as typical saline wetlands covered by salt water or contains areas of salt water in southeastern Georgia, USA. On the other hand, as soil salinity increases, reduced sulfur species such as H_2S can interfere with soil N cycling by suppressing nitrification-denitrification, as well as exerting a toxic effect on microbial communities (Larsen *et al*., 2010).

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Soil CH_4 and N_2O emissions stimulated by straw mulch

Under no tillage, the field plots for NT-WS with wheat straw mulch as compared to the NT-Control incurred a shift from CH_4 sink to emission source. While under rotary tillage, the plots with RT-WS relative to the RT-Control significantly increased soil CH_4 emissions. Basically, soil CH_4 emissions are facilitated when receiving organic amendments and decomposition of organic materials furnishes the substrates for methanogenesis. Straw mulching onto the field surface as an advocated alternative for straw incorporation practice has been reported to significantly enhance soil CH_4 emissions as compared to the control soil (Ma *et al*., 2008), although the effect varied with the straw kind, rate timing, and application mode (Minamikawa *et al*., 2006). Besides, the mulched wheat straw with higher C/N ratio (96.8) in present study may deplete the plant available N, which in turn stimulate growth and activity of methanogens, leading to more soil CH_4 emissions (Ma *et al*., 2007).

By contrast, there was no significant difference in soil N_2O emissions between the plots with or without straw incorporation under no-tillage practice. Under rotary tillage regime, however, soil N_2O emissions were greatly increased by straw amendment as compared to the control plots. Crop straw amendment offers readily available carbon (C) and nitrogen (N) into the soil, along with other nutrients (Kumar & Goh, 2000; Huang *et al*., 2004; Singh *et al*., 2008). However, decomposition of crop residue has been identified to be dependent on the residue particle size and quality (especially the C/N ratio and chemical composition), as well as the application modes and climate (Kumar & Goh, 2000; Zou *et al*., 2005a; Ma *et al*., 2009). Crop residue amendment also influences soil denitrification rate, abundance of

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denitrifier, and eventually the soil N_2O emissions (Henderson *et al.*, 2010). In general, amendment of crop residue with high C/N ratio stimulates microbial immobilization by N released from residue decomposition in soil, thereby resulting in lower N_2O emissions (Huang *et al.*, 2004; Toma & Hatano, 2007). While in this study, given the high C/N ratio (96.8) of wheat straw mulched, soil N_2O release was significantly enhanced for the plots with wheat straw amendment under the rotary tillage practice. The results of this study may agree with Millar & Baggs (2004) and Muhammad *et al*. (2011) reporting that other properties of crop residue (e.g. lignin, polyphenol and soluble C) rather than C/N ratio may contribute more to the soil N immobilization and N_2O release in some soils. This was also supported by Shan & Yan (2013) showing that C/N ratio of crop residue could only account for 18% of the variability in residual effect size by data integration with meta-analysis. Particularly, Ma *et al*. (2010) pointed out that mulching of crop residue significantly increased N_2O emissions (mean, 63%) as compared with control, which was presumably attributed to the improved microbial activities during nitrification and denitrification processes, resulting from favorable soil moisture conditions and higher soil temperature in mulched treatments.

Effects of soil practices on NGHGB and GHGI

Net greenhouse gas balance (NGHGB) of a given terrestrial ecosystem refers to sink or source of GHG. Currently, two approaches were widely used to estimate NGHGB in terms of the methods adopted in C balance estimation. In this study, the NEE referred to the difference between the soil CO_2 emissions and NPP, as in our previous studies on rice

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paddies (Zou *et al*., 2004b; Liu *et al*., 2012b). Alternatively, the C balance was determined by the annual changes in SOC, indicating the net ecosystem carbon balance (NECB) where the atmospheric CO_2 assimilated into crop biomass and other C losses were excluded in C balance estimation (Sang *et al*., 2011).

It is well recognized that China's terrestrial ecosystems have acted as a significant carbon sink in recent decades (Fang *et al*., 2001; Huang and Sun, 2006; Fang *et al*., 2007; Piao *et al*., 2009). However, it remains uncertain whether a CO_2 sink can be translated into a source for climate warming since the relatively higher source strengths of CH_4 and N_2O in terms of CO_2-equivalents in China (Chen *et al*., 2000; Yan *et al*., 2003; Ding and Cai, 2007; Huang *et al*., 2009). In present study, the annual NGHGB was negative for all the field treatments in the reclaimed fields with Jerusalem artichoke cultivation suggesting a GHG sink for the coastal saline tidal-flat zones. Particularly, relative to rotary tillage, Jerusalem artichoke cultivation significantly decreased the seasonal or annual NGHGB under no tillage management. Additionally, soil ameliorant application relative to the unamended soils reduced the seasonal or annual net NGHGB and GHGI for improved saline soil conditions under the both tillage managements. Similarly, compared with rotary tillage, the annual GHGI was significantly decreased by no tillage across field treatments. However, the net NGHGB and GHGI were comparable between the plots with crop residue incorporation or not across the tillage alternatives.

Overall, this study provided an insight into a full accounting of the net NGHGB and GHGI in response to a range of soil management practices in coastal saline bioenergy cropping systems. The NT vs. RT cropping system decreased soil CO_2 emissions, while there

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was no significant difference in soil CO_2 emissions among treatments under each tillage practice. Seasonal or annual total of CH_4 emissions was significantly distinguished by soil tillage practices. Soil CH_4 emissions were decreased by NT as compared with RT management. Soil CH_4 emissions were greatly promoted by soil ameliorant or straw incorporation. No significant differences between NT and RT managements on soil N_2O emissions were observed in this study. Soil ameliorant addition facilitated soil N_2O emissions in Jerusalem artichoke-fallow cropping rotation systems, while no significant difference in soil N_2O emissions as affected by crop residue incorporation was found in NT relative to RT cropping system. The seasonal or annual NGHGB and GHGI were lower in NT than in RT cropping system. Soil ameliorant relative to the unamended soils reduced the net NGHGB and GHGI due to improved saline soil conditions under the both tillage managements, while they were comparable between the plots with crop residue incorporation or not. Therefore, Jerusalem artichoke cultivation under no tillage with improved saline soil conditions would simultaneously achieve higher biomass and mitigate climatic impacts of coastal saline bioenergy production in southeast China.

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Table 1

Details of the experimental treatments in the Jerusalem artichoke cropping system.

Treatment[¶]	Tillage practice	Wheat straw mulch ($t\ ha^{-1}$)	Soil ameliorant applied ($t\ ha^{-1}$)	
			Peat	Phosphogypsum
NT-Control	No-till	0	0	0
NT-PP	No-till	0	4.5	2.1
NT-WS	No-till	4.5	0	0
RT-Control	Rotary-till	0	0	0
RT-PP	Rotary-till	0	4.5	2.1
RT-WS	Rotary-till	4.5	0	0

[¶] NT-Control, control treatments under no-till; NT-PP, no-tillage with soil ameliorant amendment (peat 4.5 $t\ ha^{-1}$ + phosphogypsum 2.1 $t\ ha^{-1}$); NT-WS, no-tillage with wheat straw mulch (4.5 $t\ ha^{-1}$); RT-Control, control treatments with rotary tillage (10 cm); RT-PP, rotary tillage with soil ameliorant amendment (peat 4.5 $t\ ha^{-1}$ + phosphogypsum 2.1 $t\ ha^{-1}$); RT-WS, rotary tillage with wheat straw mulch (4.5 $t\ ha^{-1}$) .

Table 2

Seasonal NEE, CH_4 and N_2O emissions from annual Jerusalem artichoke-fallow cropping systems (Mean ± SE, n = 4).

Treatments	Jerusalem cropping season					Fallow season				
	R_H	NPP	NEE	CH_4	N_2O-N	R_H	NPP	NEE	CH_4	N_2O-N
		($t\ C\ ha^{-1}$)		($kg\ ha^{-1}$)	($kg\ N\ ha^{-1}$)		($t\ C\ ha^{-1}$)		($kg\ ha^{-1}$)	($kg\ N\ ha^{-1}$)
NT-Control	0.93 ±	13.57 ±	-12.64 ±	-1.32 ±	1.09 ±	1.60 ±	1.98 ±	-0.38 ±	-2.35 ±	1.04 ±

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	0.19b	2.14b	1.47ab	0.06d	0.18b	0.20b	0.06c	0.03a	0.36e	0.16b
NT-PP	1.02 ± 0.23ab	18.54 ± 3.21a	-17.52 ± 2.96c	0.58 ± 0.07c	1.44 ± 0.23a	1.82 ± 0.19ab	4.25 ± 1.02a	-2.43 ± 0.38c	-0.64 ± 0.12d	1.47 ± 0.34a
NT-WS	1.09 ± 0.11a	15.32 ± 1.58ab	-14.23 ± 1.43b	0.94 ± 0.18b	1.18 ± 0.11b	2.22 ± 0.23a	3.18 ± 0.23b	-0.96 ± 0.24ab	-0.37 ± 0.19cd	1.23 ± 0.29ab
RT-Control	1.09 ± 0.17a	11.34 ± 2.26c	-10.25 ± 0.98a	0.68 ± 0.14c	0.81 ± 0.16bc	1.85 ± 0.19ab	2.13 ± 0.19c	-0.28 ± 0.11a	0.23 ± 0.07c	1.09 ± 0.17b
RT-PP	1.20 ± 0.09a	15.65 ± 1.12ab	-14.45 ± 1.02b	0.93 ± 0.21b	1.16 ± 0.20b	1.95 ± 0.11ab	3.26 ± 0.35b	-1.31 ± 0.69b	1.64 ± 0.28b	1.38 ± 0.22ab
RT-WS	1.22 ± 0.11a	14.13 ± 3.78b	-12.91 ± 1.86ab	1.39 ± 0.43a	1.29 ± 0.38ab	2.21 ± 0.15a	2.95 ± 0.26b	-0.74 ± 0.13ab	2.38 ± 0.43a	1.64 ± 0.35a
Tillage practice (*T*)	ns	**	**	**	ns	ns	ns	ns	***	ns
Soil amendment (*S*)	*	***	**	***	**	*	**	**	***	**
Interaction (*T*×S)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Model	*	**	*	**	*	*	**	**	***	*

Table 3

Seasonal and annual NGHGB (t CO_2-equivalents ha^{-1} yr^{-1}), tuber yield (t ha^{-1}) and GHGI (t CO_2-equivalents t^{-1} NPP yr^{-1}) over the annual Jerusalem artichoke-fallow cropping system (Mean ± SE, n = 4).

Treatments	Jerusalem cropping season			Fallow season		Annual	
	Tuber yield	NGHGB	GHGI	NGHGB	GHGI	NGHGB£	GHGI§

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NT-Control	9.85 ± 3.64b	-45.9 ± 3.1b	-3.38 ± 0.28a	-0.97 ± 0.26a	-0.49 ± 0.05ab	-46.8 ± 3.01ab	-3.01ab
NT+PP	12.35 ± 3.21a	-63.6 ± 3.9c	-3.43 ± 0.43a	-8.24 ± 2.87d	-1.94 ± 0.54c	-71.8 ± 6.49c	-3.15b
NT+WS	11.59 ± 2.85ab	-51.6 ± 2.1bc	-3.37 ± 0.49a	-2.95 ± 0.91bc	-0.93 ± 0.26ab	-54.6 ± 3.67b	-2.95a
RT-Control	10.21 ± 4.87b	-37.2 ± 1.7a	-3.28 ± 0.51a	-0.51 ± 0.26b	-0.24 ± 0.11a	-37.7 ± 1.83a	-2.80a
RT+PP	12.93 ± 2.71a	-52.4 ± 2.8bc	-3.35 ± 0.63a	-4.12 ± 1.24c	-1.26 ± 0.49b	-56.5 ± 2.65b	-2.99ab
RT+WS	12.47 ± 2.58a	-46.7 ± 4.3b	-3.30 ± 0.32a	-1.89 ± 0.41c	-0.64 ± 0.23a	-48.6 ± 3.88ab	-2.84 a
Tillage practice (*T*)	ns	***	ns	**	*	**	*
Soil amendment (*S*)	**	**	ns	***	**	*	ns
Interaction (*T*×S)	ns	ns	ns	ns	ns	ns	ns
Model	*	**	ns	***	*	*	*

[£] The IPCC GWP factors (mass basis, kg CO_2-equivalents ha^{-1}) for CH_4 and N_2O are 25 and 298 in the time horizon of 100 years, respectively (Forster et al., 2007).

[§] GHGI (t CO_2-equivalents t^{-1} NPP yr^{-1}) is calculated by dividing NGHGB by NPP of Jerusalem artichoke and natural vegetation.

[*], [**], and [***] indicate statistically significant at the 0.05, 0.01, and 0.001 probability levels by a two-way ANOVA, respectively; ns, not significant.

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Figure legend

Fig. 1 Mean air/soil temperature across the treatments and soil WFPS for all treatments at soil depth of 5–10 cm over annual whole Jerusalem artichoke-fallow cropping system.

Fig. 2 Annual pattern of soil CO_2 fluxes (mean ± S.D.) over the Jerusalem artichoke-fallow cropping cycle. NT-Control, no-tillage with urea application; NT-WS, no-tillage with urea application and wheat straw mulch (4.5 t ha^{-1}); NT-PP, no-tillage with urea and soil ameliorant application (peat 4.5 t ha^{-1} + phosphogypsum 2.1 t ha^{-1}); RT-Control, rotary tillage (10 cm) with urea application; RT-WS, rotary tillage with urea application and wheat straw mulch (4.5 t ha^{-1}); RT-PP, rotary tillage with urea and soil ameliorant application (peat 4.5 t ha^{-1} + phosphogypsum 2.1 t ha^{-1}).

Fig. 3 Annual patterns of soil CH_4 fluxes (mean ± S.D.) over the Jerusalem artichoke-fallow cropping cycle. Treatments as detailed in Fig. 2., and arrow bars refer to N fertilizer application.

Fig. 4 Annual patterns of soil N_2O fluxes (mean ± S.D.) over the Jerusalem artichoke-fallow cropping cycle. Treatments as detailed in Fig. 2., and arrow bars refer to N fertilizer application.

Fig. 5 Correlation of annual mean soil respiration (R_H) rates with soil temperature (ºC) under no tillage (NT) and rotary tillage (RT) Jerusalem artichoke cropping systems.

Fig. 6 Correlation of annual mean soil N_2O fluxes with soil WFPS under no tillage (NT) and rotary tillage (RT) Jerusalem artichoke cropping systems.

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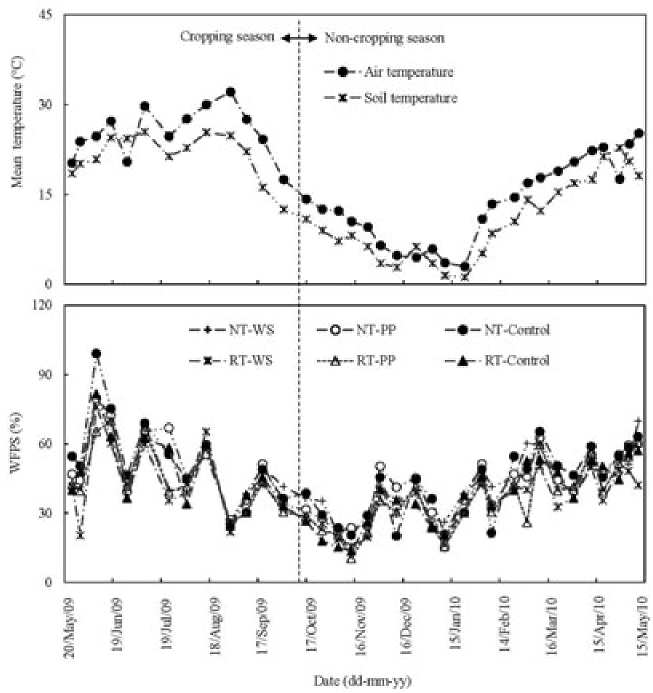
Fig. 7 Correlation of annual mean soil CH_4 fluxes with soil WFPS under no tillage (NT) and rotary tillage (RT) Jerusalem artichoke cropping systems.



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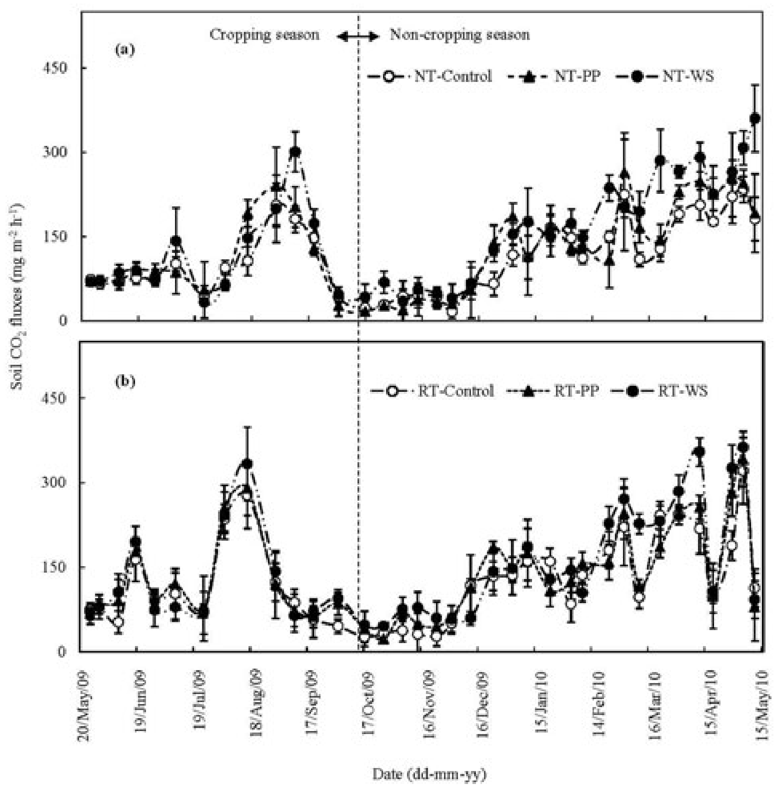

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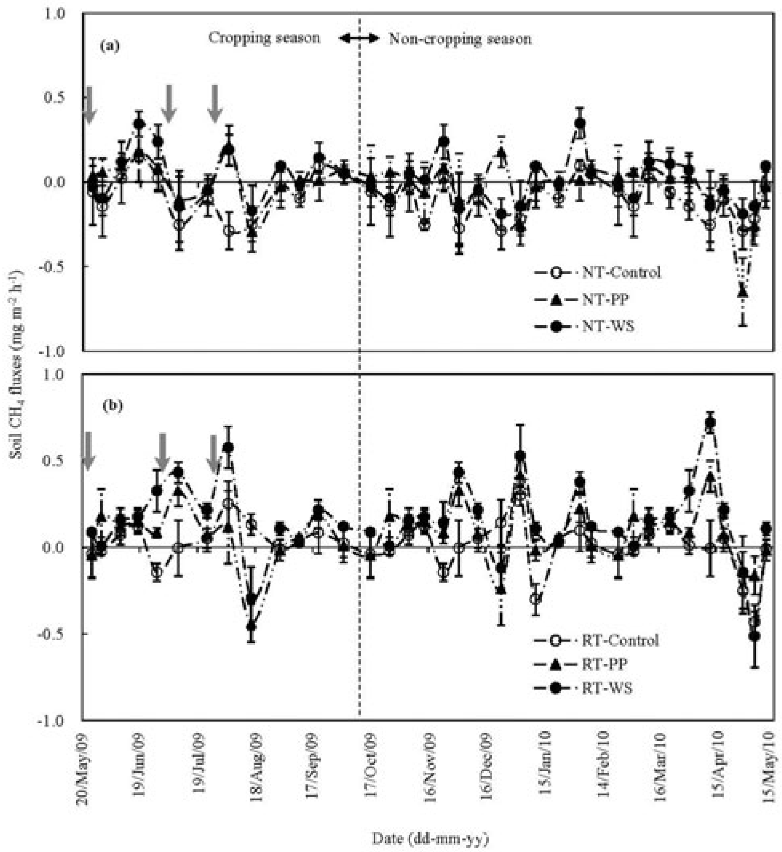

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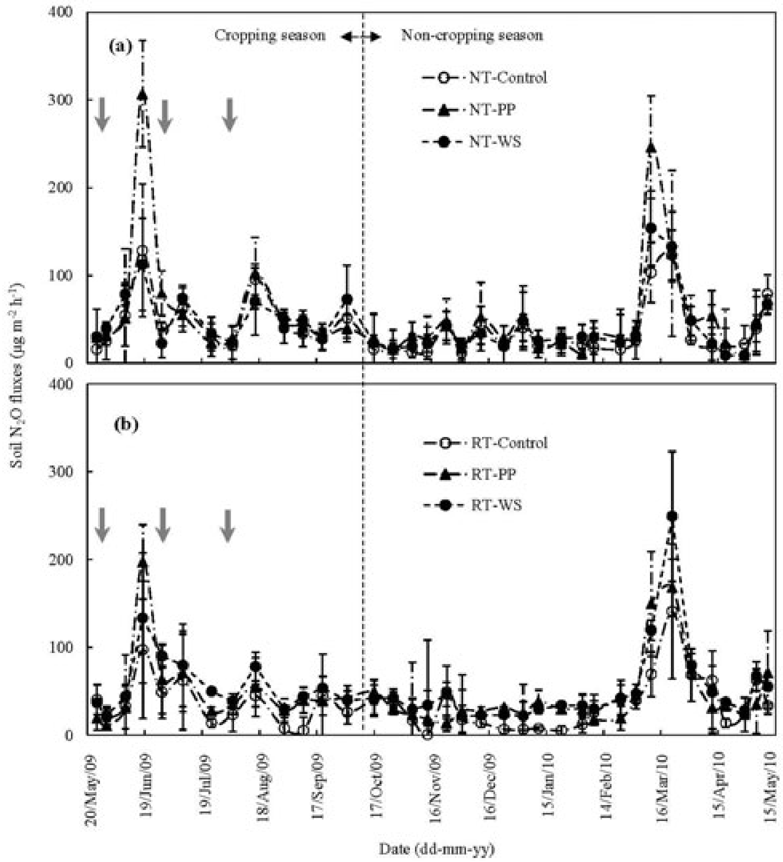

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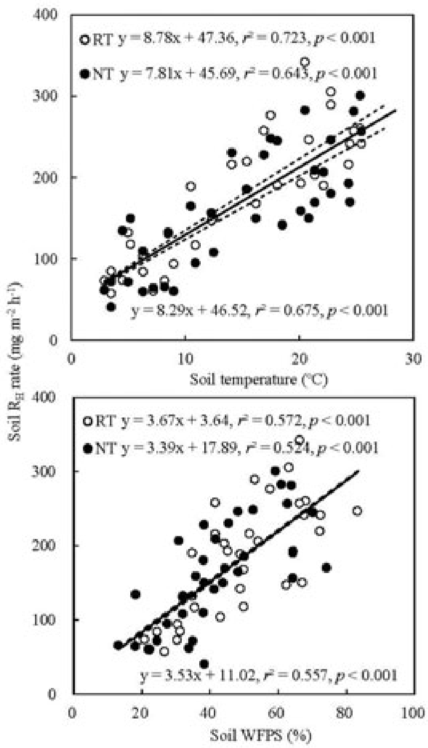

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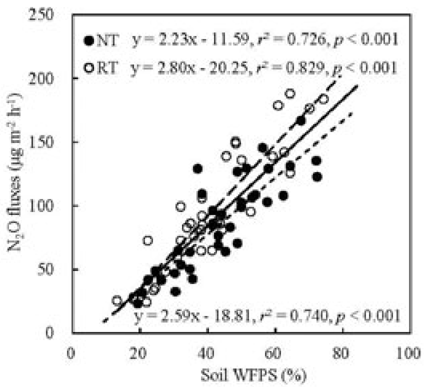

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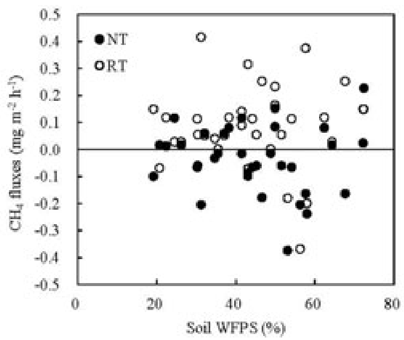

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