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Nitrogen flows in Louisiana Gulf Coast salt marsh: Spatial considerations

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Abstract. Nitrogen flux data was synthesized in developing a nitrogen flow budget for a Louisiana Barataria Basin *Spartina alterniflora* salt marsh. Results demonstrate the importance of spatial consideration in developing a nitrogen budget for coastal marshes. Using a mass balance approach nitrogen inputs balanced nitrogen sinks or losses from a marsh soil-plant system with a specific rooting depth. However, per unit areas on a local scale, marshes serve as a large sink for nitrogen due to rapid accretion which removes $17.0\,g\,N\,m^{-2}\,yr^{-1}$ through subsidence below the root zone. On a larger spatial scale (regional) it is shown that the marshes do not serve as a large nitrogen sink. The rapid marsh deterioration currently occurring in the rapidly subsiding marshes of the Mississippi River deltaic plain account for a net regional loss of $12.5\,g\,N\,m^{-2}\,yr^{-1}$. Thus, regionally the net sink is equivalent to only $5\,g\,N\,m^{-2}\,yr^{-1}$ as compared to $17.0\,g\,N\,m^{-2}\,yr^{-1}$ on a local scale.

Introduction

There has been increased interest in nitrogen cycling in coastal marshes since nitrogen has been identified as the most important nutrient regulating the wetland macrophyte production (Valiela & Teal 1974; Patrick & DeLaune 1976; Buresh 1980). Although specific details of the biochemical rates and mechanisms are still being established, the general pathways of the nitrogen cycle have been known for quite some time. The nitrogen cycle in coastal wetlands, however, is extremely complex, and many aspects are poorly understood. The nitrogen cycle relies heavily on both biological and physical processes. Microorganisms are responsible for the fixation of atmospheric nitrogen which can be transformed into forms usable by other organisms and marsh plants. Microorganisms also denitrify, i.e., convert nitrogen back into atmospheric nitrogen. Sedimentation and tidal exchanges also influence biogeochemical nitrogen cycle in salt marshes. A number of studies of nitrogen fluxes have been conducted in Louisiana salt marshes. In this

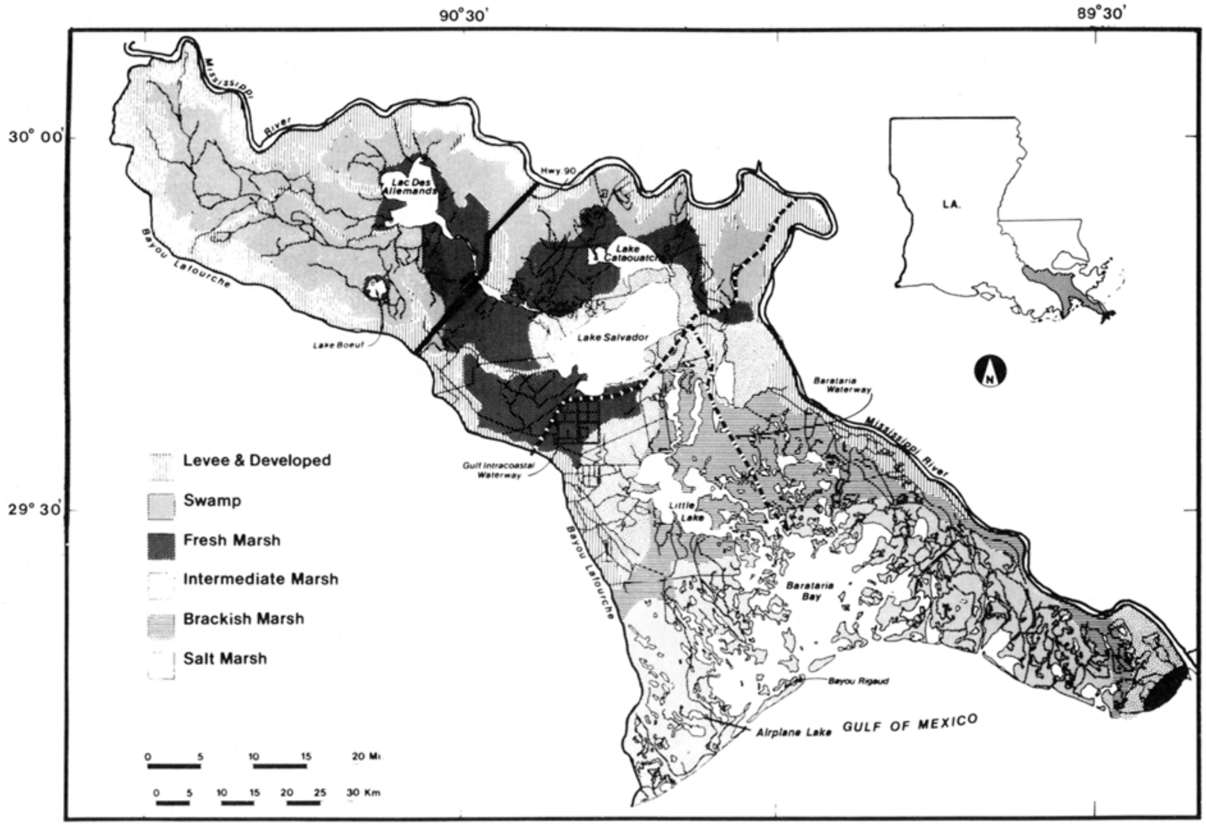

Fig. 1. Barataria Basin showing location of salt marshes (modified from Day et al. 1982).

paper, we synthesize these studies into a nitrogen budget for salt marshes in lower Barataria Basin (Fig. 1).

Nitrogen inputs

A large amount of nitrogen is required to produce the biomass of *Spartina alterniflora* found in Barataria Basin salt marsh. Nitrogen enters the marsh-estuarine ecosystem by two different mechanisms:

- fixation, and
- input from adjacent systems and wet deposition.

Molecular nitrogen is fixed by various microbial inhabitants of the marshes and estuaries.

Nitrogen fixation provides the second largest input of nitrogen to the marsh. Casselman (1981) using the acetylene reduction technique found fixation to occur in all habitats of the marsh except in the water column where no significant fixation was measured. A greater mean fixation was measured on dead plant material as compared to live plant. However, the combined rate of nitrogen fixation on both live and dead *S. alterniflora* was less than $0.2\,g\,N\,m^{-2}\,yr^{-1}$. Seasonally, the greatest measured fixation was in the streamside marsh soil where fixation rates equivalent to $15.4\,g\,N\,m^{-2}\,yr^{-1}$ were measured. Fixation was considerably less ($4.5\,g\,N\,m^{-2}\,yr^{-1}$) in the adjoining inland marsh. The streamside rates are similar to rates reported by Sherr (1977) for salt marsh soils of Sapelo Island. Reported fixation in Louisiana salt marsh closely paralleled root distribution in the soil profile. A highly significant negative relationship between nitrogenase activity and 2N KCL extractable ammonium nitrogen in the soil profile was observed. For the marsh as a whole we estimated that $10\,g\,N\,m^{-2}\,yr^{-1}$ is fixed based on acetylene reduction method using the theoretical conversion factor of 3 mole sof acetylene reduced per mole of nitrogen fixed. However it should be noted that this theoretical ratio may vary based on comparison between acetylene reduction and direct nitrogen-15 uptake rates (Hardey et al. 1973).

Another mechanism by which nitrogen enters the Barataria Basin salt marsh is sediment imported in tidal waters. Particulate nitrogenous compounds or other nitorgenous materials sorbed to the various suspended sediments may be carried into the estuary and may then be deposited on the marsh surface by tides. Limited data are available on the amount of nitrogen transported in this manner. Using sediment traps. DeLaune et al. (1981) found that an average of $17\,g\,N\,m^{-2}\,yr^{-1}$ is imported to the salt marsh surface in sediment. The sediment import figure represents averages for streamside and inland locations. Deposition of particulate-bound nitrogen is an important fertilization mechanism for the marsh grasses.

Nitrogen may also be brought into the estuary in solution by the incoming streams and, imported into the marsh by the tides and by wet deposition. In Barataria Basin, nitrogen entering from adjacent uplands is an important source in the upper Basin (Day et al. 1977; Hopkinson & Day 1979). For example, total nitrogen loading into Lac des Allemands is in excess of $30\,g\,N\,m^{-2}\,yr^{-1}$, and the lake is highly eutrophic (Day et al. 1977; Craig & Day 1977). However, this nitrogen is adsorbed or removed before reaching the salt marsh in the lower estuary. There is no information on nitrogen's input by wet deposition. We estimate import of dissolved nitrogen be less than $1\text{-}\,g\,N\,m^{-2}\,yr^{-1}$.

Nitrogen regeneration and uptake

Mineralization of soil organic nitrogen to the ammonium form is the primary source of inorganic nitrogen for *S. alterniflora*. Very little nitrate is present in these flooded marsh soils because there is a lack of oxygen for appreciable nitrification and also any nitrate which may be formed is rapidly denitrified (DeLaune et al. 1976). Laboratory studies have shown that streamside soils are capable of mineralizing approximately $9.0\,\mu g$ nitrogen per gram of soil per week through mineralization (DeLaune & Patrick 1979). Ammonium nitrogen released by mineralization from the streamside marsh soil was continuously extracted with a slow flow of oxygen-free 2% NaCl solution at 30°C. Using an active rooting depth of 30 cm and a bulk density of $0.30\,g\,cm^{-3}$ for the streamside marsh, the equivalent of $40\,g\,m^{-2}$ of nitrogen would become available over a one year period. True mineralization rates in the field would be somewhat less since mineralization is lower during winter months. We thus estimate that the marsh is supplying $25\,g\,m^{-2}\,yr^{-1}$ of ammonium nitrogen through the mineralization process. Most of this is quickly taken up by plants.

Even though the mineralization and release of nitrogen in the sediment provides a significant portion of the plant requirement, Louisiana salt marshes are still nitrogen limited as fertilization experiments have shown. Supplemental labeled inorganic nitrogen applied in the spring increased the aboveground biomass *S. alterniflora* at the streamside marsh by 155 (Patrick & DeLaune 1976; DeLaune & Patrick 1979). The added nitrogen caused a yield increase equivalent to $250\,g\,m^{-2}$. Ammonium nitrogen was used in this experiment. Practically all of the inorganic nitrogen in a reduced soil is found in the ammonium form. The use of labeled nitrogen made it possible to distinguish between plant nitrogen derived from the sediment and the added fertilizer nitrogen. The amount of plant nitrogen derived from the sediment was about 59% during June and July and increased to about 69% by September. The supply of added nitrogen diminished toward the end of the growing season, probably through nitrogen losses from nitrification-denitrification reactions as well a prior plant uptake. Only 29% of the 20 g m^{-2} of added nitrogen was recovered in the aboveground portion of the plants in September. Assuming an equal amount was incorporated in the belowground biomass, we can account for 60% of the added labeled inorganic nitrogen during this one growing season. Nitrogen balance studies have shown N-loss was less in succesive years when nitrogen entered the organic pool (DeLaune et al. 1983).

A similar experiment in which supplemental nitrogen was applied to the adjacent inland marsh which is receiving less mineral sediment showed a greater response to added nitrogen (Buresh et al. 1980). The addition of 20 g m^{-2} of labeled nitrogen in May significantly increased total aboveground plant biomass and plant height by 28% and 25%, respectively, during the growing season. The increase in plant biomass was almost twice the increase observed from the addition of an equal amount of nitrogen at the streamside location. The inland marsh sediment supplied approximately 50% of the nitrogen taken up by the plants over the growing season as compared to 69% for sediments from the streamside marsh. These fertilization experiments using labeled nitrogen show that the inland marsh soils are apparently supplying less nitrogen for plant growth than streamside marsh soils. In this study 57% of the added nitrogen was recovered in the aboveground and belowground biomass. The relatively large recovery from a single additions of large quantities of added fertilizer ammonium nitrogen indicates that *S. alterniflora* has a high capacity to assimilate soil inorganic nitrogen forms.

Nitrogen losses

The main nitrogen losses from marshes are denitrification and detrital export and sedimentation sinks. Denitrification has been hypothesized to be the major avenue of nitrogen loss from marshes. Although the potential for denitrification is very high in reduced marsh soil, the level of in situ denitrification depends upon the availability of nitrate. Nitrate must be either formed through nitrification of ammonium or else supplied from an extrinsic source of tidal input, wet deposition, or groundwater flow.

Earlier studies, as shown in this study, indicate that under natural con-

Table 1. Estimates of nitrogen loss as nitrous oxide from the three predominant marsh and open water environments found within Barataria Basin.[1]

Location	N_2O Evolution	
	Average[2] $\mu g\,N\,m^{-2}\,d^{-1}$	Annual $mg\,N\,m^{-2}\,y^{-1}$
Salt marsh	84	31
open water	27	10
Brackish marsh	130	48
open water	57	21
Fresh marsh	150	55
open water	94	34

[1] From Smith et al. 1983
[2] Measurement period: 730 days

ditions the gaseous N losses from salt and brackish marshes of the Louisiana Gulf Coast are minimal (Smith & DeLaune 1983; Smith et al. 1983). A two year study of N_2O emission from Barataria Basin salt marshes indicated annual emission of 31 mg $N_2O\,m^{-2}\,y^{-1}$ (Smith et al. 1983) (Table 1).

These reported N_2O emissions provide evidence that nitrification-denitrification occurs in coastal wetlands which are generally considered anaerobic. The low N_2O emission rates also indicate that there is a relatively small amount of N_2 being lost as a result of nitrification-denitrification reactions. Dinitrogen evolution can be estimated from the ratio N_2:N_2O. Ratios of N_2:N_2O ranging from a maximum 250:1 (Seitzinger et al. 1980) to 7:1 (Firestone et al. 1979) have been reported in the literature. Terry & Tate (1980) reported a ratio N_2:N_2O of 220:1 for organic soils. A 14:1 ratio was used to assess the amount of N_2 evolved to atmosphere from the salt marsh (Lindau et al. 1988). The ratio was measured in the northern portion of Barataria Basin by determining labelled $^{15}N_2$ and N_2O evolution following application of ^{15}N labelled nitrate and ammonium nitrogen. Applying this ratio to N_2O emission data we estimate the denitrification loss from the salt marsh to be in the order of $4\,g\,N\,m^{-2}\,yr^{-1}$.

These are limitations from the denitrification estimates based on N_2O emission and selecting a variable N_2O:N_2 ratio. However, we feel that our denitrification estimates are close to actual values since our nitrogen balance studies indicate a very efficient internal nitrogen cycle without appreciable nitrogen lost from the soil-plant system.

Our estimates of denitrification are lower than those reported for Atlantic coast salt marshes. Haines et al. (1977) estimated denitrification to be $12\,g\,N\,m^{-2}\,yr^{-1}$ in a Georgia salt marsh. Kaplan et al. (1979) and Valiela & Teal (1979) reported large losses of nitrogen through denitrification in the Great Sippewissett marsh. High denitrification rates would be expected in such marshes since they recieve large inputs of nitrate from groundwater or other sources. Louisiana Gulf coast salt marshes receive no inorganic nitrogen from groundwater sources and tidal flushing brings in only small quantities of nitrate.

Ammonia volatilization from marshes is generally assumed to be negligible. Ammonia volatilization from Barataria Basin salt marsh was less than $1\,mg\,N\,m^{-2}\,yr^{-1}$ (Smith & DeLaune 1983). This loss of nitrogen via NH_3 volatilization can be explained by the low values of NH_4^+ (Ho, 1971) and the near neutral pH (7.0–7.6) of the flood water covering these marshes. It has been shown that the presence of plants also reduces nitrogen losses from flooded systems (Buresh et al. 1981). Actively growing wetland plants compete with nitrifiers and denitrifiers for available soil N and assimilate most of the NH_4^+ in the N-limited marsh sediment before it can be lost by NH_3 volatilization and nitrification-denitrification reactions.

Such field estimates of nitrogen losses through denitrification have also been supported by greenhouse studies in which labeled ammonium nitrogen equivalent to 100 μg nitrogen per gram of soil was added in 10 μg increments to marsh soil cores containing *S. alterniflora*. The ammonium nitrogen was added in increments so as to approximate the release of nitrogen to plants by soil mineralization processes. Nitrification-denitrification reactions were presumably the mechanism of the ammonium nitrogen loss. Less than 10% of the added nitrogen was lost from such systems over a 21 week period (Buresh 1981). These results indicate that the ammonium nitrogen mineralized in Louisiana salt marsh soil systems is rapidly assimilated by *S. alterniflora* thus minimizing nitrification-denitrification losses.

^{15}N Balance studies have also demonstrated that added nitrogen is not lost to any extent during the first growing season (DeLaune et al. 1983). Losses of ^{15}N labelled nitrogen in a *Spartina alterniflora* salt marsh was measured over three growing seasons. Labelled NH_4^+-N equivalent to $100\,\mu g\,^{15}N\,g^{-1}$ of dry soil was added in four installments over an eight week period. Recovery of the added nitrogen ranged from 93% 5 months after addition of the NH_4^+-N to 52% at the end of the third growing season which represented a nitorgen loss equivalent to $3.4\,g\,N\,m^{-2}$. A significant portion of this loss was attributed to transport of nitrogen enriched plant material from the marsh. The availability of the labelled NH_4^+-N incorporated into the organic fraction was estimated by calculation of the rate of mineralization. The time required for mineralization of 1% of the tagged organic N increases progressively with succeeding cuttings of the *S. alterniflora* and ranged from 152 to 299 days. The N remaining in the system was in the organic N pool and only slowly mineralized and released. Similar results have been reported in greenhouse studies (Buresh et al. 1981).

Nitrogen losses through sedimentation is also appreciable in these rapidly accreting salt marshes. Sedimentation rates from ^{137}Cs dating shows that these marshes are vertically accreting at a rate on the order of 1 cm yr^{-1}. The range varies depending on marsh site, and measured rates were 0.75 cm yr^{-1} to 1.35 cm yr (DeLaune et al. 1978). Calculations using accretion rates, bulk density and nitrogen content of the marsh soil show that the salt marsh is undoubtedly a large sink for nitrogen. For a streamside and inland marsh location sedimentation would remove 21.0 and 13.4 g N m^{-2} yr^{-1} (Table 2). Using an average for streamside and inland marshes we estimated nitrogen is accumulating at a rate of 17 g N m^{-2} yr^{-1}. These sedimentation losses of nitrogen represent an average for the past 25–30 years. The ^{137}Cs dating technique can not depict yearly changes. Other investigations in these salt marshes have also reported nitrogen sinks on a local scale of the order reported above (DeLaune et al., 1983). These losses are considerably greater than that for Atlantic coast marshes which are accreting at a slower rate. For instance, Valiela & Teal (1979) estimated sedimentation losses to be in order of 4 g m^{-2} yr^{-1}.

Recent work on carbon flux and export in marshes of Barataria Basin (Feijtel et al. 1985) provides a basis for estimating amounts of nitrogen being exported in detrital form from the salt marshes. A mass balance approach of carbon fluxes reports 255 g cm^2 yr^{-1} of the carbon fixed in the salt marsh unaccountable or thought to be exported. Assuming a C:N ratio of 50 to 1 an equivalent of 5 g N m^{-2} yr^{-1} would be exported as detritus.

Nitrogen losses through marsh deterioration

Understanding the raltionship among land sinking, vertical marsh accretion and marsh determination is also important in understanding regional influence on salt marsh nitrogen budgets.

Water level is rapidly rising in the wetland habitats of the Louisiana's Gulf Coast primarily because of rapid subsidence (Salinas et al. 1986). Louisiana's coast, especially the Mississippi River deltaic plain, is rapidly subsiding, both locally and regionally. Basement sinking stems from a

Table 2. Sedimentation as a nitrogen sink.

	N content of marsh sediment	Sedimentation rate ^{137}Cs	N accumulation rate
Streamside	6.2 mg/g	1.35 cm yr^{-1}	21.0 g m^{-2} yr^{-1}
Inland	8.7 mg/g	0.75 cm yr^{-1}	13.4 g m^{-2} yr^{-1}

decreasing sediment load, sediment consolidation, and tectonic activity. Natural levee ridges form an elevated embankment bounding the lower interdistributary basins.

In the past century, the Louisiana Gulf Coast has been retreating at rates estimated as high as 130 km^2/yr (Gagliano 1981), and this rate of deterioration is accelerating. Portions of the salt marsh in Barataria Basin are being converted into open water, because marsh accretion is not keeping pace with water level increases.

There are 65,400 hectares of salt marsh in lower Barataria Basin (Gosselink 1984). It is estimated that the salt marshes are deteriorating at the rate of 2% per year (Leibowitz & Hill 1987). Appreciable nitrogen is stored in these highly organic soils. As the marsh breaks up and erodes nitrogen is removed. Calculations, using average soil depth (50 cm), bulk density (0.25 $g\,cm^{-3}$), and total nitrogen content of soil (5 mg N g) show that on a regional basis the equivalent of 12.5 $g\,N\,m^{-2}\,yr^{-1}$ is lost from the salt marshes due to deterioration of Barataria Basin salt marshes.

Summary and conclusion

For the soil-plant system nitrogen gains and losses are nearly balanced in Louisiana Gulf Coast salt marshes (Table 3). Nitrogen rich sediment being deposited on the marsh is the primary source of nitrogen, supplying 17 $g\,N\,m^{-2}\,yr^{-1}$. Nitrogen fixation provides approximately 10 $g\,N\,m^{-2}\,yr^{-1}$, whereas rainfall was estimated to be less than 1 $g\,N\,m^{-2}\,yr^{-1}$. For a stable marsh the primary losses are net sedimentation 17 $g\,N\,m^{-2}\,yr^{-1}$, detrital

Table 3. Local nitrogen budget (average streamside and inland site for Louisiana *Spartina alterniflora* salt marsh) representing gains and losses from plant and plant root zone.

Gains		Losses	
$g\,N\,m^{-2}\,yr^{-1}$		$g\,N\,m^{-2}\,yr^{-1}$	
[1]Nitrogen fixation	10.0	[2]Sedimentation	17.0
[2]Import	17.0	[4]Denitrification	4.0
[3]Wet deposition	< 1.0	[5]Export	5.0
		[6]Volatilization	< 1.0
Total	~27.0	Total	~26.0

[1] Casselman et al. 1981
[2] DeLaune et al. 1981
[3] Estimated
[4] Smith et al. 1983
[5] Fejtel et al. 1985
[6] Smith & DeLaune 1983

Table 4. Regional nitrogen budget (average streamside and inland site for Louisiana *Spartina alterniflora* salt marsh) representing total net gains and losses per unit area of marsh.

Gains		Losses	
$g\,N\,m^{-2}\,yr^{-1}$		$g\,N\,m^{-2}\,yr^{-1}$	
[1]Fixation	10.0	[4]Denitrification	4.0
[2]Import	17.0	[5]Export	5.0
[3]Wet deposition	< 1.0	[6]Volatilization	< 1.0
		[7]Erosion or deterioration	12.5
Total	~27	Total	~22

[1] Casselmann et al. 1981
[2] DeLaune et al. 1981
[3] Estimated
[4] Smith et al. 1983
[5] Feijtel et al. 1985
[6] Smith and DeLaune 1983
[7] Leibowitz and Hill 1987

export $5\,g\,N\,m^{-2}\,yr^{-1}$, and denitrification $4\,g\,N\,m^{-2}\,yr^{-1}$. Ammonia volatilization as a loss is insignificant. On a site-specific basis these losses balance the nitrogen inputs when developing a budget for a soil-plant system with limited rooting depth. However, per unit surface (e.g., m^2), marsh is a major sink due to the rapid accretion which remove $17\,g\,N\,m^{-2}\,yr^{-1}$ below the plant root zone. In contrast, when nitrogen loss through marsh deterioration on a regional basis is considered the marshes of the rapidly subsiding Mississippi River deltaic plain may not serve as a significant sink with only $5\,g\,N\,m^{-2}\,yr^{-1}$ accumulating (Table 4).

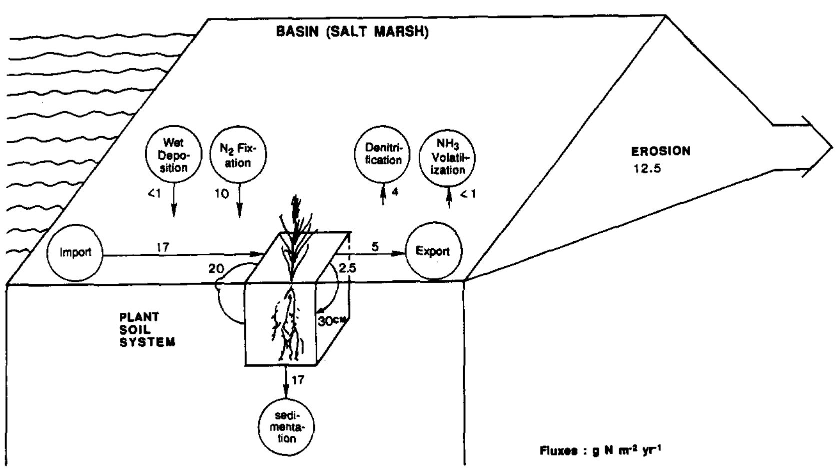

Fig. 2. Schematic model of nitrogen fluxes in Louisiana Barataria Basin salt marshes.

Results presented here demonstrate that in developing biogeochemical budgets for salt marshes, spatial difference should be considered (Fig. 2). For example, in the particular nitrogen budget developed for Louisiana's rapidly deteriorating salt marshes, the nitrogen inputs equal losses if we consider only the plant-soil system with a limited rooting depth. If only nitrogen input or losses for a unit area of marsh (e.g., 1 m^2) is considered the salt marsh serve as a major nitrogen sink as the result of rapid vertical accretion which accumulates nitrogen enriched organic matter and move below the plant root zone. On a larger spatial scale (regional) Louisiana salt marshes on a whole do not serve as appreciable nitrogen sinks due to the accelerating rate of marsh deterioration occurring along the Louisiana Gulf Coast.

Biogeochemical nitrogen cycling of Louisiana Gulf coast salt marshes is different in many aspects from reported budget for Atlantic coast marshes (Haines et al. 1977; Valiela & Teal 1979). The rapid rate of subsidence and wetland deterioration along the Louisiana Gulf Coast greatly influences nitrogen fluxes as compared to the more stable Atlantic coast salt marshes. Denitrification rates in Louisiana Salt marshes are also lower than reported for other systems (Kaplan et al. 1979; Valiela & Teal 1979; Haines et al. 1977). Louisiana salt marshes receive no nitrate through groundwater flow or any appreciable organic nitrogen form from municipal or agricultural source, suggesting that denitrification is governed by amount of inorganic nitrogen including nitrate present or entering salt marshes.

The reported budget we have developed may be unique representing only Louisiana Gulf coast marshes, but it serves to identify the effect of rapid physical changes (e.g. subsidence, wetland deterioration) on salt marsh nitrogen budget. Such nitrogen flux may not be of such significance in salt marsh located in more geologically stable coastal regions. However, if the predicted increases in global sea level due to the so-called "greenhouse effect" hold true, nitrogen budget of salt marshes in other coastal regions may closely parallel the budget reported for Louisiana salt marsh.

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