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CH_4 and N_2O fluxes in the Colorado shortgrass steppe 2. Long-term impact of land use change

A. R. Mosier,[1] W. J. Parton,[2] D. W. Valentine,[2] D. S. Ojima,[2] D.S. Schimel,[3] and O. Heinemeyer[4]

Abstract. As part of a weekly, year-round program to measure the soil-atmosphere exchange of nitrous oxide (N_2O) and methane (CH_4) in a shortgrass steppe, we examined the impact of land use change on these fluxes from 1992 through 1995. We found that conversion of grassland to croplands typically decreased the soil consumption of atmospheric CH_4 and increased the emission of N_2O. Mean annual CH_4 consumption and N_2O efflux over 3 years in native grasslands were 35 μg C m^{-2} hr^{-1} and 1.9 μg N m^{-2} hr^{-1}, respectively. Immediately after tilling a native grassland site, CH_4 consumption decreased by about 35% and remained at these lower rates for the next 3 years. Although N_2O fluxes were about 8 times higher for 18 months following plowing, the relative rates declined to 25-50% higher than the native site after 3 years. Grasslands converted to a winter wheat-fallow production system about 70 years ago consumed about 25% less CH_4 than a newly plowed site, while N_2O emissions 2 years after plowing were similar to the wheat fields. During the fallow periods when soils were typically wetter and mineralized N accumulated, CH_4 uptake rates were lower and N_2O emissions were higher than the correspondingly active wheat fields. A wheat field that was reverted back to grassland in 1987 through the conservation reserve program (CRP) continued to exhibit annual CH_4 uptake and N_2O emission rates similar to the wheat fields. Winter N_2O emissions were, however, much higher in the CRP because of greater snow accumulation and winter denitrification events. Another wheat field that was returned to grassland in 1939 exhibited the same CH_4 and N_2O flux rates as comparable native pastures.

Introduction

Cultivation of grassland soils results in depletion of soil organic matter and reduced site fertility over time [*Russel*, 1929; *Tieszen et al.*, 1982; *Aguilar et al.*, 1988; *Elliot and Cole*, 1989]. Tillage increases both erosion and decomposition, leading to decreased soil organic matter and a decrease in the ability of soil to retain mineral nutrients. Cropped areas within the shortgrass steppe that have been abandoned and reverted to grasslands appear to require >50 years to recover their typical vegetation types and distribution [*Reichardt*, 1982; *Hyder et al.*, 1975; *Briske and Wilson*, 1980]. Since relatively few measurements of CH_4 and N_2O flux in grasslands had been made, there was no information concerning the initial or long-term effect of tilling the shortgrass steppe on trace gas fluxes or how long after tillage stopped before gas flux rates returned to the normal background rates.

[1]Agricultural Research Service, U.S. Department of Agriculture, Fort Collins, Colorado.

[2]Natural Resource Ecology Laboratory, Colorado State University, Fort Collins.

[3]National Center for Atmospheric Research, Boulder, Colorado.

[4]Federal Center for Agricultural Research, Braunschweig, Germany.

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The most common agricultural conversion of Colorado grasslands has been to a dryland wheat cropping system. In the early 1900s farmers learned that water limited annual wheat cropping and a wheat-fallow, moisture conservation, crop sequence evolved. In this system each area of land is planted to wheat on alternate years, and the intervening years the land is not cropped and is kept weed-free either by tillage or in recent years by herbicides.

In the spring of 1990 we initiated a long-term gas flux measurement program to determine the impact of cultivation and other land use and management issues on CH_4 and N_2O flux in and near the Central Plains Experiment Range (CPER) in the Colorado shortgrass steppe [*Mosier et al.*, 1991, 1996]. Additional sites were added in 1992 where the soil-atmosphere exchange of CH_4 and N_2O was measured weekly, year-round in pastures and fields that were either being cultivated or had reverted back to grassland from cultivation 0-54 years earlier. *Mosier et al.* [1996] described the effect of landscape and nitrogen addition on trace gas fluxes using a 4-year data set. We refer you to that paper for a discussion of relevant literature rather than repeating the information herein.

In the *Mosier et al.* [1996] paper, from multi-year measurement of N_2O and CH_4 flux, we showed that both landscape and N deposition clearly influence flux of these gases and that temperate grasslands represent an important part of their global atmospheric budgets. We observed that the wintertime (December-February) fluxes constitute 20-40% of annual N_2O emissions and 15-30% of annual CH_4 consumption of atmospheric CH_4. Ni-

trous oxide flux maxima were frequently observed in January and February. Areas of grassland that had similar land use history and soil texture showed similar seasonal and annual N_2O emission and CH_4 uptake rates and patterns. Coarser-textured soils typically emitted less N_2O but consumed more CH_4 than did finer-textured, higher total C and N content, soils. We also found that N addition to these semiarid soils had a long-term impact on N_2O emissions and CH_4 oxidation in coarse-textured soils. In some sites, urea-N additions 13 years earlier continued to decrease CH_4 consumption by 30-40%.

Mosier et al. [1991] described a set of three adjacent wheat-fallow-grassland sites where weekly gas flux measurements were begun in May 1990. During the following 6 months, N_2O flux averaged 1.9, 2.5, and 2.2 $\mu g\ N\ m^{-2}\ hr^{-1}$, and CH_4 uptake rates averaged 7.8, 11.9, and 15.4 $\mu g\ C\ m^{-2}\ hr^{-1}$ in wheat, fallow, and grassland sites, respectively. These grassland CH_4 uptake rates were lower than the typical average annual uptake rates (30-40 $\mu g\ C\ m^{-2}\ hr^{-1}$) at native sites where soil texture and plant composition were similar [*Mosier et al.*, 1996]. During the winter of 1991-1992 we learned that this set of sites lay in an area where wind chronically deposited soil. From January-March 1992, wind deposited ~30 cm of soil across our wheat-fallow sites and 1-2 cm on the grass area. We abandoned this site and moved to another wheat-fallow site adjacent to a conservation reserve program site that had been taken out of cultivation and reverted to grassland in 1987 from wheat-fallow cropping.

As noted in the introduction section of the *Mosier et al.* [1996] paper, it is now clearly demonstrated that agricultural practices in temperate and tropical systems influence both N_2O and CH_4 exchange and thus the atmospheric composition of these gases. It has not been shown whether semiarid grassland soils once cultivated and then returned to grasslands regain their capacity to consume CH_4 at their previous rates or return to background N_2O emission levels. Therefore objectives of the studies reported here were (1) to determine the effect of plowing a native prairie on N_2O and CH_4 flux compared to adjacent native grasslands, (2) to place some bounds on the time required for soils to regain their inherent CH_4 oxidation and N_2O emission levels once cultivated grasslands were returned to grasslands, and (3) to determine if wheat-fallow cropping patterns affected trace gas fluxes. To accomplish these objectives weekly gas fluxes from native grasslands were compared to those from (1) pastures that reverted from wheat-fallow cropping in 1939, (2) another wheat-fallow site that was placed in the conservation reserve program (CRP) and planted to grass in 1987, and (3) to a pasture site that was plowed and maintained plant-free over a 2-year period.

Materials and Methods

Research Sites

We established three sets of sites in the Colorado shortgrass steppe, two within the U. S. Department of Agriculture-Agricultural Research Service Central Plains Experimental Range (CPER) and a third on privately owned land. The CPER is located about 60 km northeast of Fort Collins, Colorado (40°8'23"N, 104°45'15"W). At all three sites, annual precipitation averages about 350 mm yr^{-1} with about 80% occurring between May and September. Typically, vegetation is dominated by blue grama (*Bouteloua gracilis* Lag.). Soils at the three sites were within the same soil series and had similar textures (Table 1). Because of the similarity in texture of the soils, textural differences should not have contributed to differences in gas fluxes.

Table 1. Selected Field Site Soil Characteristics

Site	Texture, % Sand	Texture, % Clay	Bulk Density, g cm^{-3}	pH	Total N, %	Total C, %	Microbial Biomass, $\mu g\ g^{-1}$
			W-F-CRP				
WW	66	15	1.2	7.3	0.076	0.539	598
WE	67	13	1.3	6.5	0.081	0.651	270
CRP	64	16	1.4	7.3	0.091	0.742	220
			Old Plow				
FN	70	12	1.4	6.5	0.120	1.113	ND*
FT	70	12	1.4	6.5	0.098	0.856	ND
			Native-Plow				
PN	74	13	1.4	6.5	0.098	0.953	254
PP	74	13	1.3	6.0	0.108	0.889	ND

Characteristics are at 0-15 cm depth.

* ND, Not determined.

Wheat-fallow-CRP sites (WE, WW, and CRP). The first set of sites is located about 20 km southeast of the CPER on land owned by Richard Barnes. The sites were established within a wheat-fallow cropping system and an adjacent conservation reserve program (CRP) area. According to Barnes the lands were first plowed sometime after 1914, and the CRP site was first plowed after 1920. The land was cropped with wheat using the fallow system, one wheat crop every other year while being maintained plant-free during the fallow year. Fertilizers were not used on the fields until the past 15 years when chicken manure and anhydrous ammonia were used occasionally (exact records were not maintained). Starting in 1990 the fields were fertilized every other year (fallow year) with City of Fort Collins sewage sludge at the rate of about 40 kg N ha^{-1}. The sludge was broadcast to the soil surface, and then the field was harrowed, leaving much of the residue on the surface. A variety of pesticides and herbicides were used in the past for aphid and weed control.

The CRP lands were taken out of production and planted with crested wheat grass (*Agropyron* Gaertn.) in 1987 and had not been cropped or fertilized since that time. The soil on sites designated WE (wheat field east), WW (wheat field west), and CRP (conservation reserve program) are an Ascalon sandy loam (Fine-loamy, mixed mesic Ustollic Haplargids).

1992 plow-native grassland sites (PP and PN). The second set of sites was established within a native pasture (PN) that is grazed annually, 15-20 cattle/130 ha from May through October. The terrain of this pasture is essentially flat, and the soil is an Ascalon sandy loam (Fine-loamy, mixed mesic Ustollic Haplargids). On July 28, 1992, a 40-m-long by 10-m-wide area located within about 20 m of the PN gas flux measurement location was plowed, and we refer to this site as PP. The grassland area was plowed to a depth of 15-20 cm using a field-scale plow. The standing vegetation was turned under, and the plowed area was smoothed by rototilling to a depth of about 10 cm to simulate typical farmer practice. Gas flux measurements were begun the following day and continued weekly until September 1995.

1939 plow-native grassland sites (FT and FN). The third site, to which we refer as site FN, is similar in soil texture, aspect, and land use history to the PN site and was established in March 1992. Adjacent to this site on the opposite side of an old fence line the pasture had been cultivated through the early part of this century and was last cultivated in 1939 and has since reverted back to native vegetation, referred to here as site FT.

Gas Flux Measurements

We established six gas flux measurement locations within each of the above sites. Chamber anchors to establish each gas sampling location were installed in April 1990 in the PN site, on July 29, 1992, in the PP site, in March 1992 in the FN and FT sites, and in September 1992 in the wheat-fallow (W-F) and CRP sites. The permanently placed anchors were made from 20.3-cm inside diameter polyvinyl chloride (PVC) pipe which was driven 8 cm into the soil. Anchors within wheat fields were removed before each tillage operation and reinstalled later in new, nearby locations. We measured soil-atmosphere exchange of CH_4 and N_2O within each location by fitting a 7.5-cm-high closed, vented chamber [*Hutchinson and Mosier*, 1981] onto the anchor. Gas samples from inside the chambers were removed with 60-mL polypropylene syringes fitted with nylon stopcocks at 0, 15, and 30 min after the chambers were installed. We usually analyzed the samples within 6 hours by gas chromatography. Fluxes were typically measured mid morning of each sampling day, generally weekly at each site. Details of gas sampling and analyses are noted by *Mosier et al.* [1991, 1993a, b, 1996].

Ancillary Measurements

Soil samples (0-15 cm) were collected from each sampling site at the time of gas flux measurement. The soils were analyzed gravimetrically for soil water content and extracted, field moist, with 2 M KCl, and the extracts analyzed colorimetrically for ammonium and nitrate + nitrite content using a flow injection autoanalyzer. We analyzed soils from each site for total C and N content with a combustion C/N analyzer (Table 1). Soil temperature at 5 cm depth was measured at each sampling time at each site using a handheld digital thermometer that was calibrated to within 0.1°C over the temperature range observed. Air temperature before and after each sampling period was measured with the same device. The mean of initial and final air temperature was used in gas flux calculations. Weather variables were measured continuously at a meteorological site located about 1 km from the PN and PP sites. Microbial biomass, using the substrate inducible respiration method [*Anderson and Domsch*, 1978; *Heinemeyer et al.*, 1989], was measured on samples collected in June 1994. The statistical test used to compare CH_4 uptake rates or N_2O fluxes between sites was the Statistical Analysis System (SAS) NPAR1WAY procedure which used Wilcoxon Rank Sum scores to compute the test statistic. The NPAR1WAY is a nonparametric procedure used for testing that the distribution of a variable has the same location parameter across different groups [*SAS*, 1991]. Each statistical test compared gas fluxes between sites over specific time periods which are indicated within text or figures discussed in the various sections of this manuscript.

Results and Discussion

We initiated the weekly, year-round gas flux monitoring program in the several locations described above in 1991 and 1992. The soils at each site, in their native state, are similar in texture, pH, bulk density, and total C and N content (Table 1). Sites FN, FT, PN, and PP are relatively flat, while WE has a small (<5°) northwest slope, and WW and CRP sites have a small (<5°) northeast slope.

Wheat-fallow-CRP-native pasture. Gas fluxes were monitored in two areas of a wheat-fallow system, wheat field (Figure 1) and in an adjacent CRP site (Figure 2) from September 1992 through September 1995. We use the native pasture (PN) site as an undisturbed control for comparison over the same time period. Gas fluxes from these sites were made during the same time period. Site WE was planted to winter wheat in September 1992

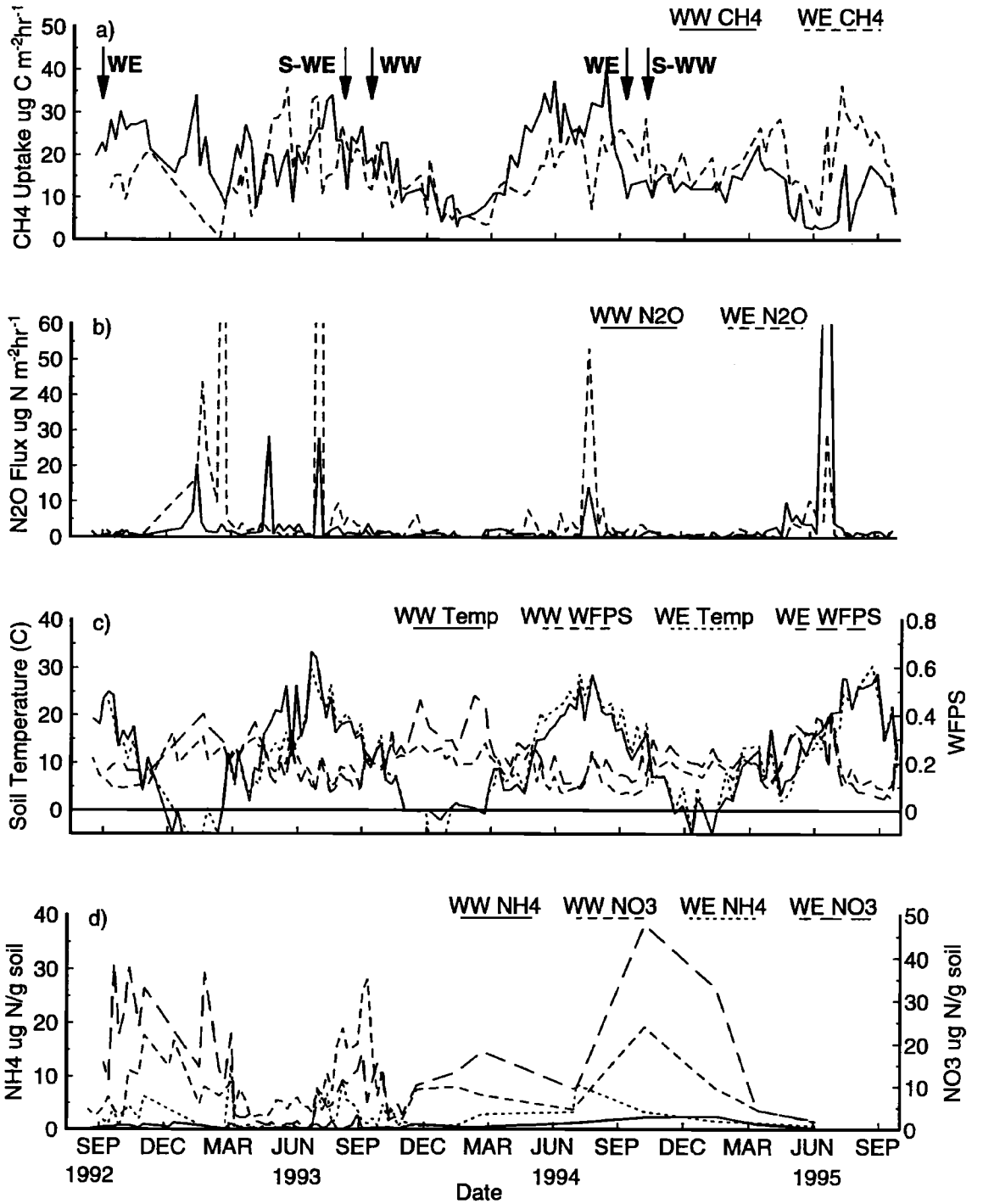

Figure 1. (a) CH_4 uptake, (b) N_2O emission, (c) soil temperature and water content, and (d) soil ammonium and nitrate contents in sites wheat field east (WE), and wheat field west (WW) during September 1992 through September 1995. Arrows with site indicator only indicate time and site of planting, and arrows with S- before the site indicator indicate time and site of sewage sludge application. Gas flux data shown represent the mean of six measurements at each time for each site.

and again in September 1994 and was fallow from September 1993 to September 1994. Site WW was fallow during these years (September 1992 to September 1993 and September 1994 to September 1995) and planted to wheat in September 1993 and 1995. Sewage sludge was applied to WE in July 1993 and to WW in July 1992 and September 1994.

Wheat-fallow. Methane uptake was typically lower during the fallow periods (Figure 1a) and remained lower after planting

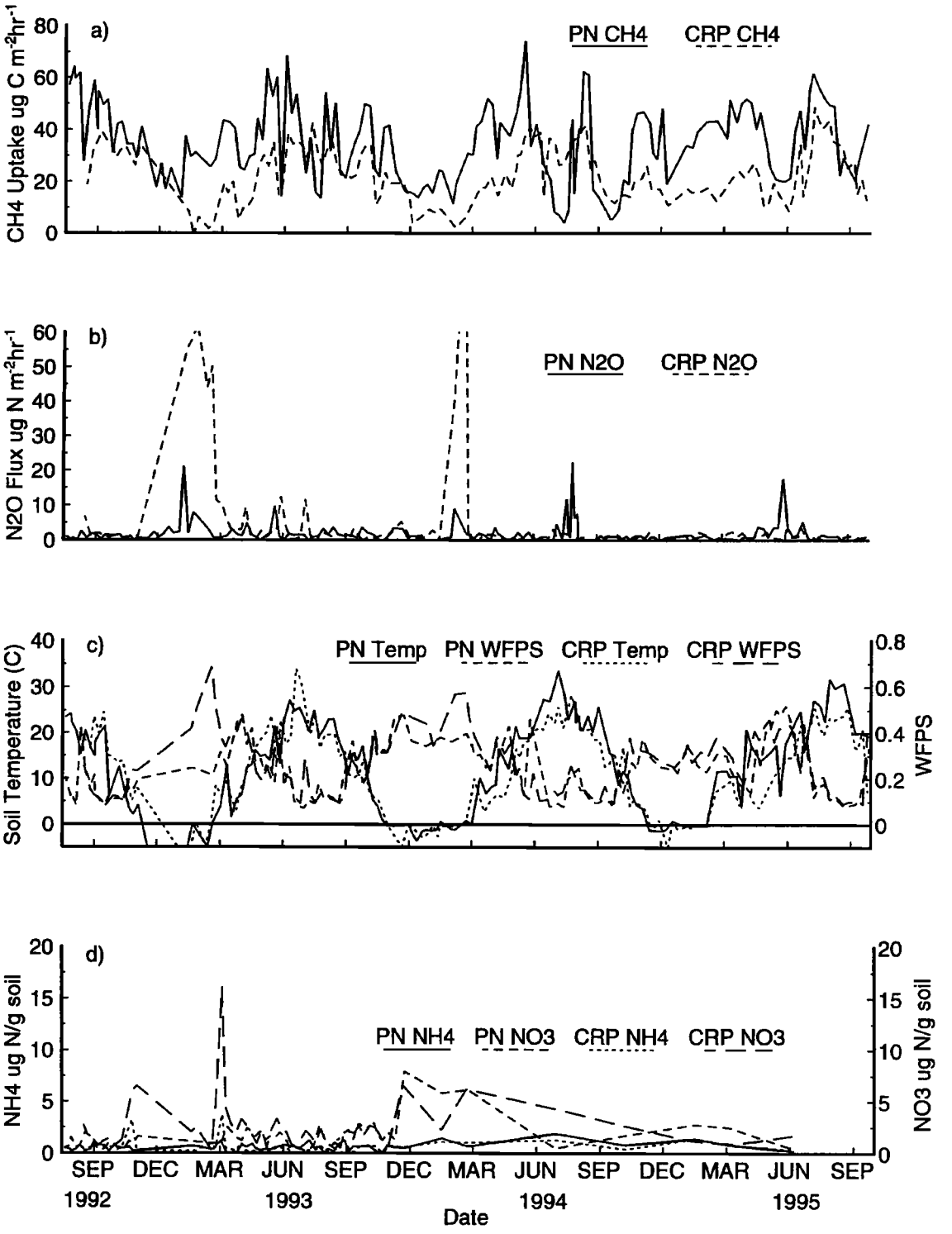

Figure 2. (a) CH_4 uptake, (b) N_2O emission, (c) soil temperature and water content, and (d) soil ammonium and nitrate contents in the conservation reserve program (CRP) and native pasture (PN) sites during September 1992 through August 1995. Gas flux data represent the mean of six measurements at each time for each site.

until the wheat crop began utilizing stored soil water. The interpretation of the 1992/1993 year CH_4 flux data is confounded by the storage of more snow on the WE site during the winter, therefore adding additional water to the field that was planted to wheat in September 1992. The next 2 years there was relatively little winter snow storage on either WE or WW, and as a result, the patterns of soil moisture between fallow and cropped sections of the field are more obvious.

Nitrous oxide emissions were generally inverse to CH_4 uptake as we observed in grassland sites [*Mosier et al.*, 1996] and thus were higher in fallow than in cropped years. The exception to this general trend is the 1992/1993 winter when snow accumulation on site WE was larger than on WW and winter time denitrification [*Parton et al.*, 1996] and N_2O emissions were very large. A second large N_2O emission event occurred in site WE coincident with surface sewage sludge application and rain.

To take a closer look at the impact of fallowing on trace gas fluxes, we examined the data collected from September 1993 until September 1995 in sites WE and WW (Figure 1). Warm-season N_2O flux was greater during the fallow season both years. Mean annual N_2O fluxes were 2.9 and 4.0 in fallow compared to 1.1 and 1.9 μg N_2O-N m^{-2} hr^{-1} in wheat-cropped areas. Methane uptake showed the expected inverse relationship to N_2O flux [*Mosier et al.*, 1996] where uptake rates were highest during the cropping year, 19.9 and 18.3 compared to fallow years 13.9 and 12.1 μg CH_4-C m^{-2} hr^{-1}. We assume that the generally higher soil water contents and higher mineral N content during fallow periods accounted for the lower rates of CH_4 uptake and higher N_2O fluxes during the fallow years [*Mosier et al.*, 1996]. In early June, microbial biomass was higher in the wheat cropped field than in the fallow soil (Table 1).

CRP and PN comparison. Methane uptake rates were generally lower in the CRP than in undisturbed grasslands (PN) (Figure 2). Wintertime soil moisture contents were frequently higher in the CRP site because the taller crested wheat grass collected more winter snow than the blue grama grassland. During the 3-year period, CH_4 uptake averaged 18.9 compared to 35.2 μg CH_4-C m^{-2} hr^{-1} within the PN site. Nitrous oxide emissions were similar during the warm seasons at the CRP and PN sites (Figure 2). During the winter of 1992/1993 and 1993/1994

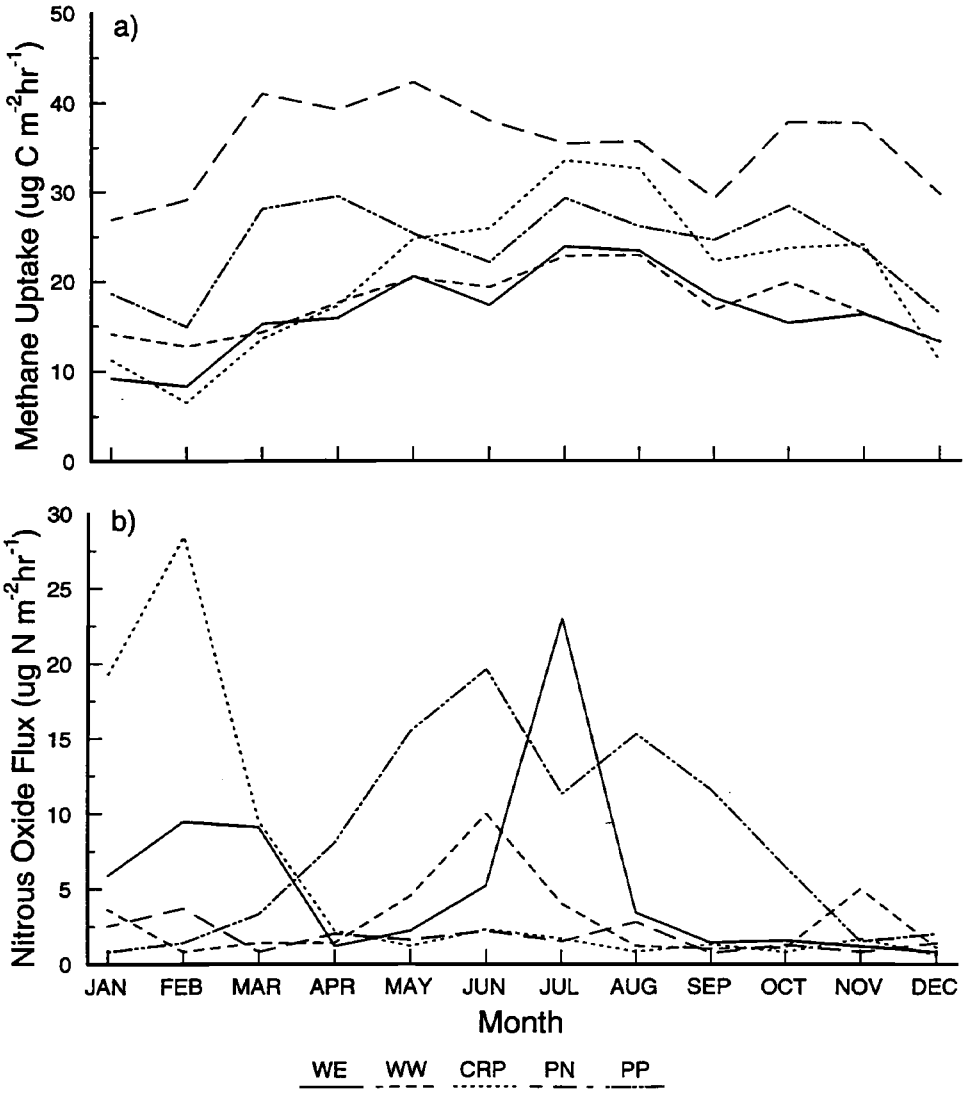

Figure 3. (a) Mean monthly CH_4 uptake rate and (b) mean monthly N_2O emission rate for five sites over the 3-year period September 1992 through August 1995. The mean gas flux is the mean of six measurements for two to five separate measurements each month at each site.

snow accumulation in the CRP led to winter denitrification events [*Parton et al.*, 1996] and large N_2O emissions. The winter of 1994/1995 was very warm with little snow.

Four-site comparison CH_4. Methane uptake in the WE, WW, CRP, and PN sites follow the same seasonal and annual patterns (Figures 3a, 4a, and 5a). Methane consumption was typically lower during the autumn and winter when soil temperatures were lower and soil water content was higher than during the spring and summer. The effect of moisture accumulation during the winter is particularly evident in the CRP site (Figure 5a) where spring-summer CH_4 uptake rates averaged 26 compared to 15 μg CH_4-C m^{-2} hr^{-1} during the autumn-winter period. In September 1992, site WE was tilled and planted to wheat, and the following 7-months CH_4 uptake was lower than in the fallow (WW) site. The two sites show little differences in CH_4 uptake the remainder of the sampling period until early 1995 while the WE site was in fallow again. Overall, the two wheat-fallow sites and CRP exhibited similar CH_4 consumption rates, a 3-year average of 16.4, 17.5, and 18.9 μg C m^{-2} hr^{-1} at WE, WW, and CRP, respectively. The mean monthly CH_4 uptake rates for sites

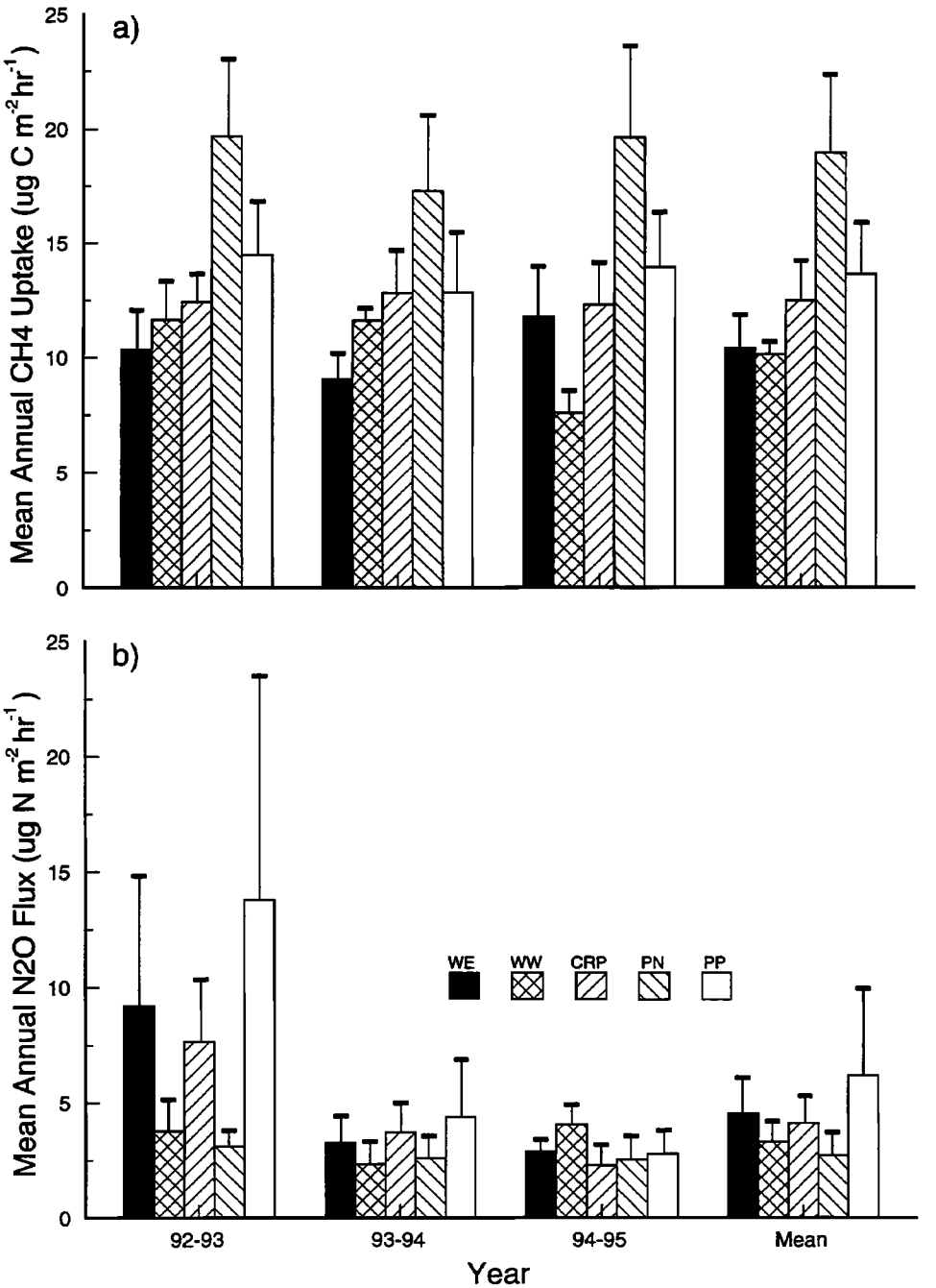

Figure 4. (a) Mean annual CH_4 uptake rate and (b) mean annual N_2O emission rate for five sites for September 1992 August 1992. Error bars represent the standard deviation of the mean of six measurement locations at each site.

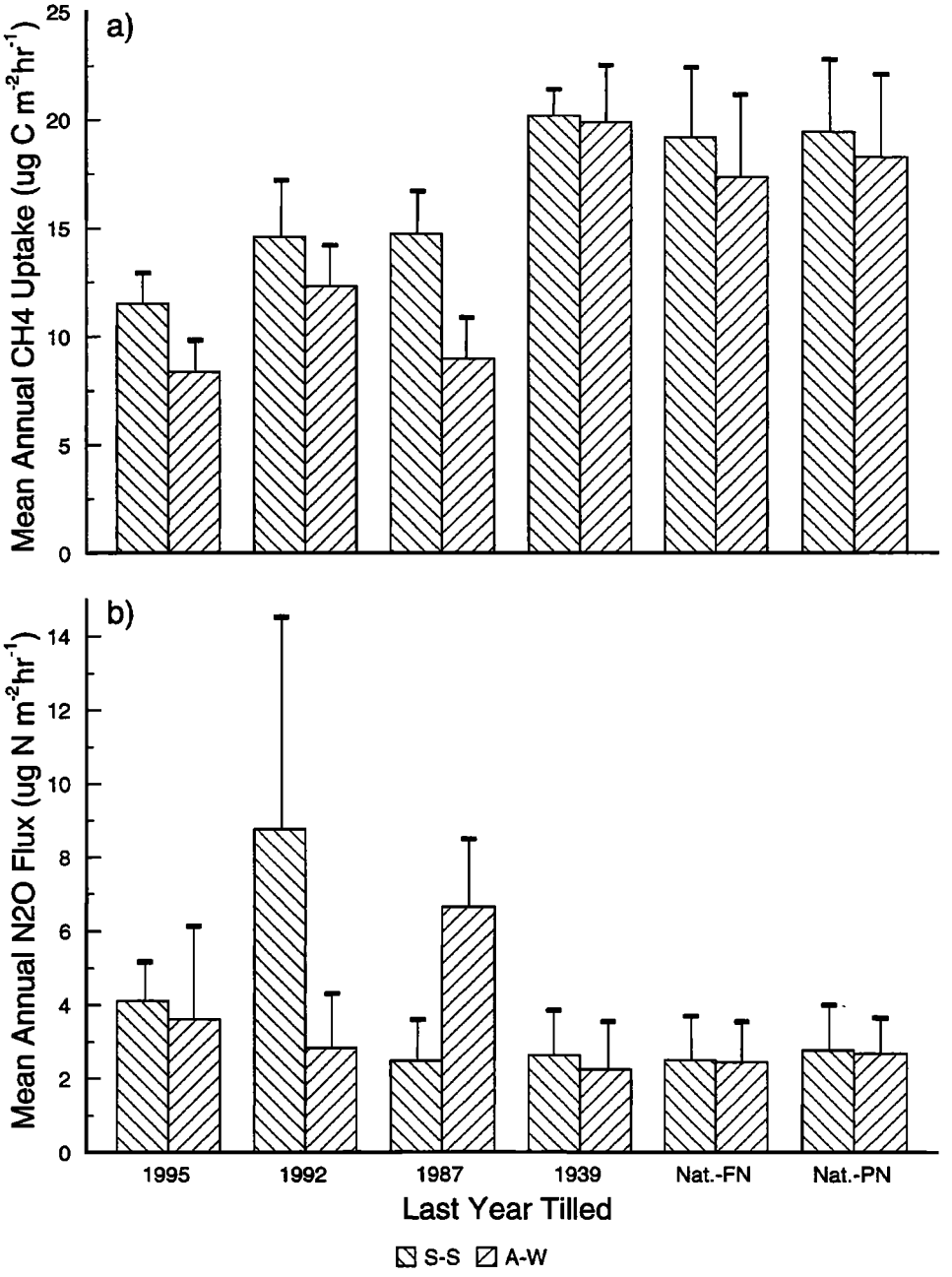

Figure 5. (a) Mean seasonal CH_4 uptake and (b) N_2O emission from sites last tilled in 1995 (mean of WE and WW), 1992 (PP), 1987 (CRP), and two native grassland sites (FN and PN). S-S is the mean of the spring and summer months (April-September), and A-W is the mean of the autumn and winter months (October-March). The 1995, 1992, 1987, and PN (PN) site data are 3-year means, while sites 1939 (FT) and native FN (FN) data are monthly means from 15 months of weekly flux data. Error bars are standard deviations from six flux locations over the time periods.

WE and WW were the same for each month (Figure 3a) but were significantly higher ($P<0.1$) in the CRP during June, July, and August. Higher uptake rates in the CRP during the summer could be attributed to lower soil water content and lower N turnover rates, since the wheat fields were biannually fertilized with sewage sludge.

Over the same 3-year time span, CH_4 uptake rates within the native grassland (PN) were significantly higher (3-year average of 35.2 $\mu g\ C\ m^{-2}\ hr^{-1}$) ($P<0.05$) than in the WE, WW, or CRP sites (Figure 4). Uptake rates were higher in the PN site each month (Figure 3a) in the PN site over the 3-years than in WE and WW (Figure 3a). Uptake rates in PN were higher than CRP each month except July and August. Although not significantly higher than the wheat fields, CH_4 uptake rates in the CRP tended higher. The 5 to 8-year time span since the last cultivation was apparently insufficient for the microbial and physical processes responsi-

ble for CH_4 oxidation to return to the native rate. During these 3 years, CH_4 uptake averaged 16.4, 17.5, 18.9, and 35.2 μg CH_4-C m^{-2} hr^{-1} in WE, WE, CRP, and PN sites, respectively. These data suggest that converting the grassland to wheat-fallow cultivation significantly decreased CH_4 uptake and that reversion to grass 7 years earlier tended to increase the CH_4 uptake rate, but not significantly.

N_2O. Nitrous oxide fluxes within the wheat, CRP, and native grassland sites did not follow the same seasonal emission patterns (Figures 1b and 2b). Although all sites showed wintertime flux maxima in 1993, only the CRP site exhibited peak February flux in 1994. The winter of 1994-1995 was very warm and dry, thus eliminating the frozen soil N_2O emission phenomena frequently observed [*Mosier et al.*, 1996].

Nitrous oxide emissions averaged 4.6, 2.6, 5.7, and 1.8 μg N m^{-2} hr^{-1} from WE, WW, CRP, and NP sites, respectively, during the 3-year measurement period (Figure 4b). Emissions were significantly lower in the PN site than from the WE and CRP sites. Reversion of the wheat-fallow fields to CRP grassland did not lead to an observable decrease in N_2O emissions after 8 years, but seasonal differences were apparent (Figure 5b). In the CRP site the autumn-winter N_2O emissions averaged 11.2 compared to the spring-summer period emissions of 1.5 μg N_2O-N m^{-2} hr^{-1}. We expect that these much larger N_2O emissions and lower CH_4 uptake rates during the winter were due to greater snow accumulation on the CRP which had not been grazed since grass establishment in 1987. There were also periods of large wintertime N_2O in the WE site but not in the WW site. The December-February emissions from the WE and CRP comprised about 43 and 84% of the annual fluxes, respectively, in 1992-1995 but were only 19% in the WW site (Figure 3b). Surprisingly, increased N_2O emissions could not be linked with the timing of sewage sludge applications in the WW or WE plots. Sludge was applied to WW in July 1992 and September 1994 and to WE in July 1993. No accumulation of mineral N was observed following sludge application, possibly because the sludge was surface applied and incorporated into the soil by harrowing. This practice left much of the organic material on the soil surface, thus allowing ammonia volatilization to continue as N was mineralized.

1992 Plowed-Native Grassland Sites

To observe the changes in trace gas flux following plowing, we plowed a small area and maintained the area free from plants for the following 2 years (Site PP). The native grassland companion site is designated PN (Figure 6).

CH_4. Methane uptake rates declined to about 65% of the PN site immediately after plowing and remained consistently lower throughout the following 3 years (Figure 6a). The PP site typically remained wetter through the year because the plot contained little vegetation (Figure 7). The combination of wetter soils and increased N cycling following plowing likely combined to limit CH_4 consumption [*Mosier et al.*, 1996, and references therein].

Methane uptake rates were typically somewhat lower during the winter, about 5 and 14% lower in autumn and winter, and highest in the spring-time in both PN and PP sites (Figures 5a and 6a). During winter, soils are generally wetter as well as colder, so lower fluxes during cold seasons are likely a combination of a small temperature effect and water effect on gas diffusion [*Mosier et al.*, 1996]. *Potter et al.* [1996a] recently published a model to be used for estimating soil consumption of atmospheric CH_4. In their model they assume that cold winter temperatures dramatically inhibit CH_4 uptake in soil in the 30°-60°N latitude land areas of the world. Our data and the data presented by *Mosier et al.* [1996] clearly show that this assumption leads to a large underestimate of annual CH_4 consumption in the shortgrass steppe. Subalpine soils covered with snow much of the year have been shown to consume appreciable amounts of atmospheric CH_4 during the time that the soils are snow covered [*Sommerfeld et al.*, 1993]. Consequently, the phenomena of cold temperature soil CH_4 consumption that are comparable to warm soil systems are more widespread than just the shortgrass steppe [*Flessa et al.*, 1995].

Over the 3-year measurement period, CH_4 uptake averaged 22.2 and 35.2 μg C m^{-2} hr^{-1} in PP and PN sites, respectively (Figure 4a). The uptake rates in the PP site were generally higher than those in the wheat field sites (WE and WW) (Figures 3a and 4a). Apparently, continued tillage and agronomic use tended to maintain CH_4 oxidation at reduced rates.

N_2O. Nitrous oxide emissions increased immediately following plowing and continued to be significantly higher the next 3 years (Figure 6b). Although N_2O emissions remained high during the second year after plowing, 2.5 and 16.4 μg N m^{-2} hr^{-1} in PN and PP sites, respectively, N_2O emissions declined markedly in the following years (Figure 4b).

Unlike the PN, CRP, and WE sites, no large winter N_2O emission events were observed (Figures 1b and 2b) at the PP site. Since the major N and C source to stimulate nitrification-denitrification were derived from decomposing plant material following plowing, the N_2O release patterns tend to follow those of plant residue decomposition. This concept is supported by the trend of decreasing N_2O emissions during the second and third years following plowing (Figure 4b). This time course also shows that the large increase in N_2O (1992 and 1993) due to a single tillage event is relatively short-lived. Nitrous oxide fluxes averaged higher, but not significantly ($P<0.05$) in the PP site in 1995 compared to the native grassland (Figure 4b).

1939 Plow-Native Grassland Sites

Gas flux measurements at this site compare the effect of reversion of a wheat cropped field back to native vegetation 50-55 years after the pasture was last cultivated (Figure 7). Over the 15-month measurement period (April 1992 to July 1993), CH_4 uptake (based on monthly means) averaged 36.0 and 36.3 μg C m^{-2} hr^{-1}, and N_2O emissions averaged 1.9 and 1.3 μg N m^{-2} hr^{-1} at FN and FT sites, respectively. Neither CH_4 nor N_2O fluxes differed significantly between sites ($P<0.05$). Gas fluxes in both the native and FT sites followed similar weekly and seasonal trends (Figures 5 and 7). There was no discernible effect of tillage on CH_4 and N_2O which are indicators of N turnover and nutrient

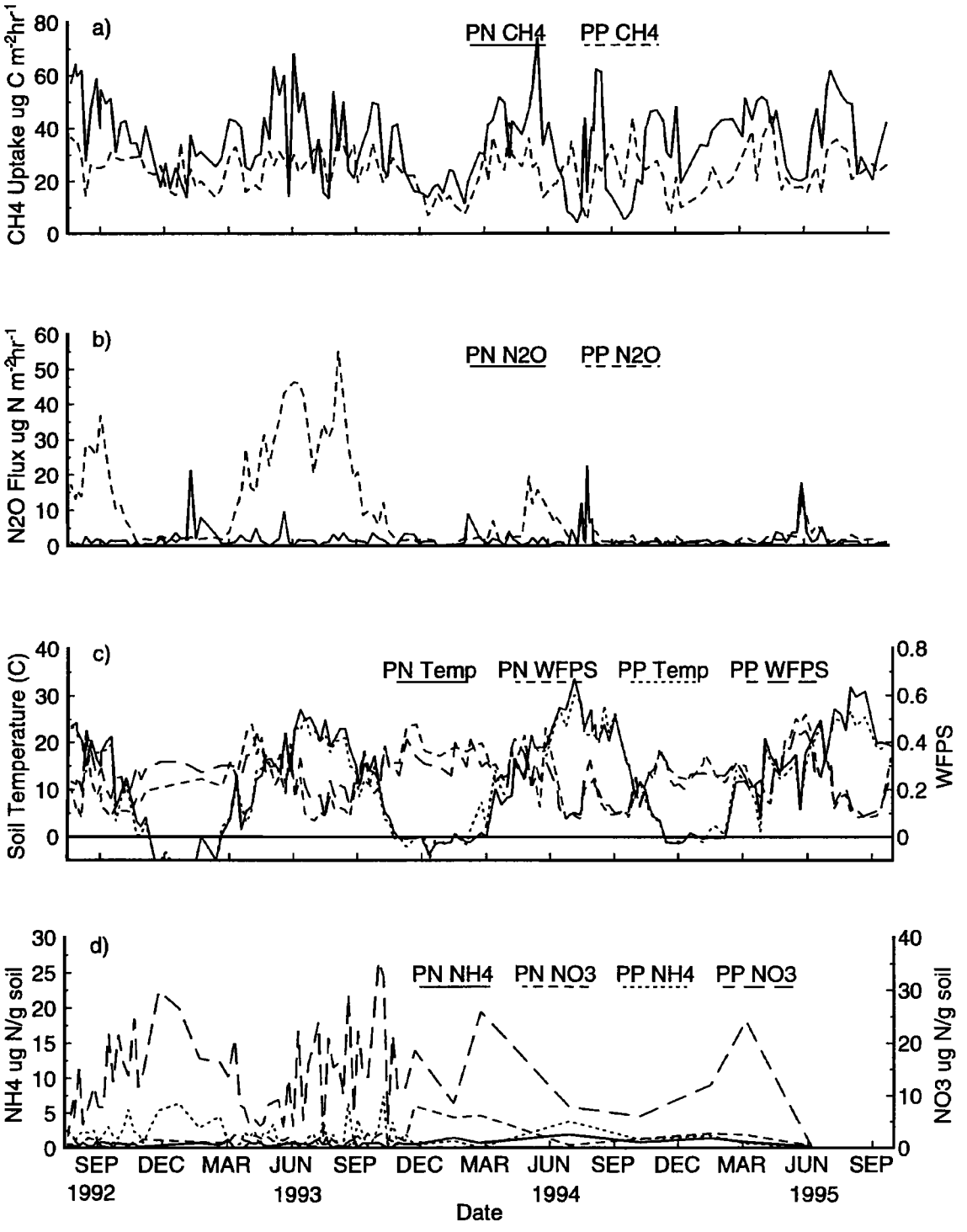

Figure 6. (a) CH_4 uptake, (b) N_2O emission, (c) soil temperature and water content, and (d) soil ammonium and nitrate contents in sites native pasture (PN) and plowed pasture (PP) from August 1992 through September 1995. The gas flux data shown are the mean from six measurement locations.

availability 50 years after site FT was last tilled. Both N_2O and CH_4 fluxes were the same in FN and FT sites compared to the PN site where CH_4 and N_2O fluxes averaged 41.5 μg C m^{-2} hr^{-1} and 2.1 μg N m^{-2} hr^{-1} over the 15-month sampling period [*Mosier et al.*, 1996].

Conclusions

Conversion of grasslands to croplands promotes changes in CH_4 and N_2O flux. Immediately after tillage, CH_4 consumption decreased by about 35% and remained at the decreased rate

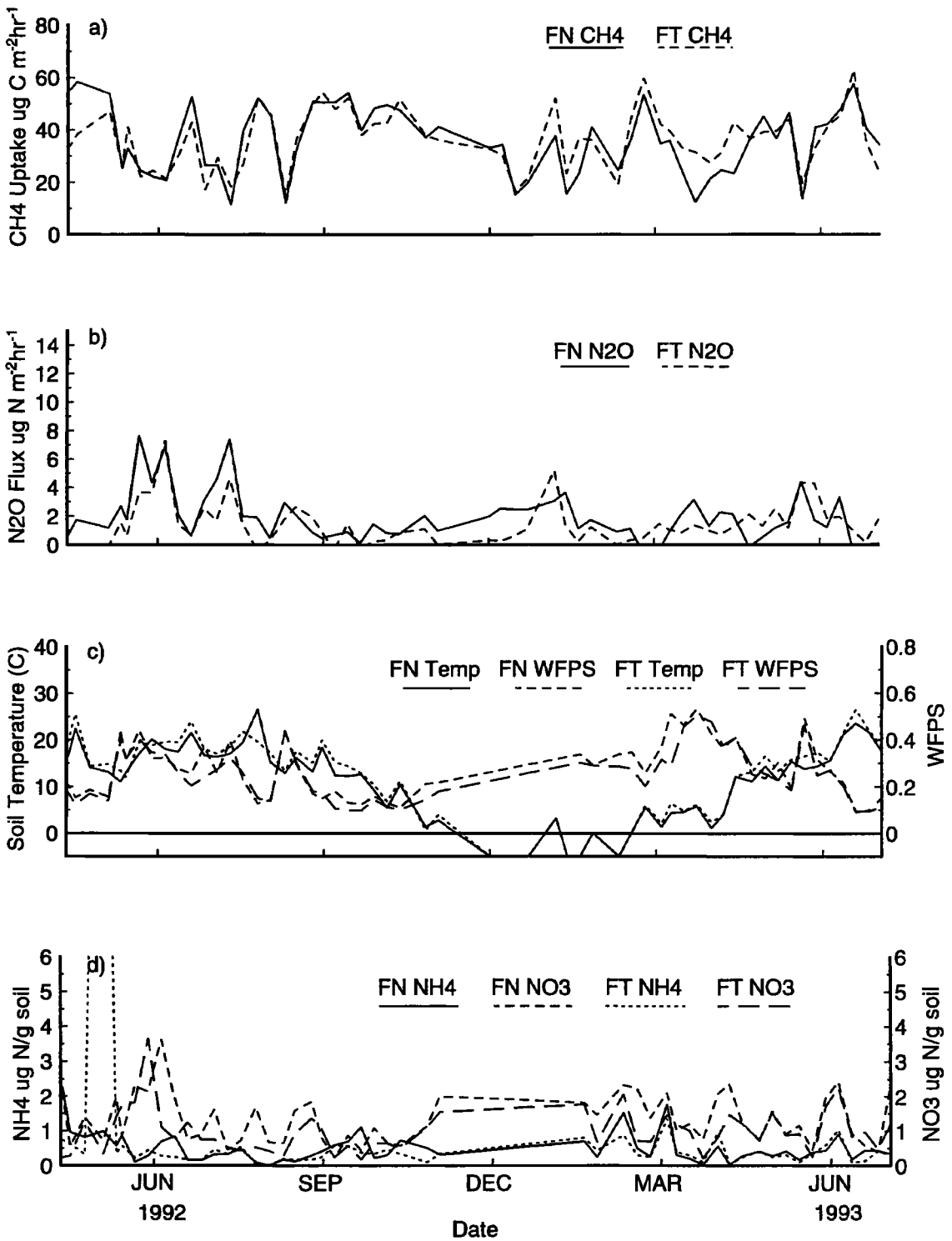

Figure 7. (a) CH_4 uptake, (b) N_2O emission, (c) soil temperature and water content, and (d) soil ammonium and nitrate contents in native pasture (FN) and a pasture that was last tilled in 1939 (FT) during April 1992 through July 1993. The gas flux data shown are the mean from six measurement locations.

during the following 3 years. Nitrous oxide emissions were about 8 times higher from the tilled soil for about 18 months following tillage. Two to 3 years later, N_2O emissions averaged only 25-50% higher in the tilled soils than the native grassland.

Fields having similar soil physical and chemical properties that have been cropped to winter wheat (wheat-fallow) continuously for the past 70+ years consumed a 3-year average of 21 and 26% less CH_4 than the site that was plowed one time in 1992 or

52 and 54% less than native sites. At these sites, continuous cultivation and past N fertilization decreased CH_4 uptake about 25% in excess of the tillage-induced decrease. Nitrous oxide emissions in 1994 and 1995 were not significantly different in the PP and WE and WW sites indicating that there was no additional cultivation-induced N_2O emissions. During wheat-fallow cropping, gas fluxes tended to follow cropping sequence patterns with N_2O emissions higher and CH_4 uptake lower during fallow.

Reversion of cultivated soils that had been cultivated in the early decades of this century back to grasslands eventually leads to soils having similar CH_4 oxidation and N_2O emissions to those of native soils of the same texture and parent material (Figure 8). Sites that were last plowed in 1939 exhibited the same CH_4 and N_2O flux rates as comparable never-tilled soils during a 15-month measurement period. A site that was taken out of cultivation and planted to grass in 1987 and placed in the CRP continued to exhibit CH_4 uptake and N_2O emission rates similar to the wheat fields, although seasonal trends differed, apparently because of greater snow accumulation in the CRP. These observations suggest that the return of the shortgrass steppe back to CH_4 oxidation and N_2O emission rates observed in the native state following tillage requires longer than 8 but less than 50 years (Figure 8).

Our data confirm that fluxes of N_2O and CH_4 within grasslands represent an important part of the global atmospheric budget [*Mosier et al.*, 1996]. Using the land cover data that was current in the work of *Bouwman* [1990], temperate grasslands comprise about 8% (about 11.5 x 10^{-12} m^{-2}) of global land surface area. Assuming a current spatial distribution in all temperate grasslands of 70% upland and 30% lowland [*Schimel et al.*, 1986], our average N_2O emission and CH_4 uptake rates are 1.6 μg N m^{-2} hr^{-1} and 31.2 μg C m^{-2} hr^{-1}, respectively, from our long-term observations presented in this paper or by *Mosier et al.* [1996]. Assuming that these values are typical of the rest of the world, N_2O emissions average 0.16 Tg N yr^{-1}, and CH_4 uptake averages 3.2 Tg CH_4-C yr^{-1} for temperate grasslands globally.

In another semiarid area, *Matson et al.* [1991] found that N_2O emissions averaged 0.21 kg N ha^{-1} yr^{-1} from a variety of ecosystem types within the sagebrush steppe in south central Wyoming [*Matson et al.*, 1991]. Extrapolating these values to similar ecosystems globally (4.92 x 10^{12} m^{-2}), they calculated an annual flux of 0.11 Tg of N_2O-N yr^{-1}. This is similar to the shortgrass steppe integrated average of 0.14 kg N ha^{-1} yr^{-1}.

The shortgrass steppe is within the Great Plains of central North America. The Great Plains covers about 2.23 x 10^{-12} m^{-2} of land area which is approximately 19% of global temperate

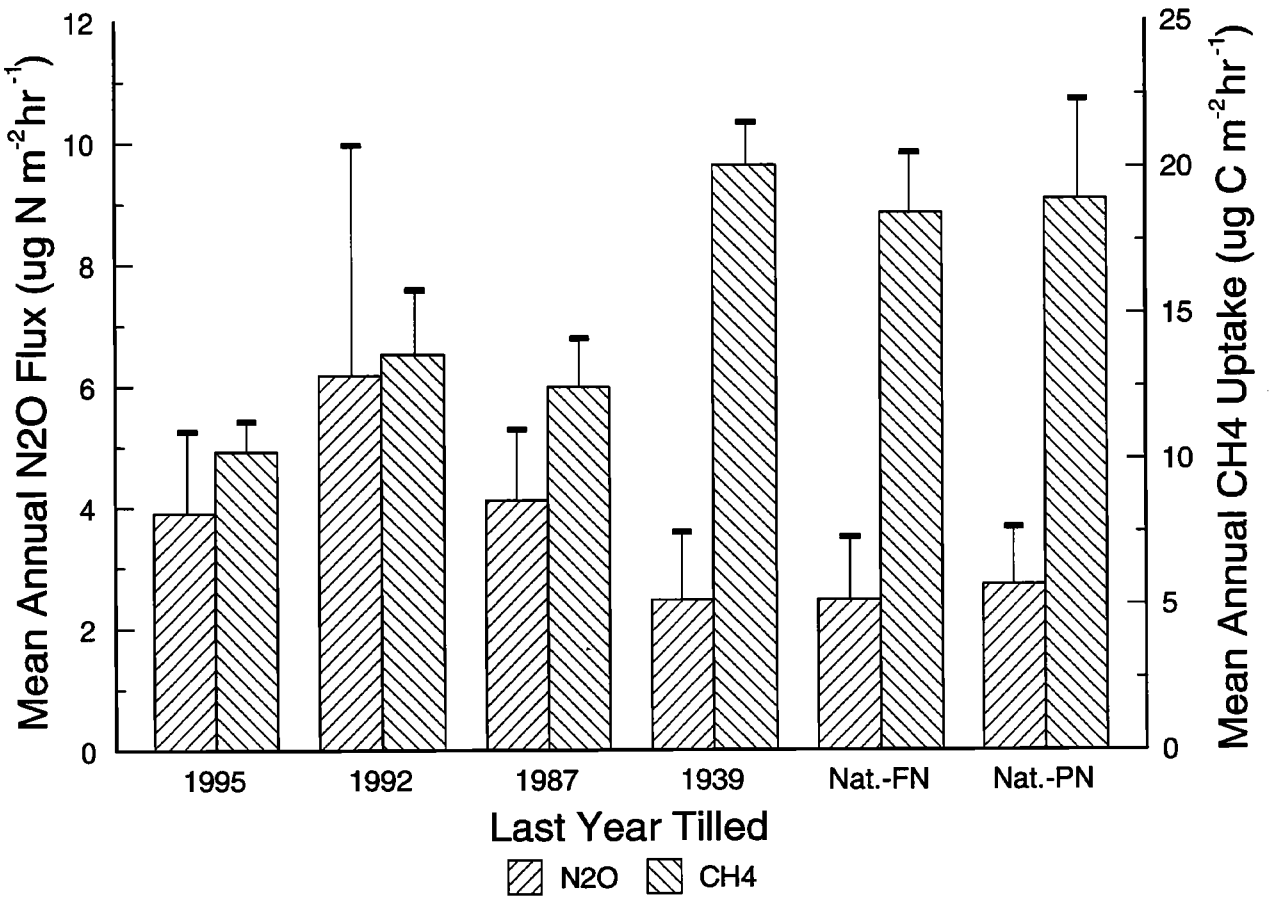

Figure 8. Mean annual CH_4 uptake and N_2O emission rates (September 1992 to August 1995) for sites that were last tilled in 1994-1995 (mean of WE and WW sites), 1992 (PP site), 1987 (CRP site), 1939 (FT site), and from two native grassland sites (FN and PN). The error bars shown are standard deviation of the mean from six flux measurement locations.

grassland [*Lauenroth et al.*, 1994; *Bouwman*, 1990]. Within the Great Plains, 0.69 x 10^{-12} m^{-2} is currently cropped, mostly to winter wheat. Assuming the same gas flux annual means and spatial distribution across the Great Plains as noted above, we can estimate the impact that converting part of the Great Plains grassland into wheat-fallow cropping has on trace gas fluxes. Approximately 1.54 x 10^{-12} m^{-2} of land remains in grassland. If we assume that wheat-fallow cropping decreased the annual CH_4 uptake to 17 μg CH_4-C m^{-2} hr^{-1} or 149 mg C m^{-2} yr^{-1} and increased N_2O emissions to 3.6 μg N m^{-2} hr^{-1} or 31.5 mg N m^{-2} yr^{-1} as we observed in our studies, then across the Great Plains CH_4 uptake would be decreased by a total of 14% and N_2O emissions increased by 35% annually, compared to the precultivation grassland.

The CH_4 consumption rate that we observed at eight different native grassland sites within the shortgrass steppe extrapolated to all temperate grasslands are much larger than those predicted by a global CH_4 consumption model [*Potter et al.*, 1996b]. They estimated an annual mean flux of only 87 mg m^{-2} yr^{-1} of CH_4-C, 3.1 times less than the average values, 273 mg m^{-2} yr^{-1} CH_4-C that we observed over a 5-year period of weekly flux measurements reported in this paper and by *Mosier et al.* [1996]. We expect that this underestimate from the *Potter et al.* [1996a, b] model is due in part to underestimates during cold seasons of the year in temperate and northern climates. Cold season CH_4 consumption comprises a significant portion of annual budgets in arable lands in Germany [*Flessa et al.*, 1995] and in subalpine forests in the U.S. [*Mosier et al.*, 1993a, b; *Sommerfeld et al.*, 1993]. Cold season trace gas fluxes from a variety of temperate and northern ecosystems are likely important for assessing global trace gas budgets.

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O. Heinemeyer, FAL, Braunschweig, Germany. (email: heinemeyer@kepler.dv.fal.de)

A.R. Mosier, Agricultural Research Service, U.S. Department of Agriculture, P.O. Box E, Fort Collins, CO 80522. (email: amosier@lamar.colostate.edu)

D.S. Ojima, W.J. Parton, and D.W. Valentine, Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO 80523. (email: dennis@nrel.colostate.edu, billp@nrel.colostate.edu, davev@nrel.colostate.edu)

D.S. Schimel, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307-3000. (email: schimel@isis.cgd.ucar.edu)

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