

## Application of AD Dairy Manure Effluent to Fields and Associated Impacts

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### Introduction

Storage and application of animal manures can have significant impacts on the amount of greenhouse gases (GHGs) released to the atmosphere, mainly in the form of carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O). CO<sub>2</sub> is released from storage facilities and soils primarily from microbial decay of the organic matter contained within the manure. N<sub>2</sub>O is emitted during the microbial transformation of nitrogen in soils and manures, and is often enhanced where available nitrogen exceeds plant requirements, especially under wet conditions. Manure applications may cause relatively high N<sub>2</sub>O emissions when the soil contains NO<sub>3</sub><sup>-</sup> and decomposition of organic carbon in manures enhances denitrification (Moeller and Stinner, 2009). Methane is produced when organic matter decomposes in oxygen-deprived conditions, notably when manures are stored in lagoons or deep pits or when applied to water-laden fields (Smith et al., 2008). Cropland and forest soils are often considered a sink for CH<sub>4</sub> because their consumption exceeds production (Brummer et al., 2009; Del Grosso et al., 2000; Haile-Mariam et al., 2008; Kammann et al., 2009). However, few data sets characterizing background GHG emissions exist for dairy farm soils and dairy manure applications. This is of particular interest because it is possible that dairy farm soils may switch from being methane sinks to sources with manure applications.

Compared to baseline anaerobic lagoon storage systems, dedicated anaerobic digestion (AD) systems have been shown to reduce atmospheric emissions of CH<sub>4</sub> through the controlled production, collection and use of CH<sub>4</sub> as an energy source. Reductions in N<sub>2</sub>O can also be expected after the land application of digested manures (van der Meer, 2008). In fact, Paul (2009) concluded that the potential for reducing N<sub>2</sub>O emissions could exceed the potential for reducing CH<sub>4</sub> emissions (on a CO<sub>2</sub>e basis). In addition, although the amount of total nitrogen remains about the same after AD (Frear, 2009), digested manures (DE) have a lower C:N ratio than do undigested manures (DLM) (Harrison, 2003; Moeller and Stinner, 2009), which may result in less CO<sub>2</sub> emissions.

Field monitoring of GHG fluxes has been highlighted as a fundamental and essential method for quantifying GHG emissions. Field monitoring data have been used by the International Panel on Climate Change (IPCC) to estimate the emission rates and to determine the gas emission factors, especially for N<sub>2</sub>O (Rochette and Eriksen-Hamel, 2008). In addition, field data are used to calibrate and verify predictions of mathematical models (Arah et al., 1997; Beheydt et al., 2007; Cai et al., 2003; Froelking et al., 1998; Smith et al., 1997). The chamber-based flux methodology is often used to measure N<sub>2</sub>O, CH<sub>4</sub>, and CO<sub>2</sub> fluxes from soils, since it is easy to conduct

at multiple sites and is less expensive than micromet techniques (Parkin et al., 2003). The static closed-chamber method (Haile-Mariam et al., 2008; Rochette and Eriksen-Hamel, 2008; Saggar et al., 2004) has been widely used to measure *in situ* GHG fluxes.

The objectives of this study were to: (i) describe and quantify the emissions of three major GHGs following various manure treatment and control applications in Washington State; (ii) assess the impacts of the various treatments, particularly differences between DE and DLM applications, on GHG emissions; and especially (iii) identify the potential of DE applications to reduce GHG emissions compared with DLM applications.

## Methods and Materials

Field studies were conducted in 2007 and 2008 to characterize trace gas fluxes from a Warden silt loam (Coarse-silty, mixed, superactive, mesic Xeric Haplocambids) soil after applications of synthetic NPK fertilizer, liquid dairy manure, anaerobic digested dairy effluent and anaerobic digested fiber. The study was conducted at the USDA-ARS Integrated Cropping Systems Research Station in conjunction with the WSU Irrigated Agriculture Research and Extension Center located in Prosser, Washington (46°15'22.07N, 119° 44'21.65 W). The region is characterized by a mean annual precipitation of 178 mm occurring primarily during the winter. The mean annual temperature is 11.2°C with average high and low of 38.7 and -13.6°C, respectively (Figure 10.1).

### *Experimental Design*

The experimental design was a complete randomized block design with four replicates planted to silage corn (*Zea mays* L.) and managed under fixed irrigation. The study area had been previously cropped to mint (*Mentha requienii*, L) from 1996 – 2006. Each plot was 8m x 5m in size. Treatments were fallow (F), unfertilized (UF), synthetic NPK fertilizer (NPK), anaerobic digested fiber (DF), anaerobic digested effluent (DE) and non-digested dairy liquid manure (DLM). The DF was collected from a static pile produced from the mechanical separation of the fiber from the digested effluent using a slope screen with a 0.20 cm mesh (U.S. Farm, Tulare, CA) on a dairy located near Sunnyside, WA. The DE was collected directly from the exit port of a GHD™ Plug Flow anaerobic digester on a dairy located near Sunnyside, WA. DLM was collected from the storage pond prior to entry into the digester and the digested effluent was collected immediately exiting the digester. Liquid materials (DE and DLM) were collected with a 5.5 hp Buffalo WP20 water pump (Buffalo Tools, St. Louis, Mo) and stored in a closed 946 L plastic tote until application. Liquid amendments remained in the tote no longer than 24 hours prior to application.

The DE, DLM and NPK fertilizer amendments were applied twice: 224 kg N ha<sup>-1</sup> prior to planting silage corn and 112 kg N ha<sup>-1</sup> applied when corn 5-6 leaf stage, for a total of 336 kg N ha<sup>-1</sup> within the crop year. The DF was only applied at pre-plant. Liquid amendments were evenly applied to the plots using a Master Plumber ½ HP

Submersible Utility Pump (Pentair Inc, Minneapolis, MN) attached to a 2 cm diameter hose equipped with a spray nozzle, powered in the field by a EU 2000i Honda Generator (Honda Inc, Japan). Plot boundaries were trenched to prevent cross-contamination among treatments.

In addition to the amendments, each plot, prior to planting, received a blended dry granular fertilizer containing 56 kg  $\text{NH}_4\text{SO}_4$   $\text{ha}^{-1}$ , 112 kg  $\text{P}_2\text{O}_5$   $\text{ha}^{-1}$ , 168 kg  $\text{K}_2\text{O}$   $\text{ha}^{-1}$ , applied with a handheld spreader. After amendments were added at pre-plant, the field was rotovated and planted with Dekalb DKC54-79 Hybrid Corn at a rate of 103740 seeds per hectare on 76cm row spacing using a John Deere 1730 Max Emergence planter (Deere and Company, Moline, IL), except in the case of the fallow treatment, which was not planted. In both years of the study, corn was planted the first week of May and harvested the first week of September at 50% milk line. Annual in-season (May-September) water applications were 71 and 80 cm for the 2007 and 2008 growing seasons, respectively. Silage yields were determined by hand harvesting 30 plants from each plot (Figure 9.1).

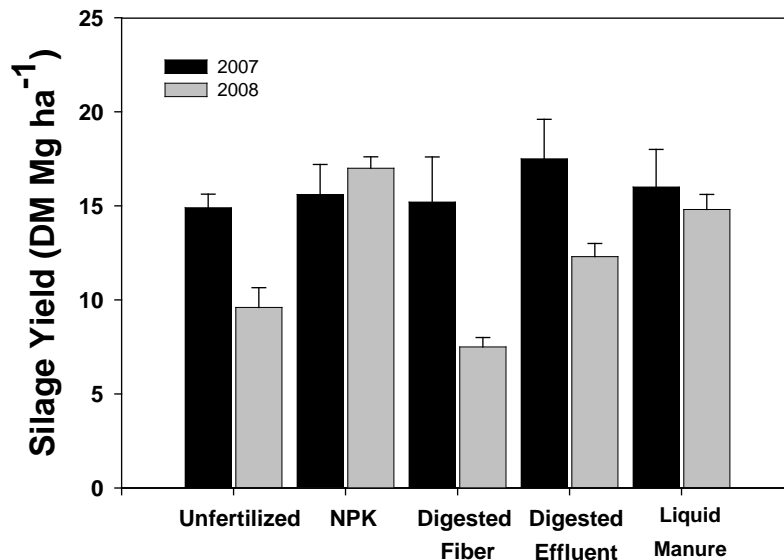


Figure 9.1: Silage corn dry matter yields for the 2007 and 2008 crop years at the Irrigated Agriculture Research and Extension Center, Prosser, WA. Error bars determined at  $p=0.05$ .

### *Soil Sampling and Analysis*

Soil samples (0-30cm depth) were collected at each gas sampling interval within a 1 m area around each sampling chamber. Gravitational moisture content, mineral N ( $\text{NH}_4^+$  and  $\text{NO}_3^-$ ) concentrations and pH were determined for each sample. Mineral N was obtained by extracting 10 g soil subsamples with 2 M KCL and analyzed on a flow-injection analyzer (QuikChem AE; Lachat Zellweger, Loveland, CO). Soil pH was measured using a 1:2 soil/de-ionized water method on a Corning 445 pH Meter (Corning Incorporated, Corning, NY).

### *Gas Flux Measurements*

*In situ* trace gas fluxes were measured using the static closed chamber method (Hutchinson and Mosier, 1981; Hutchinson and Livingston, 1993). Twenty-four chambers were installed in each of the treatment plots in the inter-row position of corn and sampled according to USDA-ARS GRACEnet (Greenhouse gas Reduction through Agricultural Carbon Enhancement network) protocols (Parkin, et al, 2003). The flux of CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub> was measured weekly throughout the corn growing season following irrigation events from May through August for the 2007 and 2008 growing seasons. Approximately 20 mm of water was applied during irrigation. Gas sampling was performed at the same time each day within the 1000 and 1500 hour window depending on irrigation scheduling. Sample collection took place within 1 hour of the irrigation.

A base frame was inserted at each sample point at the beginning of the growing season and remained in the field until removal prior to harvest. Each base frame was 30.5 cm diameter x 15cm high PVC and driven into the surface to a depth of 5cm. Trace gases fluxes (CO<sub>2</sub>, N<sub>2</sub>O, and CH<sub>4</sub>) were measured by fitting the chamber base frames with a vented PVC cap (30.5 cm interior diameter and 7.5 cm high) that contained a sampling port. The caps had a 2.54-cm hole allowing air to exit and keep air turbulence to a minimum when caps were in place. The hole was sealed with a rubber stopper during the measurement period. The change in concentration of gases within each chamber was determined by withdrawing 35 ml of air from the headspace using a 60-ml polypropylene syringe every 20 minutes over a one hour period after the cap was placed on the chamber base. Gas samples were immediately transferred to evacuated 12 ml Labco Exetainer (Labco Limited, High Wycombe, Buckinghamshire, UK) vials and taken to the laboratory for determination of N<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub> by gas chromatography (Mosier and Mack, 1980). At the time of gas sampling, inside chamber temperature (beginning and end) and air temperature before and after measurements were recorded using a digital differential thermocouple thermometer (Omega HHM290 Supermeter; Omega Engineering Inc., Stamford, CT). Samples were stored in a containment unit at a constant temperature of 25°C and analyzed immediately. A Varian CP-3800 GC (Varian, Palo Alto, CA) equipped with a thermal conductivity, electron capture, and a flame ionization detector was used to measure trace gas concentrations. Gas standards (N<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub>) were analyzed every three hours throughout the day.

In a separate experiment an intense sampling of trace gases (CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub>) was conducted over the initial 48 hour period after application. Treatments evaluated were the unfertilized fertilizer (U), anaerobic digested fiber (DF), anaerobic digested effluent (DE), dairy liquid manure (DLM), and synthetic nitrogen (N) in the form of urea. Amendments were applied at a rate of 336 kg N ha<sup>-1</sup> immediately prior to gas sampling. Gas sampling and determination of N<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub> during the 48 h experiments are as described above.

### Statistical Analysis

The N<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub> trace gas flux rates were calculated from the slope of gas concentration over time, corrected for temperature, chamber volume and surface area of the chamber (Hutchinson and Mosier, 1981). Cumulative fluxes of N<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub> from each treatment were calculated by averaging the fluxes between two sampling points and multiplying by the time interval between points (Fangueiro et al., 2008). Averages and standard error of the mean are presented for each sampling interval.

## Results

### C and N Characteristics of the Manures

Dry matter (DM) concentration of the DF was similar between the 2007 and 2008 sample years, averaging 180 g DM kg<sup>-1</sup> (Table 9.1). DM of the DE and DLM were similar in 2007 averaging 20 g DM kg<sup>-1</sup> (2%), but greater in 2008 averaging 85 g DM kg<sup>-1</sup> (8.5%) at both collection periods (pre-plant and mid-season) except for the DLM 6 May 2008 sampling which was 22 g DM kg<sup>-1</sup> (2.2%), similar to slurry collections made in 2007. It is likely that variability in holding pond mixing and efficiencies of the fiber separators influenced the DM concentrations.

Table 9.1: C and N added per treatment during the 2007 and 2008 silage corn crop years.

	Time Applied	Dry Matter %	Organic C g C kg <sup>-1</sup> DM	Total N g N kg <sup>-1</sup> DM or g N L <sup>-1</sup>	Material Applied kg DM <sup>†</sup> or L ha <sup>-1</sup>	Org. C Applied ----- kg ha <sup>-1</sup> -----	N Applied -----
<b>2007</b>							
DF	11 April	16.8	480	<b>29.8</b>	<b>7,526</b>	3,615	224
DE	11 April	2.0	416	1.7	130,770	1,088	224
DLM	21 June	1.8	416	2.0	56,325	422	112
	11 April	2.0	430	2.1	105,650	910	224
	21 June	1.9	430	2.2	51,375	420	112
<b>2008</b>							
DF	7 May	19.1	480	<b>23.6</b>	<b>9,508</b>	4,565	224
DE	6 May	8.2	416	3.6	62,188	2,121	224
	18 June	9.1	438	2.8	40,377	1,610	112
DLM	6 May	2.2	430	2.2	102,185	970	224
	18 June	8.3	430	2.4	46,195	1,650	112

<sup>†</sup> DM - Dry matter

Organic C concentrations of the dry matter in both years for the DLM, DE, and DF averaged 430, 423 and 480 g C kg<sup>-1</sup>DM, respectively. Total N for the DLM, DE, and DF averaged 2.2, 2.5 and 26.7 g N kg<sup>-1</sup>DM. The N concentration of the fiber materials within the DLM and DE averaged 20 g N kg<sup>-1</sup>DM with C:N ratios of 18 for DF and 21 for both DLM and DE. The amount of seasonal N applied as an amendment to the silage corn was 336 kg N ha<sup>-1</sup> to meet crop needs. The amount of total organic C added varied depending upon N content of the materials collected, with C inputs ranging widely, from lower values of ~400 to 2000 kg C ha<sup>-1</sup> for the liquid applications of DE and DLM, respectively, up to higher values of 3600 to 4600 kg C ha<sup>-1</sup> for the digested fiber (Table 10.1).

#### *Chamber Temperature, Soil Water Conditions and pH*

Average ambient air temperatures from the date of planting to harvest were similar during the 2007 and 2008 field seasons ranging from a low of 10.8°C to a high of 28.2°C with 36.3 mm of precipitation in 2007 compared to a low of 10.7°C and a high of 27.2°C with 23.9 mm of precipitation in 2008 (Figure 9.2).

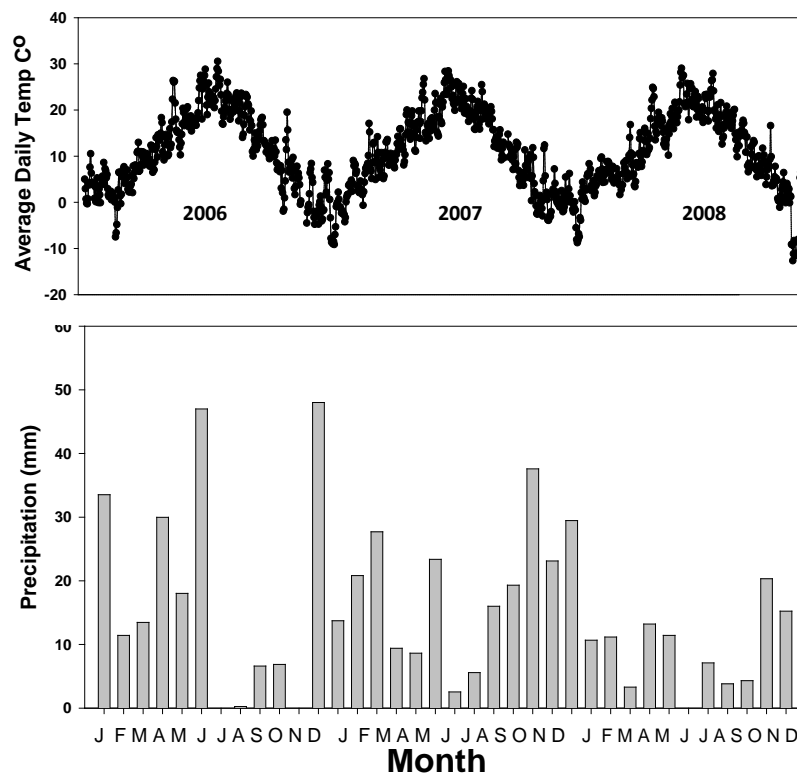


Figure 9.2: Monthly temperature and precipitation during the 2006-2008 growing seasons at Prosser, WA. Data provided courtesy of Washington State University AgWeatherNet.

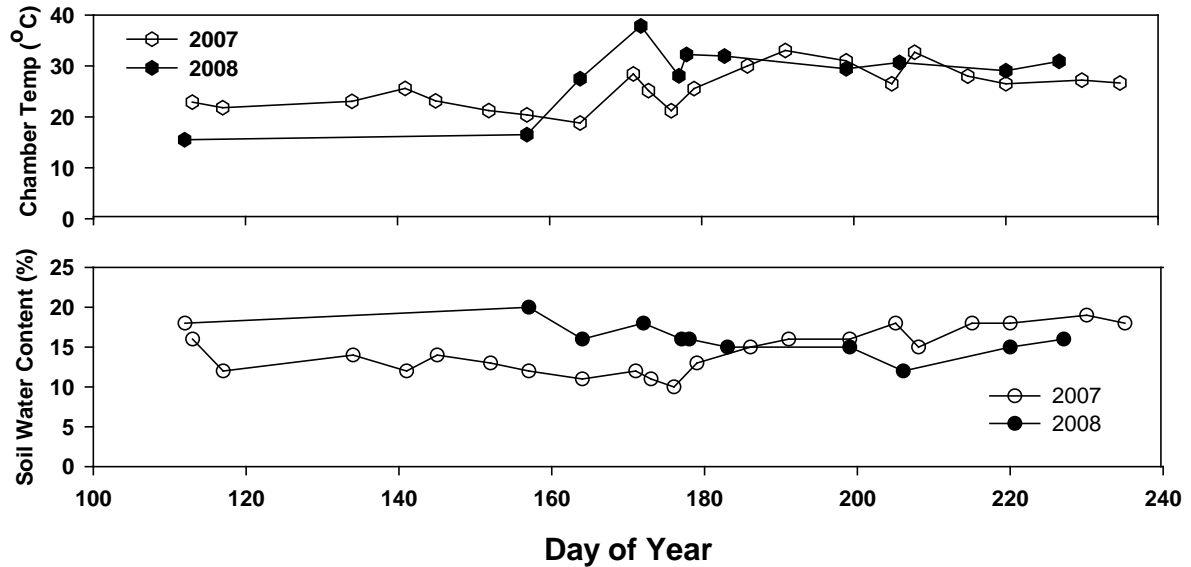


Figure 9.3: Average temperature and soil water content within trace gas flux chambers during 2007 and 2008 crop years.

Chamber temperatures averaged 23.0°C for the first half of the growing season and 30°C in the second half (Figure 9.3). The average moisture contents at the time of gas sampling for 2007 and 2008 were 14.2% and 15.4%, respectively. Soil pH averaged 7.8 throughout the study, with individual plots ranging from 6.03 to 8.43, but remaining stable from the beginning to the end of the study.

#### *Soil NO<sub>3</sub>-N and NH<sub>4</sub>-N*

Average soil ammonium (NH<sub>4</sub>-N) and nitrate (NO<sub>3</sub>-N) levels in the 0-30 cm depth increment during the 2007 and 2008 growing seasons are presented in Table 9.2.

Table 9.2: Average soil ammonium (NH<sub>4</sub>-N) and nitrate (NO<sub>3</sub>-N) levels in the 0-30 cm depth increment within the 2007 and 2008 silage corn growing seasons

Year	Treatment	1 <sup>st</sup> half		2 <sup>nd</sup> half	
		d113 - d176		d177 - d235	
		NH <sub>4</sub> -N	NO <sub>3</sub> -N	NH <sub>4</sub> -N	NO <sub>3</sub> -N
		--- kg/ha <sup>-1</sup> ---		--- kg/ha <sup>-1</sup> ---	
2007	Fallow	4.5 (2) <sup>†</sup>	73.0 (17)	5.1 (2)	8.7 (2)
	Unfertilized	3.6 (1)	52.6 (15)	6.1 (1)	10.2 (4)
	NPK- Fertilized	4.7 (3)	58.8 (10)	6.4 (3)	6.3 (3)
	Digested Fiber	8.0 (7)	71.2 (29)	11.1 (8)	9.7 (3)
	Digested Effluent	11.2 (12)	94.8 (29)	8.9 (7)	14.8 (3)
	Liquid Manure	8.0 (7)	99.7 (28)	5.2 (1)	13.0 (8)
2008	Fallow	10.0 (9)	30.0 (11)	5.5 (2)	11.2 (6)
	Unfertilized	5.8 (5)	15.4 (5)	8.1 (6)	7.0 (2)
	NPK- Fertilized	9.0 (6)	80.6 (35)	6.2 (2)	25.2 (6)
	Digested Fiber	9.1 (7)	17.6 (3)	8.4 (4)	7.9 (3)
	Digested Effluent	30.2 (24)	70.7 (13)	8.2 (6)	12.2 (3)
	Liquid Manure	31.7 (38)	63.4 (28)	9.1 (5)	12.4 (3)

<sup>†</sup>Values in parentheses are standard error of the mean

Figure 9.4 presents the soil NO<sub>3</sub>-N concentrations found in the 0-30 cm depth increment on each sampling date for both 2007 and 2008 crop years. Total available soil N (NH<sub>4</sub>-N plus NO<sub>3</sub>-N) was significantly higher in the first half of the growing season (day 113-day 176) than the second half of the growing season (day 177-day 235) in both years (Table 9.2). During the first half of the 2007 growing season, average soil NO<sub>3</sub>-N concentrations were 73, 53, 59, 71, 95 and 100 kg NO<sub>3</sub>-N ha<sup>-1</sup> for the F, UF, NPK, DF, DE and DLM treatments, respectively (Table 9.2). In 2008, soil NO<sub>3</sub>-N concentrations were 60, 72, 75, 25 and 37% lower in the F, UF, DF, DE and DLM treatments, respectively, than in 2007. Potential reasons for lower NO<sub>3</sub>-N concentrations include losses of N due to leaching in F as the treatment was irrigated with no crop; no fertilizer added to the UF silage corn; limited N-mineralized from the DF to supply silage corn uptake requirements; and a greater concentration of N as NH<sub>4</sub>-N in the DE and DLM slurries in 2008 compared to 2007. Total available soil N (NH<sub>4</sub>-N plus NO<sub>3</sub>-N) was similar for the NPK, DE and DLM both years. Over the second half of the growing season soil nitrate concentrations averaged 12 kg NO<sub>3</sub>-N ha<sup>-1</sup> (range 6 – 25 kg NO<sub>3</sub>-N ha<sup>-1</sup>) among all treatments for both years, reflecting N-uptake as the silage crop matured.



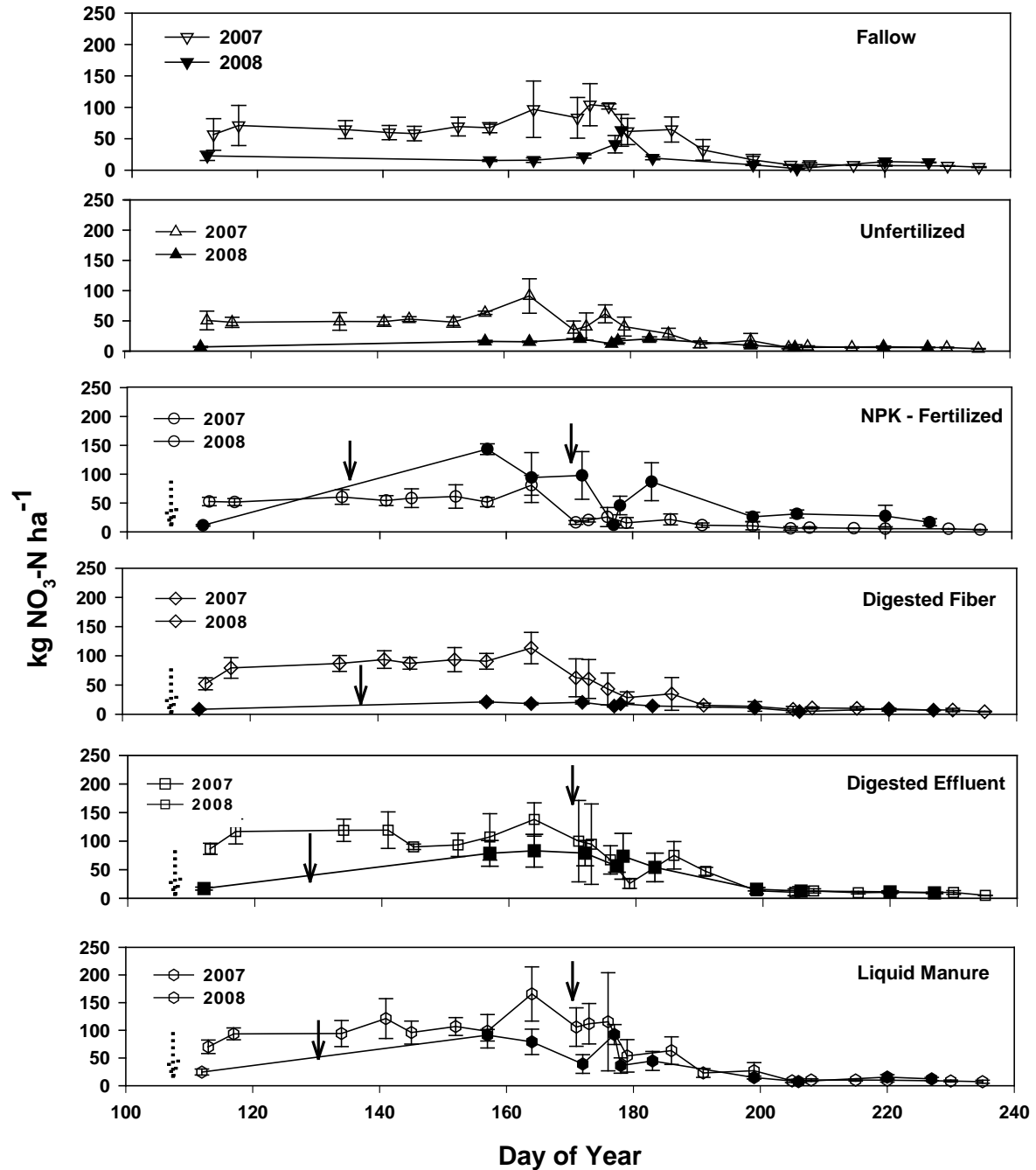


Figure 9.4: Soil NO<sub>3</sub>-N within the 0-30 cm depth increment of each treatment during the 2007 and 2008 growing seasons. Error bars determined at p=0.05. The dashed arrow identifies the addition of amendments in 2007, the solid arrows in 2008.

### *Seasonal Trace Gas Fluxes*

#### Carbon Emissions (CO<sub>2</sub>-C, CH<sub>4</sub>-C)

Weekly CO<sub>2</sub>-C flux patterns among treatments were similar for both years showing a steady increase during the growing season as the silage crop matured, averaging 6 kg CO<sub>2</sub>-C ha<sup>-1</sup> d<sup>-1</sup> from day 112 -- day 157; 13 kg CO<sub>2</sub>-C ha<sup>-1</sup> d<sup>-1</sup> from day 157 -- day 172; and 22 kg CO<sub>2</sub>-C ha<sup>-1</sup> d<sup>-1</sup> from day 172 – day 227 with no significant differences among the F, UF, NPK, and DE treatments (Figure 9.5). The CO<sub>2</sub>-C flux from the DF treatment showed a similar trend as the other treatments for both years through day 172 but increased from 35 to 105 kg CO<sub>2</sub>-C ha<sup>-1</sup> d<sup>-1</sup> on day 183 in 2007 then declined to pre-application levels afterward. In 2008, the CO<sub>2</sub>-C increase occurred earlier and was maintained longer. Application of DLM on day 172 increased CO<sub>2</sub>-C from 20 kg CO<sub>2</sub>-C ha<sup>-1</sup> d<sup>-1</sup> to 40 and 66 kg CO<sub>2</sub>-C ha<sup>-1</sup> d<sup>-1</sup> in 2007 and 2008, respectively, for the following 2 days then declined to pre-application levels. That CO<sub>2</sub>-C emissions showed no response to the first application (~day 105) of the amendments in both crop years, was attributed to a lack of sampling until the week following treatment applications.

Methane (CH<sub>4</sub>-C) emissions showed little variation throughout the growing season except for the time period around day 172 following the application of the DE and DLM (Figure 9.6). Seasonal methane emissions averaged -0.54 g CH<sub>4</sub>-C ha<sup>-1</sup> d<sup>-1</sup> among treatments in 2007 and -0.64 g CH<sub>4</sub>-C ha<sup>-1</sup> d<sup>-1</sup> in 2008, indicating methane uptake by the soil, except at times of manure amendments. Methane emissions increased significantly relative to the F, UF and NPK treatments after application of the DE and DLM slurries, while no significant effect was observed after application of the solid DF material early in the season. The day after application of DE and DLM, methane emissions in those treatments averaged 32 g CH<sub>4</sub>-C ha<sup>-1</sup> d<sup>-1</sup>, except for the DE in 2007 which was 10 g CH<sub>4</sub>-C ha<sup>-1</sup> d<sup>-1</sup>. These very high methane emissions from the DE and DLM decreased to pre-application levels and were indistinguishable from other treatments within two days. It is likely that most of the emissions observed after application may be attributed to the release of dissolved or super-saturated CH<sub>4</sub>-C produced prior to application during storage (DLM) or dissolved in the effluent (DE) from the AD digester and not from the soil.

Total cumulative fluxes of CO<sub>2</sub>-C and CH<sub>4</sub>-C are presented in Table 9.3. Carbon dioxide emissions from these treatments represent both microbial and plant root respiration over the 115-day growing season in both years. Cumulative CO<sub>2</sub>-C was different between years for all treatments. The highest cumulative CO<sub>2</sub>-C emissions were observed in the DF treatment, averaging 3,396 kg CO<sub>2</sub>-C ha<sup>-1</sup> in 2007 and 4,719 kg CO<sub>2</sub>-C ha<sup>-1</sup> in 2008 compared to an average of 1835 kg CO<sub>2</sub>-C ha<sup>-1</sup> in 2007 and 2350 kg CO<sub>2</sub>-C ha<sup>-1</sup> in 2008 among other cropped treatments (UF, NPK, DE, DLM). The fallow treatment had the lowest cumulative emission of 1,285 kg CO<sub>2</sub>-C ha<sup>-1</sup> in both years.

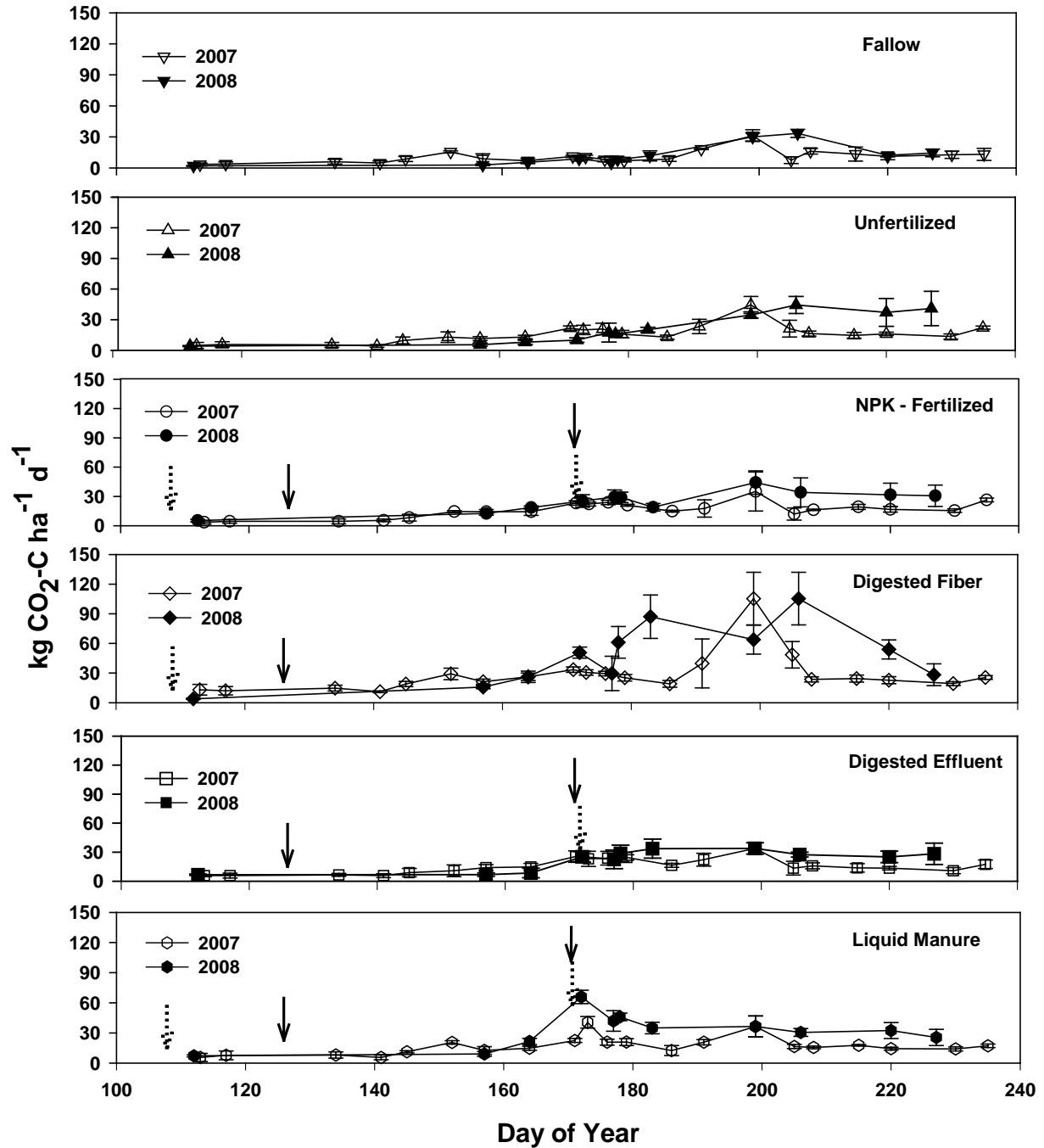


Figure 9.5: Carbon dioxide (CO<sub>2</sub>-C) flux rates from corn silage plots receiving treatments of fallow, unfertilized, fertilized, digested fiber, digested effluent and liquid dairy manure during the 2007 and 2008 growing seasons. Error bars determined at p=0.05. The dashed arrow identifies the addition of amendments in 2007, the solid arrows in 2008.

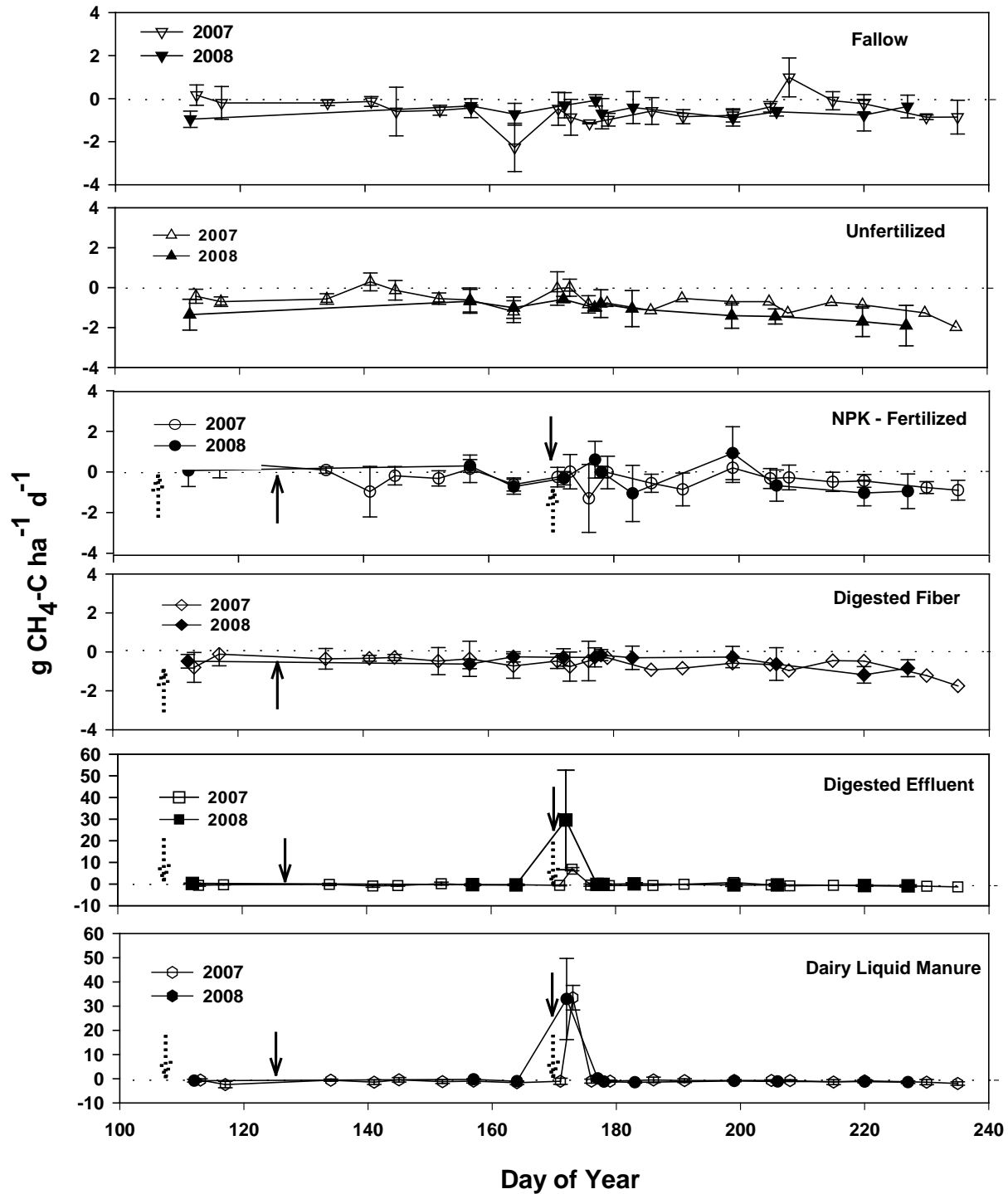


Figure 9.6: Methane (CH<sub>4</sub>-C) flux rates from corn silage plots receiving treatments of fallow, unfertilized, fertilized, digested fiber, digested effluent and liquid dairy manure during the 2007 and 2008 growing seasons. Error bars determined at p=0.05. The dashed arrow identifies the addition of amendments in 2007, the solid arrows in 2008.

Table 9.3: Cumulative CO<sub>2</sub>-C, CH<sub>4</sub>-C and N<sub>2</sub>O-N emitted and global warming potentials (GWP) for 2007 and 2008 silage corn growing seasons

	Year	Carbon Dioxide		Methane		Nitrous Oxide		Total GWP <sup>†</sup>
		Season <sup>‡</sup>		Season <sup>‡</sup>	GWP	Season <sup>‡</sup>	GWP	
		CO <sub>2</sub> -C kg ha <sup>-1</sup>	kg CO <sub>2</sub> e ha <sup>-1</sup>	CH <sub>4</sub> -C g ha <sup>-1</sup>	kg CO <sub>2</sub> e ha <sup>-1</sup>	N <sub>2</sub> O-N g ha <sup>-1</sup>	kg CO <sub>2</sub> e ha <sup>-1</sup>	
F	2007	1320 (64) <sup>†</sup>	4840 (230)	-65 (30)	-2.2 (1.0)	114 (30)	54 (14)	21.0 (7)
	2008	1251 (130)	4588 (475)	-71 (30)	-2.4 (1.0)	70 (20)	33 (10)	12.4 (4)
UF	2007	1823 (111)	6684 (518)	-87 (14)	-2.9 (0.5)	96 (39)	45 (18)	17.0 (9)
	2008	2074 (177)	7604 (649)	-93 (23)	-3.1 (0.7)	156 (28)	73 (13)	28.3 (6)
NPK	2007	1801 (224)	6604 (820)	-47 (50)	-1.6 (1.7)	113 (23)	53 (11)	26.1 (5)
	2008	2429 (441)	8908 (1616)	-31 (12)	-1.0 (0.4)	392 (86)	184 (40)	74.1 (16)
DF	2007	3396 (175)	12454 (643)	-51 (13)	-1.7 (0.4)	202 (70)	95 (33)	37.8 (14)
	2008	4719 (683)	17306 (1876)	-60 (23)	-2.0 (0.8)	112 (35)	53 (16)	20.6 (7)
DE	2007	1779 (210)	6525 (771)	27 (35)	+0.9 (1.2)	157 (40)	74 (19)	30.4 (9)
	2008	2103 (179)	7713 (655)	126 (57)	+4.2 (1.9)	336 (150)	157 (70)	65.3 (28)
DLM	2007	1931 (150)	7083 (551)	38 (69)	+1.3 (3.3)	288 (81)	135 (36)	55.4 (16)
	2008	2788 (223)	10223 (818)	86 (25)	+2.9 (3.5)	380 (38)	178 (18)	73.2 (9)

<sup>†</sup>Values in parentheses are standard error of the mean. <sup>‡</sup>GHG emissions were measured over the silage corn growing season (120 d) each year and interpolated to estimate cumulative trace gas losses. CO<sub>2</sub>e = CO<sub>2</sub> equivalents based on the global warming potential (GWP) of greenhouse gasses, relative to CO<sub>2</sub>; CO<sub>2</sub> equivalents of N<sub>2</sub>O and CH<sub>4</sub> are 298 and 25 times that of CO<sub>2</sub>, respectively (IPCC, 2007).

<sup>††</sup>Net GWP/growing season = CH<sub>4</sub>-GWP + N<sub>2</sub>O-GWP; where column 9, kg CO<sub>2</sub> eq. acre<sup>-1</sup> = (column 6 + column 8)/2.47.

Cumulative CH<sub>4</sub>-C emissions averaged -68, -90, -40, -55 g CH<sub>4</sub>-C ha<sup>-1</sup> among the F, UF, NPK and DF treatments, respectively, over both years, indicating that these soils were sinks for methane. Exclusive of the time immediately following DE and DLM applications, soil methane uptake in these treatments was similar to the other treatments, averaging - 51 g CH<sub>4</sub>-C ha<sup>-1</sup>. The cumulative methane flux for the two days around the application of DE and DLM averaged 33 g CH<sub>4</sub>-C ha<sup>-1</sup> in 2007 and 61 g CH<sub>4</sub>-C ha<sup>-1</sup> in 2008 as seen by the methane spike in Figure 9.6.

### Nitrogen Emissions (N<sub>2</sub>O-N)

Weekly N<sub>2</sub>O-N flux patterns were similar in both years for the F, UF, and DF treatments, remaining steady throughout the growing season at an average of 1.1 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> (Figure 9.7). In 2007, the DF treatment showed an increase in N<sub>2</sub>O-N seven days after the first and only fiber application, averaging 6 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> from day 112 – day 120. Nitrous oxide flux for the NPK, DE and DLM treatments showed minor increases following applications in the spring of the year and major increases following the second applications around day 172. N<sub>2</sub>O-N flux rates from day 112 – day 160 for the NPK and DE treatments were similar, averaging 1.7 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup>. The average flux for DLM over the same time period was 5.0 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup>.

At the second application date (day 172) N<sub>2</sub>O-N emissions increased significantly for the NPK, DE and DLM treatments relative to the F, UF and DF treatments. In 2007, peak emission rates after the second application were 1, 5 and 10 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> for the NPK, DE and DLM treatments, respectively. In 2008 peak N<sub>2</sub>O emissions were 13, 15 and 22 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> and remained elevated for up to 20 days, after which fluxes returned to pre-application levels. As with methane, the DF application had only a small effect on N<sub>2</sub>O emissions.

At the end of the growing season, the cumulative N<sub>2</sub>O emitted in 2007 was 114, 96, 113, 202, 157 and 288 g N<sub>2</sub>O-N ha<sup>-1</sup> for the F, UF, NPK, DF, DE and DLM treatments, respectively (Table 9.3). In 2008, cumulative N<sub>2</sub>O emitted was 3.5, 2.1 and 1.3 fold higher for the NPK, DE and DLM treatment, respectively. The total amount of N<sub>2</sub>O emitted in the amended treatments represented 0.03 and 0.12%; 0.09 and 0.05%; 0.05 and 0.10%; and 0.09 and 0.11% of the total N applied in the NPK, DF, DE and DLM treatments in 2007 and 2008, respectively. When based on the amount of total inorganic N (TIN=NH<sub>4</sub>-N, NO<sub>3</sub>-N) present during the 15-20 d period following applications; N<sub>2</sub>O fluxes represented 0.18%, 0.27%, and 0.27% for the NPK, DE and DLM treatments respectively. The majority of the cumulative seasonal N<sub>2</sub>O flux occurred over the 15-20 d period following the second application of amendments, accounting for 23, 45 and 62% of the total N<sub>2</sub>O flux for the NPK, DE and DLM in 2007 and 42, 79 and 72% in 2008.

#### *48 hr Studies: CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O Flux Rates*

In both years of the study, separate experiments were conducted to intensively measure the 48-hour flux rates of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O following application of NPK, DF, DE and DLM amendments (Figure 9.8). In 2007 DE and DLM slurries were applied within 18 hours of collection, whereas in 2008 slurries were applied within 2 hours of collection. Soil moisture and temperature were similar between the 2007 and 2008 sample years. Peak CO<sub>2</sub> and CH<sub>4</sub> fluxes occurred 2 hours after application in 2007 and 6 hours after application in 2008. Peak N<sub>2</sub>O flux occurred 6 to 12 hours after application in both years. Maximum flux rates for CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O were 10 kg CO<sub>2</sub>-C ha<sup>-1</sup>h<sup>-1</sup>; 500 g CH<sub>4</sub>-C ha<sup>-1</sup>h<sup>-1</sup> and 2 g N<sub>2</sub>O-N ha<sup>-1</sup>h<sup>-1</sup>.

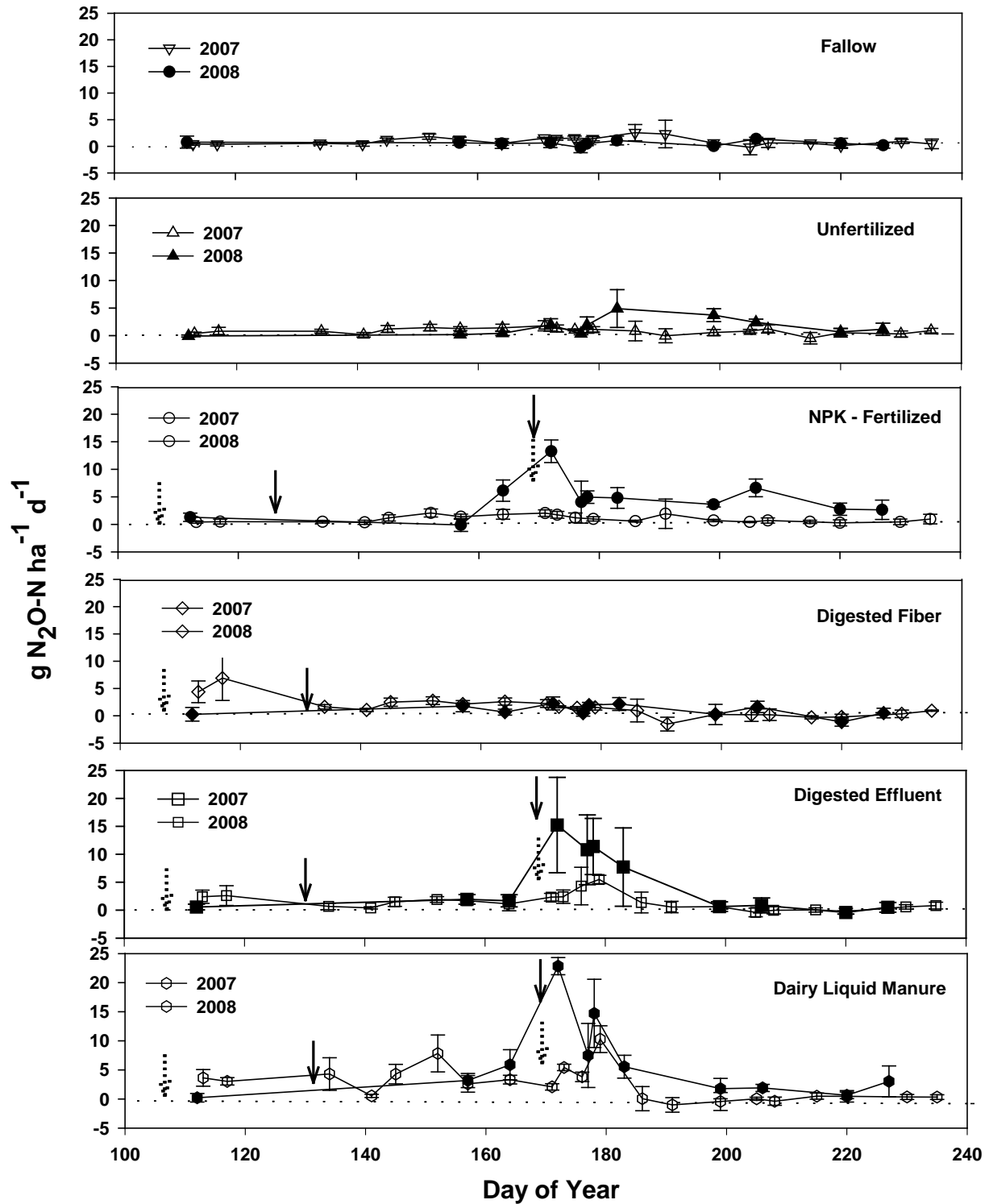


Figure 9.7: Nitrous oxide ( $N_2O-N$ ) flux rates from corn silage plots receiving treatments of fallow, unfertilized, fertilized, digested fiber, digested effluent and liquid dairy manure during the 2007 and 2008 growing seasons. Error bars determined at  $p=0.05$ . The dashed arrow identifies the addition of amendments in 2007, the solid arrows in 2008.

2007

2008

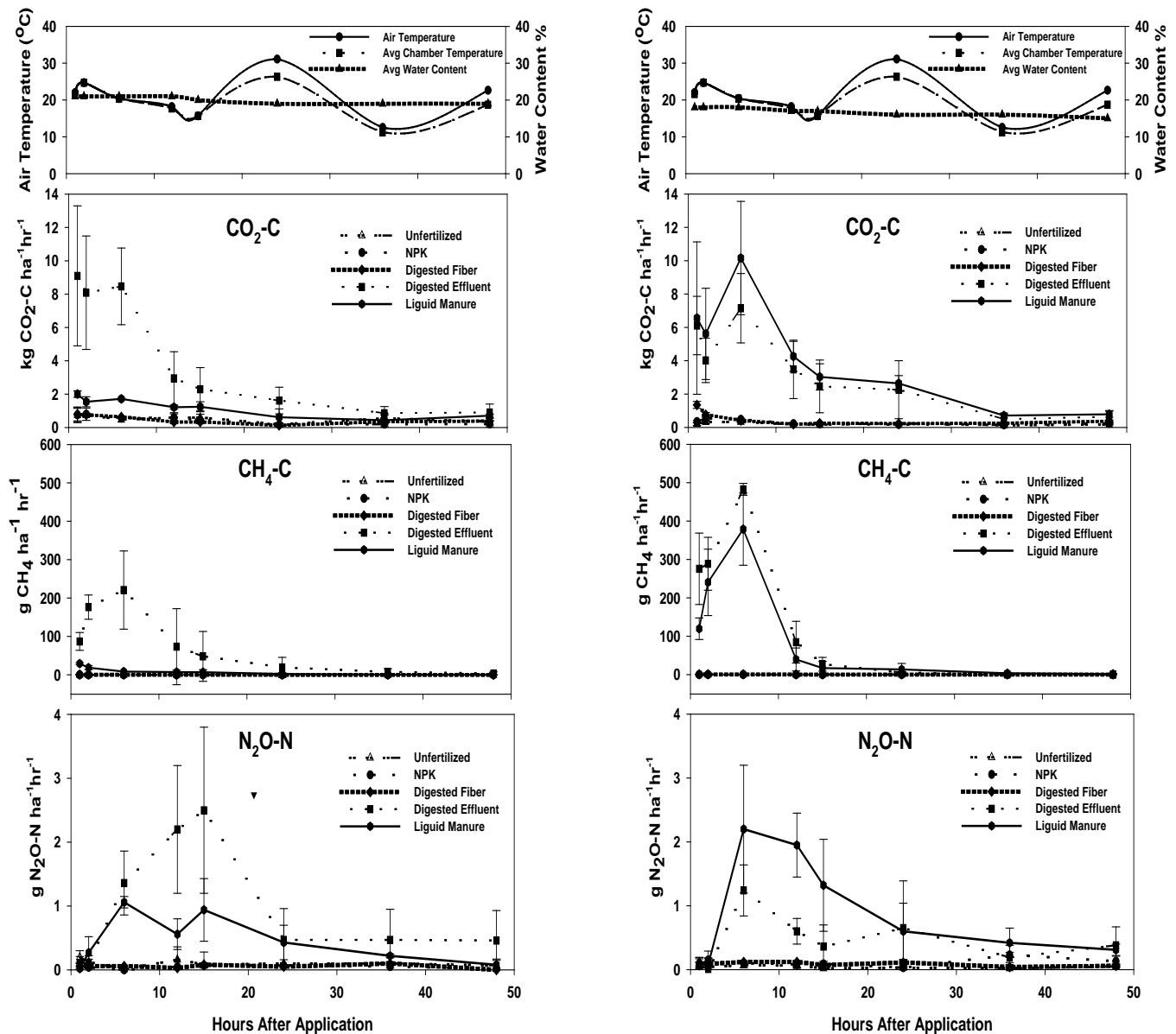


Figure 9.8: Trace gas flux rates 48 hr after application of treatments in the 2007 and 2008 crop years. Error bars determined at  $p=0.05$ .

Cumulative 48-hour  $\text{CO}_2$  emissions were 8 fold greater for the DE and DLM treatments compared to the UF, NPK and DF (Table 9.4). Carbon dioxide and methane emissions were significantly higher in the 2008 treatment of the DLM than in 2007. The differences in methane flux between years can be attributed to the longer interval between collection and application in 2007. The DE was collected just prior to where effluent exits the AD; therefore incomplete removal or degassing of  $\text{CH}_4$  from the slurry exiting the digester led to the high emissions after soil application of the DE and DLM. This release is reported other studies with releases of methane reported within the range found here (Fanguerio et



al., 2008; Liu et al., 2006). Cumulative methane emissions of the DE and DLM during the 48-hour studies averaged 3.1 kg CH<sub>4</sub>-C ha<sup>-1</sup>. The estimated net CH<sub>4</sub> uptake by soil over the growing season averaged 70 g CH<sub>4</sub>-C ha<sup>-1</sup>, while the CH<sub>4</sub> lost exceeded the entire growing season emissions by a factor of 43. Recovery systems for CH<sub>4</sub> are needed for the DE and DLM before application to soil systems if methane emissions are to be minimized.

Table 9.4: Cumulative CO<sub>2</sub>-C, CH<sub>4</sub>-C and N<sub>2</sub>O-N emitted and global warming potential for the initial 48 hrs after amendment applications in the 2007 and 2008 silage corn crop years

	Year	Carbon Dioxide		Methane		Nitrous Oxide		Net GWP <sup>†</sup>
		48 h <sup>‡</sup>		48 h <sup>‡</sup>	GWP	48 h <sup>‡</sup>	GWP	
		CO <sub>2</sub> -C kg ha <sup>-1</sup>	kg CO <sub>2</sub> e ha <sup>-1</sup>	CH <sub>4</sub> -C g ha <sup>-1</sup>	kg CO <sub>2</sub> e ha <sup>-1</sup>	N <sub>2</sub> O-N g ha <sup>-1</sup>	kg CO <sub>2</sub> e ha <sup>-1</sup>	
UF	2007	22 (7)	79 (26)	0.3 (0.3)	0.01 (0.08)	2.0 (2)	0.9 (0.07)	0.4 (0.03)
	2008	9 (1)	35 (3)	0.3 (0.4)	0.01 (0.01)	1.6 (1)	0.7 (0.03)	0.3 (0.01)
NPK	2007	16 (3)	59 (11)	0.3 (1)	0.01 (0.04)	2.2 (1)	1.0 (0.02)	0.4 (0.02)
	2008	11 (1)	41 (2)	0.4 (1)	0.01 (0.03)	5.6 (3)	2.6 (1.3)	1.1 (0.53)
DF	2007	17 (2)	62 (7)	2.0 (2)	0.07 (0.06)	2.8 (1)	1.3 (0.2)	0.6 (0.10)
	2008	15 (2)	53 (6)	3.9 (2)	0.13 (0.07)	3.8 (1)	1.7 (0.02)	0.7 (0.01)
DE	2007	127 (48)	466 (176)	2305 (849)	77 (6)	45 (17)	18.0 (17)	38.5 (9)
	2008	113 (49)	414 (178)	3880 (864)	129 (29)	23 (4)	10.0 (7)	56.3 (14)
DLM	2007	42 (12)	156 (45)	212 (120)	7 (4)	22 (7)	10.0 (3)	6.9 (1)
	2008	147 (47)	537 (172)	3030 (869)	91 (30)	37 (20)	17.0 (9)	43.7 (12)

<sup>†</sup>Values in parentheses are standard error of the mean. <sup>‡</sup>GHG emissions were measured over the 48 h after manure applications each year and interpolated to estimate cumulative trace gas losses. CO<sub>2</sub>e = CO<sub>2</sub> equivalents based on the global warming potential (GWP) of greenhouse gasses, relative to CO<sub>2</sub>; CO<sub>2</sub> equivalents of N<sub>2</sub>O and CH<sub>4</sub> are 298 and 25 times that of CO<sub>2</sub>, respectively (IPCC, 2007). <sup>††</sup>Net GWP = CH<sub>4</sub>-GWP + N<sub>2</sub>O-GWP; where Column 9, kg CO<sub>2</sub>e ac<sup>-1</sup> = (column 6+ column 8)/2.47.

#### *Effect of Manure Applications on Global Warming Potentials (GWP)*

GWP (kg CO<sub>2</sub>e ac<sup>-1</sup>) for CH<sub>4</sub> and N<sub>2</sub>O were estimated for the crop season (120 days) and 48 hours immediately following application. These calculations used values of 25 and 298 for CH<sub>4</sub> and N<sub>2</sub>O, respectively, to convert to carbon dioxide equivalents for a 100-year time frame (Column 9, Tables 9.3 and 9.4). GWP for the F and UF treatments averaged 20 kg CO<sub>2</sub>e ac<sup>-1</sup> compared to 56 kg CO<sub>2</sub>e ac<sup>-1</sup> for the DE and DLM treatments. The

GWP of the DF treatment was only slightly higher than the F and UF treatments averaging 30 kg CO<sub>2</sub>-eq ac<sup>-1</sup> over both years of the study. Nitrous oxide emissions contributed more than 90% to the GWP over the growing season, whereas in the 48 hours immediately after application, methane emissions from the DE and DLM were 80-90% of the total GWP.

## Conclusion

Weekly CO<sub>2</sub>-C flux patterns among treatments were similar for both years showing a steady increase during the growing season as the silage crop matured, averaging 6 kg CO<sub>2</sub>-C ha<sup>-1</sup> d<sup>-1</sup> from day 112 – day 157; 13 kg CO<sub>2</sub>-C ha<sup>-1</sup> d<sup>-1</sup> from day 157 – day 172; and 22 kg CO<sub>2</sub>-C ha<sup>-1</sup> d<sup>-1</sup> from day 172 – day 227 with no significant differences among treatments.

Global Warming Potentials for the fallow and unfertilized treatments averaged 20 kg CO<sub>2</sub>-eq ac<sup>-1</sup> compared to 56 kg CO<sub>2</sub>-eq ac<sup>-1</sup> for the AD effluent and liquid dairy manure. The DF was only slightly higher than the F and UF treatments averaging 30 kg CO<sub>2</sub>-eq ac<sup>-1</sup> over both years of the study. Nitrous oxide emissions contributed more than 90% to the GWP over the growing season, whereas in the 48 h studies methane emissions from the DE and DLM were 80-90% of the total GWP immediately after application.

The total amount of N<sub>2</sub>O emitted in the amended treatments represented 0.03 to 0.12%; of the total N applied in the NPK, DF, DE and DLM treatments. When based on the amount of total inorganic N (TIN=NH<sub>4</sub>-N, NO<sub>3</sub>-N) present during the 15-20 d period following applications; N<sub>2</sub>O fluxes represented 0.18%, 0.27%, 0.27% for the NPK, DE and DLM treatments, respectively. The majority of the cumulative seasonal N<sub>2</sub>O flux occurred over the 15-20 day period following the second application of amendments. This period accounted for 23, 45 and 62% of the total flux for the NPK, DE and DLM treatments in 2007 and 42, 79 and 72% in 2008.

Methane (CH<sub>4</sub>-C) emissions showed little variation throughout the growing season except for around day 172 following the application of the liquid manure amendments. Seasonal daily methane emissions among treatments averaged -0.54 g CH<sub>4</sub>-C ha<sup>-1</sup> d<sup>-1</sup> in 2007 and -0.64 g CH<sub>4</sub>-C ha<sup>-1</sup> d<sup>-1</sup> in 2008, except at times of manure amendments. Emissions after manure applications were large (~58 fold higher than the average uptake of -0.51 g CH<sub>4</sub>-C ha<sup>-1</sup> d<sup>-1</sup> for the fallow (F), unfertilized (UF), fertilized (NPK) and digested fiber (DF) treatments) and occurred for both the dairy liquid manure and for digester effluent. Methane emissions observed after application may be caused by the release of dissolved CH<sub>4</sub>-C produced prior to application during storage (DLM) or dissolved in the effluent (DE) from the AD digester and not from the soil. These emissions were very short-lived; two days after applications methane emissions rates among all treatments were not significantly different. While digester effluent did not have any larger methane emissions than dairy liquid manure (indicating that it likely is no worse than the baseline land application of manure from liquid lagoons that occurs on dairy farms), these methane emissions are not ideal from a climate perspective. To minimize methane emissions, a recovery system for CH<sub>4</sub> is needed for the DE (and potentially also the DLM) before application to soil systems.

### *Comparison with CropSyst Modeling*

A CropSyst simulation was used as a means to corroborate the above field trials regarding GHG emissions from the application of manure treatments (DLM or DE) to fields after an assumed 6-month winter lagoon storage of the manure. In order to run the simulation, the following steps were undertaken:

- First, parameters for flush manure, similar to that utilized in the above field trials plus a 6-month lagoon storage period were determined using data from Frear et al (2009). Those parameters are given in Table 9.5

Table 9.5: Flush manure parameters for CropSyst simulation—assumed 6-month storage

	Units	DLM	DE
Total Organic Matter	kg/1000 gallons	56.08	38.19
Total Nitrogen	kg/1000 gallons	2.53	2.29
Total Organic Nitrogen	kg/1000 gallons	1.08	0.64
Total Organic Carbon	kg/1000 gallons	27.14	18.85
Total Ammonia Nitrogen	kg/1000 gallons	1.46	1.65
C/N Ratio	----	25.16	29.65

- Parameters were then incorporated into CropSyst for the following crop management protocol:
  - Corn and triticale were raised for silage during a two year rotation.
  - Manure N applications were pumped from a lagoon after 6-months of winter storage.
  - Triticale was harvested in mid April and followed by an application of 168 kg N/ha.
  - The field was roto-tilled a day or two prior to seeding silage corn in mid May.
  - Another 168 kg N/ha were applied in mid June.
  - Silage corn was harvested in early to mid September. 224 kg N/ha was applied in mid September after the corn was harvested.

A tandem disk followed by a cultipacker was used prior to seeding triticale in early October.

Figure 9.9 shows the amount of carbon input to the fields under the simulation, with a comparison given to inorganic fertilizer applied in a near equivalent amount of N determined to produce a similar yield as that of the manure treatments. As can be seen, the manure treatments add a considerable amount of carbon to the soil, primarily as a result of the suspended solids and fibrous material still remaining in the lagoon manure. No notable difference in carbon input is seen between the two manure treatments even though Table 9.5 does show a distinct difference in organic matter content between the two. This is because the simulation assumed a constant nitrogen application and the reduced levels of

nitrogen in the stored DE meant more DE needed to be applied, compensating for the reduced carbon.

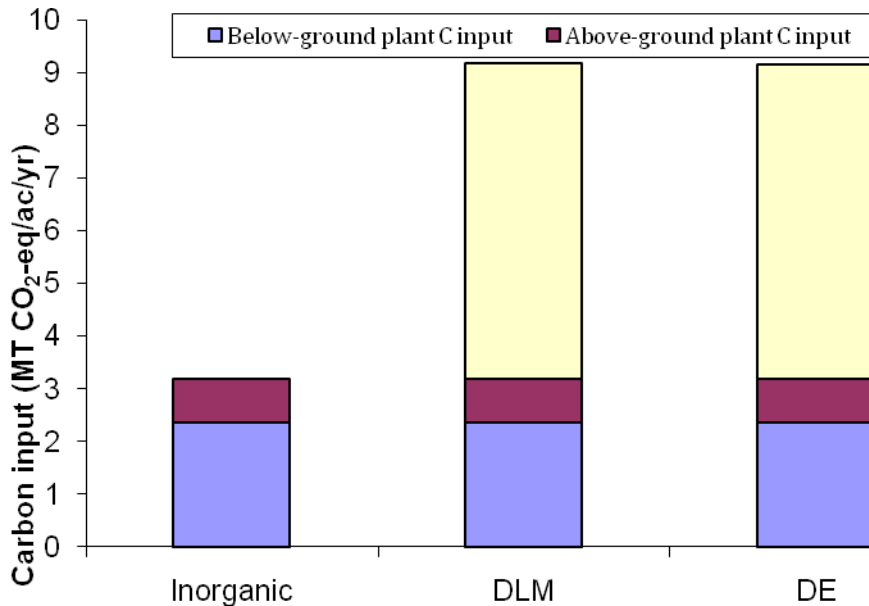


Figure 9.9: Carbon input to field under various treatments, assumed constant N-loading

The input of carbon by the manure treatments has a profound effect on the CropSyst simulation of soil carbon sequestration, with the manure treatments leading to significantly higher carbon sequestration within the soil as compared to an inorganic fertilizer control (Figure 9.10). The expected rate of carbon sequestration differs with a 12 and 30 year time frame, due to expectations that sequestration slows as a higher SOC level is achieved.

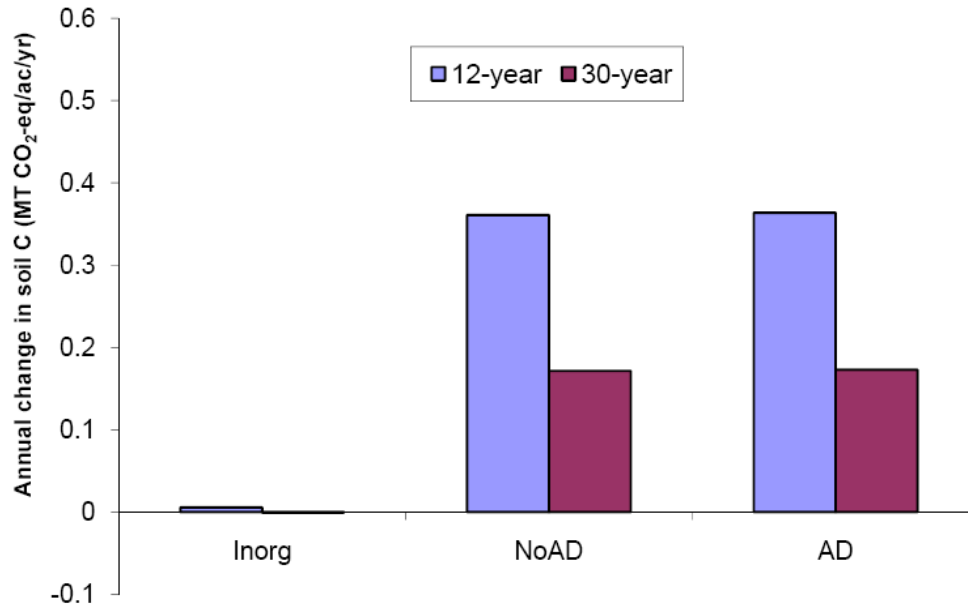


Figure 9.10: Annual soil C sequestration (0-15 cm profile) under two lengths of simulation

Two very different outcomes result when N<sub>2</sub>O emissions from the simulated field applications are considered (Figure 9.11). First, N<sub>2</sub>O emissions for both manure treatments are quite similar showing no significant difference. This result is in line with data from the two-year field trial above from which no statistical difference could be found for N<sub>2</sub>O fluxes between DLM and DE treatments. However this is contradicted by a study which showed that a DE treatment resulted in notable reductions in N<sub>2</sub>O credited to the AD process reducing the mass of available organic carbon required during de-nitrification (van der Meer, 2008). One reason for this difference could be that under our simulation and field trials, sufficient soil carbon was available and did not slow de-nitrification.

Second is the large increase in N<sub>2</sub>O flux when manure treatments are compared to the inorganic fertilizer control. Possible reasons for this could include slightly lower N application rate in the inorganic treatment (N application rate was based on expected equivalencies in crop biomass production rather than precisely equal N rates), excessive moisture in the manure application which may have created anaerobic soil conditions, and, the possibility of a limiting amount of available organic carbon within the inorganic treatment. Additional research will be required to test these hypotheses.

Figure 9.12 details the combined effect of carbon sequestration and emissions of N<sub>2</sub>O and CH<sub>4</sub> from our simulated application of digested and raw manure.

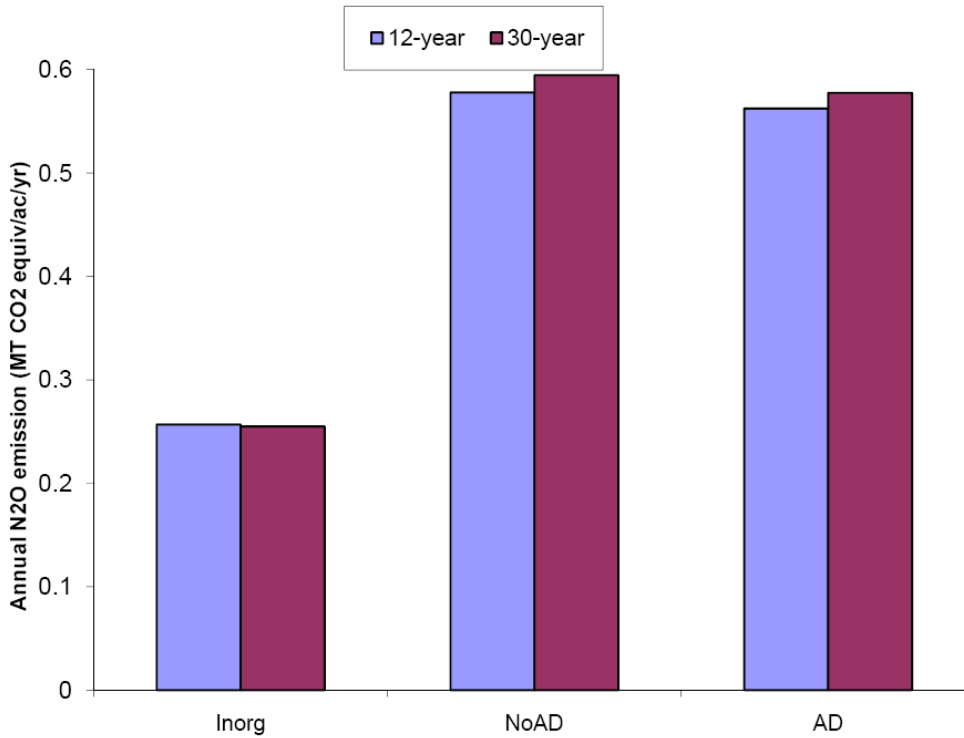


Figure 9.11: Annual N<sub>2</sub>O emission (CO<sub>2</sub> eq/ac/yr) across treatments and for two lengths of simulation

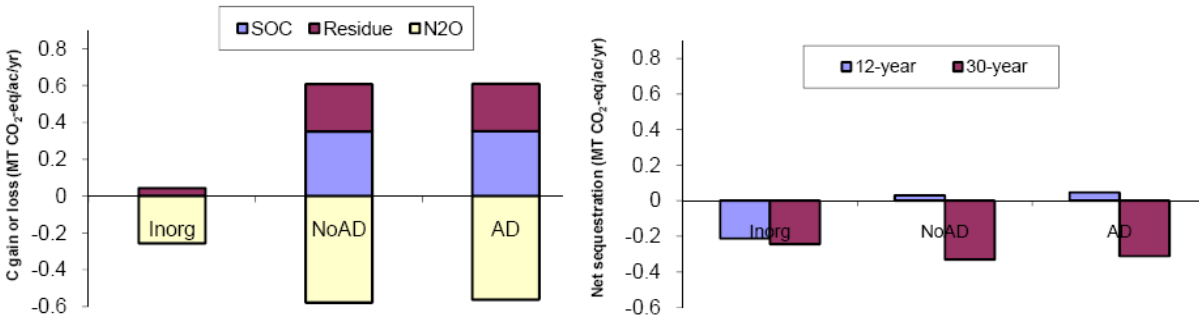


Figure 9.12: SOC, residue, and N<sub>2</sub>O unit GHG fluxes from a 12 year simulation (left) and net GHG fluxes for 12 and 30 year simulations (right) (expressed as CO<sub>2</sub>e/ac/yr).

*Conclusions from Comparing Experimental and Simulated Studies*

In summation, as compared to an inorganic fertilizer both digested and raw manure treatments result in:

- Significantly greater N<sub>2</sub>O fluxes, which is corroborated by experimental results that showed N<sub>2</sub>O emissions accounting for 90% of annual emissions.
- Addition of either digested or raw manure has considerable potential to increase SOC.
- The effect of CH<sub>4</sub> is captured in the simulation. However, it is clear from the field experimentation that current anaerobic digesters could be better engineered to degas and recover the super-saturated CH<sub>4</sub> trapped in the AD manure effluent prior to field application [or lagoon storage], thereby significantly reducing huge spike in CH<sub>4</sub> emissions within 48 hours after application.
- Lastly, the net GHG impact of the application of either AD or raw manure appears superior to inorganic fertilizer during the 12 year simulation. However, the opposite is the case for the 30 yr simulation as SOC levels approach equilibrium. As seen in some other cropping systems simulations in this report (see Stockle et al., Ch. 23), large emissions of N<sub>2</sub>O plus CH<sub>4</sub> are predicted to overwhelm potential C sequestration benefits and cause all treatments to be net GHG negative in the future, indicating the importance of continued efforts to improve nitrogen use efficiency and losses of CH<sub>4</sub> from manure.

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