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Annual nitrous oxide flux and soil nitrogen characteristics in sagebrush steppe ecosystems

PAMELA A. MATSON[1], CAROL VOLKMANN[1], KARYN COPPINGER[2] & WILLIAM A. REINERS[2]

[1] *Ecosystem Science and Technology Branch, NASA-Ames Research Center, Moffett Field, CA 94035-1000, USA;* [2] *Department of Botany, University of Wyoming, Laramie, WY 82071, USA*

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Abstract. Soil nitrogen transformations and nitrous oxide fluxes were measured in a range of sagebrush steppe ecosystems in south-central Wyoming. Net nitrate production, measured in laboratory incubations, was highest in the ecosystem type dominated by *Artemisia tridentata* ssp. *vaseyana*, especially early in the growing season. Fluxes of nitrous oxide, measured in closed chambers and analyzed by gas chromatography, also tended to be higher in the same type, but only for short periods in the spring. Thereafter, all nitrous oxide fluxes were low and did not differ consistently among types. Estimated average annual fluxes for three *Artemisia* ecosystem types (dominated by *Artemisia tridentata* ssp. *vaseyana, Artemisia tridentata* ssp. *wyomingensis*, and *Artemisia nova*) were 0.32, 0.23 and 0.13 kg N_2O-N $ha^{-1}y^{-1}$ repsectively. Average annual flux, weighted by the areal extent of these and other vegetation types in the region, was approximately 0.21 kg N_2O-N $ha^{-1}y^{-1}$. Assuming this landscape is representative of sagebrush steppe, we calculate a flux of 9.5×10^9 g y^{-1} of N_2O-N from U.S. sagebrush steppe, and a flux of 1.1×10^{11} g y^{-1} of N_2O-N from analogous desert and semi-desert shrublands of the world.

Introduction

Nitrous oxide is a greenhouse gas whose atmospheric concentration is increasing at the rate of 0.25 to 0.31% per year (Weiss 1981; Prinn et al. 1990). In addition to its role in absorption of infrared energy reradiating from Earth's surface, N_2O participates in the destruction of stratospheric ozone, and it can represent a significant pathway for loss of nitrogen from terrestrial ecosystems (Matson & Vitousek, in press). Consequently, numerous studies have examined the flux of nitrous oxide from a variety of natural and human-influenced ecosystems. Measurements of nitrous oxide flux from semi-desert and shrubland ecosystems are sparse, however, despite the fact that such ecosystems comprise at least 5 million km^2

(3% of total land surface) and are thought to be especially responsive to climate change (NRC 1986).

Sagebrush steppe is a semi-desert shrubland occurring in temperate, semi-arid areas where most precipitation falls as snow. It covers 0.45×10^6 km^2 in the western United States (West 1983a). Sagebrush steppe is dominated by a number of shrubs in the genus *Artemisia*, with other shrubs, grasses, and forbs also present (West 1983a). Within the overall type, variation in topography interacts with strong winds and winter precipitation to cause a complex of shrub communities that are related to landscape position (Burke 1989; Burke et al. 1989). These different communities have different patterns of nitrogen cycling that are controlled proximally by environmental and edaphic characteristics that are in turn controlled by landscape features (Burke 1989).

Because nitrogen cycling varies among plant communities within the sagebrush steppe, emission of nitrogen trace gases could also be expected to vary. Nitrous oxide can be produced during both nitrification and denitrification; although a variety of factors affect the fraction of nitrogen emitted as N_2O, the amount is constrained by the amount of nitrogen moving through those pathways (Firestone & Davidson 1989; Matson & Vitousek 1987). In this study, we examined the temporal and spatial variation in N_2O-N flux from the soil to the atmosphere, and their relationships with patterns of nitrogen cycling.

Methods

Study area

Research sites were located on sandstone parent material of the Browns Park Formation in south-central Wyoming (Love & Christianson 1985). Sites were in the Stratton Sagebrush Hydrology Study Area (SSHSA; Sturges 1982). Terrain in SSHSA is gently rolling, with approximately 100-m relief and average elevation of 2400 m. Most soils are classified in the Argic Cryoboroll great group (Sturges 1986); they range from deep and well-developed in the areas of snow accumulation to shallow and poorly developed on windswept ridges (Burke et al. 1989; Burke 1989). Average annual temperature is 2.7 °C and annual precipitation averages 525 mm with 75% occurring as snow (Sturges 1986).

Vegetation types are controlled by snow accumulation and redistribution (Burke et al. 1989). In areas of deep snow accumulation, such as riparian zones and nivation hollows, grasses and forbs dominate. Along drainages and on leeward slopes where snow accumulation is moderate to

deep, *Artemisia tridentata* ssp. *vaseyana* (mountain big sagebrush) is dominant and is often mixed with *Festuca idahoensis* (ARTRVA type). On slightly drier slopes, *Artemisia tridentata* ssp. *wyomingensis* (Wyoming big sagebrush) dominates (ARTRWYO type). On windward slopes, *Artemisia nova* (black sagebrush) dominates in combination with cushion-forming plants (ARNO type). The most windswept areas are characterized by cushion plants (Burke et al. 1989). Two other vegetation types are common in SSHSA. One is dominated by *Purshia tridentata*, and the other is dominated by *Populus tremuloides*. Both occur in sites with moderate to high moisture levels.

Burke (1989) examined trends in nitrogen pools and processes as they varied among the three *Artemisia* community types. Net nitrification (measured with *in situ* incubations) and nitrate pools in the mineral soil were significantly higher in ARTRVA sites than in the other two types, but only in the spring and early summer months. Soil moisture was also significantly higher in the ARTRVA type during these times.

Nitrous oxide measurements and other soil measurements were carried out in ARTRVA, ARTRWYO, and ARNO community types during the snow-free months of 1986 and 1987. Measurements were also taken in riparian areas dominated by grasses in 1986, and in communities dominated by either *Purshia tridentata* or *Populus tremuloides* in 1987. Sampling in the ARTRVA, ARTRWYO, ARNO, and riparian communities was carried out immediately adjacent to 5 × 5 m permanent plots that were distributed throughout a 360 by 960 m intensive study site in SSHSA. Descriptions of plot layout and vegetation characteristics are presented in Burke et al. (1989). *Purshia* and *Populus* plots were located in draws located within 3 km of the *Artemisia* plots. In 1986, three plots of each community type were sampled; in 1987, replication was increased to four plots.

Nitrous oxide flux measurements

Nitrous oxide fluxes were measured at three points randomly-placed around the perimeter of each replicate plot. Field sampling for N_2O flux utilized 2-piece chambers made of molded white acrylonitrile-butadiene-styrene (ABS) plastic. For each subsample, a sharpened ring 25 cm in diameter was driven several cm into the ground and left in place. At each measurement, the ring was capped tightly with a chamber top; gas samples were withdrawn through an injection port at 0, 5, 10, 15, and 30 minutes after closure, and were injected into specially prepared Venoject™ evacuated vials (Matson & Vitousek 1987). Any vial that did not draw a

strong suction on sampling was discarded, and another sample taken. Vials were resealed with Apiezon™ grease and shipped by air to NASA-Ames for analysis.

Preparation of the venojects involved removing the silicon coated stoppers from the vials and boiling the stoppers for 10 minutes to remove N_2O contamination. After drying, stoppers were greased lightly with Apiezon™ and reinserted in the glass vials, which were then evacuated. After removal from the evacuation system, stoppers were sealed with Apiezon, and shipped to the field for gas collections. Laboratory and field tests indicated that the evacuated vials lost less than 5% of an injected standard over a two-week period.

At the field sites, nitrous oxide standards (0.5 and 1.0 ppmv N_2O in N_2) were injected into five vials for each set of 80 samples. The coefficient of variability of these standards was nearly always less than 5%.

Nitrous oxide concentrations were determined by gas chromatography using a Hewlett Packard 5890 gas chromatograph with a Porapak Q column maintained at 55 °C with a ^{63}Ni electron capture detector. N_2O and CO_2 were separated, but only N_2O concentrations were quantified. Fluxes were estimated as the change in N_2O concentration over time corrected for the ratio of chamber volume to soil surface area covered.

Nitrous oxide flux measurements were taken over the snow-free season, with sampling at more frequent intervals during the relatively wet spring and early summer months. Fluxes were measured 7 times in 1986 and 6 times in 1987; sampling times were pre-arranged and were not timed to coincide with rain events. Average fluxes for each community type at each sampling time were calculated as the mean of 3 (in 1986) or 4 (in 1987) plot values; plot values were mean of three flux measurements. Because of the few flux measurements per plot, it is difficult to determine the skewness of the distribution of fluxes. However, if all flux measurements per community type at a given sampling date are examined together, the distributions are not highly skewed. Combining all flux measurements for a given community type across all sampling dates results in distributions that are highly skewed.

For estimation of annual rates of nitrous oxide emission, fluxes (ng N_2O-N cm^{-2} h^{-1}) at a given date were considered representative for the period until the date of the next sampling. In 1986, the first flux measurements in the *Artemesia* types were taken immediately after snowmelt on May 1; for riparian areas, flux measurements began after snowmelt was complete in June. Fluxes measured at the last 1986 sampling date were used to calculate fluxes until October 1, when they were assumed to be zero. In 1987, the first sampling date was May 13 (a zero flux was assumed up until that date, based on 1986 May data). The last sampling

date (September 22) was used to calculate fluxes until October 1, when they were again assumed to be zero.

Surprisingly, no diel variations in flux were detectable during a series of diel measurements (starting at 0600 hr and ending at 1700 hr) on five chambers. Because these hours encompassed the warmest and coldest soil temperatures of the diel cycle, we assumed constant diel rates of emission. Finally, we assumed that no flux occurred from snow-covered and usually frozen soils, occurring from October to variable dates in May.

Soil sampling

Nitrous oxide measurements in 1986 were carried out in the same areas and at approximately the same times as the measurements of soil nitrogen pool size and microbial transformations reported by Burke (1989). For each sampling time in 1987, one soil core 15 cm in depth was collected adjacent to each of the three chambers per replicate plot. These were mixed together, resulting in one composite sample per plot (4 composites per community type) for each sampling date. Subsamples were extracted in 2N KCl within 12 hours after sampling. Nitrate and ammonium concentrations in the extracts were analyzed colorimetrically in the laboratory at the University of Wyoming. Additional subsamples were placed in cups, covered, and incubated for 10 days in the dark at 20 °C, and were then extracted as described above. Net nitrification was calculated as final minus initial nitrate-N, and net nitrogen mineralization was calculated as final minus initial ammonium-N plus nitrate-N. Soil moisture content was measured on subsamples that were dried for 48 h at 100 °C.

Statistical correlations of soil data with the nitrous oxide fluxes were carried out using a Pearson correlation matrix and paired and stepwise multiple linear regression. Differences in nitrous oxide flux and in soil variables among community types at each sampling time were analyzed with analysis of variance. Individual comparisons of means were made using Tukey's honestly significant difference test.

Results and discussion

Soil nitrogen and nitrous oxide flux

Net nitrification and soil nitrate concentrations in all vegetation types varied seasonally in 1987, with relatively high values early in the growing season, dropping by late June (Fig. 1). Ammonium, on the other hand, remained elevated throughout the summer. Net nitrogen mineralization,

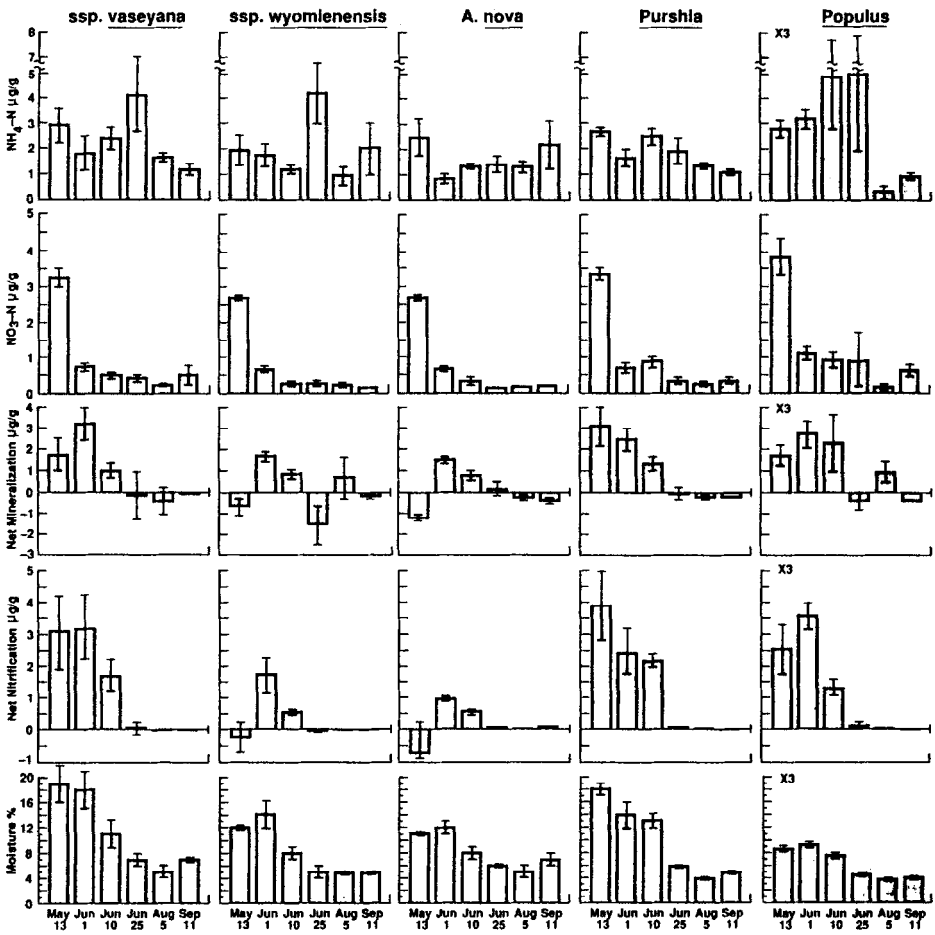

Fig. 1. Soil ammonium and nitrate concentrations (ug g^{-1}), net nitrogen mineralization and nitrification (ug g^{-1} 10 $days^{-1}$, and moisture content (%) for *Artemisia tridentata* ssp. *vaseyana* (ARTRVA), *Artemisia tridentata* ssp. *wyominensis* (ARTRWYO), *Artemisia nova* (ARNO), *Purshia* and *Populus*, for all sampling dates in 1987. Bars are means (± standard error).

net nitrification, and ammonium concentrations were significantly greater in *Populus* plots than in the other types through June 1, 1987 ($p < 0.05$). On June 10, 1987 ammonium concentrations in *Populus* were greater than in the *Artemesia* types; nitrate was greater in *Populus* and *Purshia* than in ARTRWYO and ARNO ($p < 0.05$). Net nitrification was higher in the ARTRVA type than in the other *Artemisia* types for all dates through June 10, with significant differences on May 13 and June 1, 1987 ($p < 0.05$). Similar patterns were also reported by Burke (1989) for 1986.

In both 1986 and 1987, mean nitrous oxide fluxes usually tended to be highest in May or early June, and the lowest fluxes usually occurred in mid to late June (Fig. 2a, b, c). Relatively high fluxes early in the growing season have been reported in a number of temperate sites (Parton et al. 1988; Schmidt et al. 1988).

Differences in nitrous oxide flux among ecosystem types were generally not significant using analysis of variance, but were relatively consistent. ARTRVA plots had higher fluxes than the other types at a majority of the sampling times in both 1986 and 1987 (Fig. 2a, b, c). The ARTRWYO type had higher fluxes than the other *Artemisia* types on June 1, 1987.

Nitrous oxide flux, soil nitrification and soil nitrate pools were highest early in the growing season. Across all sampling dates and sites in 1987, mean nitrous oxide flux was significantly related to mean nitrate pools (Table 1), but relatively little of the variation was explained ($r^2 = 0.042$, $p < 0.02$). No other variable or combinations of variables were significantly related. Within specific community types, nitrous oxide flux was also related to soil nitrogen characteristics (Table 1), and was highest during periods when inorganic soil N pools and N transformation rates were highest. Within specific dates (pooling all community types), nitrous oxide flux was again significantly related to soil nitrogen, and was greatest where inorganic soil nitrogen concentrations were highest (Table 1).

Nitrous oxide flux was not significantly related to soil temperature or moisture in any paired comparison or in stepwise multiple linear regression, even though those both varied seasonally and between types. However, soil nitrogen concentrations and transformations were significantly related to soil moisture and temperature across the entire season (Table 2).

Relationships between nitrous oxide flux and soil nitrogen processes like those found here have also been reported for tropical forests (Matson & Vitousek 1987; Matson et al. 1990). However, in the sagebrush ecosystems, variation in nitrous oxide fluxes could not be explained on the basis of variations in N pools or processes alone. In these systems, the complex interactions among soil warming, moisture availability, nitrogen cycling and plant physiological activity may control fluxes; the importance of such interactions cannot be evaluated by this study.

Annual and regional estimates of nitrous oxide flux

Annual estimates of nitrous oxide flux for each ecosystem type are summarized in Table 3. ARTRVA sites had the highest fluxes both years; ARTRWYO had similar fluxes in both years, but the ARNO type had higher fluxes in the second year. The elevated ARNO fluxes in 1987

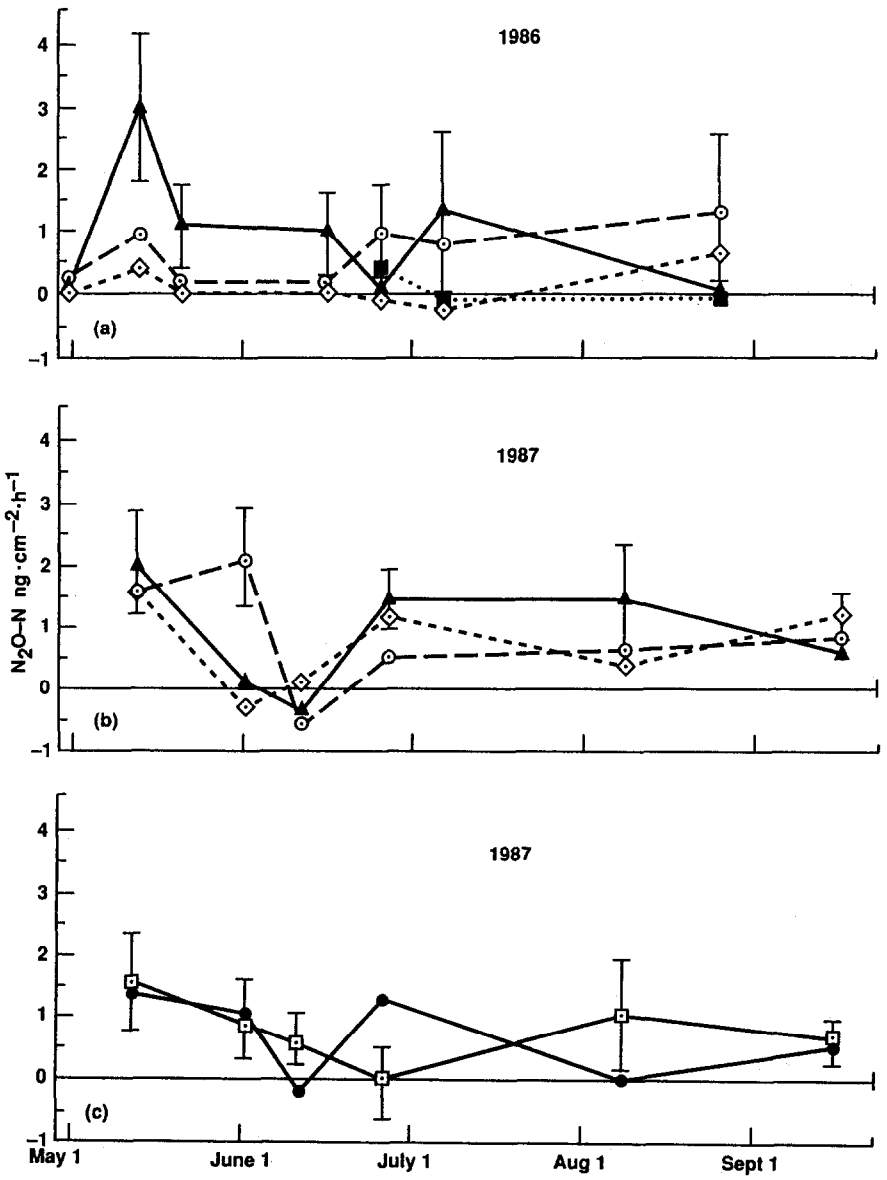

Fig. 2. Mean nitrous oxidee fluxes (ng cm^{-2} h^{-1}) for different ecosystem types across the snow-free seasons. (a) 1986 fluxes: ▲ *Artemisia tridentata* ssp. *vaseyana* (ARTRVA); ⊙ *Artemisia tridentata* ssp. *wyomingensis* (ARTRWYO); ◇ *Artemisia nova* (ARNO); ■ riparian area. (B) 1987 flux measurement for the *Artemisia* types. Symbols are as in Fig. 1a. (C) 1987 fluxes for *Populus tremuloides* (⊡) and *Purshia tridentata* (●). Vertical bars indicate largest standard error of the mean at each sampling date.

Table 1. Significant correlation coefficients (r) from stepwise multiple linear regressions between site means of nitrous oxide flux and soil temperature, moisture, and nitrogen characteristics (1987 data only).

	r	
Across all community types and times		
(5 community types × 4 replicates × 6 dates = 120 n)		
N_2O vs. nitrate	0.204	$p < 0.02$
Within community types and across all dates		
(4 replicates × 6 dates = 24 n)		
ARNO		
N_2O vs. N mineralization	0.378	$p < 0.05$
ARTRWYO		
N_2O vs. nitrate	0.344	$p < 0.05$
P. tremuloides		
N_2O vs. nitrate	0.327	$p < 0.05$
Across all community types at specific dates		
(5 community types × 4 replicates = 20 n)		
May 13, 1987		
N_2O vs. nitrate	0.374	$p < 0.05$
June 10, 1987		
N_2O vs. ammonium	0.473	$p < 0.05$
September 11, 1987		
N_2O vs. nitrate	0.402	$p < 0.05$

Table 2. Correlation coefficients (r) and significance levels between temperature at 5 cm (°C) and moisture (%) and soil net nitrogen mineralization (ug g^{-1} 10 d^{-1}), net nitrification (ug g^{-1} 10 d^{-1}), and ammonium and nitrate-nitrogen concentrations (ug g^{-1}), from pairwise linear regression.

	Temperature	Moisture
Net N mineralization	0.420 $p < 0.001$	0.688 $p < 0.001$
Net nitrification	0.502 $p < 0.001$	0.793 $p < 0.001$
NH_4-N	0.175 $p < 0.05$	0.435 $p < 0.001$
NO_3-N	0.354 $p < 0.001$	0.595 $p < 0.001$

cannot be explained by differences in temperature or moisture between the two years (Burke 1989; Fig. 1).

To estimate overall flux for the study area, annual flux estimates for each type, averaged over 2 years, were multiplied by the areal extent of the types within a region of the Browns Park Formation. Total flux for the 933-km^2 region described by Reiners et al. (1989) is approximately

Table 3. Mean annual nitrous oxide fluxes (kg N_2O-N ha^{-1} y^{-1}) for 1986 and 1987, areal extent (km^2), and extrapolated nitrous oxide flux (using annual fluxes averaged over 2 years) for different ecosystem types in a 933 km^2 region is south-central Wyoming.

	Annual flux kg ha^{-1} y^{-1}		Area* km^2	Total annual flux kg
	1986	1987		
ARTRVA	0.27	0.37	310	9900
ARTRWYO	0.24	0.23	182	4200
ARNO	0.01	0.24	243	3200
All other vegetation			194	
Riparian	−0.01		(97)**	−100
Populus		0.24	(97)**	2200
Purshia		0.23		
Water			4	0***
			Total 933	19400
Area weighted flux	0.21 kg ha^{-1} y^{-1}			
Sagebrush steppe flux	0.21 kg ha^{-1} y^{-1} × 45 × 10^6 ha = 9.45 × 10^9			

* Based on thematic mapper data analysis (Reiners et al. 1989)
** Assumed 50 percent of all other vegetation based on visual examination of remote sensing data (L. Strong, pers. comm.).
*** Assumed zero flux from water.

19400 kg N_2O-N y^{-1} (Table 3). ARTRVA covers around 33% of this area, but accounts for over 50% of the annual nitrous oxide flux.

The average annual flux for this region, weighted by the areal extent of the community types, is 0.21 kg N ha^{-1} y^{-1}. This is twice the simulated annual flux of 0.104 kg N ha^{-1} y^{-1} from shortgrass prairie, which was weighted by upland and lowland positions (Parton et al. 1988). Similarly, Goodroad & Keeney (1984) estimated N_2O flux from Wisconsin prairies at around 0.100 kg N ha^{-1} y^{-1}. In general, the estimated annual fluxes from sagebrush steppe fall within the range of temperate zone forests and prairies (Bowden 1986).

Nitrogen inputs in wet and dry deposition at SSHSA have been estimated at approximately 8.2 kg ha^{-1} y^{-1} in ARTRVA, 6.9 in ARTRWYO, and 6.4 in ARNO types (Ojima, pers. comm.; Reiners et al. 1989). The area-weighted input for the 933 km^2 region described above is approximately 7.4 kg ha^{-1} y^{-1}. The area-weighted annual nitrous oxide flux of 0.21 kg ha^{-1} y^{-1} represents a loss of 2.8% of N inputs.

If we assume that the proportions of area covered by the various communities in our study region are representative of all of the U.S.

sagebrush steppe (covering 0.45×10^6 km^2), we can calculate a total annual flux of about 9.2×10^9 g y^{-1} from sagebrush steppe (Table 3). If we assume a similar flux for the U.S. sagebrush semi-desert (0.17×10^6 km^2, West 1983b) and for analogous deserts and semi-deserts of Eurasia (4.92×10^6 km^2, West 1983c), we can calculate a contribution of 1.1×10^{11} g N_2O-N y^{-1} from these ecosystems. This value is one to two orders of magnitude less than the range of estimates from tropical forests ($2.5 - 7.5 \times 10^{12}$ g y^{-1}; McElroy & Wofsy 1986; Matson & Vitousek 1990). While our calculation for semi-desert ecosystems is based on very limited data collected over a very small region of sagebrush steppe, it does suggest that such systems represent a relatively small contribution to the flux of nitrous oxide to the atmosphere on a global scale. Understanding of the impacts of climate or management changes (especially those that alter nitrogen cycling processes) on nitrous oxide fluxes from these ecosystems, however, requires research at a mechanistic level in a much broader array of semi-desert ecosystems.

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