Assessing Seasonal Greenhouse Gas Emissions and Belowground C and N Processes Under Different Fire Frequencies in Soils of Sierra Nevada Chaparral Shrublands

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Summary

Chaparral shrubland covers more than 13 million acres in California, accounting for 13% of the total land area. Information on contributions of greenhouse gases (GHG) to the atmosphere from this biome is lacking. Historically, fire played a critical role in shaping the autosuccession of chaparral ecosystems, returning every 20-30 years on average in Sierra Nevada foothills. As this ecosystem undergoes rapid human population growth and increasing development, often coupled with fire suppression policies, there is need for better understanding of how resulting ecological changes impact chaparral ecosystem resiliency. We hypothesized that fire-induced type conversion from dense chaparral to grass-shrub mosaic initiated by two or more short-recurrence-interval fires provides ecological benefits which, in turn, reduce flux of GHG to the atmosphere. The purpose of this research was to define the effects of three different fire return intervals (20-year, 4-year, and fire-suppressed) in two predominant soil types (granitic and metabasic) on GHG flux, Global Warming Potential (GWP) estimates and soil C and N pools. This report summarizes the complete set of data for our two-year seasonal inventory. More frequent fire intervals reduce N_2O flux and increase CH_4 assimilation. Fire intervals of 20 years and long-term fire suppression reduce capacity to assimilate CH_4 and increase N_2O emissions and, therefore, increase GWP estimates. There are large seasonal differences in GHG fluxes between wet and dry seasons, significant inter-annual variability in CO_2 production driven by soil water content availability, and greater CH_4 assimilation by metabasic soils. Soil CO_2 flux and CH_4 assimilation correlate well with soil water content and soil temperature, but there is no relationship between GHG fluxes and soil labile C and N pools. The chaparral biome is an important sink for CH_4, especially during hot and dry seasons. Annual GWP estimates for chaparral can be reduced with more frequent fires. Seasonal GWP estimates show the lowest values for hot and dry seasons such as summer and fall and prolonged periods of drought in winter. Soils beneath 4-y chaparral have negative GWP balance during dry seasons and can be important sinks for GHG emissions.

Objectives

The purpose of this research was to define the effects of three different fire return intervals in two predominant soil types on seasonal GHG flux and soil C and N dynamics in Sierra foothills chaparral shrubland.

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Approach and Procedures

Location: West slope of the central Sierra Nevada Range near Moccasin, CA (120º15" LAT and 37º45" LONG), 600m elev., MAT: 14.4ºC, MAP: 600mm.
Landscape Position: Shoulders and upper backslopes, 8 to 25 percent slopes
Soils:

GS: Fine-loamy, mixed, superactive, thermic Mollic Haploxeralfs formed in colluvium and residuum of **metabasic igneous or sedimentary rocks**. Loam texture

GR: Fine-loamy, mixed, semiactive, thermic Ultic Haploxeralfs formed in colluvium and residuum of **granitic rocks**. Sandy loam texture.

Fire History:

FS: Fire-suppressed: **No recorded fires** in last ~100 years.
20-y: 20-year frequency: **Fires in 1950, 1972, and 1992**.
4-y: 4-year frequency: **Fires in 1997 and 2001**.

Following measurements were taken each season(4) for two years (2005 and 2006) during five consecutive rain-free days, replicated five times on each site (total of 1200 measurements):

- GHG flux (obtained using static chambers deployed on soil surface for 30 minutes) (Hutchinson and Mosier, 1981);
- soil samples (0-10 cm depth) collected every time air samples were taken within 2 m of GHG chambers.
- Litter and soil samples: collected once in the summer for site description

Samples were analyzed for:

Air: CO_2, N_2O and CH_4;
Soil: water content (gravimetric), 0.5M K_2SO_4-extractable inorganic N, dissolved organic C (DOC) and dissolved organic nitrogen (DON), TOC, TN, bulk density (clod method), % sand, silt and clay, pH
Litter: biomass, lignin, TN
Additional on-site measurements: soil and air temperature, soil moisture (TDR probe)

Laboratory Analyses: Gas samples were analyzed using Automated Gas Chromatograph (Varian 38001) equipped with thermoconductivity, flame ionization and electron capture detectors to capture **CO_2, CH_4** and **N_2O** respectively (Mosier and Mack 1980). Best fluxes were estimated from the rate of change of the gas concentration in the chamber headspace. Extractable inorganic N in soils was obtained by shaking 10 g of soils in 50 ml of 0.5*M* K_2SO_4 for 30 minutes, and filtered through Whatman # 40 paper. Extracts were analyzed on Lachat (Lachat Instruments, Hach Company, Loveland, CO) for NH_4^+-N using sodium salicylate based method and NO_3^--N by cadmium reduction method. DOC was analyzed using the UV-persulfate TOC Analyzer (Phoenix 8000, Tekman-Dorhmann, Cincinnati, OH). DON was analyzed using alkaline N persulfate oxidation (Cabrera and Beare 1993).

Statistical Design: The statistical design was split-plot with soils as fixed variable nested in random fire frequency treatments. The effects of soils on GHG fluxes were tested using site replication (3) x year (2) x season (4) x day (5) error term derived from random and repeated measurements. The effects of seasons were tested using year as repeated measurement. We used ANOVA in the PROC MIXED SPSS package, due to the fact that some of our variables were random, repeated or fixed.

Results

Our results showed inter-annual variability of air temperature and soil moisture content (*table 1*). Average annual air temperature was 0.9^{o}C higher and soil moisture content was 3% lower in 2006 than in 2005. The greatest differences in air temperature and soil water content occurred in winter months (*table 2*). Differences in soil nutrients and CO_2 flux also occurred. In 2005 soils had higher pH, NH_4 and NO_3 concentrations, and lower DOC concentrations compared to 2006. The average annual CO_2 flux declined from 38.5 mg CO_2-C m^{-2} hr^{-1} in 2005 to 31.6 mg CO_2-C m^{-2} hr^{-1} in 2006. There were no inter-annual differences in soil DON concentrations, CH4 assimilation and N2O flux (*tables 1 and 3*). Two-year average of CH_4 assimilation was (-4.7 ug m-2 hr-1) and N_2O flux was 1.2 ug m^{-2} hr^{-1}.

Table 1. *Mean values for air temperature, soil temperature, soil water content and nutrient pools.*

	Air temp	Soil temp	SWC	NH4	NO3	DON	DOC	Avail P (Bray)	Avail P (Olsen)	pH
Year										
2005	22.2 (0.24)	14.3 (0.28)	0.13 (0.004)	2.49 (0.07)	0.23 (0.02)	8.2 (0.11)	90.11 (2.14)	5.3 (0.5)	2.4 (0.2)	6.54 (0.01)
2006	23.1 (0.23)		0.10 (0.004)	2.37 (0.05)	0.08 (0.004)		98.28 (2.18)	na	na	6.22 (0.01)
Season										
spring	21.1 (0.2)	13.4 (0.1)	0.23 (0.00)	2.8 (0.09)	0.13 (0.00)	5.15 (0.17)	63.3 (0.98)	4.61 (0.60)	1.51 (0.23)	6.23 (0.01)
summer	26.8 (0.3)	27.1 (0.1)	0.02 (0.00)	2.3 (0.09)	0.22 (0.03)	11.7 (0.26)	160.01 (3.13)	4.83 (0.62)	1.88 (0.37)	6.28 (0.02)
fall	25.5 (0.2)	17.9 (0.1)	0.04 (0.00)	2.5 (0.11)	0.19 (0.03)	8.13 (0.16)	80.05 (1.99)	9.03 (0.78)	2.33 (0.25)	6.54 (0.02)
winter	17.3 (0.2)	10.0 (0.1)	0.17 (0.00)	1.8 (0.09)	0.07 (0.01)	7.5 (0.14)	73.50 (1.79)	2.50 (0.43)	3.84 (0.84)	6.45 (0.02)
Soil										
Metabasic (GS)			0.12 (0.004)			7.69 (0.14)	89.45 (1.95)	4.3 (0.4)	1.9 (0.2)	
Granitic (GR)			0.11 (0.003)			8.72 (0.18)	98.96 (2.35)	6.2 (0.6)	2.9 (0.3)	
Fire history										
fire supp	21.6 (0.25)	16.0 (0.32)		2.1 (0.08)	0.07 (0.003)	7.5 (0.18)		4.5 (0.5)	1.7 (0.2)	6.3 (0.02)
20-year MFI	23.1 (0.25)	17.0 (0.35)		2.5 (0.09)	0.15 (.002)	8.9 (0.21)		3.6 (0.4)	1.4 (0.1)	6.5 (0.01)
4-year MFI	23.3 (0.32)	17.1 (0.20)		2.4 (0.05)	0.23 (0.003)	8.2 (0.20)		7.6 (0.8)	4.1 (0.7)	6.5 (0.01)

Seasonal differences showed that in spring, CO_2 and N_2O fluxes were the highest and CH_4 assimilation was the lowest compared to other three seasons (*table 3*). In addition, soil moisture content and soil NH_4 concentrations were the highest in spring, while DON, DOC, available P (Olsen) concentrations and pH were the lowest of all seasons (*table 2*). In summer, average air and soil temperatures were the highest of all seasons (26.8ºC and 27.1ºC, respectively). Soils in summer had the lowest average moisture content (0.02 g g-1) and the highest soil NO_3, DON and DOC concentrations. The average CH_4 assimilation significantly increased and CO_2, N_2O fluxes declined in summer compared to spring, with N_2O reaching the lowest levels of all seasons. In fall, air temperature measurements remained high, but soil temperatures declined compared to summer, probably because of cool night-time temperatures. Soil moisture content remained low.

Soil NO_3, DON and DOC concentrations were lower in fall compared to summer. Available P (Bray) and soil pH in fall were the highest of all seasons. The average CO_2 flux was the lowest in fall (9.9 mg CO_2-C m^{-2} hr^{-1}), CH_4 assimilation was the highest (-6.25 ug CH_4-C m^{-2} hr^{-1}) and N_2O slightly increased compared to summer. In winter, air and soil temperatures were the lowest. Soil moisture content increased compared to fall and became the second highest of the year next to spring. Soils had the lowest NH_4, NO_3, DON and available P (Bray) concentrations. Average CO_2 and N_2O fluxes increased compared to fall, while CH_4 assimilation declined.

Table 2. *Seasonal soil water content, air temperature and soil temperature.*

	Soil WC (g H_2O g^{-1} soil)			Air Temp (°C)			Soil temp (°C)		
2005	**fsupp**	**20-y**	**4-y**	**fsupp**	**20-y**	**4-y**	**fsupp**	**20-y**	**4-y**
Spring	0.25	0.23	0.22	19.6	22.4	22.8	11.8	13.6	16.2
Summer	0.03	0.02	0.02	24.9	29.4	25.7	24.5	27.7	29.5
Fall	0.04	0.03	0.03	23.6	24.8	26.2	16.8	18.6	20.4
Winter	0.24	0.23	0.21	15.7	15.1	14.8	12.8	13.6	11.5
2006									
Spring	0.23	0.24	0.24	20.4	21.5	19.7	12.5	14.1	12.2
Summer	0.01	0.01	0.01	25.7	25.8	29.2	26.7	27.2	26.8
Fall	0.05	0.05	0.05	25.3	25.6	27.7	16.4	18.9	10.5
Winter	0.11	0.10	0.12	18.3	19.4	19.0	10.5	9.7	11.5

Soil texture and bulk density estimates revealed that GS soils had slightly higher BD (1.59 vs. 1.54 g cm^{-3}), more silt (37.3 vs. 35.7 %) and less sand (51.3 vs. 53 %) compared to GR soils (Table 4). Soil moisture content was higher by 1%, and DON, DOC and available P (Bray and Olsen) concentrations were lower in GS soils compared to GR soils. There were no statistical differences in CO2 and N2O fluxes between the soils but CH_4 assimilation was greater in GS than GR soils (-5.00 vs. –4.43 ug CH_4-C m^{-2} hr^{-1}).

Fire history had a significant impact on GHG fluxes and nutrient concentrations in soils beneath chaparral. The lowest air and soil temperatures were in FS chaparral and the warmest temperatures were in 4-y chaparral (2ºC degree difference). Highest soil TOC and TN contents were observed in soils beneath FS chaparral and the lowest in 4-y chaparral (*table 4*). Soils beneath FS chaparral also had the highest surface litter biomass accumulation (6.6 kg m-2) and the lowest litter decomposability. The lowest surface litter accumulation (1.6 kg m-2) and the highest litter decomposability were observed in soils beneath 4-y chaparral.

Fire history did not affect soil moisture content, but influenced soil nutrient concentrations, N_2O flux and CH_4 assimilation. Soils beneath FS chaparral had the lowest NH_4 and NO_3 concentrations while soils beneath 4-y chaparral had the highest concentrations of all treatments. Soils beneath 20-y chaparral had the highest pH and DON concentrations while soils beneath FS had the lowest. The highest N_2O flux was from soils beneath FS chaparral and the lowest N_2O flux from soils beneath 4-y chaparral. Soils beneath 4-y chaparral also demonstrated the highest rate of CH_4 assimilation compared to FS and 20-y chaparral. There was no effect of fire history on CO_2 flux.

Table 3. *Soil GHG emissions.*

	CO_2 (mg CO_2-C m^{-2} hr^{-1})	CH_4 (ug CH_4-C m^{-2} hr^{-1})	N_2O (ug N_2O-N m^{-2} hr^{-1})
Year			
2005	38.5 (1.3)a	-4.7 (0.08)	1.2 (0.04)
2006	31.6 (1.4)b		
season			
spring	80.4 (2.5)d	-2.73 (0.11)d	1.42 (0.08)c
summer	17.5 (0.7)b	-5.59 (0.16)b	1.02 (0.07)a
fall	9.9 (0.3)a	-6.25 (0.15)a	1.17 (0.05)b
winter	32.4 (0.9)c	-4.31 (0.04)c	1.24 (0.03)b
soil			
Metabasic (GS)		-5.00 (0.12)a	
Granitic (GR)		-4.43 (0.04)b	
fire history			
fire suppressed		-4.43 (0.13)b	1.45 (0.07)c
20-year fire return ('50, '72, and '92)		-4.41 (0.13)b	1.33 (0.06)b
4-year fire return ('97 and '01)		-5.31 (0.16)a	0.94 (0.04)a

Table 4. *Soil characteristics.*

	GSfsuppressed	GRfsupressed	GS20-year	GR20-year	GS4-year	GR4-year
Soil						
Bulk density	1.49	1.53	1.60	1.51	1.69	1.58
% TOC	0.13	0.19	0.14	0.12	0.12	0.14
%TN	2.56	3.75	2.45	2.42	2.80	2.58
% sand	45	47	52	55	57	57
% silt	43	40	36	35	33	32
% clay	12	13	12	10	11	10
Litter						
Litter Biomass kg m^{-2}	6.7	6.4	2.6	2.3	1.0	2.1
Litter lignin:N	61	66	42	54	16	28

A significant interaction between season and fire history was observed (*fig. 1*). In the spring, the greatest CO_2 flux and the smallest N_2O flux was generated by 4-y chaparral. The same 4-y chaparral demonstrated higher CH_4 assimilation in summer and fall compared to other fire intervals. Soils beneath FS chaparral showed the lowest rate of CH_4 assimilation in spring and winter while 20-y chaparral had the lowest rate of CH4 assimilation in summer and fall. The same 20-y chaparral had the greatest N_2O flux in the spring and high flux, similar to the FS chaparral, in the fall, both significantly greater than N_2O flux from soils beneath 4-y chaparral.

Soil CO_2 flux was positively correlated with soil water content and negatively correlated with soil temperature (*table 5*). Significant slope differences between fire histories revealed CO_2 flux from soils beneath 4-y chaparral was most responsive to increased soil water content. The CO_2 flux in 4-y chaparral occurred at a rate of 286.6 mg CO_2-C m^{-2} hr^{-1} g H_2O^{-1}, followed by 20-y (245.5 mg CO_2-C m^{-2} hr^{-1} g H_2O^{-1}) and FS

(210.9 mg CO_2-C m^{-2} hr^{-1} g H_2O^{-1}). The greatest negative response to soil temperature was also in 4-y chaparral where the CO_2 flux occurred at a rate of -2.21 mg CO_2-C m^{-2} hr^{-1} $^oC^{-1}$. In addition, CH_4 assimilation was positively correlated with soil water content and negatively correlated with soil temperature in 4-y and FS chaparral only.

Estimates of the cumulative GWP calculated for each season and fire history showed significant treatment differences (*fig. 2*). The greatest cumulative GWP estimates were obtained for soils beneath FS chaparral (20.0 meq g CO_2 m^{-2} y^{-1}), followed by 20-y chaparral (18.0 meq g CO_2 m^{-2} y^{-1}) and the lowest values were obtained for 4-y chaparral (8.8 meq g CO_2 m^{-2} y^{-1}). Seasonal GWP estimates showed the greatest GWP in spring and winter of 2005 and spring of 2006 and the lowest in fall of both years. Soils beneath 4-y chaparral had negative GWP in summer 2005 and fall 2006 and the estimates for fall 2005, summer 2006 and winter 2006 were close to zero.

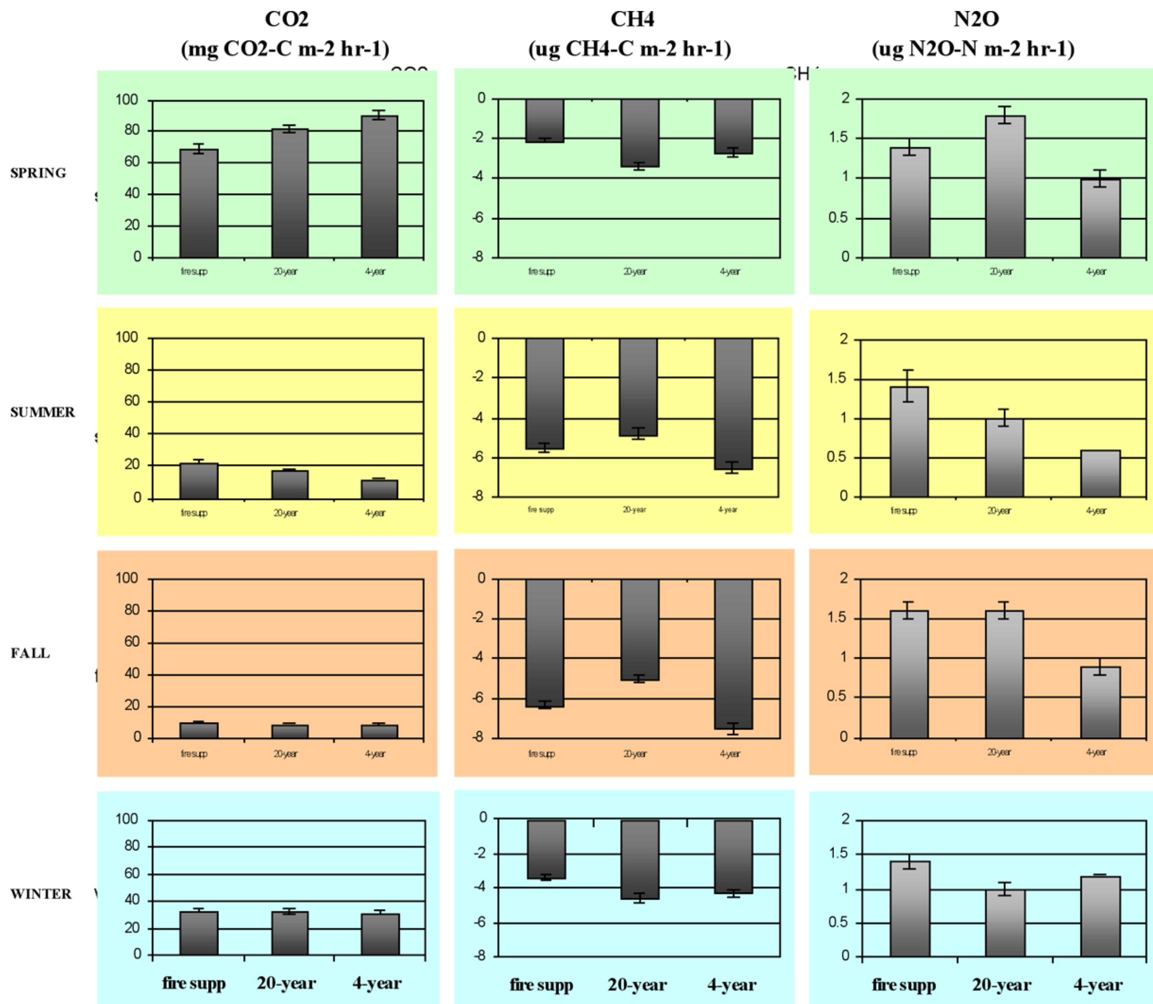

Figure 1. Seasonal GHG emissions from 4-y chaparral, 20-y chaparral and fire suppressed (FS) chaparral.

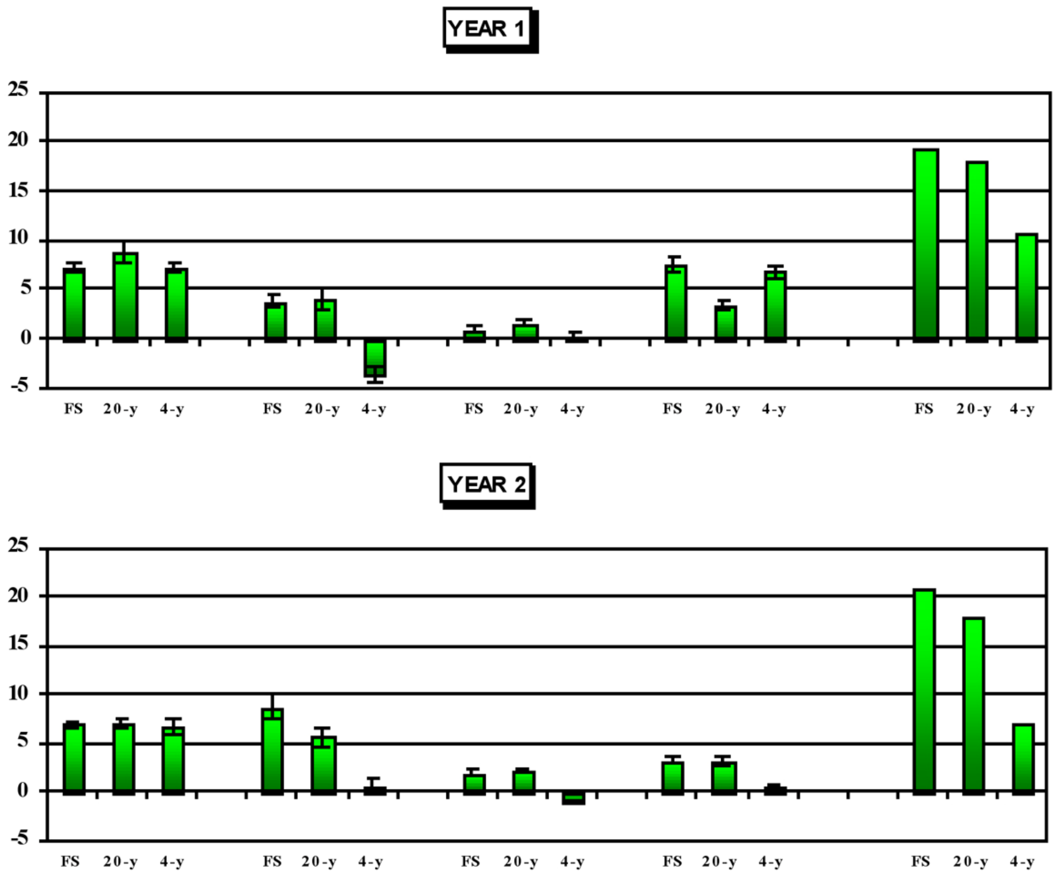

Figure 2. Seasonal estimates of cumulative GWP.

Discussion

Our results suggest strong relationships between inter-annual climate variability and CO_2 flux from chaparral soils. Factors that correlated well with CO_2 flux were soil water content and soil temperature. The difference of 0.9ºC in air temperature and 0.03 g g^{-1} in soil water content between 2005 and 2006 reduced CO_2 flux by 18% but had no impact on CH_4 assimilation and N_2O flux. The factors affecting CO_2 flux, and the activity of microorganisms generating it, include the abiotic environment, such as temperature, water, and aeration (CAST, 2004). The lower CO_2 production and higher soil DOC concentrations observed in 2006 compared to 2005 suggest staggered microbial activity and organic matter decomposition. Microbial availability of N was also low in 2006, as demonstrated by reduced soil NH_4 and NO_3 concentrations compared to 2005.

Seasonal climatic variability of air temperature and rainfall, typical of Mediterranean climate, create a natural shift from wet and cool season (winter and spring) to hot and dry (summer and fall)(Keeley 2000). The shift from wet to dry season stimulates changes in microbial community structure, activity and microbial growth (Fierer and Schimel 2003). Such changes can have a significant impact on soil biochemical processes, nutrient pools, and especially GHG fluxes. The CO_2 flux was on average 76% greater and N_2O flux was on average 18% greater in wet seasons than in dry seasons. Our results agree with model simulations of Li et al. (2006), who projected the greatest GHG fluxes during December-March and the lowest in the summer. High microbial activity and CO_2 and N_2O production corresponded with increased microbial immobilization, which was demonstrated by significantly smaller soil DON and DOC concentrations determined for wet versus dry seasons.

***Table 5**. Correlation significance between fire history and GHG emissions.*

	Fire history	CO2 Rsq	CO2 Slope	CH4 Rsq	CH4 Slope
SWC	**FS**	0.550**	210.85c	0.309**	14.56b
	20-y	0.550**	245.48b	NS	
	4-y	0.590**	286.6a	0.370**	19.66a
Soil temperature	**FS**	0.124**	-1.56b	0.151**	-0.15b
	20-y	0.100**	-1.48b	NS	
	4-y	0.176**	-2.21a	0.150**	-0.18a

Gaseous N emissions are thought to be a major pathway of N loss from chaparral ecosystems (Li et al. 2006). The soil processes that result in N_2O production are associated with nitrification or denitrification. Denitrification generates N_2O only when soils are saturated, which happens sporadically when soils are wet (Mosier et al. 1997). The correlation of N_2O production with soil C abundance has been observed in a wide scope of field and laboratory measurements. For example, (Ambus and Christensen 1995) observed that dissolved organic carbon, a direct source of energy for denitrifiers, is one of the major limiting factors for N_2O production. During our experiment, soils never came close to saturation, and we did not find a strong correlation between soil DOC concentrations and N_2O fluxes, which led us to conclude that nitrification was the major driver of N_2O production. This is also suggested by Castaldi et al. (2006).

Interestingly, our results demonstrated that, during the dry period of the year when CO_2 and N_2O fluxes were minimal, summer soil CH_4 assimilation was as high as twice that of spring, and fall CH_4 assimilation was as high as 2.25 that of spring. High soil CH_4 assimilation was also observed in soils beneath Mediterranean shrubland of Southern Italy during the driest and the warmest seasons by Castaldi and Fierro (2005). Methane present in the atmosphere is removed from the air as a result of biological oxidation conducted by soil microbes under aerobic conditions (Smith et al. 2000). Since soil water content during the warm and dry seasons was very low (0.02 g g^{-1} in summer and 0.04 g g^{-1} in fall) and air and soil temperatures were very high, it is likely that environmental constrains impeded the CH_4 assimilation in the top surface of the soil. Therefore, the majority of the biological CH_4 oxidation likely took place below the top 10 cm of soil as proposed by Castaldi and Fierro (2005). Factors affecting CH_4 assimilation include soil NH_4^+-N concentrations (high enzymatic similarity and preferential substrate use) and soil water content (Mosier et al. 1991). In our study, high CH_4 assimilation in dry seasons corresponded with low soil NH_4 concentrations.

Soil texture and mineralogy are well recognized as factors influencing GHG emissions and SOM levels (Mosier et al. 1991). Soil C tends to increase with higher clay content and therefore CO_2 flux rates also increase (Burke et al. 1989). Our results show that there was no effect of soil mineralogy and texture on CO_2 and N_2O fluxes. The textural differences were too small to have an influence on these two trace gases. However, there was a significant difference in CH_4 assimilation between GS and GR soils. It seems that though the difference between GS and GR soils was 0.57 ug CH_4-C m^{-2} hr^{-1}, it can have a significant impact on the ecosystem scale estimates of global warming potential. Mosier et al. (1991) suggested that soil structure (ability to impede or promote oxygen diffusion), texture, and soil water content are some of the factors affecting CH4 assimilation. Castaldi and Fierro (2005) suggested that coarse texture soils favor gas-phase transport through the profile. Our results were not able to attribute greater CH_4 assimilation to more coarse-textured soils, as GS soils appear to have less sand. It is likely, however, that GS soils were more efficient in soil water retention critical to support CH_4 oxidizers in deeper soil layers in which the CH_4 assimilation was taking place.

Soils beneath chaparral exposed to different fire histories demonstrated a variety of characteristics that reflected changes in GHG fluxes and nutrient availability. Li et al. (2006) projected significant fire effects on GHG emissions for three years after fire. Interestingly, our results suggested the presence of fire effects beyond this period of time.

With increasing fire intervals, soils beneath chaparral gradually accumulated more TOC and TN in mineral soil and surface litter biomass. Litter accumulation becomes a significant reservoir of nutrients sequestered in highly recalcitrant plant residues (Schlesinger and Hasey 1981). Foliage of many chaparral species are rich in allelopathic compounds (Kaminsky 1981) and the mean residence time is estimated at 4.6 years (Schlesinger and Hasey 1981). These findings agree with our results of declining litter decomposability with increasing fire return interval.

The highest CO_2 flux was generated in spring by soils beneath 4-y chaparral. Presence of annual grasses in 4-y chaparral supported microbial activity by increasing nutrient availability (i.e. NH_4, NO_3, available P) also observed by Jones et al. (1983) and in keeping with comparisons between annual grassland and shrub-dominated plant communities (e.g., Norton et al. 2004). Not only did the annual grasses contribute highly decomposable litter, but the soils beneath 4-y chaparral also demonstrated the greatest CO_2 flux response to increasing soil water content.

Contrary to our expectations of high CO_2 fluxes from soils beneath FS chaparral, these soils had CO_2 fluxes comparable to 4-y and 20-y in three out of four seasons, and had the lowest of all CO_2 flux in spring. Thus, high soil TOC content and surface litter biomass were not good predictors of CO_2 fluxes. Furthermore, FS soils had the slowest CO_2 flux response to increasing soil water content, suggesting the presence of different microbial populations in soils beneath FS chaparral compared to soils beneath 4-y chaparral. It is likely that microbial populations in soils beneath FS chaparral were also nutrient limited as demonstrated by low NH_4, NO_3, DON, and available P concentrations. Nutrient retention rates can change with stand age, as older stands become nutrient deficient (Hanes 1971). It seems that nutrient accumulation in litter can play an important role in developing deficiencies in mature chaparral stands. However, their N and P pools are usually lower than in most temperate forest ecosystems due to lower productivity and less accumulation of detrital material in chaparral stands (Gray and Schlesinger 1981).

Interestingly, soils beneath 4-y chaparral showed the lowest N_2O flux of all soils. The average flux was 43% lower than from 20-y chaparral and 60% lower than FS chaparral. Lower N_2O flux in 4-y chaparral could mean that microbial populations efficiently immobilize labile N in response to available soil water content. Soils beneath FS and 20-y chaparrals demonstrated high N_2O fluxes throughout most of the year, except in the fall when N_2O flux in 20-y chaparral was the lowest of all. McLain and Martens (2006) proposed that an important contribution of N_2O in semi-arid environments is made by microbial fungi carrying out the process of heterotrophic nitrification. Soils beneath FS and 20-y chaparral had relatively high TOC and surface organic matter accumulation, yet soil NO_3 concentrations were low. Castaldi and Aragosa (2002) found that mineralization rates in old-growth chaparral are low as a result of allelopathic compounds leached from plants. In contrast, soils associated with grass vegetation usually have high mineralization rates in which build up of soil NO_3 concentration in dry seasons is associated with the process of autotrophic nitrification (Booth et al. 2003). Thus, we propose that with increasing fire occurrence intervals, the resulting shift in N_2O flux from low values four years after fire to high values 20 years and longer after fire, was likely facilitated by different soil N transformations. Soils beneath 4-y chaparral were mainly supporting autotrophic nitrification, and soils beneath 20-y and FS transitioned to supporting heterotrophic nitrification.

Our results showed decreasing efficiency of CH_4 assimilation with increasing fire occurrence interval, with 20% higher assimilation in 4-y chaparral than the 20-y and FS chaparral, but no significant difference between the two longer intervals. Castaldi and Fierro (2005) reported no statistical change in CH_4 oxidation immediately after fire, suggesting that direct effects of fire suppress microbes carrying out CH_4 assimilation, resulting in assimilation rates comparable to those of soils beneath unburned chaparral. In our study, the 20% increase in CH_4 assimilation in soils beneath 4-y chaparral compared to 20-y and FS soils indicates that microbial populations capable of carrying out CH_4 assimilation recovered within four years after fire.

Fire management in chaparral biome can have significant impact on GWP estimates from Mediterranean ecosystems. More frequent fire intervals can lower annual GWP by increasing CH_4 assimilation and reducing N_2O flux compared to 20-y and FS chaparrals. Drier years can further decrease GWP contributions by 4-year chaparral as demonstrated by 34% GWP decrease in 2006 compared to 2005. Interestingly, despite high seasonal GWP variability between 20-y and FS chaparrals, cumulative yearly GWP estimates were comparable between 2005 and 2006. Low fall GWP estimates were associated with high CH_4 assimilation and low N_2O flux while high spring GWP estimates were associated with high CO_2 and N_2O fluxes. Interestingly, soils beneath 4-y chaparral have negative GWP in dry and hot seasons and can become a sink for trace gases. This pattern of low GWP in 4-y chaparral can continue during dry parts of winter season until wet up occurs.

In general, information on trace gas emissions from chaparral is lacking, in spite of this ecosystem being a major component of the landscape both globally (Castaldi et al. 2006) and in California. According to a review by Davidson and Kingerlee (1997), the chaparral/thorn forest biome has one of the largest estimates of nitric oxide (NO) and considerable amounts of nitrous oxide (N_2O) emissions. Unfortunately, these estimates are based on a very limited amount of scientific data (Anderson and Poth 1989) and there are no estimates for other greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4) (CAST, 2004). Thus this research was able to contribute to knowledge on GHG emissions from foothills chaparral, and factors affecting their variability.

Our research did not show a clear relationship between GHG fluxes and soil nutrient pools. The only good predictors we found were soil water content and soil temperature for CO_2 flux and CH_4 assimilation.

With vegetation type conversion from nearly continuous brush to a mixture of grass and shrubs, as occurred with two fires within four years on our 4-y chaparral site, recurring fires can be less intense and established grass will recover following fire much more rapidly than brush. A diverse mixture of woody and herbaceous vegetation could create stronger ecological resistance to and resiliency following catastrophic fire. Competition for nutrients and labile C and N can mitigate GHG emissions and lower GWP estimates over the long-term through more dynamic microbial activity and organic matter turnover. Though soils beneath 4-y chaparral demonstrate low GWP estimates, GHG emissions throughout the year vary considerably, especially in spring when CO_2 fluxes attributed to rapid annual grass turnover can be very high. However, with the increasing fire occurrence interval to 20-y or complete fire suppression in chaparral, soils beneath can gradually reduce their capacity to assimilate CH_4 and increase their N_2O emissions and therefore, increase their GWP estimates. Restoration of native perennial grasses in grass-shrub mosaics could mitigate the rapid turnover associated with the exotic annual grasses.

Approximately 40% of the global terrestrial CH_4 assimilation occurs in chaparral, savannas, semi arid steppes and other seasonally dry forests (Potter et al. 1996). Therefore chaparral/thorn forest can have an important impact on atmospheric CH_4 assimilation, especially during dry seasons, which in Mediterranean climates can last longer than seven months. Therefore, any management practices that would improve ecosystem functioning, enhancing capacity to assimilate CH_4 and reducing N_2O flux, could have a great impact on ecosystem GWP budgets. Decisions regarding proper fire management to increase CH_4 assimilation also need to consider site characteristics, especially soil physical characteristics related to site geology.

References

Ambus, P., and S. Christensen. 1995. Spatial and seasonal nitrous oxide and methane fluxes in Danish forest-, grassland-, and agroecosystems. *Journal of Environmental Quality* 24:993-1001.

Anderson, I.C., and M.A. Poth. 1989. Semiannual losses of nitrogen and N_2O from unburned and burned chaparral. *Global Biogeochemical Cycles* 3:121-135.

Booth, M.S., J.M. Stark, and M.M. Caldwell. 2003. Inorganic N turnover and availability in annual- and perennial-dominated soils in a northern Utah shrub-steppe ecosystem. *Biogeochemistry* 66:311-330.

Burke, I.C., C.M. Yonker, W.J. Parton, C.V. Cole, K. Flach, and D.S. Schimel. 1989. Texture, climate, and cultivation effects on soil organic matter content in U.S. grassland soils. *Soil Science Society of America Journal* 53:800-805.

Cabrera, M.L., and M.H. Beare. 1993. Alkaline persulfate oxidation for determining total nitrogen in microbial biomass extracts. *Soil Science Society of America Journal* 57:1007-1012.

CAST. 2004. Climate change and greenhouse gas mitigation: Challenges and opportunities for agriculture. Council for Agricultural Science and Technology, Ames, Iowa.

Castaldi, S., and D. Aragosa. 2002. Factors influencing nitrification and denitrification variability in a natural and fire disturbed Mediterranean shrubland. Biology and Fertility of Soils 36:418-425.

Castaldi, S., and A. Fierro. 2005. Soil-atmosphere methane exchange in undisturbed and burned Mediterranean shrubland of Southern Italy. *Ecosystems* 8:182-190.

Castaldi, S., A. Ermice, and S. Strumia. 2006. Fluxes of N_2O and CH_4 from soils of savannas and seasonally dry ecosystems. *Journal of Biogeography* 33:401-415.

Davidson, E.A., and W. Kingerlee. 1997. A global inventory of nitric oxide emissions from soils. *Nutrient Cycling in Agroecosystems* 48:37-50.

Fierer, N., and J.P. Schimel. 2003. A proposed mechanism for the pulse in carbon dioxide production commonly observed following the rapid rewetting of a dry soil. *Soil Science Society of America Journal* 67:798-805.

Gray, J.T., and W.H. Schlesinger. 1981. Nutrient cycling in Mediterranean type ecosystems. In Ecological Studies No.39, Resource Use by Chaparral and Matorral, A Comparison of Vegetation Function in Two Mediterranean Type Ecosystems (P.C. Miller Eds.). New York: Springer.

Hanes, T.L. 1971. Succession after fire in the chaparral of southern California. *Ecological Monographs* 41:27-52.

Hutchinson, G.L., and A.R. Mosier. 1981. Improved soil cover method for field measurement of nitrous oxide fluxes. *Soil Science Society of America Journal* 45:311-316.

Jones, M.B., R.L. Koenigs, C.E. Vaughn, and A.H. Murphy. 1983. Converting chaparral to grassland increases soil fertility. *California Agriculture* 7:23-24.

Kaminsky, K.R. 1981. The microbial origin of the allelopathic potential of *Adenostoma fasciculatum* H&A. *Ecological Monographs* 51:365-382.

Keeley, J.E. 2000. Chaparral, p. 203-253, *In* M. G. Barbour and W. D. Billings, eds. North American Terrestrial Vegetation. Cambridge, U.K.:Cambridge University Press.

Li, X., T. Meixner, J.O. Sickman, A.E. Miller, J.P. Schimel, and J.M. Melack. 2006. Decadal-scale dynamics of water, carbon and nitrogen in a California chaparral ecosystem: DAYCENT modeling results. *Biogeochemistry* 77:217-245.

Mosier, A.R., and L. Mack. 1980. Gas chromatographic system for precise, rapid analysis of nitrous oxide in soil. *Soil Science Society of America Journal* 44:1121-1123.

Mosier, A.R., D.S. Schimel, D.W. Valentine, K. Bronson, and W.J. Parton. 1991. Methane and nitrous oxide fluxes in native, fertilized and cultivated grasslands. *Nature* 350:330-332.

Mosier, A.R., W.J. Parton, D.W. Valentine, D.S. Ojima, and D.S. Schimel. 1997. CH_4 and N_2O fluxes in the Colorado shortgrass steppe 2. Long-term impact of land use change. *Global Biogeochem Cycles* 11:29-42.

Norton, J.B., T.A. Monaco, J.M. Norton, D.A. Johnson , and T.A. Jones. 2004. Soil morphology and organic matter dynamics under cheatgrass and sagebrush-steppe plant communities. *Journal of Arid Environments* 57:445-466.

Potter, C.S., E.A. Davidson, and L.V. Verchot. 1996. Estimation of global biogeochemical controls and seasonality in soil methane consumption. *Chemosphere* 32:2219-2246.

Schlesinger, W.H., and M.M. Hasey. 1981. Decomposition of chaparral shrub foliage: Losses of organic and inorganic constituents from deciduous and evergreen leaves. *Ecology* 62:762-774.

Smith, S.D., T.E. Huxman, S.F. Zitzer, T.N. Charlet, D.C. Housman, J.S. Coleman, L.K. Fenstermaker, J.R. Seemann, and R.S. Nowak. 2000. Elevated CO_2 increases productivity and invasive species success in an arid ecosystem. *Nature* 408:79-82.

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