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Greenhouse Gas Emissions and Crop Yields From Winter Oilseed Rape Cropping Systems are Unaffected by Management Practices

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Winter oilseed rape is traditionally established via plough-based soil cultivation and conventional sowing methods. Whilst there is potential to adopt lower cost, and less intensive establishment systems, the impact of these on greenhouse gas emissions have not been evaluated. To address this, field experiments were conducted in 2014/2015 and 2015/2016 to investigate the effects of 1) crop establishment method and 2) sowing method on soil greenhouse gas emissions from a winter oilseed rape crop grown in Ireland. Soil carbon dioxide, nitrous oxide and methane emission measurements were carried out using the static chamber method. Yield (t seed ha^{-1}) and the yield-scaled global warming potential (kg CO_2-eq. kg^{-1} seed) were also determined for each management practice. During crop establishment, conventional tillage induced an initially rapid loss of carbon dioxide (2.34 g C m^{-2} hr^{-1}) compared to strip tillage (0.94 g C m^{-2} hr^{-1}) or minimum tillage (0.16 g C m^{-2} hr^{-1}) ($p < 0.05$), although this decreased to background values within a few hours. In the crop establishment trial, the cumulative greenhouse gas emissions were, apart from methane, unaffected by tillage management when sown at a conventional (125 mm) or wide (600 mm) row spacing. In the sowing method trial, cumulative carbon dioxide emissions were also 21% higher when plants were sown at 10 seeds m^{-2} compared to 60 seeds m^{-2} ($p < 0.05$). Row spacing width (125 and 750 mm) and variety (conventional and semi-dwarf) were found to have little effect on greenhouse gas emissions and differences in seed yield between the sowing treatments were small. Overall, management practices had no consistent effect on soil greenhouse gas emissions and modifications in seed yield per plant countered differences in planting density.

Keywords: crop management, tillage, row spacing, seed rate, variety, GHG (greenhouse gases), oilseed rape

INTRODUCTION

Atmospheric concentrations of the greenhouse gases (GHG) carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) continue to rise globally due to anthropogenic activities. Agriculture is responsible for approximately 12% of global GHG emissions with livestock systems, soil cultivation, rice production and crop residue management making the more significant contributions (Ciais et al., 2014). In terms of land use impacts, croplands make one of the major contributions to agricultural GHG emissions through various farming and management activities. Field operations

such as soil tillage, sowing, fertilizer addition and chemical treatment that are normally required to maximize plant productivity and yield can have significant impacts on GHG emissions through perturbations in the carbon (C), nitrogen (N) and water dynamics of these ecosystem (Bondeau et al., 2007; Osborne et al., 2010). Mitigation of GHG emissions from agricultural sources involves measures that aim to increase soil organic carbon (SOC) sequestration, reduce GHG emission rates, or both, through improved management practices (Smith et al., 2007; Minasny et al., 2017; Ogle et al., 2019). Cropland management practices that involve the adoption of less intensive soil cultivation and agronomic interventions that improve agricultural productivity may can lead to reductions in GHG emissions and determine whether these ecosystems function as sinks or sources of C (Ceschia et al., 2010).

Soil CO_2 is produced by autotrophic and heterotrophic processes. Autotrophic respiration is derived from roots and/ or the metabolism of photosynthetic substrates released by roots (Högberg and Read, 2006) whereas heterotrophic respiration is associated with the microbial decomposition of SOC or root exudates (Trumbore, 2000). Agriculture accounts for ~60% of the global anthropogenic N_2O emissions primarily due to increased N-fertilizer use (Smith, 2017), with croplands accounting for at least 80% these emissions (Tian et al., 2019). Nitrous oxide production in soils arise from nitrification; the conversion of ammonium (NH_4^+) to nitrite (NO_2^-) and subsequently nitrate (NO_3^-) in aerobic soils, and denitrification, the sequential reduction of NO_3^- to gaseous N_2O or N_2 in anaerobic soils (Butterbach-Bahl et al., 2013). The soil-atmosphere exchange of CH_4 is largely governed by the balance between net CH_4 production by methanogens and net CH_4 oxidation/uptake by methanotrophs (Serrano-Silva et al., 2014). Although upland arable soils are generally aerobic and considered CH_4 sinks, intensive soil management practices have reduced the capacity of many soils to oxidise CH_4 (Suwanwaree and Robertson, 2005). Land management practices thus often govern whether cropland soils are net sinks or sources of GHGs (Ceschia et al., 2010).

Tillage and sowing are management practices that influence crop establishment, plant growth, nutrient uptake, canopy/soil microclimate and yield (Sharratt and McWilliams, 2005; Malhi et al., 2006; Soane et al., 2012), and subsequently impact on C and N and the GHG balance in croplands (Ceschia et al., 2010; Moors et al., 2010). Conventional tillage (CT) encompasses soil inversion, and crop residue incorporation, facilitating seedbed preparation for the succeeding crop. However, CT practices result in the mechanical disruption of soil aggregates and the release of protected organic C from soil organic matter (SOM) resulting in enhanced CO_2 emissions. Altering the turnover rate of SOM can directly impact C sequestration and the emissions of CO_2, N_2O and CH_4 (Six et al., 2004; Abdalla et al., 2013; Abdalla et al., 2016; Shakoor et al., 2021). Agricultural practices that minimize or reduce tillage operations can increase soil aggregate formation potentially retaining ~30% of crop residues on the soil surface increasing nutrient availability and reducing soil erosion (CTIC, 2004). These practices include minimum tillage (MT), involving shallow cultivation to a depth of

5–10 cm, and strip tillage (ST), combining cultivated strips (25 cm depth) with direct drilling whilst leaving the inter-row spaces unaffected, have been promoted as alternative management practices to CT (Davies and Finney, 2002; Morris et al., 2010) that could reduce GHG emissions and increase C sequestration. In combination with these approaches crop residues may also be retained on the soil surface to protect the C in soil aggregates. The argument being that these non-inversion tillage systems will reduce the exposure and subsequent oxidation of SOC and lower GHG emissions.

In addition to CO_2, soil tillage can also affect the emissions of N_2O and CH_4. Both N_2O and CH_4 have global warming potentials (GWP) that are 265 and 28 times higher than CO_2, respectively (Myhre et al., 2013). In some cases, reductions in CO_2 emissions that have been attributed to a particular tillage management may be off-set by increases in the emissions of N_2O (Six et al., 2004). The rate of N_2O production is controlled by factors that are affected by tillage intensity, such as the soil water-filled pore space (WFPS), soil organic C availability and temperature (Butterbach-Bahl et al., 2013). The reported effects of RT operations on N_2O emissions are equivocal, showing either increases (Ball et al., 1999; Shakoor et al., 2021), decreases (Kessavalou et al., 1998; Chatskikh and Olesen, 2007; Ussiri et al., 2009) or similar N_2O emissions (Abdalla et al., 2010; O'Neill et al., 2020).

Methane fluxes are regulated by factors such as soil moisture, temperature, oxygen availability, SOM content and C and N availability (Jacinthe and Lal, 2005). Therefore, tillage practices, through their effects on soil physicochemical properties, can influence net CH_4 emissions (Hütsch, 1998). Well-aerated soils with higher oxygen availability that facilitate CH_4 diffusion to methanotrophic sites tend to have higher rates of CH_4 uptake than poorly drained soils that restrict CH_4 oxidation (Prajapati and Jacinthe, 2014). Soils may also differ in their capacity to oxidise methane, however, the mechanism(s) involved is not fully understood (Lang et al., 2020).

Oilseed rape (*Brassica napus* L.; OSR) is the third most important oil crop in the world after oil palm and soybean (FAOSTAT, 2021). The winter OSR variety is predominantly cultivated in temperate climatic regions of Europe, where the mean yield of winter and spring OSR varieties (2.7 t ha^{-1}) consistently exceed the global average (2.1 t ha^{-1}) (FAOSTAT, 2021). In Ireland, WOSR is cultivated as a break crop in cereal production systems on ~10,000 ha annually (Zahoor et al., 2015; CSO, 2020) and traditionally established via CT sowing operations (Forristal and Murphy, 2010). Compared to CT practices, the crop area under reduced tillage in Ireland is small at 40,000 ha (Meade and Mullins, 2005) although there is increasing interest by growers in the adoption of RT approaches for crop establishment for environmental and economic reasons.

Several studies have quantified GHG emissions from WOSR and/or canola systems. Management practices varied considerably between these experiments spanning 3 decades of research where the soil was cultivated by CT, RT or NT practices or the crops were established using a wide range of row

TABLE 1 | Management practices and GHG emission measurement methodologies as described in previous studies of OSR.

Study	Tillage	Row spacing (mm)	Seed rate (m^2)	Cultivar	Chamber methodology
Ball et al. (1999)	CT/NT	—	—	—	Inter-row spacing
Chatskikh et al. (2008)	CT/RT/DD	—	—	—	Plant + Soil
Dobbie et al. (1999)	—	—	—	—	Plant + Soil
Drewer et al. (2012)	DD	—	—	—	Inter-row spacing
Hénault et al. (1998)	—	—	—	—	Inter-row spacing
Jeuffroy et al. (2013)	CT	—	52	Mendel	Plant + Soil
Kaiser et al. (1998)	CT	—	—	—	Plant + Soil
Kavdir et al. (2008)	—	—	—	—	Inter-row spacing
Keane et al. (2018)	DD	—	—	—	Plant + Soil
Kern et al. (2012)	CT	—	—	—	Inter-row spacing
Li et al. (2016)	CT/NT	250	4 kg ha^{-1}	Hyola555 TT	Plant + Soil
Merino et al. (2012)	CT	300	—	Standing	Inter-row spacing
Ruser et al. (2017)	CT	360	40–45	Visby	Inter-row spacing
Schwenke et al. (2015)	NT	500	—	Hyola 50	Inter-row spacing
Thers et al. 2019; Thers et al. 2020	CT[a]	480–500	—	DK Exclusiv	Inter-row spacing
Vinzent et al. (2018)	—	125	40	Xenon and Avartar	Inter-row spacing
Wagner-Riddle and Thurtell (1998)	CT	—	—	—	Inter-row spacing

[a]Winter barley straw was removed prior to ploughing.
CT = Conventional tillage; RT = Reduced tillage; NT = No-tillage; DD = Direct drilling.

spacing's and seed rates (**Table 1**; Walter et al., 2015 and references therein). Another confounding factor in previous studies is that the chambers used for GHG emission measurements were either placed in the inter-row space between plant rows or enclosed both the plant row and inter-row areas. This could complicate an assessment of the impact of different management practices as the presence of plants could directly or indirectly have an impact on GHG emissions. Given the broad range of management practices used it is also difficult to generalize about the reason(s) for any observed differences in GHG emissions.

Other agronomic management practices, such as row spacing and seed rate, are often optimized by growers to encourage rapid plant emergence, canopy closure and development from sowing to harvest. Crop row spacing and plant density influence canopy architecture, which affects solar radiation interception, and the utilization of water and nutrients. Increasing row width and/or reducing the seed rate may expose surface soils to increases in solar radiation, precipitation and wind, resulting in microclimate-related modifications in soil temperature and moisture that influence GHG emissions.

Although there are some studies that have examined the link between WOSR yields, tillage practice, row spacing or seed rate (Christian and Bacon, 1990; Vann et al., 2016) the link between cultivation practices, GHG emissions and yield has not yet been examined. The objectives of this study were to examine the effects of: 1) non-inversion tillage and row spacing, 2) row spacing and seed rate, using two WOSR cultivars, on CO_2, N_2O and CH_4 emissions, compared to the conventional management practice typically used on Irish farms (CT; 125 mm row spacing, 60 seeds m^{-2}). Given the importance of agronomic practices that can contribute to GHG mitigation whilst having no yield penalty we also assess the effects on GWP per unit of yield (i.e., the yield-scaled GWP) in different WOSR cultivation systems.

MATERIALS AND METHODS

Experiment 1: Crop Cultivation

The different cultivation treatments ("Exp. 1") were established in the Hockey field at Knockbeg (52°51′42″N, 6°56′28″W) around 5 km from the Teagasc Crops Research Facility in 2014/2015 (**Figure 1B**). The soil at this site is a sandy loam-to-loam texture (Conry, 1987) and before cultivation had been under a permanent pasture for at least 10 years. Since the 1990s the site has been under CT with continuous crop cultivation (van Groenigen et al., 2011).

Winter oilseed rape (*Brassica napus* L. cv. Compass) was cultivated using CT, strip tillage (ST) and MT. The CT treatment consisted of a primary cultivation, soil inversion to a depth of 200–250 mm, with a 5-fin mouldboard plough followed by one pass of a roller to consolidate the soil after ploughing. Secondary cultivation (power harrowing) was performed immediately prior to sowing the seed. The ST treatment is a modified non-inversion tillage technique where strips of soil (200 mm) are cultivated to the conventional plough depth (200–250 mm) whilst the inter-row spacing between plants is left uncultivated with the previous crop residue retained on the soil surface (He-va Sub-Tiller, Denmark). The MT treatment consisted of non-inversion soil cultivation to a depth of 100–125 mm using a stubble cultivator with tines spaced 300 mm apart followed by leveling discs and a cage roller (Horsch, Terrano FX3, United States). A dynamic 3 m cultivator drill (Vaderstad, Rapid 300S, Sweden) capable of working in a range of seedbed types delivered seed through individual hydraulic metering units to a disc coulter.

Plants were sown at a rate of 60 seeds m^{-2} at two row spacing's, 125 and 600 mm, giving a total of five treatments as there was no 125 mm spacing for the ST treatment. The treatments (25 m × 5 m) were laid out in a randomised block design with four replications. Calcium ammonium nitrate (CAN) was applied

in two split applications of 76 kg N ha^{-1} (March 16, 2015) and 150 kg N ha^{-1} (April 1, 2015). Management details are listed in the **Supplementary Table S1** of the Supplementary Information. The crop was harvested on the August 8, 2015.

Experiment 2: Sowing Treatments

The sowing treatments ("Exp. 2") were established in a privately-owned field in Goresbridge, Co. Kilkenny (52°38′8″N, 7°0′43″W) in 2015/2016 (**Figure 1C**). The soil is a loam texture and has been under continuous wheat cultivation for >10 years. The field was cultivated by deep MT (200–250 mm) (Horsch, Terrano Simba, United States) on the August 22, 2015 and conventional (cv. Compass: C) and semi-dwarf (cv. Troy: T) varieties of WOSR were sown on the August 31, 2015. Plants were sown at four row spacing's (125, 250, 500 and 750 mm) and four seeding rates (10, 15, 30 and 60 seeds m^{-2}). The experiment was a laid out in a randomised split-plot design with four replications. The main plots (variety) were divided into sub-plots (30 m × 5 m) each containing a combination of different row spacings and seed rates. For logistical reasons, only eight treatments that considered the row spacing/seed rate "extremes" were examined in this study: 1) C125/10, 2) C125/60 (control), 3) C750/10, 4) C750/60, 5) T125/10, 6) T125/60, 7) T750/10 and 8) T750/60. Nitrogen fertiliser (188 kg N ha^{-1}) was supplied in three split applications: 53 kg ha^{-1} ammonium sulphate nitrate, 80 and 55 kg N ha^{-1} (both CAN). Fungicide, insecticide and herbicide were applied throughout the season and the crop was harvested on the July 29, 2016. Further management details are listed in **Supplementary Table S1** of the Supplementary Information. Soil chemical properties for each site are described in **Table 2**.

Soil CO$_2$, N$_2$O and CH$_4$ Emission Measurements

Circular stainless-steel collars (225 mm ∅, area = 0.03 m^2) with rubber gaskets were inserted into the inter-row spacing (100 mm depth) of all cultivation treatments. Soil CO$_2$ emission measurements were carried out using an infrared gas analyzer (EGM-4, PP Systems, United Kingdom) by slowly sealing an unvented chamber (0.0034 m^3) onto a rubber O-ring gasket lining the collar. The enclosure time was 120 s with readings taken every 20 s. After sampling, the chamber was removed, and the CO$_2$ concentration was allowed to equilibrate before placement on the next collar. Gas accumulation was linear within the headspace and measurements with $R^2 > 0.8$ were retained for analysis (Widén and Lindroth, 2003). Additionally, in Exp. 2, four PVC Collars (160 mm ∅) were inserted into bare soil which had plants removed adjacent to the main experimental plots to estimate soil basal/heterotrophic respiration (R$_h$).

Emissions of N$_2$O and CH$_4$ were measured using the manual closed chamber method (Chadwick et al., 2014). Accumulation of N$_2$O within the chamber headspace, measured at four time points over 1 hour (T$_0$, T$_{20}$, T$_{40}$, T$_{60}$), was determined to be linear on 84% of occasions (O'Neill et al., 2020). The unvented chambers (above) were sealed onto the collars for an enclosure period of 40 min (T$_{40}$) and sampling carried out between 9.00 and 13.00 h (Barton et al., 2015). The chambers were covered with aluminium foil to prevent solar radiation induced temperature changes inside the headspace during the enclosure period.

For gas sampling, headspace air was withdrawn through a stopcock fitted to the chamber vent using a 20 ml polypropylene syringe (BD Plastipak, Spain). The chamber headspace was mixed by flushing air slowly with the syringe plunger twice prior to the withdrawal of the gas sample. Using a hypodermic needle, samples were immediately transferred into pre-evacuated 7 ml glass exetainers (Sigma-Aldrich, United Kingdom) fitted with double wadded septa (Labco, High Wycombe, United Kingdom). The exetainers were injected with a 12 ml sample to create an overpressure and prevent back diffusion of ambient air during storage. Four ambient air samples were also taken near ground level before and after each sampling occasion to obtain a surrogate time zero (T$_0$) sample for each chamber (Chadwick et al., 2014; Charteris et al., 2020). Sampling frequency was increased during the period of fertilizer application: four times per week for 2 weeks, then twice a week for 2 weeks, then once a week until harvest. Additional samples were taken before or after precipitation events, which are known to stimulate denitrification (Butterbach-Bahl et al., 2013).

Analysis of N$_2$O and CH$_4$ concentrations were carried out with a Gas Chromatograph with a 63Ni electron capture detector (ECD) at 60°C with a flame ionization detector (FID) at 300°C (Bruker Scion 456, Germany). Samples were injected into the GC using a Combi-PAL auto-sampler (CTC Analytics AG, Switzerland). Results were expressed in parts per million by volume (ppmv).

Daily GHG emissions were calculated using the **Eq. 1**:

$$F(GHG) = (\Delta C/\Delta t) \times ((MW \times P)/(R \times T)) \times (V/A) \qquad (1)$$

where ΔC/Δt is the rate of change of CO$_2$ (T$_o$ to T$_2$; IRGA) N$_2$O and CH$_4$ concentration (T$_0$ to T$_{40}$; GC), where ΔC is the change in concentration of the gas in the headspace volume (ppmv or ppbv), Δt is the enclosure time period (minutes), MW is the molar mass of CO$_2$-C (12 g), N$_2$O-N (28 g) or CH$_4$-C (12 g), P is the atmospheric pressure at the time of sampling (Pa), R is the gas constant (8.314 J mol^{-1} K^{-1}), T is the air temperature at the time of sampling (K), V is the headspace volume within the chamber (m^3) and A is the area covered by the base (m^2). Cumulative GHG emissions (±SE) were calculated by trapezoidal integration of the daily means.

The global warming potential (GWP) was calculated for each management practice by converting N$_2$O and CH$_4$ emissions to CO$_2$ equivalent emissions (CO$_2$-eq.) for a 100 years time horizon. The radiative forcing potential used relative to CO$_2$ was 265 for N$_2$O and 28 for CH$_4$ (Myhre et al., 2013). Yield-scaled GWP was calculated by dividing the CO$_2$-equivalent emissions by the seed yield (harvested at 9% moisture) and expressed in units of kg CO$_2$-eq. kg^{-1}. The contribution of CO$_2$ to GWP was excluded based on: 1) the assumption that the soil CO$_2$-C efflux was largely off-set by high rates of net primary productivity (C input) and biomass removal at harvest (C export) (Smith et al., 2007) and 2) the absence of accurate crop residue (straw and root C) data to quantify the annual change in SOC (Mosier et al., 2006).

Soil and Climatic Measurements

Soil mineral N (NH$_4^+$ and NO$_3^-$) concentrations were determined during the spring-summer growth period. Soil cores (0–10 cm depth) were taken weekly after fertilization for 1 month and every 3–4 weeks thereafter until harvest. Soils were

initially stored at 4°C and extracted either on the same day of collection, or within 24 h, using 2 M KCL at a ratio of 5:1 (v:w) water: soil (Maynard et al., 1993). The NH_4^+ and NO_3^- concentrations of the extract were analyzed with an Aquakem 600 discrete analyzer (Thermo Fisher Scientific, United States).

Soil volumetric moisture content (%) (GS3, Decagon Devices, United States) and soil temperature (°C; Exp. 2 only) (ELE International, Bedfordshire, United Kingdom) were measured (50–100 mm depth) in the inter-row spacing adjacent to the collars. Water-filled pore space (WFPS) was calculated using **Eq. 2**:

$$WFPS(\%) = VWC/[1 - Bd/Pd] \times 100 \qquad (2)$$

where Bd is the bulk density measured at the soil surface (70 mm depth) and Pd is particle density estimated at 2.65 g cm^{-3} (Linn and Doran, 1984).

Climatic measurements of mean air temperature (°C), atmospheric pressure (Pa), rainfall (mm) and soil temperature (°C) were taken from the Met Eireann automated weather station at Oakpark, Co. Carlow, Ireland, which was located 5 km from the Exp. 1 and 30 km from the Exp. 2 sites.

Statistical Analysis

Statistical analysis was conducted using SAS 9.4 (Cary, NY, United States) and R software (R 3.6.1, R Core Team, 2019). Normality and homogeneity of variance were checked using histograms and residual graphs. Where necessary, log or square root transformations (y or y + constant) were applied to data to achieve homogeneity of variance. For Exp. 1, the PROC GLIMMIX procedure in SAS was used to test for differences between the treatments. Tillage (CT, MT, and ST) and row spacing (125 and 600 mm) were the main effects. To account for the missing treatment (i.e., ST125) in the model, additional parameters were created, each with two levels: a "Nested Group" (Factors = CT + MT; Single = ST) and a "Variable Group" (1 = CT125, 2 = all others). The _residual_ option was used in the RANDOM statement. Significant pairwise differences were determined according to the _simulate_ post-hoc test ($p < 0.05$). For Exp. 2, a linear-mixed effects model (_lmer_) in the "lme4" (Bates et al., 2012) and "lmerTest" packages (Kuznetsova et al., 2017). Variety (cvs. Compass and Troy), row spacing (125 and 750 mm) and seed rate (10 m^{-2} and 60 m^{-2}) were set as the main effects with _block_ and _block x variety_ set as the random effects. Model effects were examined using the _emmeans_ function (Lenth, 2019) where ANOVA and pairwise comparisons (normal and back-transformed data) were examined by the Tukey method at a significance level of $p < 0.05$. Plots were made using the "ggplot2" package in R (Wickham, 2016).

RESULTS

Crop Cultivation

Meteorological data was similar for both sites during the gas measurement periods (**Figure 2**). The mean air temperatures were 10.9°C (2.9–19.9°C) and 11.0°C (3.6–19.8°C) for Exp. 1 and Exp. 2, respectively. Cumulative rainfall was similar from the period of 27th February to 22nd July each year in Exp. 1 (261 mm) and Exp.

2 (265 mm), representing 28 and 37% of the annual rainfall, respectively. During the growing seasons, the wettest months for Exp. 1 and Exp. 2 were May (90 mm) and April (64 mm) whilst the driest months were April (26 mm) and July (24 mm), respectively.

A rapid loss of CO_2 was observed after the implementation of CT (maximum recorded value of 2.34 g C m^{-2} hr^{-1}) at a rate 2.5 times that of ST (maximum recorded value of 0.94 g C m^{-2} hr^{-1}) and 14.6 times that of MT (maximum recorded value of 0.16 g C m^{-2} hr^{-1}) (**Figure 3**). These decreased rapidly to 0.16 g C m^{-2} hr^{-1} (CT) and 0.07 g C m^{-2} hr^{-1} (ST) after the tillage events and then remained largely stable for the rest of the measurement period. Excluding the anomalously high value found in the MT treatment after 3 days, the daily soil CO_2 emissions ranged from 0.04 to 1.38 g C m^{-2} h^{-1} across all treatments during the 12 days period.

Daily soil CO_2 emissions where generally higher during the early part of the growing season and showed two peaks, each occurring around 7 days after the first and second N fertilizer applications, respectively (**Figure 4A**). Soil CO_2 emissions tended to be greater in the CT125 system with maximum daily emissions of 4.0 and 4.2 g C m^{-2} d^{-1}. The emissions of CO_2 converged towards similar values in all systems by mid-April until June, where the mean CO_2 loss was 1.16 ± 0.07 g C m^{-2} d^{-1}. Higher CO_2 emissions were generally observed between 32 and 70% WFPS, with a tendency for lower emissions under both drier (25% WFPS) and wetter (85% WFPS) conditions. Cumulative CO_2 emissions were not significantly affected by the crop cultivation treatment, with values ranging from 1,083 to 1,683 kg C ha^{-1}, although higher CO_2 emissions were generally found in the 125 mm row spacing treatment (**Table 3**).

Slight increases in N_2O were observed in the ST600 system (11.6–27.3 g N ha^{-1} d^{-1}) _ca._ 10 days after the first fertilization (**Figure 4B**). The highest N_2O emissions were observed in the MT125 (53.8 g N ha^{-1} d^{-1}), MT600 (62.8 g N ha^{-1} d^{-1}) and ST600 (70.0 g N ha^{-1} d^{-1}) treatments 4 days after the second N application and a second peak occurred in the ST600 (69.3 g N ha^{-1} d^{-1}) treatment 2 days later. These were observed at 72–79% WFPS when the soil temperature was >10°C (Supplementary Information, **Supplementary Figure S1**), however, the majority of the N_2O emissions occurred across a wide range of WFPS (25–90%) (**Figure 4B**). Maximum N_2O emissions were lower in the CT125 and CT600 treatments, with values of 30.5 and 18.5 g N ha^{-1} d^{-1}, respectively, occurring 58 days after fertilization. There was no significant effect of tillage or row spacing on the cumulative N_2O emissions, with values ranging from 0.81 to 2.05 kg N ha^{-1} (**Table 3**).

Daily CH_4 emissions displayed similar temporal patterns and ranged from −10.7 to 5.4 g C ha^{-1} d^{-1} (**Figure 4C**). Net CH_4 emissions preceded by significant uptake of CH_4 were observed after the second N application. With some exceptions, net CH_4 uptake was generally sustained until June. For the cumulative CH_4 uptake values, a significant tillage x nested effect ($p < 0.05$) was observed with a 55% increase in uptake in the CT (−0.34 ± 0.03 kg C ha^{-1}) compared to the MT systems (−0.22 ± 0.03 kg C ha^{-1}), with the total CH_4 uptake in the ST treatment midway between the CT and MT treatments (**Table 3**).

FIGURE 1 | Geographical overview of Ireland (A) and the locations of the study sites in (B) Knockbeg, Co. Laois and (C) Goresbridge, Co. Kilkenny, with the surrounding agricultural land uses (Google Earth; created on 31st July 2021). Orange lines indicate the location of the experimental trial plots.

Sowing Treatments

Daily GHG emissions for the two WOSR varieties are illustrated in **Figure 5**. Transient fluctuations in soil CO_2 emissions were found during the season, ranging from 0.11 to 3.20 g C m^{-2} d^{-1} (**Figure 5A**), with no clear seasonal trend. Nitrogen fertilizer application tended to initially suppress CO_2 emissions, which was followed by increases in CO_2 emissions 1–2 weeks later. Soil CO_2 emissions increased temporarily in the 125/10 and 750/10 plots in June, however, little variation existed between sowing treatments during the main growing season.

Daily soil N_2O emissions were clearly associated with N fertilizer applications (**Figure 5B**). Higher N_2O emissions were found from the cv. Troy plots particularly the 125/10 treatment, and were also observed for soil temperatures >10°C and WFPS values approaching 80% (Supplementary Information, **Supplementary Figure S1**). Nitrous oxide emissions fell to background rates around 1 month after the final N application.

Daily soil CH_4 emissions ranged from −38.2 to 26.3 g C ha^{-1} d^{-1} across all sowing treatments (**Figure 5C**). Low net CH_4 uptake rates occurred after mineral N was applied to the soils. The sharp increase in CH_4 uptake in April coincided with a decrease in soil NH_4^+ and NO_3^- concentrations in late-April (Supplementary Information, **Supplementary Figures S2, S3**). Several treatments associated with the Compass and Troy cultivars displayed transient net CH_4 emission peaks but, in general, there was a consistent trend

of increasing net CH_4 uptake towards the summer months. The highest net CH_4 uptake rates occurred within a narrow temperature range of 13–15°C but a broader range (26–45%) of WFPS. Combining the data from Exp. 1 and Exp. 2, WFPS explained around one quarter of the variance ($R^2 = 0.29$) in the CH_4 emissions (Supplementary Information, **Supplementary Figure S4**). Neither the cumulative N_2O nor CH_4 emissions were affected by row spacing, seed rate or variety (**Table 4**).
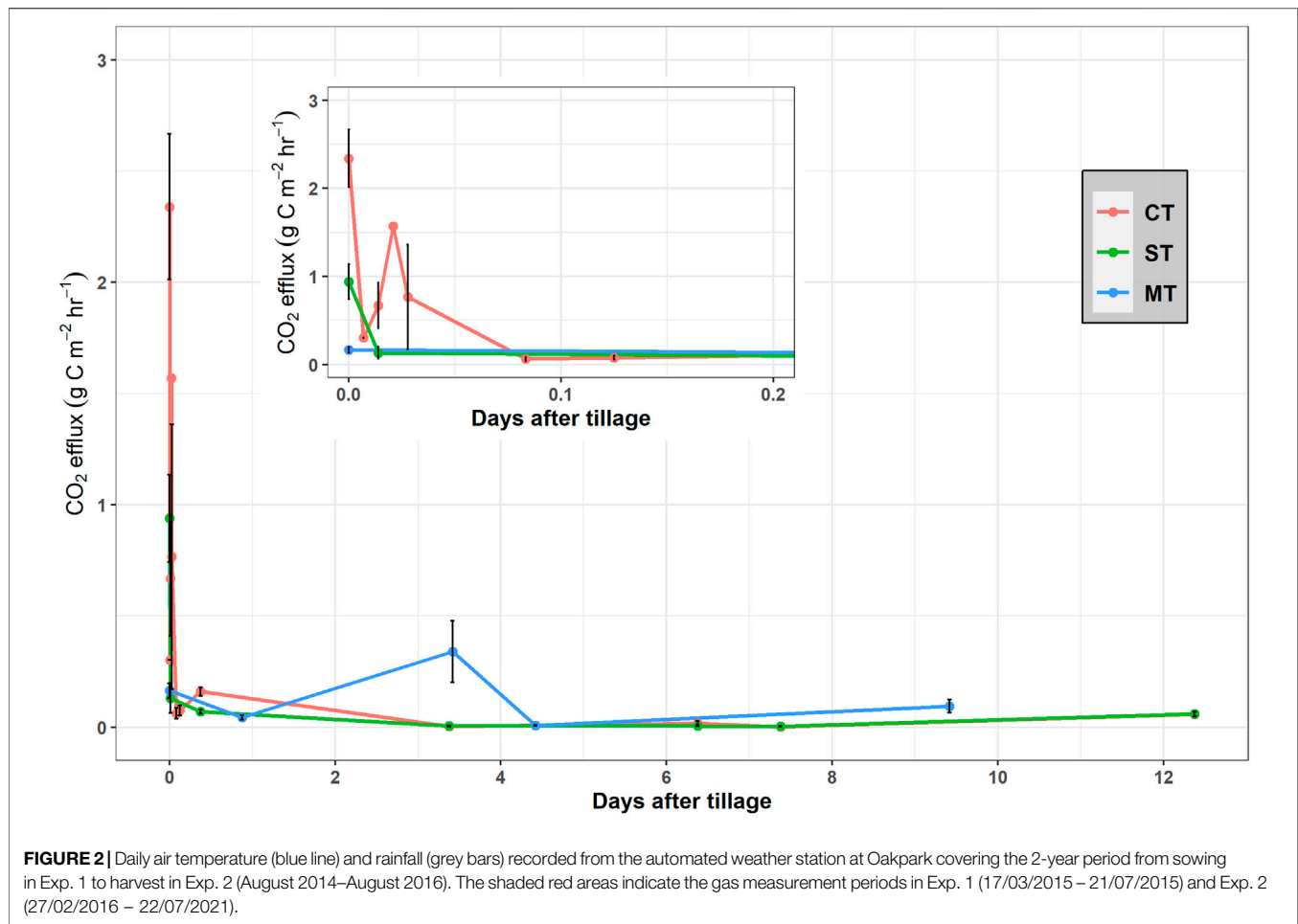
Yield and Yield-Scaled GWP

Seed yields were unaffected by crop cultivation treatment, canopy management or sowing method (**Tables 3, 4**). Yields averaged 4.98 t seed ha^{-1} in Exp. 1 and 4.56 t seed ha^{-1} in Exp. 2. Yield-scaled GWP values ranged from 0.06 to 0.16 kg CO_2-eq. kg^{-1} in Exp. 1 and 0.05–0.19 kg CO_2-eq. kg^{-1} in Exp. 2. In the latter experiment, the mean yield-scaled GWP of cv. Troy (0.12 kg CO_2-eq. kg^{-1}) was double that of the cv. Compass sown plots (0.06 kg CO_2-eq. kg^{-1}) ($p < 0.05$).

DISCUSSION

Crop Management and GHG Emissions
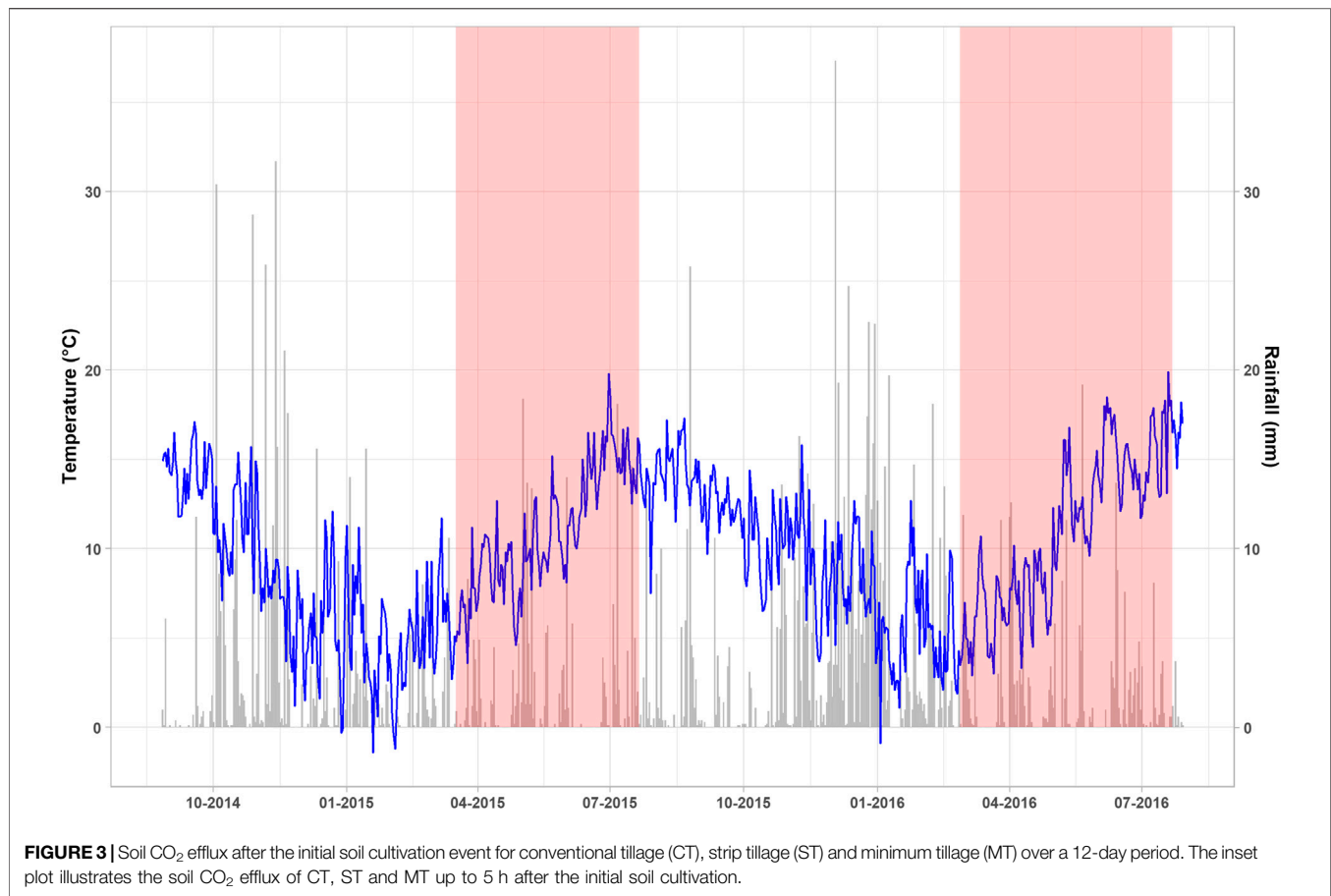
In this study, short-term CO_2 emissions after tillage operations were characterized by an initially rapid increase followed by a fast

FIGURE 2 | Daily air temperature (blue line) and rainfall (grey bars) recorded from the automated weather station at Oakpark covering the 2-year period from sowing in Exp. 1 to harvest in Exp. 2 (August 2014–August 2016). The shaded red areas indicate the gas measurement periods in Exp. 1 (17/03/2015 – 21/07/2015) and Exp. 2 (27/02/2016 – 22/07/2021).

exponential decline (**Figure 3**). The CT treatment resulted in a maximum CO_2 efflux rate *ca.* 2.5 times that of ST and 14.6 times that of MT which is consistent with an effect of gaseous diffusion due to soil disturbance (Jackson et al., 2003; La Scala et al., 2006; Reicosky and Archer, 2007; Morell et al., 2010). The large loss of CO_2 from the MT plot (0.34 g C m^{-2} hr^{-1} or 8.15 g C m^{-2} d^{-1}) *ca.* 3.5 days after tillage coincided with a rainfall event, a phenomenon often called the "Birch Effect" (Gebremichael et al., 2019). Increased organic matter mineralization after MT in combination with favorable soil moisture and temperature may have led to the relatively larger efflux of CO_2 compared to CT and ST (Franzluebbers et al., 1995; Jabro et al., 2008). Overall, however tillage had very little impact on short-term CO_2 emissions.

Soil CO_2 emissions during spring-summer were unaffected by variations in tillage intensity (**Table 3** and **Table 4**) in line with earlier studies that reported no significant effects of RT systems on CO_2 emissions (Kessavalou et al., 1998; Chatskikh et al., 2008; Abdalla et al., 2014). Tillage management can affect soil CO_2 emissions through its influence on soil moisture, soil temperature and soil organic C accumulation (Buyanovsky et al., 1986;

Hendrix et al., 1988; Franzluebbers et al., 1995; Fortin et al., 1996). In RT systems this is often associated with the retention of crop residues that lower soil temperatures and increase soil moisture content (Chen and McKyes, 1993). However, daily soil temperatures and WFPS values varied little between treatments indicating that the effect of contrasting tillage regimes on residue retention had little effect on CO_2 emissions. In this study, the highest soil CO_2 emissions occurred during the spring period of the growing season suggesting that phenology, through its effects on root respiration processes and/or the rhizodeposition of labile C, contributed to CO_2 production (Rood et al., 1984; Whipps, 1990; Franzluebbers et al., 1995; Rochette and Flanagan, 1997; Jans et al., 2010). In OSR, the highest values for leaf area index were reached close to flowering, which is consistent with the higher soil CO_2 emissions observed in March and April across all experiments (except cv. Troy in Exp. 2). Crops allocate, on average, 21% of their photosynthetically fixed C to their roots of which a smaller proportion of this C is released to the soil in root exudates (Pausch and Kuzykayov, 2018). The absence of variation between tillage management may reflect either a low

FIGURE 3 | Soil CO_2 efflux after the initial soil cultivation event for conventional tillage (CT), strip tillage (ST) and minimum tillage (MT) over a 12-day period. The inset plot illustrates the soil CO_2 efflux of CT, ST and MT up to 5 h after the initial soil cultivation.

supply of labile C belowground or labile C substrate was not limiting CO_2 production.

Tillage management had little impact on N_2O emissions in this study (**Table 2** and **Table 3**) in line with earlier work examining CT and RT systems (Abdalla et al., 2010; Liu et al., 2016). Peak N_2O emissions that were found in the MT and ST but not in the CT treatments coincided with a higher WFPS (>70%) and higher temperatures (>10°C) as noted in previous studies (Adviento-Borbe et al., 2007; Abdalla et al., 2010; Žurovec et al., 2017; O'Neill et al., 2020). This indicates that denitrification is the main source of N_2O production and the N_2O emissions are largely dependent on the extent of soil anaerobiosis. A lower WFPS and an associated increase in soil oxygenation may explain the absence of any impact of fertilization on N_2O emissions in the CT systems (**Figure 4B**).

Cumulative CH_4 uptake was *ca*. 55% greater in the CT compared to the MT treatments ($p < 0.05$, **Table 2**). Plaza-Bonilla et al. (2014) also reported a significantly higher cumulative uptake of CH_4 in CT (2.69 kg C ha^{-1}) compared to NT (1.16 kg C ha^{-1}) under Mediterranean dryland conditions ($p < 0.05$). The authors suggested that the greater CH_4 oxidation found under CT might be explained by the short duration of NT (3 years) and the possible lack of differences in soil pore structure and methanotrophic communities between

CT/NT plots. Reduced tillage practices can however result in a more porous and stable soil structure that facilitates CH_4 diffusion (Ball et al., 1997; Hütsch, 1998; Ussiri et al., 2009) and the long-term implementation of RT (>40 years) has been shown to restore the CH_4 oxidation capacity of arable soil (Ussiri et al., 2009; Jacinthe et al., 2014). Although the reason(s) for the observed differences between tillage treatments in this study are not clear, it could be explained by both the enhanced diffusion of atmospheric CH_4 into the soil and the greater CH_4 oxidation rates under CT as the soils became drier in summer.

Soil WFPS had the largest effect on CH_4 emissions and explained approximately one quarter of the variability in the daily CH_4 emissions (Supplementary Information, **Supplementary Figure S4**). Higher soil water content inhibits the diffusive transport of CH_4 and oxygen to active microbial sites, consequently reducing CH_4 uptake in arable soils (Flessa et al., 1995; Drewer et al., 2012). The results of this study are consistent with the recent review by Cowan et al. (2020) who found soil volumetric water content as the strongest predictor of CH_4 emissions across agricultural soils in the United Kingdom and Ireland ($R^2 < 0.1$). This indicates that soil water content and its impact on diffusion processes may override the effect of tillage management in regulating CH_4 exchange in arable soils.

TABLE 2 | Soil chemical properties for each site.

	Depth (cm)	SOM (%)	SOC (%)[a]	TN (%)	Soil pH
Knockbeg-Hockey Field	0–30	4.80	2.40	0.157	7.21
	30–60	3.12	1.56	0.057	7.94
	60–90	2.58	1.29	0.041	8.13
Goresbridge	0–30	4.70	2.35	0.190	7.16
	30–60	2.20	1.10	0.048	7.87
	60–90	1.20	0.60	0.071	8.42

[a]SOC = (SOM × 0.5) (Pribyl, 2010).
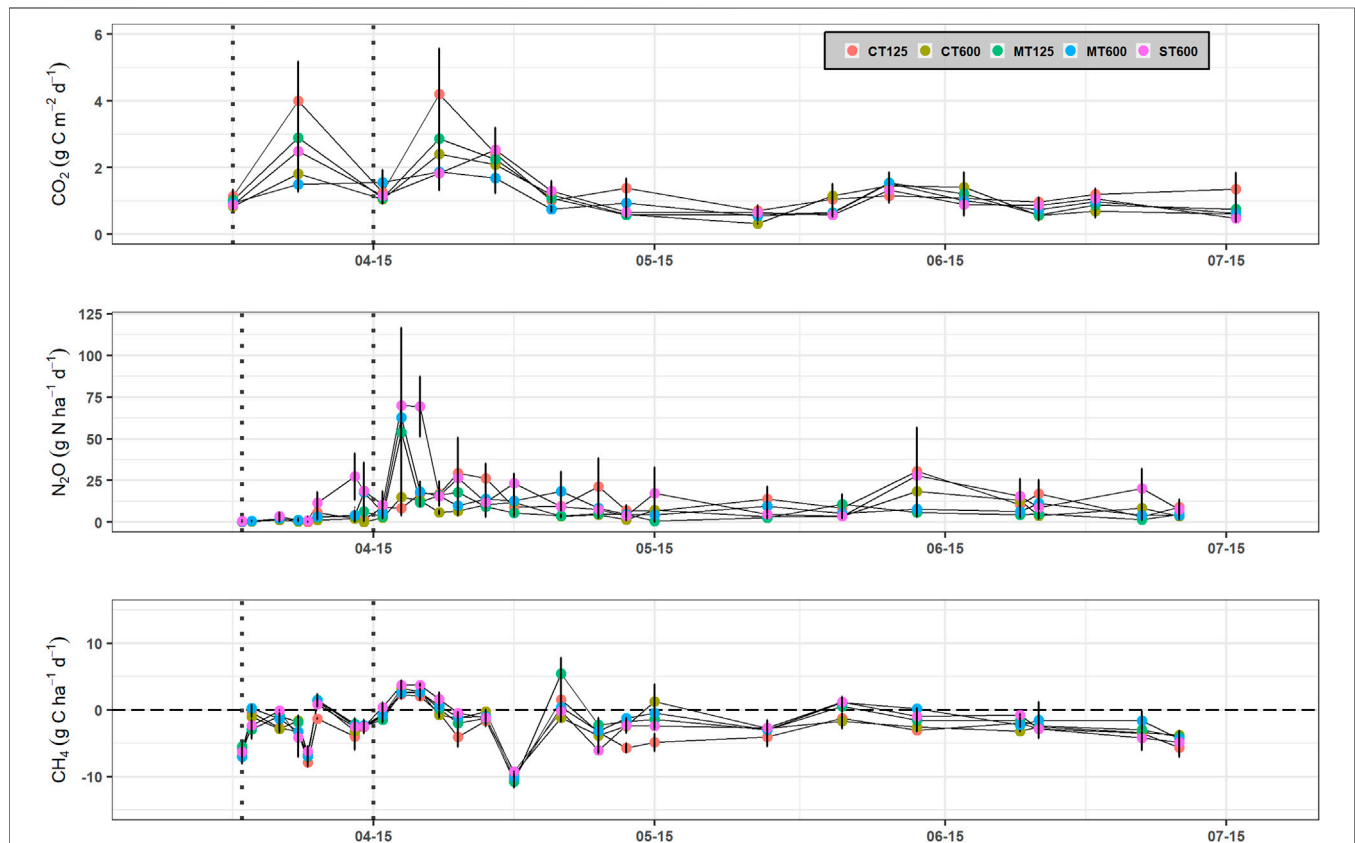
FIGURE 4 | Soil CO_2, N_2O and CH_4 emissions for each crop establishment system in Exp. 1: conventional tillage at 125 (CT125) and 600 mm (CT600) row spacing, minimum tillage at 125 (MT125) and 600 mm (MT600) row spacing, and strip tillage at 600 mm row spacing (ST600). Vertical dashed lines indicate fertilizer application and vertical lines on each data point represent the standard error of the means.

Row spacing was found to have no significant effect on GHG emissions. In OSR, row spacing influences plant height, branching, leaf area, pod number and the overall canopy architecture. Plants sown in narrow rows reach canopy closure quicker than wide row cropping systems and thus, it was hypothesised that row spacing would influence factors such as root distribution, root C input, water use, N uptake, light interception and soil temperature, and directly or indirectly influence GHG emissions (Sharratt and McWilliams, 2005). Zapata et al. (2021) reported higher CO_2 emissions from soybean compared to wheat (wide vs. narrow row spacing) due to prolonged exposure of surface soil to direct

sunlight and high intensity rainfall. The absence of a row spacing effect in this study may be due to comparable above-ground vegetative growth rates and rapid canopy closure, irrespective of plant stand structure, thereby limiting the potential microclimatic effects of row spacing on GHG emissions.

Seed rate was a significant factor affecting GHG emissions in Exp. 2 (**Table 3**). Mean cumulative CO_2 emissions (Compass and Troy) were 21% higher in the 10 seeds m^{-2} compared to the 60 seeds m^{-2} treatments ($p < 0.05$). Seed rate determines the plant density and the canopy architecture and, like row spacing, will influence light interception, water and nutrient use and soil

TABLE 3 | Cumulative GHG emissions, seed yield and yield-scaled GWP for Exp. 1.

Tillage	Row spacing (mm)	CO_2 (kg C ha^{-1})	N_2O (kg N ha^{-1})	CH_4 (kg C ha^{-1})	Yield (t DM ha^{-1})	Yield-scaled GWP (kg CO_2-eq. kg^{-1} seed)
Conventional tillage	125	1,683 ± 277	1.45 ± 0.48	−0.39 ± 0.03a	4.82 ± 0.15	0.11 ± 0.04
Conventional tillage	600	1,108 ± 137	1.00 ± 0.50	−0.29 ± 0.04a	5.00 ± 0.06	0.09 ± 0.05
Minimum tillage	125	1,289 ± 89	0.81 ± 0.15	−0.24 ± 0.05b	5.14 ± 0.13	0.06 ± 0.01
Minimum tillage	600	1,083 ± 126	1.13 ± 0.18	−0.21 ± 0.03b	5.00 ± 0.10	0.09 ± 0.01
Strip tillage	600	1,218 ± 116	2.05 ± 0.86	−0.27 ± 0.03ab	4.98 ± 0.22	0.16 ± 0.07
ANOVA						
Nested		NS	NS	NS	NS	NS
Tillage*Nested		NS	NS	$p < 0.05$	NS	NS
Row*Nested		NS	NS	NS	NS	NS
Tillage*Row*Nested		NS	NS	NS	NS	NS

Different lowercase letters indicate significant variation between treatments.

TABLE 4 | Cumulative GHG emissions, seed yield and yield-scaled GWP for Exp. 2.

Variety	Row spacing (mm)	Seed rate (m^2)	CO_2 (kg C ha^{-1})	N_2O (kg N ha^{-1})	CH_4 (kg C ha^{-1})	Yield (t DM ha^{-1})	Yield-scaled GWP (kg CO_2-eq. kg^{-1} seed)
Compass	125	10	1,555 ± 215b	1.38 ± 0.29	−1.58 ± 0.24	4.64 ± 0.07	0.09 ± 0.03a
	125	60	1,110 ± 33a	1.01 ± 0.10	−1.81 ± 0.46	4.59 ± 0.18	0.05 ± 0.01a
	750	10	1,312 ± 118b	1.34 ± 0.36	−2.07 ± 0.68	4.80 ± 0.22	0.07 ± 0.02a
	750	60	1,166 ± 180a	1.14 ± 0.33	−3.15 ± 1.50	4.58 ± 0.13	0.03 ± 0.02a
Troy	125	10	1,280 ± 212b	2.28 ± 0.70	−1.29 ± 0.22	4.41 ± 0.14	0.19 ± 0.07b
	125	60	1,189 ± 113a	1.12 ± 0.26	−2.35 ± 0.60	4.37 ± 0.05	0.05 ± 0.03b
	750	10	1,304 ± 99b	1.66 ± 0.36	−1.61 ± 0.49	4.46 ± 0.07	0.12 ± 0.03b
	750	60	1,028 ± 40a	1.89 ± 0.48	−1.65 ± 0.65	4.64 ± 0.15	0.13 ± 0.04b
ANOVA							
Variety			NS	NS	NS	NS	$p < 0.05$
Row			NS	NS	NS	NS	NS
Seed			$p < 0.05$	NS	NS	NS	NS
Variety*Row			NS	NS	NS	NS	NS
Row*Seed			NS	NS	NS	NS	NS
Variety*Row*Seed			NS	NS	NS	NS	NS

Different lowercase letters indicate significant variation between treatments.

microclimate. For OSR crops, Roques and Berry (2016) found that high seed rate plots accelerated flowering and earlier maturation whereas plots with low seed rates remain greener for longer. The longer a plant retains its leaves, or delays leaf senescence, the greater the photosynthetic capacity of the stand and the amount of labile C that is released via root exudates to the rhizosphere. Soil CO_2 emissions in the bare soil plots (R$_h$) also tended to be higher during pod development in June (data not shown). This result points to a parallel increase in the rate of OM decomposition in the cropped soils caused by a reduction in shading and increases in soil temperature in the 10 seeds m^{-2} treatments. An increase in belowground OM inputs during vegetative growth and/or decomposition of native SOM at maturity may have both contributed to the greater soil CO_2 emissions.
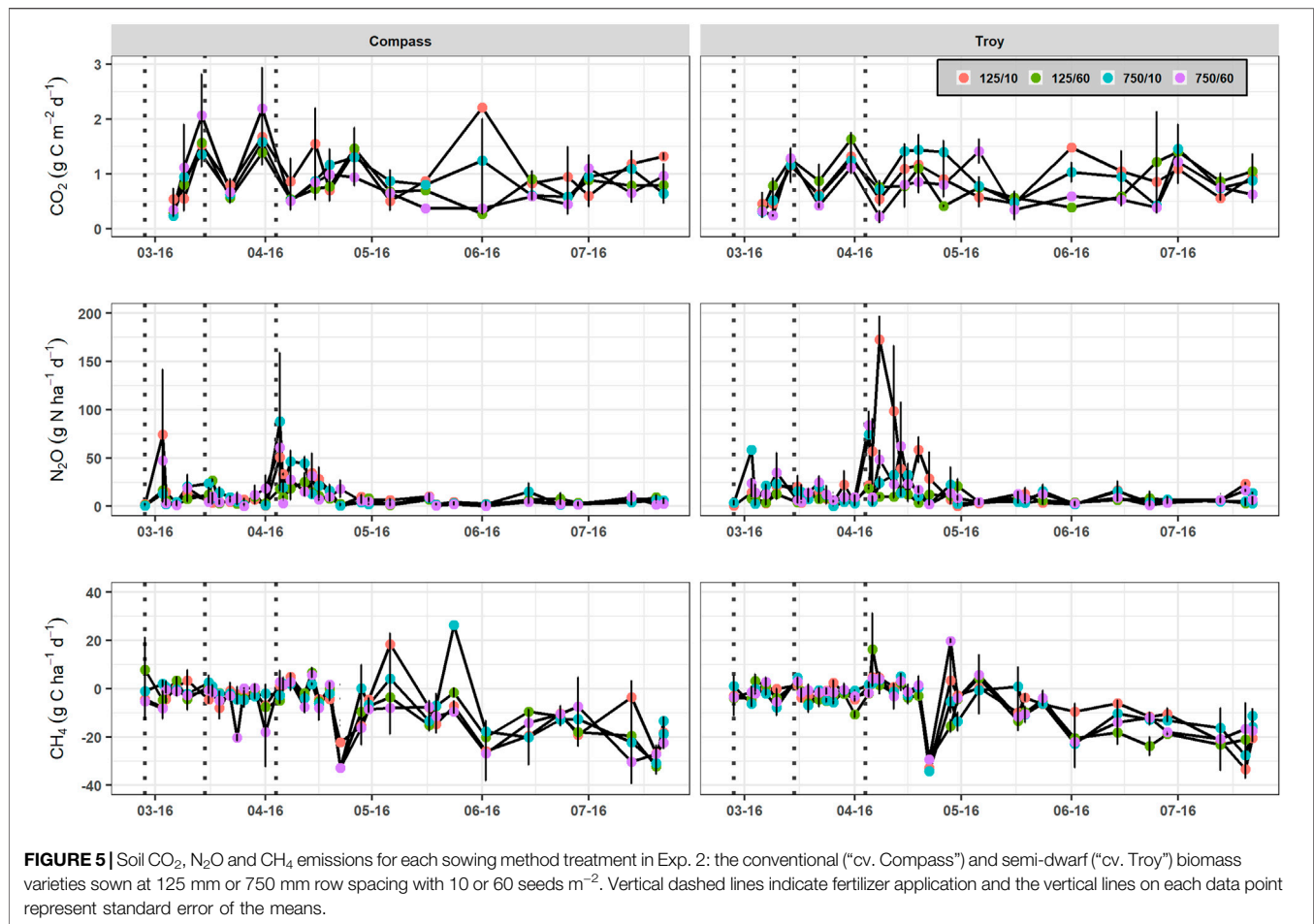
Variation in Yield and GWP Across Different Management Practices

Despite the use of a wide range of a management practices (tillage intensity, row spacing, seed rate and variety), seed yield was unaffected (**Table 2** and **Table 3**). These results support earlier studies that found no effect of tillage, row spacing and seed rate on final seed yields (Degenhardt and Kondra, 1981; Christensen and Drabble, 1984; Christian and Bacon, 1990; Bonari et al., 1995; Vann et al., 2016; Wynne et al., 2020).

Although seed yield and yield components are determined by plant density (Leach et al., 1999; Diepenbrock, 2000; Rathke et al., 2006; Kuai et al., 2015), individual OSR plants can counter variations in plant density by increasing yield per plant (Diepenbrock, 2000), so that the seed yield is not compromised by sowing technique.

The two varieties also produced similar seed yields (**Table 3**). The shorter height of the cv. Troy plants had no detrimental impact on yield components and many of the commercially available semi-dwarf genotypes produce similar yields to conventional varieties (Sieling and Kage, 2008). Miersch et al. (2016) noted that semi-dwarf varieties yielded higher than the conventional types when N is the limiting resource. The non-limiting soil mineral N concentrations in this study (0–10 cm)

FIGURE 5 | Soil CO_2, N_2O and CH_4 emissions for each sowing method treatment in Exp. 2: the conventional ("cv. Compass") and semi-dwarf ("cv. Troy") biomass varieties sown at 125 mm or 750 mm row spacing with 10 or 60 seeds m^{-2}. Vertical dashed lines indicate fertilizer application and the vertical lines on each data point represent standard error of the means.

may have resulted in the similar yields, although semi-dwarf varieties, such as cv Troy, may also perform better in low N input systems compared to conventional varieties. Semi-dwarf varieties may also be favoured by farmers for their higher lodging resistance plus easier harvesting and pesticide applications (Sieling and Kage, 2008).

Yield-scaled GWP values were unaffected by crop management practice. In Exp. 2, cv. Troy had a yield scaled GWP that was double that of cv. Compass ($p < 0.05$). Cumulative N_2O emissions did not significantly differ between treatments, however, the greater GWP was attributed to N-fertilizer applied in excess in the 10 seeds m^{-2} cv. Troy plots, as indicated by the large N_2O emission peaks after the third N application (**Figure 5**). Sowing at a higher seed rate may circumvent the high GWP of cv. Troy but puts the variety at an inferior position to cv. Compass insofar as low seed rates can achieve similar yields to conventional sowing without adversely affecting GWP.

Our yield-scaled GWP values 0.05–0.16 kg CO_2-eq. kg^{-1} are within the range of those for crops reported in the literature. Linquist et al. (2012) calculated a yield-scaled GWP of 0.166 for wheat and 0.185 kg CO_2-eq. kg^{-1} for maize in their meta-analysis of 57 cropland sites which included rice 0.657 kg CO_2-eq. kg^{-1}. Rajaniemi et al. (2011) found slightly higher yield-scaled GWP values for barley, oats, wheat and rye

(0.57, 0.57, 0.59 and 0.87 kg CO_2-eq. kg^{-1}). Gan et al. (2012) calculated a farm-scale carbon footprint of 0.281–0.317 kg CO_2-eq. kg^{-1} for barley succeeding oilseed rape. These studies, however, included the GWP of additional upstream sources such as fuel emissions, production and use of fertilizers and seed production.

The short measurement campaign (6-months) may pose some limitations for the longer-term interpretation of results. We did not take gas measurements after tillage in Exp. 2 meaning we may have missed any transient emissions of CO_2, N_2O or CH_4, whilst the low temporal frequency of measurements in the winter/spring of Exp. 1 could have introduced large errors in the estimation of the cumulative GHG emissions when determined by linear interpolation. To reduce any bias, only the higher temporal frequency measurements made during spring were considered as representative of yield scaled GWP. Annual GWP values are also required to cover the fallow and post-tillage periods as these can be a large source of GHG emissions from croplands (Linquist et al., 2012). Including all factors leading to CO_2 emissions on-farm (tillage, herbicide, pesticide, fertilization) as well as upstream activities (harvest, fertilizer manufacturing, other chemical inputs, transport) (Sainju, 2016) would provide a more complete assessment of the GHG balance of WOSR production systems.

CONCLUSION

Overall, management practice had a minimal effect on GHG emissions, crop yield and yield scaled GWP. Soil tillage and row spacing had no significant impact on CO_2 and N_2O emissions. Consequently, the management approach used for WOSR cropping systems can be tailored to the particular conditions and economic factors. The low seeding rate resulted in higher CO_2 emissions irrespective of WOSR variety, whilst the yield-scaled GWP of cv. Troy was, on average, higher than that of the cv. Compass. Sowing the semi-dwarf variety at low seeding rates may therefore increase the risk of higher C and/or N emissions from OSR systems. The overall findings indicate that considerable flexibility is possible in the way that OSR crops are established, grown and managed according to local/regional conditions and economics, without compromising yield or GHG emissions. Longer-term, high temporal resolution measurements are required to examine whether the observed GHG and GWP values can be attributed more to management or climatic effects.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because The data analyzed in this study is subject to the following licenses/restrictions: confidential. Requests to access the datasets should be directed to Macdara O'Neill, macdara.oneill@teagasc.ie.

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SUPPLEMENTARY MATERIAL

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