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Emissions of Sulfur Gases From Marine and Freshwater Wetlands of the Florida Everglades: Rates and Extrapolation Using Remote Sensing

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Rates of emissions of the biogenic sulfur (S) gases carbonyl sulfide (COS), methyl mercaptan (MSH), dimethyl sulfide (DMS), and carbon disulfide (CS_2) were measured in a variety of marine and freshwater wetland habitats in the Florida Everglades during a short duration period in October using dynamic chambers, cryotrapping techniques, and gas chromatography. The most rapid emissions of >500 nmol m^{-2} h^{-1} occurred in red mangrove-dominated sites that were adjacent to open seawater and contained numerous crab burrows. Poorly drained red mangrove sites exhibited lower fluxes of ~60 nmol m^{-2} h^{-1} which were similar to fluxes from the black mangrove areas which dominated the marine-influenced wetland sites in the Everglades. DMS was the dominant organo-S gas emitted especially in the freshwater areas. Spectral data from a scene from the Landsat thematic mapper were used to map habitats in the Everglades. Six vegetation categories were delineated using geographical information system software and S gas emissions were extrapolated for the entire Everglades National Park. The black mangrove-dominated areas accounted for the largest portion of S gas emissions to the area. The large area extent of the saw grass communities (42%) accounted for ~24% of the total S emissions.

INTRODUCTION

Sulfur (S) gases are important components of the global cycle of S [*Andreae*, 1985; *Möller*, 1984]. Through their atmospheric oxidation to sulfate they influence the pH of precipitation [*Charlson and Rodhe*, 1982] and they affect global radiation balance and possibly climate [*Bates et al.*, 1987a; *Charlson et al.*, 1987; *Crutzen*, 1976; *Rampino and Volk*, 1988; *Shaw*, 1983]. Although anthropogenic emissions constitute a large source of gaseous S, mass balance considerations indicate that the release of biogenic S into the atmosphere makes up a significant percentage of S that enters the troposphere annually. Emissions of oceanic dimethyl sulfide (DMS) are a large source of this biogenic S gas [*Andreae*, 1986; *Bates et al.*, 1987b]. However, continental habitats are much more diverse and their role as producers of biogenic S gases remains as one of the most uncertain aspects of our understanding of the atmospheric S cycle [*Andreae*, 1985].

Waterlogged areas are conducive to the production and emission of reduced gases such as methane and reduced S compounds. When considered on an area basis, wetlands are strong sources of atmospheric S gases such as hydrogen sulfide (H_2S), DMS, methyl mercaptan (MSH), carbonyl sulfide (COS), carbon disulfide (CS_2), and dimethyl disulfide (DMDS) [*Hines*, 1993]. The majority of previous work on continental S gas exchange was conducted in salt marshes which emit large quantities of H_2S and DMS [*Jørgensen and Okholm-Hansen*,

1985; *Morrison and Hines*, 1990; *Steudler and Peterson*, 1985]. However, it appears that high fluxes of DMS from salt marshes are restricted to regions inhabited by certain species of *Spartina* and that other marsh areas do not emit unusually large amounts of gaseous S to the atmosphere [*Dacey et al.*, 1987; *Morrison and Hines*, 1990]. In addition, the small spatial extent of salt marshes precludes them as major global sources of gaseous S [*Carroll et al.*, 1986]. Freshwater wetlands and organic rich soils, in some cases, emit relatively large amounts of gaseous S [*Adams et al.*, 1981; *Goldan et al.*, 1987; *Staubes et al.*, 1989], while other freshwater sites, such as Alaskan tundra [*Hines and Morrison*, 1992], emit very little. *Cooper et al.* [1987b] reported that several freshwater wetlands emitted S gases at rates similar to some marine habitats. Because of the uncertainty in the rates of emissions of biogenic S gases, global estimates of the annual emissions of S from terrestrial sources have decreased from ~25 Tg yr^{-1} in 1984 [*Möller*, 1984] to <0.4 Tg yr^{-1} today [*Bates et al.*, 1992].

One approach to refining estimates of regional and global emissions of biogenic gases is to utilize remote sensing data from airborne or orbital platforms to map the distribution and extent of various habitat types. These data, in conjunction with gas flux measurements in these habitats and geographic information system (GIS) software, can be used to derive estimates of gas flux at large spatial scales. *Matthews and Fung* [1987] used this approach with several habitat categories to calculate global CH_4 emissions. *Bartlett et al.* [1989] used a much higher resolution remotely sensed data set and a suite of actual flux measurements to examine variability in emissions of CH_4 from a region of the Florida Everglades.

The present study was conducted to determine the magnitude and range of emission rates of organo-S gases from a variety of

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Sample loops were transported to the South Florida Research Center where they were analyzed within a maximum of 5 hours. In laboratory tests, samples could be stored in loops under liquid N_2 for over 8 hours without loss [*Morrison*, 1988]. Sulfur gases were remobilized by heating loops in a hot water bath, separated on a column packed with 1.5% XE-60, 1% H_3PO_4, 60/80 Carbopack B (Supelco), and quantified by a CS_2-doped flame photometric detector on a Shimadzu model 9A gas chomatograph. The total GC run time was ~6 min with baseline separation of all compounds. Occasionally, when DMS concentrations were high, CS_2 eluted as a skimmed peak on the following edge of the DMS peak. Calibration was conducted using sulfur gases liberated from gravimetrically calibrated permeation devices maintained in a permeation oven. The minimum fluxes that could be detected under the conditions used were <0.4 nmol m^{-2} h^{-1}. Hydrogen sulfide (H_2S) could be detected but could not be quantified because it eluted on the tail of negative peaks due to hydrocarbons and CO_2.

REMOTE SENSING AND CALCULATION OF REGIONAL S FLUXES

To scale up S gas emissions for the Everglades system, we utilized an approach which was similar to that used by *Bartlett et al.* [1989] for CH_4 fluxes in the Shark River slough region of the central Everglades. The distribution of habitats (vegetation types) was inventoried using interpretation of orbital remote sensor data collected by the Landsat thematic mapper (TM) on November 2, 1985. The TM uses seven spectral bands encompassing the visible and infrared regions, and the pixels are 30 x 30 m cells. The TM scene covered much of South Florida, including most of the Everglades National Park, except for the very northwestern edge and some of the islands in Florida Bay to the south. All data processing was done with ELAS software [*Junkin et al.*, 1980]. A vegetation classification was developed to coincide with habitats from which the ground gas flux measurements were taken. Considering these habitats, a parallelepiped classification scheme [*Addington*, 1975] offered the best overall classification results when compared with several other classification procedures (e.g., maximum likelihood). Ground truthing of the classification was based on field inspections during the in situ sampling and partly by interpretation of color infrared photography for the more inaccessible locations. We also utilized vegetation maps provided by the National Park Service. The TM geographic information data base was combined with S emission data for the selected vegetation classes and a regional map was produced which was used to calculate S fluxes for the majority of the Everglades National Park.

RESULTS

Marine Sites

The marine sites exhibited a wide range in rates of S gas emissions (Figure 2). In all instances, except the site dominated by *Batis*, DMS emissions were highest. The well-drained sites (type 1) released the most S gas with summed fluxes of nearly 600 nmol m^{-2} h^{-1} at one location. At this site and the second most active site, enclosures were placed over bare soils that contained openings to crab burrows. The soils within an enclosure placed over a live mangrove in this area did not have any noticeable crab burrows and S emissions were
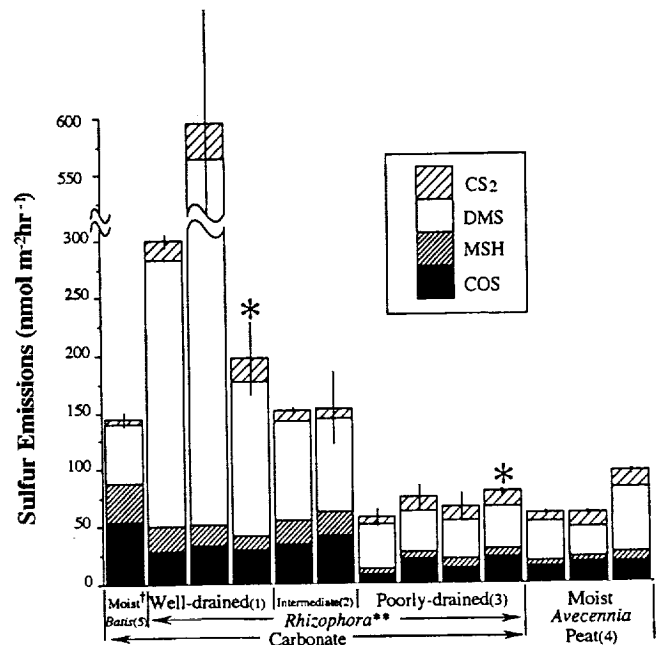

Fig. 2. Rates of sulfur gas emissions from the marine wetland sites in the Everglades. The three types of red mangrove areas (*Rhizophora*) and the *Batis* sites were in carbonate sediments, while the black mangrove sites (*Avecennia*) were in peat sediments. The asterisk represents sites where whole mangrove plants were entrapped within the emission chamber. Site numbers described in the text are included within parentheses. Error bars are standard deviations of replicate measurements at each site.

~200 nmol m^{-2} h^{-1} which were the lowest rates of the well-drained sites. All of these sites were within 2 m of open Florida Bay water.

The intermediate sites (type 2), which were considered transitional between the well drained coarser sediments and the less drained finer-grained sediments, exhibited S fluxes of ~150 nmol m^{-2} h^{-1} which was less than half of the average rate in the well-drained mangrove sites (Figure 2). Differences in S fluxes among all five of the drained sites were attributable to variations in DMS emissions.

Fluxes of S gases from the poorly drained mangrove sites (type 3) were <80 nmol m^{-2} h^{-1} (Figure 2). We noted little variation (<30%) in S gas emissions between these four sites despite the fact that one site included a live mangrove tree and one site was located over one kilometer away from the others.

Fluxes of S gases from the black mangrove sites (type 4) ranged from 60 to 95 nmol m^{-2} h^{-1} (Figure 2). These sites were located ~4 km from open water (Figure 1). Despite the extreme differences in soils between this site and the poorly drained sites described above, S emissions were similar in magnitude and speciation for both types of habitats.

Emissions of S gases from the *Batis*-dominated site (type 5) were twice those of the poorly drained mangrove area (which was ~3 m away) and similar in magnitude to the intermediate mangrove area at ~150 nmol m^{-2} h^{-1} (Figure 2). More than half of the S gas emission from *Batis* was due to COS, and COS and MSH fluxes were the highest recorded for all of the marine sites.

Freshwater Sites

Emissions of S gases from the freshwater sites were generally lower than the marine sites (Figure 3). The dwarf
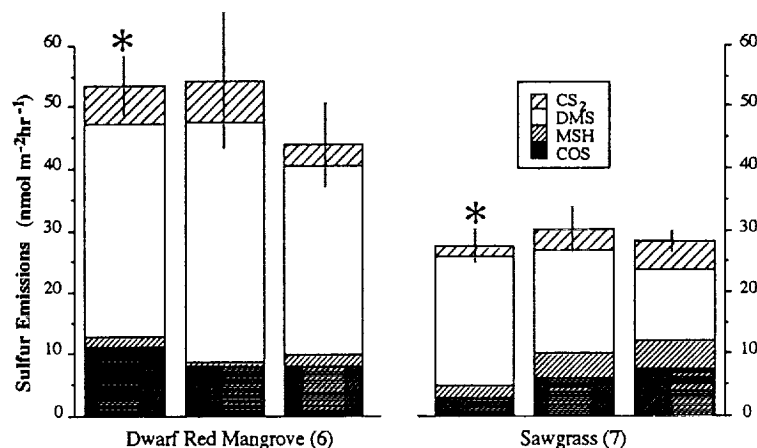
Fig. 3. Rates of sulfur gas emissions from the dwarf red mangrove and wet saw grass sites. The asterisks are sites where plants were entrapped within the emission chamber. At the dwarf mangrove site, the plants within the chamber were *Eleocharis* sp. Site numbers described in the text are included within parentheses. Error bars are standard deviations of replicate measurements at each site.

mangrove sites (type 6), which are influenced by marine waters, exhibited fluxes which were nearly identical in magnitude to the poorly drained red mangrove and the black mangroves sites, while the saw grass sites (type 7) emitted less S than any of the other sites studied. There was very little variation in emissions for each of the replicates examined at the two freshwater sites. The occurrence of plants within the flux chambers had no significant effect on flux rates at these sites (Figure 3). However, the plant biomass was quite low and bare areas (periphyton alone) were common.

Fluxes of S gases from the recently burned sites (type 8) were ~2-fold higher than from the adjacent unburned sites (Figure 4). Flux rates from the unburned site were similar to those in the saw grass site discussed above despite the fact that the emergent biomass was visually much more dense in the unburned area. Emissions from the burned area were similar to those in the dwarf mangroves. Burned and unburned sites containing live plants emitted nearly twice as much gaseous S as bare soils. Plant density at the burned sites was much lower than at the unburned sites and it was possible to place enclosures over areas containing solely hair grass or saw grass. The unburned site was a relatively well-mixed stand of both these species and both were included in enclosures.

Scaling S Emissions to the Region

A color-infrared simulated image of the park derived from TM bands 3, 4, and 5 is depicted in Plate 1. Red shades represent green vegetation (generally, the redder the shade the more vigorously growing or denser the vegetation). Blue and black shades represent water or significant wetness. Greyish shades represent inert materials such as roads, beach sands, rock outcrops, and in some cases yellowing grasses.

Several modifications were made to the initial vegetation classification obtained from the TM image and to the relative grouping of S flux data to provide a useful final categorization. Some of the vegetation classes were not easily discernible because of their small spatial extent and/or spectral similarity to other vegetation types. In some instances the water background predominated over vegetation in spectral response which resulted in mixed vegetation classes. Upland tree species were occasionally spectrally similar to mangroves. By considering the separation between the freshwater and the more

saline environments, the upland pines and the hardwood hammocks were carefully regrouped differently from the mangroves. Widely spaced dwarf mangrove, *Eleocharis* sp., and other related plant communities that had a water-dominated background were also clustered together in a dwarf mangrove category. It was possible to separate other classes of vegetation spectrally, but these were clustered to obtain the six final classes examined during the S flux sampling.

Red mangroves did not spectrally separate consistently from black or white mangrove species. At least part of this was due to their tendency to border along waterways and fall within mixed pixel areas on a frequent basis. Therefore a red mangrove class was artificially incorporated as a border class along all open water bodies within the more saline regions of the image. Any larger clusters were incorporated into the black mangrove class. Since we observed that the well-drained red mangrove sites (type 1) occupied a very small region within a few meters of open water, fluxes from these areas were not used to calculate the regional flux of S gases. The red mangrove regional calculations were made using flux data derived from the mean of the intermediate drained sites (type 2) and the poorly drained sites (type 3).

Salt marsh grasses such as *Juncus* and *Spartina* spp. were moderately separable but were clustered with the *Batis* sp. and other coastal prairie plant communities just as was done in a generalized vegetation map published by the National Park Service. We did not measure emissions from areas dominated
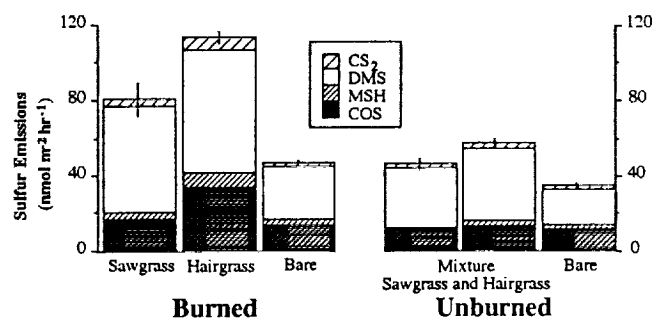

Fig. 4. Rates of sulfur gas emissions from the burned and unburned sites (site 8 in the text). Error bars are standard deviations of replicate measurements at each site.

Plate 1. Thematic mapper image of the Everglades National Park taken on November 2, 1985. The image has been trimmed to include only the park.

Red Mangroves
Coastal Prairie
Black Mangroves
Dwarf Mangroves
Wet Sawgrass
Dry Sawgrass
Pines and Hammocks
Clouds
Cloud Shadows
Water

Plate 2. Map of the classes, derived from thematic mapper data, used for scaling up the S emissions for regional estimates.

TABLE 1. Regional Estimate of Sulfur Gas Emissions From Various Wetland Habitats in the Everglades

Vegetation Category (Site Type[†])	No. of Samples	S Flux,[*] nmol m^{-2} h^{-1}, Mean (SE)	Category Area, km^2	Category Flux, moles h^{-1}	Total Flux, %
Red mangrove (2 and 3)	11	108 (14)	200	21.6	11.9
Black mangrove (4)	8	77 (5.9)	810	62.4	34.4
Coastal prairie (Batis) (5)	1	145	210	30.5	16.8
Dwarf mangrove (6)	6	51 (4.4)	470	24.0	13.2
Wet saw grass (7)	4	29 (6.7)	770	22.3	12.3
Dry saw grass (8)[‡]	6	46 (4.2)	450	20.7	11.4
Regional total	36	62	2940	181.5	100

[*]Total emission combining all four S gases measured.
[†]Refers to habitat types listed in study site section of text.
[‡]Emissions from unburned saw grass community.

by these former species which were restricted largely to areas northwest of where emission measurements were made. However, since these sites were mostly indistinguishable on the image and only occupied a small percentage of the scene, for scale up purposes, we used S flux data from the *Batis* site only. This grouping of classes is partially justified by the finding of *Cooper et al.* [1987b] that rates of S gas fluxes were similar for *Batis* and *Juncus* sites in Florida. However, sites dominated by *Spartina* can emit large quantities of DMS depending on the species of *Spartina* present [*Morrison and Hines*, 1990].

The saw grass sites were divided between those similar to the mahogany hammock sites (type 7) and the saw grass community represented by the unburned sites (type 8). The former contained less biomass with standing water and was designated as wet saw grass, while the latter canopies were more dense, devoid of standing water and designated as dry saw grass.

The final six vegetation classes selected from the TM image analysis and recategorized for scaling up S gas emissions were (1) red mangroves, (2) coastal prairie (*Batis* and salt marsh plants), (3) black mangroves, (4) dwarf mangroves, (5) wet saw grass, and (6) dry saw grass. A few other classes, e.g., clouds, cloud shadows, pines, hardwood hammocks, and water, were included in the mapping exercise to fill out the remainder of the image. We did not measure S fluxes from open water or upland habitats, so these areas were omitted from the scale up.

Plate 2 shows a color-coded distribution map of the vegetation classes utilized here for scaling up S emissions. These vegetation category areas and S gas fluxes were used to calculate gas flux rates for all of the Everglade wetlands (Table

1). Although individual fluxes varied 20-fold throughout the study area, the contribution of each vegetation category to the regional flux varied by a maximum of a factor of ~3 (Table 1). Black mangroves were the most abundant category on an area basis and accounted for the largest percentage of the S gas flux at ~34%. All the other categories accounted for 11 to 17% of the regional wetland flux. Combining both wet and dry saw grass areas accounted for 24% of the flux even though saw grass covered 42% of the total vegetated area considered.

As expected from data for individual sites, DMS dominated the flux of S gases from all sites regardless of whether they were marine or freshwater (Table 2). In fact, the highest percentages of DMS emitted were from the predominantly freshwater sites.

DISCUSSION

Rates of emissions of the sulfur gases studied varied between sites by a factor of ~25. However, spatial variation within sites was usually much less than a factor of 3 and in most instances less than 10%. The fact that all samples were collected within less than a 2-week period, at similar temperatures and during the same time of day made it possible to compare these data without severe complications due to seasonal, diel, or temperature variations. Hence variations were due primarily to spatial variability. This is an important consideration for studies of S gases since diel variations can be large and related to temperature variation [*Goldan et al.*, 1987].

The S flux rates reported here were similar in magnitude to those reported by others for a variety of marine and freshwater wetland habitats (Table 3). The notable exceptions are the rapid fluxes of S gases from salt marsh soils inhabited by *Spartina alterniflora*. In particular, DMS is emitted at high rates from *S. alterniflora* since the DMS precursor, dimethylsulfoniopropionate (DMSP), is abundant in this species [*Dacey et al.*, 1987]. However, when *S. alterniflora* areas are omitted, the sites that we studied emitted S gases at rates that were similar to other habitats regardless of whether they were marine or freshwater. Emissions from the Everglade wetlands were much higher than those from Alaskan tundra [*Hines and Morrison*, 1992] but similar to or less than fluxes of DMS from the ocean [*Bates et al.*, 1992].

Cooper et al. [1987b] measured emissions of gaseous S from some similar sites in the Everglades (Table 3). Their DMS fluxes at sites inhabited by black mangroves, *Batis*, and saw grass ranged from <0.5 to up to 5.5 times those reported here. Their data were collected over a 24-hour period which explains the wide range. Their chambers were not shaded during the day,

TABLE 2. Percentage of Total Regional Flux of S Gases Attributable to Individual Gases

Vegetation Category (Site Type[*])	COS	MSH	DMS	CS_2
Red mangrove (2 and 3)	26	12	52	9.6
Black mangrove (4)	21	10	54	14
Coastal prairie (Batis) (5)	38	23	36	3.3
Dwarf mangrove (6)	18	2.8	69	11
Wet saw grass (7)	19	12	58	11
Dry saw grass (8)[†]	25	4.0	65	5.7
Regional total	26	13	58	9.7

[*]Refers to habitat types listed in study site section of text.
[†]Emissions from unburned saw grass community.

TABLE 3. Ranges of Emission Rates of Biogenic Sulfur Gases From Various Habitats

Location	Emission Rate, nmol m^{-2} h^{-1}				
	DMS	MeSH	COS	CS$_2$	Reference
Marine subtropical wetlands					
red mangrove, *Rhizophora**, Oct.[†]	40 - 600	5 - 22	8 - 42	5 - 30	1
black mangrove, *Avicennia*, Oct.[†]	25 - 56	5 - 8	14 - 19	7 - 14	1
Avicennia, Jan.[‡]	9 - 310	NR[§]	NR	0 - 19	2
Batis, Oct.[†]	52	34	54	5	1
Batis, Jan.[‡]	31 - 220	NR	NR	3 - 9	2
Marine temperate wetlands					
Spartina alterniflora[‡]	0 - 2x10^4	0 - 300	-40 to 140	0 - 700	3-7
S. patens[‡]	0 - 130	0 - 60	10 - 36	NR	5
Juncus romerianus	100 - 650	5 - 75	17 - 41	7 - 30	7,8
Distichlis spicata	19 - 720	NR	NR	6 - 53	7,8
Freshwater subtropical wetlands*					
Cladium, Oct.[†]	16 - 57	1.9 - 4	3.0 - 17	1.5 - 4	1
Cladium, Jan., March, May[‡]	0 - 220	NR	NR	0 - 16	2
Muhlenbergia, Oct.[†]	39 - 65	2.5 - 8	12 - 34	2.9 - 7	1
dwarf mangroves, Oct.[†]	34	1.7	11	6.2	1
Freshwater temperate wetlands					
swamps[‖]	14 - 700	NR	18 - 85	21 - 78	9
decaying cattails	0.4 - 3	NR	10 - 19	NR	7
Subarctic freshwater tundra[¶]	0 - 12	0	0.2 - 12	0 - 3	10
Subarctic marine tundra[¶]	0 - 250	0 - 5	6 - 21	2 - 10	10
Ocean average	170 - 340				11

(1) This study; (2) *Cooper et al.* [1987b]; (3) *Cooper et al.* [1987a]; (4) *de Mello et al.* [1987]; (5) *Morrison and Hines* [1990]; (6) *Steudler and Peterson* [1985]; (7) *Goldan et al.* [1987]; (8) *Aneja et al.* [1981]; (9) *Adams et al.* [1981]; (10) *Hines and Morrison* [1992]; (11) *Bates et al.* [1992].
*All sites in Florida.
[†]Samples collected midday.
[‡]Samples collected over a 24-hour period.
[§]Not reported.
[‖]Includes histosols (peat and muck), areas in Florida that may be subtropical, and one fen in Minnesota.
[¶]Midsummer values.

so depending on weather conditions, it was possible that temperatures inside the chambers were unusually high on some occasions. Although some of the sites studied by *Cooper et al.* [1987b] were in the Everglades, in some cases, such as the black mangrove sites, they sampled areas which were several kilometers from the sites we investigated. However, the flux rates measured in both studies were quite similar. This was surprising since the degree of inundation and the tidal and temperature regimes might have differed enough to cause large dissimilarities in fluxes for sites which were spatially separated and studied several years apart. The similarity noted may indicate that this type of habitat is relatively uniform with regard to emissions of S gases from soils.

The greatest variation in S emissions in the present study was due to the high DMS fluxes from the well-drained carbonate soils inhabited by red mangroves. When mangrove sediments were poorly drained and relatively fine grained, emissions were much slower. The bulk of this difference was due to DMS fluxes which were high in the well-drained carbonates. In addition, highest DMS fluxes occurred in sites containing crab burrows. *Smith et al.* [1991] found that these crabs transport virtually all of the mangrove leaf litter into their burrows where the leaves decompose. It appears that the decomposition of leaves in burrows was responsible for the high DMS fluxes noted. The presence of small (60 cm) mangroves within enclosures did not result in any increase in DMS flux relative to sediments alone. Hence the positive relationship between live plant biomass and DMS flux noted for *S. alterniflora* [*de Mello et al.*, 1987; *Morrison and Hines*, 1990] was not apparent in the red

mangrove sites. However, the decomposition of dead leaves in burrows appeared to generate significant quantities of DMS.

Recently burned sites emitted twice the quantity of S gases as unburned sites which were only 10 m away. Photosynthesis and CH$_4$ emissions, which were measured at these sites within a few days of the measurements reported here, were twice as high in the burned areas as well [*Whiting et al.*, 1991]. Since the biomass in the burned areas was sparse compared to the unburned sites, the plant activity per unit of live biomass must have been much higher in the burned sites. It was unclear whether the enhancement in S fluxes from burned areas was due to enhanced plant metabolism or the sedimentary utilization of S that was liberated from biomass during burning. Within both the burned and the unburned sites, faster rates of S gas release occurred within enclosures placed over plants suggesting they were involved in S gas exchange. Because of the frequency of fires in the Everglades, burning should be considered when gas exchange is estimated.

Data on emissions of COS must be viewed with caution since it was likely that the dynamic enclosure system used here resulted in data which made it appear that all sites were net sources of this gas. However, data from enclosure systems which contain ambient or COS-supplemented air demonstrated that some habitats are net sinks for COS [*Hines and Morrison*, 1992; *Morrison and Hines*, 1990; *Steudler and Peterson*, 1985]. Plants are known to consume COS [*Fall et al.*, 1988; *Goldan et al.*, 1988; *Kluczewski et al.*, 1983, 1985] and it has been proposed that this consumption is a major global sink for the gas [*Brown and Bell*, 1986; *Goldan et al.*, 1988]. However,

since COS is abundant in the atmosphere compared to other S gases, when dynamic chambers use S-free sweep air, there can be an increase in COS concentration within the chamber relative to the S-free sweep gas which is interpreted as a net flux even though a net removal may be occurring at ambient COS levels [*Hines and Morrison*, 1992]. We have not observed this artifact for the other S gases measured. If COS is indeed consumed by the system rather than emitted by it, which is likely, then the total organo-S gas fluxes from the Everglades will be ~25% lower than calculated in Table 1. The percentage of flux due to the other S gases will also increase accordingly (Table 2), making DMS account for over 70% of the total flux.

The scaling of S gas emissions to a regional area using vegetation classes and remote sensing data was intended to provide a "snapshot" of S flux and to help decipher which habitats, if any, deserve attention in future work. It was not intended that the regional data would serve as benchmark of S fluxes in this system, particularly with the small data set employed. Unlike CH_4, S flux data are difficult and tedious to obtain and relatively large data bases, such as those used for regional estimates of CH_4 flux by *Bartlett et al.* [1989], are not available. Furthermore, biogenic S fluxes from terrestrial sources, including the Everglades [*Cooper et al.*, 1987b, 1989], exhibit strong diel variability. Emissions of CH_4 apparently do not vary greatly throughout a 24-hour period unless plants actively transport gas. In addition, the present study was conducted over a relatively short time period with measurements made over a small portion of the day. Since all of the measurements here were determined under similar climatic conditions for each of the sites, it was assumed that flux data for each site could be compared. However, the scaling exercise yields a regional estimate of flux for the conditions of this study only and are not applicable to nighttime or any other season.

We had insufficient data to adequately address the variability within each habitat. In all sites except *Batis*, chambers were deployed in more than one location and the variation between these local sites was usually less than 15% (expressed as percent of the standard error/mean). However, the individual emissions chambers were never more than 36 m apart. *Bartlett et al.* [1989] reported that sample sizes greater than 20 were needed to achieve a variability of <15% (calculated as above) for CH_4 fluxes along a 1 km transect in a particular freshwater habitat in the Everglades. The lower variability noted here for S gases may be due simply to the fact that all the samples for a particular habitat type were collected in close proximity to each other. Hence the S gas data probably provided a much cruder estimate of regional flux than the variability alone indicated. In addition, *Bartlett et al.* [1989] found no correlation of flux with temperature and *Harriss et al.* [1988] found that CH_4 flux in the Everglades was not sensitive to seasonal changes in temperature. However, *Cooper et al.* [1987b] found that DMS emissions from a saw grass site in the Everglades increased ~10-fold from January to May.

The "snapshot" approach to estimating regional S gas emissions suggested that over half of the S flux from regions harboring emergent vegetation in the Everglades was from marine-influenced wetlands, i.e., mangroves and the *Batis*/salt marsh sites. The saw grass sites were less important because of the low area flux from saw grass areas with standing water such as those at mahogany hammock. However, if emissions of S gases from open waters (depths greater than 30 cm) were significant then the freshwater areas could have been similar to

the marine sites. We did not determine S gas emission rates for open water sites. However, other studies have demonstrated that both marine [*Bates et al.*, 1987b] and fresh [*Richards et al.*, 1991] open water sites can emit significant quantities of S gases to the atmosphere. Although open water sites deserve some attention in the future, the Landsat thematic mapper sensor is designed for delineating terrestrial vegetated habitats and is not suited for discriminating water bodies on the basis of variations in water color. Since emissions of S gases from water should vary depending on their particular chemistries and productivities, our scaling up exercises were restricted to sites with emergent vegetation. In addition, if the burned saw grass areas were to occupy a large area of the Everglades then S fluxes for the whole region would increase slightly as well.

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