NASA Conference Publication 2316

Global Biology Research Program

Biogeochemical Processes in Wetlands

Report of a workshop conducted at
Arlington, Virginia
March 22-24, 1983

NASA

NASA Conference Publication 2316

Global Biology Research Program

Biogeochemical Processes in Wetlands

David S. Bartlett, *Editor*
Langley Research Center
Hampton, Virginia

Report of a workshop conducted at
Arlington, Virginia
March 22–24, 1983

National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

1984

ACKNOWLEDGMENTS

This report is the result of the efforts of many people who gave freely of their time and expertise. The participants in the workshop (see appendix A) spent many hours explaining, debating, writing, and reviewing all aspects of the material which follows. The editor is grateful to session rapporteurs - Kristine Butera, Christopher Martens, and Scott Nixon - for the extensive written summaries of science issues and recommendations on which the report is based. The editor is also grateful for the careful review and many helpful suggestions provided by Wendell Ayers, Robert Harriss, and Joel Levine. Patricia Russel and Donald Beem of the American Institute of Biological Sciences made arrangements and provided meeting facilities in support of the workshop activities, and Shirley Morton of the NASA Langley Research Center provided valuable clerical assistance.

CONTENTS

EXECUTIVE SUMMARY

Background

The objective of the NASA Global Biology Research Program is to apply NASA technology and expertise, in conjunction with the private and university communities, to establish a greater understanding of the influence of biology on global processes. The emphasis is placed on biogeochemical cycling as revealed in the interactions of the biota with their chemical and physical environment. Because of the importance of wetlands to the overall understanding of global biology, a specialized workshop was held March 22-24, 1983, to focus on problems which lend themselves to unique and important contributions through the support of wetland studies by NASA. Leading scientists from academia as well as NASA were brought together to assess the state of the art and to make recommendations regarding future plans for wetlands research sponsored by the Global Biology Program. This report summarizes the results of that workshop and provides a framework for the planning of wetlands research.

Wetlands systems display high rates of activity in virtually all of the biogeochemical processes of interest to the Global Biology Program. Among the most productive natural ecosystems on Earth, wetlands fix and store large quantities of atmospheric carbon despite their relatively small areal extent in relation to other major ecosystem types. High productivity also produces high rates of exchange of other important plant nutrients, especially nitrogen and phosphorus. Wet, oxygen-deficient soils with high proportions of organic material provide a favorable habitat for a wide variety of anaerobic microbial communities which are postulated to produce significant proportions of global biogenic gas flux (CH_4, H_2S, NO, etc.) to the troposphere and stratosphere. Wetlands in various forms are often the boundary between terrestrial and fresh or marine aquatic systems, and thus are sites of dynamic exchanges of organic and inorganic nutrients between land and water. In addition, wetlands around the world are subject to intense pressure to convert to other land uses, and thus their role in global processes is expected to change at a rapid rate. Wetlands thus provide an excellent model system in which many important issues related to natural cycling processes and human impacts can be addressed.

Issues Addressed

The first task undertaken during the workshop was the identification of research topics linking wetland systems with global biogeochemical processes. Three major issues emerged from the discussions: geographic distribution of wetland parameters, processes of wetland material fluxes, and linkages required for extrapolation of local fluxes to global scales.

Geographic distribution of wetland parameters.- Knowledge of the geographic distribution of various types of wetlands and of important functional parameters is a prerequisite to any quantitative assessment of the role of wetlands in global biogeochemical cycles. "The Global Biology Research Program Plan" (Rambler, 1983) prescribes an effort to develop a better understanding of disturbances to the vegetation and soils of the Earth through the inventory and monitoring of changes in globally important environments, largely through the use of remote-sensing technology. Wetlands certainly constitute an important family of biogeochemical environments with significant and often unique impacts on large-scale material cycles. An inventory of the extent and distribution of wetlands parameters and its incorporation into an easily manipulated data base is therefore a critical step in identifying important wetland types or regions and in future assessments of the global impacts of wetland material cycling processes.

Processes of wetland material fluxes.- The second important element in wetlands-oriented research is an improved understanding of the biogeochemical processes underlying wetland impacts on global material cycles. Exchanges of materials between wetlands and other segments of the environment have been a focus, albeit on a local scale, of wetland research for some time. Extensive efforts in quantifying wetland material exchanges with aquatic environments have been ongoing for several decades. Recently, attention has also been directed at exchanges with the atmosphere through the consumption and evolution of gases. Awareness of, and contributions to, this growing body of wetlands research must be an important element of NASA-sponsored efforts in expanding attentions to global scales of interaction.

Linkages for extrapolation of local fluxes.- Implicit in the emphasis of the Program on global scales of interaction is the capacity to relate important material exchange processes to the factors being inventoried on a global basis: vegetation type, climatic and hydrologic regime, physiographic setting, etc. Thus, a unique category of research is required to establish linkages or transfer functions between inventoried parameters and biogeochemical cycling processes and rates.

Conclusions

Detailed examination of aspects of the above research issues resulted in a consensus among the workshop participants on the following conclusions:

1. At present there is no centralized inventory of wetland type and extent for the Earth as a whole or for any of the large land masses, although an effort to produce such an inventory for the United States is under way (Montanari and Townsend, 1977). The objectives of the Global Biology Program appear to impose specific requirements on any wetland inventory undertaken. Simply designating and mapping "wetlands" as an ecosystem type will have little value in future attempts to estimate wetland contributions to global biogeochemical cycles. Rather, categories of wetlands carrying vegetative, soil, and hydrologic information will be required. As a minimum, distinction of the following wetland categories would provide information required for inference of some conditions controlling biogeochemical cycling processes:

- Tidal salt marshes
- Tidal fresh marshes
- Mangrove swamps
- Freshwater swamps (forested)
- Freshwater marshes (unforested)
- Riverine swamps (forested)
- Flooded agricultural systems
- Wet tundra

In addition to the geographical distribution of wetland types, information on climatic regimes, hydrology, and significant anthropogenic modifications is necessary. Such an inventory would be useful in assigning priority to the types and locations of wetlands chosen as representative test sites and would form the foundation of a geographical data base for use in extrapolating test-site measurements to calculate global exchanges relevant to the carbon, sulfur, nitrogen, and phosphorus cycles.

Parallel development of new remote-sensing techniques addressing environmental variables of interest should also be pursued.

2. Although biogeochemical cycling within wetland systems has been the subject of many years of research, gas-phase exchanges with the atmosphere remain relatively unexplored despite their postulated importance in global cycles. NASA is in a unique position to contribute in this area. This contribution would initially be through advanced instrument and technique development and would later be through extension of local measurements to global scales through inventories such as described previously.

There are several important components to a research program in wetland-atmosphere interactions. (1) Direct measurements of net gas fluxes across the wetland-atmosphere interface can provide primary data from representative circumstances for inclusion in models of material cycles. Techniques for such measurements are, for the most part, in the early stages of development but have already benefited from NASA technology. (2) The mechanisms of gas transport in soils and interstitial water control fluxes to the atmosphere. An understanding of transport phenomena, when combined with ambient concentration distributions, can yield predicted fluxes based on more easily estimated physical parameters such as temperature and wind stress. (3) An increased understanding of the rates of gas production and consumption at the level of the natural microbial community (as opposed to laboratory culture) is essential to assessing flux of biogenic gases.

Gas-phase fluxes between wetlands and the atmosphere are important in cycles of carbon, nitrogen, and sulfur. Measurements of seasonally varying methane (CH_4) flux from a variety of wetland environments are currently being obtained using a NASA-developed technique. Methane is an important trace component of the atmosphere, and wetlands are postulated as a major CH_4 source. The flux of carbon dioxide (CO_2) from undisturbed sections of wetlands has only occasionally been measured, and additional work is needed to complement the CH_4 studies. The flux of nitrogen from wetlands as elemental nitrogen (N_2), nitric oxide (NO), and nitrous oxide (N_2O) has only been measured on an areal basis in two or three salt marshes, although it is commonly supposed that denitrification and nitrification are important transformations taking place in salt- and fresh-water wetlands. While measurement of these fluxes is more problematic than for CH_4 or CO_2, recent progress suggests that only a minimum of development may be necessary to provide a practical method of obtaining seasonal measurements of N_2, NO, NH_3, and N_2O evolution from a variety of wetland test sites.

Fluxes of sulfur compounds, particularly hydrogen sulfide (H_2S) and dimethyl sulfide (DMS), should constitute important components of coastal wetland nutrient cycles. However, the techniques for obtaining an ecologically meaningful measurement of these fluxes on an areal basis are not yet available and should be the object of development efforts.

3. Exchanges of material with the aquatic environment and storage in accumulating wetland sediments are important and multifaceted processes which occupy a large body of the current research in wetland ecology. There is no doubt that aquatic

fluxes of materials and storage in organic-rich wetland soils will be important in the modeling of wetland processes. However, the workshop participants concluded that there are methodological and institutional factors associated with these areas of research which make them better suited for support by agencies and institutions other than NASA. For example, with regard to aquatic fluxes, only a few relatively large, well-supported efforts are currently able to evaluate the complex dynamics of tidal hydrology necessary to compute waterborne material fluxes in coastal wetlands. In addition, the significant and long-standing support for these types of research provided by other agencies serves to limit the contributions which could be made by a relatively new program such as the NASA Global Biology Research Program. While close monitoring of existing research and the undertaking of cooperative or complementary work in these areas are to be encouraged, it is the feeling of the workshop participants that the Global Biology Program should not support new research in these areas at this time.

4. The necessity for large-scale inventories on one hand, and for localized studies of wetland biogeochemical processes on the other, requires that significant interdisciplinary efforts be directed at establishing linkages between inventoried parameters such as vegetation type and climate and physical-chemical variables controlling material fluxes. Referred to here as transfer functions, these links are complex and elusive but are vital to the realization of the Global Biology Program goals. Development of process-level models is suggested as a basis for specifying transfer functions. Research is also required in remote sensing of functional variables such as plant biomass and inundation levels, as well as in studies of the role of wetland type, climate, and physiographic setting in determining rates of important processes.

Recommendations

In summary, the working group on the role of wetlands in global biogeochemical cycles recommends the following:

1. Development of a geographic wetlands data base is vital to fulfilling Program goals. The data base should make extensive use of remote-sensing technology, especially as it can be applied to a large-area inventory of wetland cover types. The data base should also incorporate functional parameters which may or may not be accessible to remote sensing, and must allow easy access to and manipulation of all variables. Assessment of emerging remote-sensing technologies for gathering relevant data should continue.

2. Research in wetland-atmosphere exchange processes should be a significant component of the Global Biology Research Program. NASA stands in a unique position to contribute technology, expertise, and support to efforts to assess the fluxes of gas-phase carbon, nitrogen, and sulfur compounds across the wetland-atmosphere interface. Studies should include the development and implementation of techniques for direct measurement of net fluxes of gases in wetland environments and, where required, for assessment of production and flux processes. Because of the embryonic status of this area of research, the probability for significant contributions resulting from NASA-supported studies is high.

3. Research in establishing transfer functions between inventoried parameters such as wetland type and climatic setting and estimates of actual rates of material exchange processes is a new and vital class of study required by Program goals. The basis for assessment of global biogeochemical processes can only come from

extrapolation of local measurements to regional and global scales - a task which must rely on modeling of flux rates based on major environmental variables which are accessible to remote sensing and are included in large information systems. NASA is the most logical sponsor of the hybrid research programs required. Initial emphasis should be on field research, combining process-oriented studies of material fluxes with quantitative evaluation of remote-sensing capabilities for making correlated measurements.

1. INTRODUCTION

This report summarizes the results of a workshop on the role of wetlands in global biogeochemical processes held in Arlington, Virginia, on March 22-24, 1983. The workshop was sponsored by the NASA Division of Life Sciences as a part of its research program in Global Biology. The Global Biology Research Program seeks to apply NASA technology to establish a greater understanding of planetary scales of interaction between the Earth's biota and their physical/chemical environment.

The general objectives and research strategies of the Global Biology Program have been documented in Rambler (1983). Stated briefly, the research objectives are as follows:

1. "Establish a basis for assessing the major pathways and rates of exchange for carbon, nitrogen, sulfur, and phosphorus moving into and out of terrestrial ecosystems."

2. "Establish a basis for extrapolating local rates of anaerobic activities to biospheric effects, with particular attention on the role of reduced gases and their key oxidation products."

3. "Establish a basis for assessing the major pathways and rates of exchange for carbon, nitrogen, sulfur, and phosphorus moving into and out of the world's oceans."

4. "Develop mathematical models that accurately represent the dynamics of the global cycles of carbon, nitrogen, phosphorus, and sulfur, including their interactions."

The program plan identifies four ecosystem types as having high priority for experimental work: large-scale temperate agriculture, boreal and tropical forests, savannahs, and wetlands.

Wetlands display high rates of activity in virtually all the biogeochemical processes of interest to the Global Biology Program. Among the most productive natural ecosystems on Earth, wetlands fix and store large quantities of atmospheric carbon despite their relatively small areal extent in relation to other major ecosystem types (Bolin et al., 1979). High productivity also produces high rates of exchange of other important plant nutrients, especially nitrogen and phosphorus. Wet, oxygen-deficient soils with high proportions of organic material provide a favorable habitat for a wide variety of anaerobic microbial communities. Anaerobic metabolism in wetland soils is postulated to produce significant amounts of biogenic gas flux (CH_4, H_2S, DMS, NO, etc.) to the troposphere on a global basis. Wetlands in various forms often constitute the boundary between terrestrial and fresh or marine aquatic systems and thus are sites of dynamic exchanges of organic and inorganic nutrients between land and water. In addition, wetlands around the world are subject to intense pressure for conversion to other land uses, and thus their role in global processes is expected to change at a rapid rate. Therefore, the wetland working group was organized to identify problems where unique and important contributions could be made through NASA support of wetland research.

The wetland working group saw the following as its primary goals: (1) the enumeration of major ecological research issues having particular relevance to marine and freshwater wetlands, and (2) the identification of research tasks which should be given special emphasis because of their scientific importance and close match with NASA interests and program goals. In the process, every effort was made not to reiterate the findings of the comprehensive "Global Biology Research Program Plan" (Rambler, 1983). Thus, little time was devoted to developing a rationale for including wetlands as a high-priority research area for global biology as this was already a part of the Program plan. In addition, some important research issues which had been specifically identified by the Program plan received little or no discussion. For example, the role of wetland vegetation in fixing atmospheric CO_2 is a clearly mandated research issue which is inseparable from the comprehensive inventories of global vegetation and biomass called for in the Program plan. Although the importance of such information was recognized (and a scenario for wetland vegetation inventories was recommended), the working group saw no reason to repeat the cogent arguments already made for research of this type.

Rather, the workshop participants sought to produce a reasonably specific suite of recommendations for uniquely wetland-oriented research. A broad range of interests and training was represented within the group, including microbiology, ecology, aquatic and atmospheric chemistry, and instrumentation and remote-sensing science. (See Appendix A.) This report documents the efforts of the group to provide a concise and timely framework for the planning of short- and long-term NASA research on the role of wetlands in global biogeochemical processes.

2. RESEARCH ISSUES IN ASSESSING GLOBAL IMPACTS OF WETLAND BIOGEOCHEMICAL PROCESSES

One of the accomplishments of ecology during the past 30 years is the documentation of the extraordinary productivity of many wetland ecosystems. The high rates of fixation of atmospheric CO_2 and associated uptake of nutrients such as nitrogen and phosphorus suggest that these environments may also be sites of intense metabolic activity leading to large fluxes of various materials between wetlands and adjacent water bodies and the atmosphere. While many of the biochemical transformations thought to occur in wetlands have been known for a long time, we presently have very few credible estimates of the rates of those processes. For this reason it is not possible to use current information to make a realistic, quantitative assessment of the role of wetlands in the global cycles of major elements of biological importance, such as carbon (C), nitrogen (N), phosphorus (P), and sulfur (S).

In order to significantly increase our ability to make such an assessment, it will be necessary to embark on a long-term (5-10 year) research program with several interrelated components. Three major issues need to be addressed: the geographic distribution of various wetland types and associated variables, the processes of wetland material cycling, and the linkages between these two families of information. Early stages of this work will be largely exploratory and will involve some development of measurement technology. Later phases will need to concentrate more on causal mechanisms and regulatory processes underlying the various net transformations that are observed and measured.

2.1 Geographic Distribution of Wetland Parameters: The Foundation of a Data Base

Knowledge of the distribution of various wetland types is a prerequisite to any quantitative assessment of the role of wetlands in global biogeochemical cycles. At present there appears to be no centralized inventory available for the Earth as a whole or for any of the large land-mass areas apart from the U.S. The tendency has been to "lump" all wetlands together and assign them a single value for primary production, carbon storage, etc. (e.g., see Bolin et al., 1979). An early step in this research effort should be the preparation of a more detailed wetland inventory, using appropriate data from satellites, aircraft, or existing information, and maps such as the National Wetlands Inventory now available for much of the United States.

The National Wetlands Inventory (NWI) has been a major effort of the U.S. Fish and Wildlife Service for several years (Montanari and Townsend, 1977). The inventory is based on interpretation of aerial photography and produces maps at scales of 1:100 000 and 1:250 000 for use as resource management tools. The NWI classifies wetlands using a system (Cowardin et al., 1979) based primarily on hydrologic regime (e.g., intertidal estuarine, intermittent riverine, littoral lacustrine) and secondarily on cover type (e.g., rock bottom, emergent wetland, forested). Cowardin et al. (1979) also propose a hierarchical regional classification system which differentiates between "ecoregions" based primarily on climate (polar, humid temperate, subtropical, etc.) and on vegetative "provinces" and "sections" (Outer Coastal Plain Forest, Prairie, Southern Floodplain Forest, etc.). This system is based on that of Bailey (1978) with the addition of coastal and estuarine provinces containing similar physiographic and biotic factors (e.g., Artic Province, and Carolinian Province). The NWI system also encourages the use of modifiers related to salinity, pH and soil type. Such a system appears to be well suited to inferring critical variables related to biogeochemical cycles, and the National Wetland Inventory as a whole should provide an important source of data for early choice of test sites and estimates of the extent of various wetland types in the U.S.

Although the U.S. National Wetlands Inventory provides a high level of detail, the workshop participants recognized that its reliance on aerial photography and a complex system of classification would probably prove unfeasible for a truly global inventory. It is therefore suggested, as a practical compromise, that the following 8 categories would provide adequate ecological detail, while limiting the level of resolution and interpretive sophistication required of a large-area inventory (see appendix B for detailed definitions):

1. Tidal salt marshes

2. Tidal fresh marshes

3. Mangrove swamps

4. Freshwater swamps (forested)

5. Freshwater marshes (unforested)

6. Riverine swamps (forested)

7. Flooded agricultural systems

8. Wet tundra

These categories combine generic, descriptive, vegetative, and some climatic criteria and should permit the classification of the vast majority of worldwide wetland systems. Associated with such an inventory should be the compilation of basic information such as the distribution of wetland types as a function of latitude, mean annual temperature, and probable innundation regime. The results of the inventory would be used in assigning priority to the types and locations of wetlands chosen as test sites and to form the foundation of a geographic data base to be used in extrapolating test-site flux measurements to calculate large-area cycling rates.

The approach suggested here assumes that three major features of wetlands are the most important variables influencing the magnitude of their impact on the global cycles of C, N, P, and S. These features are the dominant general type of vegetation (gross plant morphology, species composition, and gross physiology), the general hydrologic setting of the wetland (water depth, salt water, fresh water, tidal, riverine, etc.), and the annual temperature regime of the wetland. All these can be determined using current or evolving remote-sensing capabilities in combination with other data sources. It is therefore critical that advanced remote sensors and data-interpretation techniques continue to be explored.

2.2 Processes of Wetland Material Fluxes

Another important element in wetland research should be an improved understanding of the biogeochemical processes underlying wetland impacts on global material cycles. The flux measurements themselves are complicated by the array of different compounds that are potentially of interest, by the often unsatisfactory state of the art of existing analytical methods, and by the difficulties of obtaining an adequate measure of hydrology and water transport in many wetlands. If a mass balance is used as the framework for viewing wetland-biosphere interactions, it is useful to distinguish between exchanges with the atmosphere and exchanges with water.

2.2.1 Material exchanges with the atmosphere.- The wet and dry deposition of C, N, P, and S on wetlands from the atmosphere, although poorly understood, is the subject of a number of ongoing research programs. The NASA research program should take full advantage of these existing studies sponsored by other agencies, filling in data only where significant gaps in information exists. The fixation of carbon in plant biomass has been reasonably well documented for many major wetland types and shows promise of eventually being estimated on a large scale from remote-sensing data. (See section 3.1.4.) This aspect of remote-sensing development should continue to be pursued. The remaining atmospheric input, nitrogen fixation, is only poorly known for a few wetland types. It has been suggested, however, that about half of the total oceanic and coastal nitrogen fixation takes place in salt marshes and mangrove swamps (Capone and Carpenter, 1982). There are a number of methodological questions regarding the measurement of this process, though progress in the past few years has been encouraging. An effort should continue to be made to check and calibrate the acetylene reduction technique with ^{15}N and to obtain at least seasonal measurements of area-based nitrogen fixation in test sites where nitrogen fixation has been determined or where other nitrogen flux measurements are being made.

The fluxes of C, N, and S to the atmosphere are more difficult to address since a number of gaseous forms are involved. There appears to be no significant transport of phosphorus in this direction. Of the various forms of gaseous carbon, it is probably most important for NASA to focus initially on the transport of methane (CH_4). This emphasis is justified by the potential importance of wetlands in the global CH_4 balance (Ehhalt and Schmidt, 1978) and by the recent development (Sebacher and Harriss, 1982) of a rapid and accurate measurement technique for CH_4 fluxes. (See section 3.2.) It is recognized that the proportion of fixed carbon returned to the atmosphere as CH_4 relative to carbon dioxide (CO_2) will likely vary strongly as a function of salinity because of decreased methane production and possible oxidation in the presence of dissolved sulfate (Martens and Goldhaber, 1978). However, this relationship has yet to be quantified and CH_4 evolution should be measured in saltwater and freshwater wetlands. The flux of CO_2 from undisturbed sections of wetlands has only occasionally been measured, and additional work is much needed to complement the CH_4 studies.

The flux of nitrogen from wetlands as N_2, nitric oxide (NO), and nitrous oxide (N_2O) has been measured on an areal basis in only two or three salt marshes (e.g., Kaplan et al., 1979), though it is commonly supposed that denitrification and nitrification are important transformations taking place in saltwater and freshwater wetlands. While measurement of these fluxes is more difficult than for CH_4 or CO_2, recent progress suggests that only a minimum of development may be necessary to provide a practical method of obtaining seasonal measurements of N_2, NO, and N_2O evolution from a variety of test sites. In addition, fluxes of gaseous ammonia (NH_3) may be significant, and appropriate measurement systems are under development.

A similar situation appears to exist with respect to the fluxes of sulfur compounds, the most important of which may be hydrogen sulfide (H_2S) and dimethyl sulfide (DMS). However, the techniques for obtaining an ecologically meaningful measurement of these fluxes on an areal basis are not yet well developed. These techniques must be extensively field tested before a measurement program can proceed.

In developing a research program for the fluxes discussed above, it is critical that the same technique be used in all of the test areas, so that methodology is eliminated as a variable in the comparison of wetland behavior. Whenever possible, it would be desirable to have one group responsible for all of the flux measurements of a given type. When this is not practical, a rigorous intercalibration protocol must be maintained throughout the study. The development of process-level models relating measured fluxes to physical variables should also be a significant objective of this research.

2.2.2 Material exchanges with adjacent waters.- The exchange of dissolved and particulate C, N, P, and, occasionally, S between wetlands and the fresh or salt waters which flow over and through them has only been measured directly in a few areas. There are two major approaches to the problem - in situ chamber incubations or exchange measurements across a transect of water entering and leaving the wetland. The first provides data similar to those obtained in the gas flux measurements, but the situation in the water is more complicated. Most of the materials of interest - dissolved organic nitrogen (DON), ammonia (NH_3), nitrate (NO_3), dissolved organic phosphorus (DOP), phosphate (PO_4), CH_4, CO_2, dissolved organic carbon (DOC), and H_2S - are biologically very reactive, and there is little reason to assume that exchanges across the sediment-water or plant-water interface at a particular spot will necessarily be reflected in similar exchanges from the wetland as a whole.

The second approach, measurement of fluxes from the wetland as a whole, is conceptually attractive and straightforward. Unfortunately, experience has shown that it is practical for most systems only if substantial resources are available to obtain sufficient data on water transport to convert constituent concentration measurements into a statistically meaningful flux estimate (Boon, 1975; Kjerfve and Proehl, 1979). Except for unusual conditions when the input and output of water can be readily determined, this problem has proved to be a stumbling block to all but the most ambitious and well-supported efforts. Other agencies, notably the National Science Foundation, through its "Long Term Ecological Research" program, are currently supporting significant efforts in this area. These and other studies of aquatic fluxes should be monitored closely and, when possible, existing study sites should be given high priority for global biology programs.

2.2.3 Accumulation in sediments.- Since wetlands are areas of active sediment accretion and produce soils having high concentrations of organic material, it is important to assess their role as a sink of C, N, P, and S through long-term burial. Atjay et al. (1979), for example, estimate that 14 percent of total global storage of carbon in soils resides in the Earth's wetlands which cover only about 2 percent of the terrestrial surface. A number of radioisotope techniques have recently become available to estimate accretion rates, including ^{137}Cs and ^{210}Pb and ^{14}C dating. Associated with accretion measurements should be determinations of the C, N, P, and S composition of the peat and sediments. Such data are surprisingly lacking for wetland environments. Along with fluxes, storage terms are critical in accurate modeling of material cycles. It is important that the Global Biology Program monitor progress in this area and, where possible, choose study sites where processes of material flux related to sedimentation are actively being studied.

2.3 Transfer Functions for Extrapolation of Local Fluxes

The need to extrapolate local measurements of material fluxes and storage to large geographic areas requires a special class of research linking the results of process-oriented studies, NASA and non-NASA, to the global distribution of wetland types, seasonal changes in temperature and hydrology, and other variables identified through inventory (section 2.1). Referred to here as "transfer functions" these connections may take many forms, linking, for example, vegetation type and primary productivity; temperature and biogenic gas flux; and wetland type and particulate or dissolved carbon flux. Many transfer functions will be complex and interrelated, and few, if any, will provide as precise a data set as an all-encompassing program of direct field measurements could. Nevertheless, the realities of an undertaking as large as global biosystems research preclude a field-oriented approach. A useful context in which to view transfer-function research is through the development of conceptual, empirical, and mechanistic models of ecosystem cycling processes.

An important element of the Global Biology Program is the use of mathematical models to represent the dynamics of global material cycles (Rambler, 1983). Table I describes a hierarchical system of model types proposed for simulation of global biogeochemical cycles, and figure 1 shows the relationships among these model types (table I and fig. 1 are from Rambler, 1983). Models at levels S-1 and S-2 have a high priority for early development, while more sophisticated, data-rich models at levels S-3 and S-4 require time and more experience with less complex levels of simulation.

In the context of the ecosystems themselves, it is the process-level models which provide the vital link - the transfer function - between major environmental variables accessible to global inventories and the rates of material flux required for system-level simulation. Although accurate simulation of complex ecosystem processes is still far from a reality, the state of the art for process-level modeling is somewhat more advanced than that for global multisystem dynamics. Conceptual, empirical, and mechanistic models all have roles to play in characterizing ecosystem impacts on global material cycles.

TABLE I.- DESCRIPTION OF MODEL TYPES
[From Rambler, 1983]

System Level.

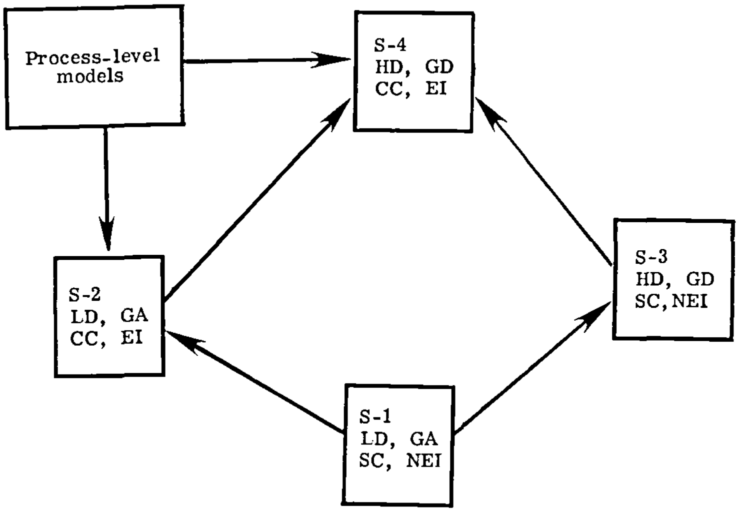
S-1: Low-dimensional, globally aggregated models for C, N, P, and S.
Focus: Cycle-specific; time horizon 1-1000 years.
Objective: Basic budget, macrodynamical characteristics without elemental interaction.

S-2: Low-dimensional, globally aggregated models for C, N, P, and S with elemental interactions.
Focus: Interaction of cycles over a variety of time horizons (e.g., 1-1000, 10,000-100,000 years).
Objective: For shorter term models, the primary objective will be the importance of elemental interaction in systems subject to perturbation, including systems where there is direct perturbation of more than one cycle (e.g., fossil fuel burning releases not only carbon but also nitrogen and sulfur). In longer time frames, an investigation of non steady state is a prime objective.

S-3: High-dimensional, data-rich, globally disaggregated models employing relatively simple (though perhaps numerous) causalities without elemental interaction.
Focus: Regional and subsystem exchanges within the global context with a 1-1000 year time horizon.
Objectives: There are two overlapping objectives for these models: first, to consider more carefully the details of recent (last 100 years) human perturbations of the C, N, P, and S cycles; and second, to check the consistency of (S-3) models with the models developed within (S-1) and partly within (S-2).

S-4: High-dimensional, data-rich, globally disaggregated models employing possibly complex causalities including elemental interactions.
Focus: Regional and subsystem exchanges within the global context over a variety of time frames (1-1000, 10,000-100,000 years).
Objective: An order of magnitude improvement upon our current understanding of the cycles of C, N, P, and S.

Process Level: Certain terrestrial and aquatic ecosystems and oceanic regions may contain features whose clarification would lend major insights when modeling at the system level (particularly elemental interactions in S-2 and S-4); consequently, the program should seek to insure the development of process-level models that will significantly clarify important global-level dynamics.



LD - Low dimensional
HD - High dimensional
GA - Globally aggregated
GD - Globally disaggregated
SC - Simple causalities
CC - Complex causalities
NEI - No elemental interaction
EI - Elemental interaction

Figure 1.- Relationships among model types.
(From Rambler, 1983.)

Significant experience with various modeling approaches to wetland processes has been gained in the last 5-10 years. Many wetland models have been designed to trace the flow of energy or of major elements (C, N, P) and are therefore well suited to application in a program which seeks to examine biogeochemical cycling. Wiegert et al. (1981) give a detailed summary of a tidal wetland carbon model. With the exception of tundra models (e.g., Bunnell and Dowding, 1974), similar comprehensive models of elemental cycles have not been completed for freshwater wetlands. However, elemental budgets have been developed within the framework of conceptual models for several freshwater sites (Mitsch et al., 1979; Mulholland, 1981).

Contributions to existing modeling efforts will undoubtedly be made through experimental studies of wetland material fluxes such as described in section 2. In addition, these studies should strive to place their results in a modeling context, when appropriate, to facilitate their incorporation into the larger Global Program. These process models may be quite empirical, at least initially, with progressively more complex, mechanistic approaches paralleling similar development of the global models.

An important characteristic of advanced global biogeochemical models is their inherent spatial context - incorporating, as they must, multiple subunits of varying distribution and extent. In contrast, most process models assume spatial homogeneity and focus on temporal dynamics. The geographic data base resulting from remote-sensing inventory, as well as from other data sources (section 2.1), can be viewed as a spatial model, allowing simulation of the large-area effects of spatial heterogeneity and of changes in spatial distribution through time. Ultimately, this spatial model will itself be composed of multiple process-level models linking inventoried parameters to specific materials cycling rates; providing inputs to system-level models as required.

2.4 Conclusions

It is obvious that many interrelated processes must be understood if quantitative evaluation of biogeochemical cycles is undertaken for wetlands or any other ecosystem type. Furthermore, the Global Biology Program goals require that process-oriented information be placed in a large-area geographical context. The only feasible mechanism for accomplishing this objective relies heavily on remote-sensing technology and on the use of efficient, large, digital data bases. None of the issues described in this section can be neglected if meaningful assessment of wetland impacts on global material budgets is to be accomplished. However, the working group's premise in formulating recommendations is that NASA cannot, and should not, attempt to address all the identified issues with equal vigor. Two questions were therefore asked for each potential research problem: "Is there a significant shortfall in existing efforts to study the problem?" and, "Can NASA make a special contribution through its particular interests and expertise?" A research issue is recommended for focused Global Biology Program support only when the working group's answer to both of these questions is substantially "yes". Exclusion of an issue should not be interpreted as an indication of its relative importance, only of the working group's feeling that it is the subject of significant research supported by other sources and/or that the research would not benefit from the special capabilities of NASA. Close communication and cooperation with other institutions and agencies, both domestic and foreign, will therefore be absolutely required in assembling all the information needed to accomplish the Program goals.

2.5 Recommendations

Of the major current issues related to the impact of wetlands on global biogeochemical cycles, the working group recommends that NASA Global Biology Program emphasis be placed on the following:

1. Development of a geographic data base containing information on the distribution of wetlands and including information on areal extent, climatic regime, general vegetation type, and hydrologic setting. Advanced remote-sensing techniques for gathering relevant data should continue to be developed.

2. Studies of the processes and rates of material exchanges between wetlands and the atmosphere for important species of carbon, nitrogen, and sulfur.

3. Research to identify transfer functions linking inventoried parameters with rates of material cycling. Use of existing process-level models of wetland systems and development of new models when necessary are recommended to provide basic inputs to simulation of global biogeochemical dynamics.

No priority is assigned to these tasks as all are critical in relating wetlands studies to the objectives of the Global Biology Program. Addressing these issues will provide data input to all four major program goals cited in section 1. Specifically, assessment of several major pathways and rates of exchange of C, N, S, and P for both terrestrial and oceanic ecosystems are uniquely combined in studies of wetland processes. While emphasizing wetland-atmosphere pathways in its own process-oriented research, the Global Biology Program should monitor other research programs for critical data on wetland-water pathways and burial. Research on wetland-atmosphere pathways is also intimately tied to the goal of identifying rates of anaerobic activities, with particular attention paid to reduced gases. Wetland studies are perhaps more important than any other in progressing towards this objective. The tasks of extrapolating local rates to biospheric effects and developing mathematical models that accurately represent the dynamics of global cycling can be accomplished in part through development of a geographic wetlands data base and extrapolation of empirical and model-derived wetland process rates.

The currently available technological and conceptual tools required are clearly in a very early stage of development, and a long-term program is necessary for substantial completion of Program goals. Nevertheless, it was the strong feeling of the working group that substantial short- and long-term contributions to our understanding of the role of wetlands in global processes could be made through an experimental and developmental program. A more detailed framework for a program addressing the issues identified is presented in the following section.

3. A FRAMEWORK FOR WETLANDS RESEARCH

3.1 Development of a Wetlands Data Base

One of the goals of the Global Biology Program (Rambler, 1983) is to establish a geographic data base which can serve as a foundation for deriving descriptive statistics and other information useful to global modelers. A data base for wetlands is an important component of global studies and the methods used must be integrated with those applied to other ecosystem types (for examples of proposed systems, see Macdonald et al., 1981; NASA, 1983). Several general issues related to the assembly of a comprehensive global data base were discussed at the workshop and are described below.

It is essential to agree at an early date on what size data cells are needed to support various aspects of the Global Biology Program. This decision is based on a consideration of both feasibility and user requirements. Factors to be considered include the data-cell size of existing data, the geographic mapping systems to be utilized in defining the locations of data cells, the optimum cell size for Global Biology Program users, and the capabilities available for converting polygonal data to a raster format and vice versa. A discussion of data-cell size considerations for a wetlands inventory is found in the next section (3.1.1).

The types of data considered for this data base include the distribution and biomass of vegetation, soil characteristics, hydrologic parameters, and important physical-chemical environmental control variables such as temperature, salinity, insolation, nutrient concentrations, and pollutant levels. Decisions will have to be made on the precision and accuracy required and the sampling frequency required for data updating. Existing suitable data will have to be converted to the format required for the Global Biology data base. The volume of information generated may necessitate advances in computer data handling and storage. Table II is a list of suggested wetland categories containing vegetative, hydrologic, and salinity information.

Table II.- WETLAND CLASSES

Primary classes	Secondary classes
1. Forested wetland	
	1.1 Freshwater swamps (palustrine forested wetland)
	1.2 Riverine swamps (palustrine forested wetland)
	1.3 Mangrove swamps (estuarine intertidal forested wetland)
2. Nonforested wetland	
	2.1 Tidal salt marshes (estuarine intertidal emergent wetland)
	2.2 Tidal fresh marshes (palustrine tidal emergent wetland)
	2.3 Freshwater marshes (palustrine emergent wetland)
	2.4 Flooded agricultural systems (palustrine emergent wetland farmed)
3. Wet tundra	

The data storage system should be optimized for interrogation of the data base. This would include statistical algorithms and data sorting and recombination functions. Some thought should be given to networking the Global Biology data base with other data bases existing at the national or international level. At the very least it should be developed for compatibility with other data bases. This requirement may generate demands for particular hardware configurations and for the standardization of software.

Output products from this data base should be available in map or statistical form, relating the significance of various ecosystems to global elemental cycling. Maps showing critical areas within different world regions would be valuable to international organizations concerned with monitoring supply and demand of natural resources and to those studying global biogeochemical cycles.

A schematic design for a generalized global biosystem study is presented in figure 2. Important elements include a variety of data sources, each oriented towards different degrees of detail and organized to provide a stratified information base in land cover and ecosystem parameters (AVHRR, MSS, TM, aircraft, existing data, and field studies) and in climate and atmospheric variables (meteorological satellites, NOAA data bases, field studies). These data bases provide information for large-scale models of biogeochemical cycles, the ultimate objective of the Global Biology Program.

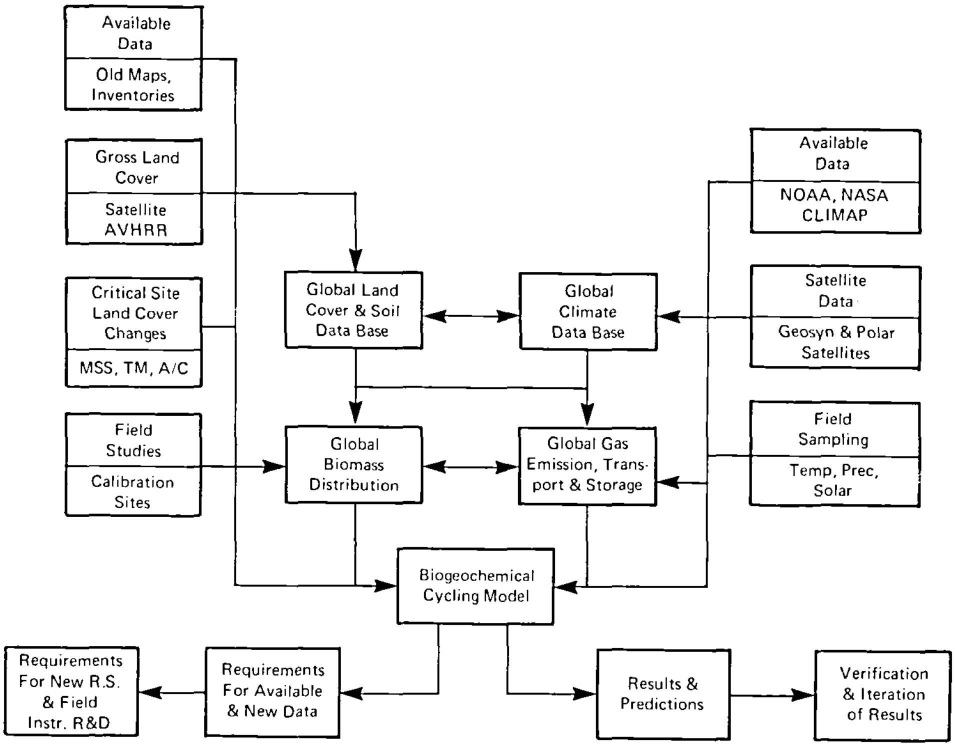


Figure 2.- Global biosystem study.

The objectives of an information system for wetlands are (1) to collect relevant data for wetland ecosystems using existing sampling methods (both in situ and remote), and (2) to make that information accessible to global models in which wetlands constitute one of several important biospheric elements. Close contact between designers of global data bases and models and providers of wetlands data are required to achieve the second of the preceding goals. A strategy for effectively addressing the first goal through remote-sensing inventories of wetland distribution is the subject of the discussion which follows.

3.1.1 Wetlands Inventory.- The development of a remote-sensing strategy for global wetlands inventory centers on the relationship between remotely sensible phenomena and the cycles of C, S, P, and N identified through transfer-function studies. (See section 3.3.) The first consideration is the definition of an ecological sampling unit (ESU) for wetlands ecosystems which can be represented by a set of transfer functions. The characterization of the sampling unit depends on such factors as the latitudinal position, spatial extent, biological characteristics, elevation, substrate, climate, hydrology, and physiography of wetland systems of interest. The ESU will also define data-cell size (area) for which information is required. The cell size for data input may differ from that established for the data analysis cell size in the global data base.

The ecological sampling unit for wetlands can most effectively be defined through a categorization scheme which hierarchically groups wetland types having similar vegetation and hydrologic characteristics, in combination with consideration of the spatial sampling unit used. These two parameters are discussed in some detail below.

1. Wetland-Type Classification:

As outlined in section 2.1, several categories of wetlands have been identified which, based on vegetation, physiography, and hydrologic criteria, may be expected to have distinct characteristics relative to important biogeochemical cycles. A suggested classification scheme for use in the global data base is shown in table II. Operational definitions of each category are given in appendix B.

The three primary classes correspond to "Level II" categories of "A Land Use and Land Cover Classification System for Use With Remote-Sensor Data" (Anderson et al., 1976). They are therefore expected to be compatible with the system used by many current efforts to inventory land use and land cover using remote sensors in the United States. The U.S. National Wetlands Inventory (NWI) uses a hydrology/cover type classification system described in section 2.1 (Cowardin et al., 1979). The secondary classes shown in table II are compatible with this system, as they are based on the same criteria (their designation using the NWI system is noted in parentheses), although some ambiguities exist unless "modifiers" are attached to NWI classes. The NWI makes no distinction of freshwater forested wetlands based on association with a well-defined river channel; therefore, classes 1.1 and 1.2 are both "palustrine forested wetland". The secondary classes represent an attempt to identify a concise list of ecologically meaningful categories which are also expected to be accessible to remote-sensor data when applied in concert with some ancillary knowledge of physiographic, hydrologic, and salinity regimes. The extent of the primary and some secondary classes should be spatially compatible with low resolution (e.g., AVHRR) data. However, attempts to distinguish forested wetlands from adjacent upland forests using remote sensing have encountered problems due to spectral similarities between trees of both habitats (Gammon et al., 1979). Ancillary sources of information may have to be used to delineate forested wetlands. Active microwave remote sensors may be useful for detection of areas of surface water beneath an otherwise uniform forest canopy. (See section 3.1.2.) Wetlands should be discriminable into the secondary classes using higher resolution orbital data (e.g., Landsat MSS and Thematic Mapper). Again, problems may be encountered distinguishing fresh and riverine forested wetlands from adjacent upland forests; however, discrimination between tidal and upland forests has been accomplished (Butera, 1978).

In general, knowledge of the distribution of the secondary classes of wetlands (plus "tundra") is probably required for application of transfer functions (section 3.3.). The primary classes are too generalized for meaningful ecological inferences to be made. Not all the classes are of equal importance, of course, but there is insufficient evidence for restricting the proposed list any further at this time. It is assumed that data relative to nonvegetative variables, such as temperature and salinity, will be required which may or may not be derived from remote-sensor data.

2. Spatial Sampling:

The Global Biology Program Plan (Rambler, 1983) suggests a stratified information system to reduce quantities of data to manageable limits. Initially, 5°-latitude by 5°-longitude cells may be required for global coverage, but little information on anthropogenic alterations, a high priority for the global program, will be available at this level of resolution. A 0.5° by 0.5° grid has been suggested, but this cell size also seems better suited to integration of climatic and physiographic data into the data base than to examining anthropogenic effects. Of the four high-priority ecosystem types (large-scale temperate agriculture, boreal and tropical forests, savannahs, and wetlands), wetland environments place the most rigorous constraints on spatial data resolution. The importance of wetlands in global cycles results from high rates of biogeochemical processes rather than from large areal extent. It seems unlikely that the large cell sizes appropriate for analysis of forest or grassland systems would allow any but the most cursory assessment of wetland distributions. At present there is no basis for choosing a particular value for a useful wetland ecological sampling unit. It seems reasonable to describe a sampling plan in terms of a multi-stage, stratified scheme based on existing orbital remote sensors. The availability of satellite sensor data of varying spatial and spectral resolution makes the use of multiple sensor data in a multistage sampling design a feasible, cost-effective approach.

For global monitoring, the use of the NOAA satellite-borne Advanced Very High Resolution Radiometer (AVHRR) may be the most efficient means to provide a surface cover delineation (NASA, 1983). Table III compares the volume of digital data that would have to be processed for each of the alternative sensors to equate to the geographical coverage provided by one scene of AVHRR data, illustrating the need for a multistage sampling approach to minimize the data handling and processing effort. The AVHRR resolution cell diameter of 1100 m minimizes the volume of digital data, and its frequency of data collection (daily) increases the probability of acquiring cloud-free, seasonally desirable data for global coverage. In a multistage sampling plan, the results of classifying AVHRR data provide the basis for identifying primary sampling units, i.e., data cells generically representing wetlands with a resolution cell dimension of 1100 m or larger. This primary unit can be subsampled (secondary, tertiary units) to identify more specific characteristics of the primary unit with finer resolution data as is schematically represented in figure 3. Such satellite sensors as the Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM), along with in situ measurements, can provide the subsampled data that relate to specific parameters of ecological significance (fig. 3). Table IV is a list of the spectral and spatial characteristics of these sensors. An early priority in remote-sensing development should be the evaluation of the most frequently encountered scales of occurrence of various wetland parameters so that a more precise projection of spatial-resolution requirements can be made.

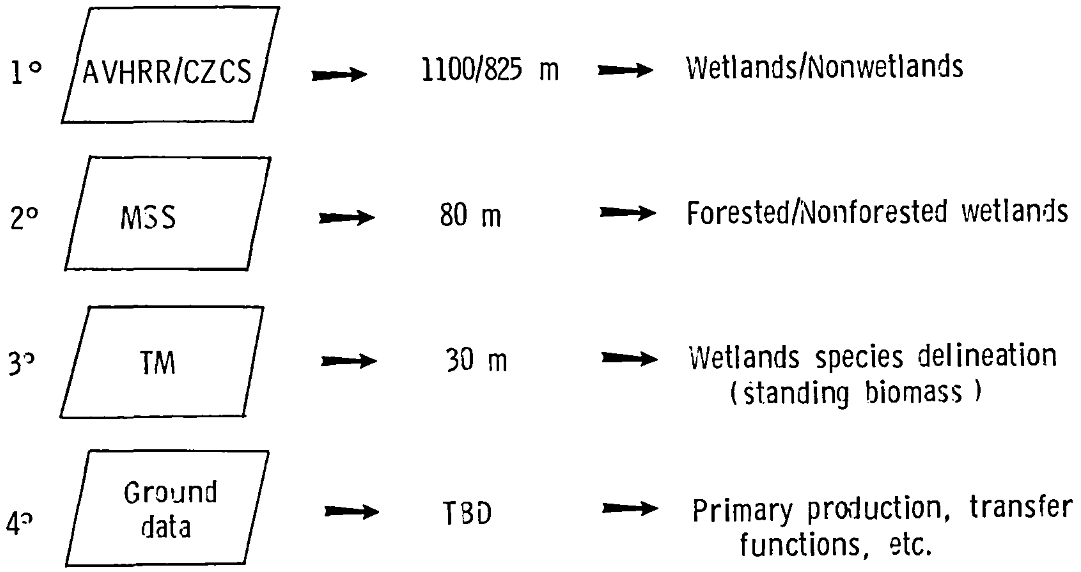


Figure 3.- Multistage sampling approach.

Table III.- COMPARISON OF SENSOR SCENE AREA, PIXEL VOLUME, AND SAMPLING FREQUENCY

Sensor	Scene area, km^2	Number of scenes equivalent to AVHRR area	Number of pixels per scene	Number of pixels equivalent to AVHRR area	Number of spectral channels	Sampling frequency
AVHRR	126.00×10^5	1	8.192×10^6	8.192×10^6	5	Once per day: visible and near infrared. Twice per day: thermal infrared.
CZCS	14.40×10^5	8.8	1.909×10^6	16.799×10^6	6	6 days
MSS	0.34×10^5	370.6	10.584×10^6	$3\,922.430 \times 10^6$	4	16 days
TM	0.34×10^5	370.6	41.551×10^6	$15\,398.800 \times 10^6$	7	16 days

Table IV.- SPECTRAL AND SPATIAL CHARACTERISTICS - CURRENT REMOTE-SENSING PLATFORMS

Sensor	Digitization	Frequency	Spectral range	Resolution, m	Swath width, km
AVHRR	10	0.5	VIS NIR TIR	1100	2800
CZCS	8	6	VIS NIR TIR	825	1200
MSS	6	16	VIS NIR	80	185
TM	8	16	VIS NIR TIR	30	185

A number of applications of remote sensing to inventories of wetlands have been reported (e.g, Butera, 1976 and 1978; Brown, 1977; Carter, 1978; Bartlett and Klemas, 1980; Finn, 1982), and a thorough review of existing literature will provide much information on methods, capabilities, and problems. Any gaps in existing knowledge need to be filled by small, pilot inventories of relevant sites. For the most part, however, technology currently exists to begin a large-area and temporally sensitive inventory of wetlands as a part of the Global Biology inventory of cover types and land uses.

3.1.2 Change monitoring.- One of the primary objectives of the global monitoring effort is the identification of areas experiencing land-cover changes between specified update intervals. The systematic framework for monitoring natural and anthropogenic changes on a regional scale should be based on the analysis of low-resolution orbital imagery. For example, the approach for regional change monitoring may focus on multispectral analysis of NOAA-7 AVHRR data for detecting, but not necessarily classifying, land-cover changes. The global monitoring may also rely on reports from international organizations (e.g., UNEP, FAO, etc.) concerning land-use changes. As these are recognized and categorized according to the impacted ecosystems, a shift from regional to local scope in analysis methodology will occur. It will be necessary, under some circumstances, to use finer resolution to detect areas of critical environmental change which are below the detection capability of AVHRR data.

If land-cover changes are identified within critical ecosystems, then change-detection analysis techniques based on high-resolution remote-sensing data (MSS, TM, aircraft, etc.) should be employed. These techniques would address the specific type, as well as the areal extent, of change.

Accurate change-detection analysis within a critical area will necessitate development of baseline information, either by analysis of a "pre-change" satellite data set or by consolidation of existing land-cover information. The "pre-change" baseline land-cover information and a "post-change" land-cover classification would then be comparatively analyzed to determine the extent of change or disturbance. Correlations would be made between disturbed areas and the appropriate conversion factors to determine regional impact on primary productivity, gas fluxes, model outputs, etc. Baseline critical ecosystems update intervals of once a year would be a minimum requirement for making regional impact assessments and determining rates of change.

Along with monitoring man-caused land-cover alterations comes the need to monitor the impact of episodic events on critical ecosystems. These events, in the form of floods, fire, etc., can be the dominant forcing functions in biogeochemical pathways in a variety of ecosystems. For example, in coastal systems, pulses of fresh water resulting from flood conditions or high tides resulting from storm surges can significantly affect nutrient and sediment exchange, such that the exchange occurring under these conditions may be orders of magnitude greater than under normal conditions. As the opportunity arises, experimental assessment of a major episodic perturbation of a wetland system should be undertaken. Information resulting from change detection would be assimilated in the global data base for use in assessing cumulative impacts of natural and man-caused disturbances on biogeochemical cycles at regular intervals - a capability which is currently unavailable.

3.1.3 Critical-site monitoring.- Ecologically important areas which are changing rapidly (e.g., loss of habitat due to deforestation or wetland conversion) or exhibiting exceptionally high cycling rates should be addressed with more frequent and detailed monitoring than other parts of the biosphere. Research should be conducted to select critical areas and to determine what parameters need to be monitored and with what coverage frequencies and resolutions. Sampling of such critical ecosystems is also important for

1. Having control information for comparison with similar areas experiencing change.

2. Observing the long-term effects of succession on biogeochemical pathways.

3. Conducting in situ experiments to compare measurements of elemental sinks, emissions, etc. in areas of change to those of noncritical or nonchanging areas.

Land-cover analysis over these critical areas might typically involve a classification of Thematic Mapper (30-m cell size) and/or Shuttle Imaging Radar (approximately 25-m cell size) data to provide quantitative information about surface change for correlation with biogeochemical process transfer functions. These classifications should eventually be conducted at minimum intervals of once a year. This sampling frequency should allow predictions to be made concerning the magnitude of surface change and may provide the basis for recommendations for appropriate land-use management. The parameters which should be addressed at each site are yet to be identified but would certainly include vegetation type and extent, climate, topography, soils, hydrology, sediment characteristics, and dissolved nutrient concentrations.

3.1.4 Development of remote-sensing techniques.- In addition to the inventory-related research and development described, continuing studies of remote-sensor design and data-analysis techniques will be required to fully exploit the potential of the technology.

While capabilities for use of existing sensors in mapping of natural vegetative cover types have been extensively documented, interpretative techniques focusing more directly on biogeochemical processes of interest require further study. Sensing of the physiological status of vegetative canopies, for example, has potential for addressing rates of primary production, soil nutrient dynamics, and anthropogenic impacts through air and water pollution. Considerable progress has been made in prediction of agricultural yields, for example, using remote sensing in combination with climatic and other variables influencing growth (MacDonald and Hall, 1980). In some cases, primary productivity of wetland vegetation may be measurable using periodic remote estimates of standing biomass (Bartlett and Klemas, 1981; Hardisky et al., 1983). Similar studies employing in situ measurements of canopy radiative properties and correlation with simultaneous biometric and geochemical data should be pursued with the objective of detecting vegetative responses to physical and chemical variables of potential interest. (See section 3.3.)

Active remote-sensing systems using microwave- or laser-generated radiation have the potential to contribute to studies of wetlands. For the most part, such systems are currently restricted to aircraft platforms and are likely to address the tertiary or quaternary levels of detail shown in figure 3. Significant exceptions are the Seasat Imaging Radar data available from its orbit in 1978 and the Shuttle Imaging Radar orbited periodically on the Space Shuttle.

Active microwave systems generally penetrate clouds and vegetation, providing an all-weather capability to detect standing water beneath a thick canopy (Hanson and Moore, 1976; Waite, et al., 1981; MacDonald et al., 1980). Microwave systems have also been used experimentally to measure soil conditions affecting biogenic gas production (Schmugge et. al., 1980). Microwave altimeter systems may contribute to the estimation of canopy volume from orbital platforms (Brooks and Norcross, 1983).

Pulsed laser systems (LIDAR - LIght Detection And Ranging) can also penetrate canopies and allow measurement of the thickness of the canopy (McDonough et al., 1980). Such data would be useful in estimating biomass in dense, inaccessible sites such as tropical forested wetlands. These and other developing remote-sensing systems should continue to be examined for their application to wetlands studies.

3.1.5 Related programs.- An ongoing program of the U.S. National Marine Fisheries Service (NMFS) offers a useful test of many of the considerations and techniques used in large-area wetlands inventory. The Coastal Habitat Assessment, Research and Mensuration (CHARM) program sponsored by the Northeast Fisheries Center is designed to use Landsat-MSS data to aid NMFS in its mission of monitoring and commenting upon development projects in coastal habitats, particularly wetlands, as they might impact fisheries. Undertaken in several phases, CHARM's objectives are (1) to provide a baseline measurement of coastal habitat in the Northeast from Maine to North Carolina; (2) to detect changes occurring between the base year and subsequent years; (3) to attempt measurement of plant biomass; and, (4) to estimate primary productivity of the wetland habitats (Finn, 1982). Phase 1 is currently near completion, and future activities should be closely monitored. One salient feature of the early progress reports has been the difficulty in timely acquisition of cloud- and noise-free Landsat data when a consistent inventory of an area encompassing multiple scenes (≈15) is undertaken (Finn, 1982). Approximately 6 months were required to obtain digital data tapes, followed by data "conditioning" and processing before analysis could begin. This experience serves to emphasize the preceding observations, that obtaining and managing the large quantities of data required for high-resolution, regional-scale inventory, even when orbital sensors are employed, is far from a trivial undertaking, and concerted efforts will be required to improve the data storage, transmittal, management, and analysis techniques currently in use. Later objectives of the CHARM program - change detection, biomass, and productivity assessment - are also relevent to Global Biology Program interests and will bear close observation and, perhaps, collaboration during initital stages of inventory development.

Several other programs in the U.S. are directed at assessment of wetland habitat through remote-sensing techniques. The National Wetlands Inventory is described in section 2. The U.S. Fish and Wildlife Service has also produced coastal "Ecological Characterizations" for selected areas (e.g., Barclay, 1978; Fefer et al., 1978) and has undertaken joint research with NASA in developing models of wetland nutrient flux using remote sensing to specify important variables (Butera and Browder, 1983). The U.S. Army Corps of Engineers, Vicksburg Waterways Experiment Station, is examining "wetland values" related to permits for coastal development (Struve and Kirk, 1980). The Southeast Fisheries Center of NMFS has sponsored a review of remote-sensing capabilities for surveying coastal wetlands (Bartlett and Klemas, 1980).

Finally, many studies of wetland ecology and biogeochemistry are being carried out in the U.S. and elsewhere. Notably, the National Science Foundation sponsors "Long Term Ecological Research" at several sites including a coastal marsh at the Belle Baruch Institute in South Carolina, and an inland swamp, the Okefenokee Swamp in Southern Georgia. These and other sites of existing research should be considered when choosing experimental test areas for global biology research.

3.1.6 Conclusions.- The Global Biology Program should undertake a pilot study to establish protocols and techniques for the development of a large-area data base incorporating coastal and inland wetlands. Several data sources, including existing maps and the three orbital sensors described (AVHRR, MSS, and TM) should be evaluated as contributors to a multistage, stratified sampling system. In addition, development-oriented research on new interpretive techniques and active and passive microwave and LIDAR sensors, should be pursued.

3.2 Research in Wetland-Atmosphere Exchange Processes

NASA possesses the resources and expertise, developed through a long-term concern with atmospheric processes, to make significant and potentially unique contributions to studies of gas-phase exchanges between wetlands and the atmosphere. As described in section 2.2.2, the fluxes of biogenic C, N, and S gases in wetland habitats comprise a new and exciting area of study with important consequences for the understanding of wetland ecology, atmospheric chemistry, and the relationships between the two. The study of biogenic trace-gas fluxes would thus direct NASA capabilities and interests at an area of biogeochemical research which lies at the heart of the Global Biology Program goals - namely, biogenic impacts upon the atmospheric environment. The discussion which follows first identifies important elements of a research program on biogenic gas fluxes and then describes an experimental scenario for the program. As noted in the "Introduction" the important process of fixation of atmospheric carbon by photosynthetic organisms is not specifically addressed because of ample prior documentation of the significance of this component of the carbon cycle. The reader is referred to other sections of this report (3.1 and 3.3) for a discussion related specifically to the assessment of primary productivity in wetland habitats.

3.2.1 Elements of a research program on wetland biogenic gas flux.- Figure 4 illustrates the components of a program of research related to fluxes of biogenic gases. The diagram also serves to illustrate one of the working group's major conclusions, that successful regional- and global-scale flux measurements will most likely follow the successful development and completion of a number of smaller local-scale projects aimed at (1) directly measuring net trace-gas fluxes from soils and sediments and improving methodologies for multiple-gas direct flux measurements, (2) quantitatively understanding trace-gas transport phenomena from wetland soils, and (3) gaining a better understanding of microbial controls on the generation and consumption of trace gases when required by studies of net gas transport. Progress in these project areas would be enhanced through collaborative efforts of several investigators conducting complementary research at accessible field sites. Brief descriptions of each research task follow below.

1. Net gas flux measurements:

Measurement of gas transfer rates at air-water and air-sediment interfaces are generally inferred from measurements of gas concentration increases with time in a chamber placed over the interface to trap the emitted gases. Primary shortcomings of most chamber measurements include small sampling areas that may not be representative of the environment being studied, artificial conditions in the chamber atmosphere that perturb natural physical exchange processes (wind, pressure, temperature, etc.), and chemical-biological changes in water, soil, or plants induced by prolonged chamber sampling. However, recent advances in chamber-system design and operation have demonstrated that most, if not all, measured errors due to chamber effects and soil disturbance can be minimized to a level where significant data can be obtained for gas emissions from air-soil and air-water interfaces (Schwartzkopf, 1978; Matthias et al., 1978; Denmead, 1979; Sebacher and Harriss, 1980; Seiler and Conrad, 1980). To overcome potential chamber effects, gas flux systems have been developed for several gases which (1) have sufficient analytical sensitivity and rapid response time to permit quantitative measurement of flux in measurement periods of 5-20 min., depending on the source strength; (2) are continuous monitoring systems that enable separation of any pulses produced by chamber placement or movement from the steady-state emission used for flux determination; (3) are portable and floatable, enabling measurements at remote locations; and (4) have the capability of quantitatively controlling air velocity over the surface within the chamber sampling area to determine air velocity effects on gas exchange (Sebacher and Harriss, 1982; Sebacher et al., 1983). The in situ gas flux measurements provide an important cross check on soil or sediment column gas production and consumption rates obtained through radiotracer or other methodologies. Ultimately, these independently measured rates must sum to agree with net flux rates.

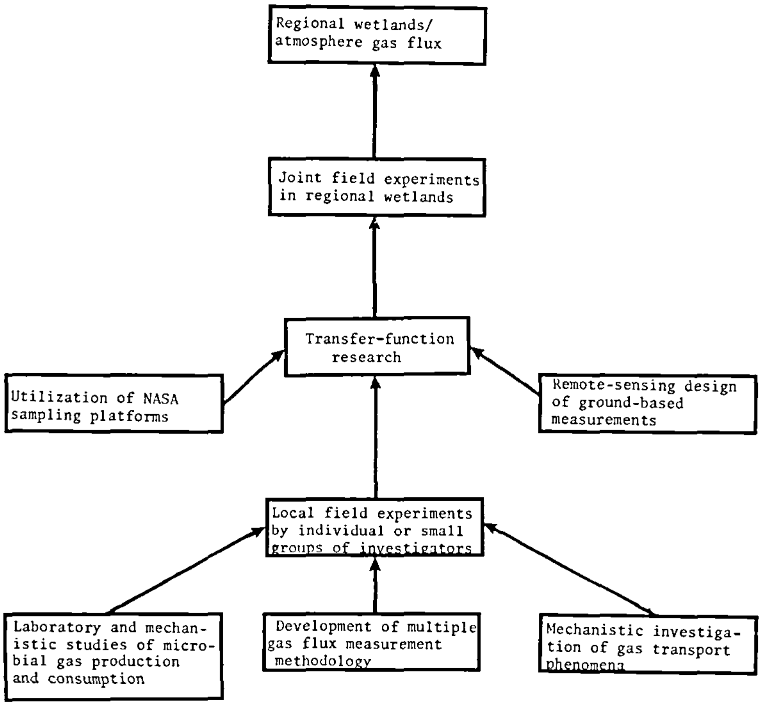


Figure 4.- Components of research in biogenic gas flux.

Capabilities for both ambient concentration and direct in situ flux measurements now exist for CH_4, CO, CO_2, N_2O, and some other compounds. Extensive CH_4 flux measurements have now been obtained by NASA-Langley using a fast-response infrared absorption technique (gas filter correlation analyzer) integrated with an open-bottom chamber (Sebacher and Harriss, 1982). These chambers sample an area of approximately 1 m^2, and the flux measurements can be completed in less than 30 minutes. This technique has the capability for very fast response times (less than 1 second) and may be further developed for aircraft sampling. CO and CO_2 also exhibit strong infrared absorption bands which are generally clear of interfering atmospheric gases and may be monitored by the gas filter correlation technique.

Recent development of commercially available, small, high-quality gas chromatographs presents the opportunity for assembling flux measurement systems for CO, CO_2, and N_2O where these gases can be monitored repetitively on a time scale of minutes or less on site. A 1-minute analytical time limitation is generally sufficient for CO, CO_2, and N_2O flux measurements, and each chamber can be set up to measure all three gas fluxes simultaneously because of small sample-size requirements.

Carbon monoxide can be detected by either flame-ionization gas chromatography or the mercuric-oxide method. Flame-ionization detection involves catalytic reduction of CO to CH_4 over hot (325°C) nickel catalyst in the presence of hydrogen by the method of Porter and Volman (1962). Following methanization, the sample is passed through a gas chromatographic column. CH_4 in the sample elutes first, followed by the methanized CO because of separation by the column just before entering the detector.

Detection of CO using the reaction with mercuric oxide ($H_gO + CO \rightarrow H_g + CO_2$) consists of a chromatographic column followed by a preheating column, heated reaction chamber, and optical cell. CO is detected as mercury vapor using the principle of atomic absorption (Seiler and Junge, 1967).

The possibility of including flux measurements of other gases important to global biogeochemical cycles (e.g., NH_3, NO, NO_2, H_2S, carbonyl sulfide and dimethylsulfide) depends on instrument development now under way (e.g., Levine and Allario, 1982) as well as additional refinements of existing techniques.

2. Gas transport phenomena:

In order to develop predictive capabilities for understanding trace-gas cycling phenomena, an understanding of transport phenomena between sites of gas generation and consumption in wetland soils and the atmosphere must be obtained. Modeling of ambient distributions and their time variations within wetland soils or surficial water bodies will obviously require a detailed understanding of redistribution phenomena. A mechanistic understanding of transport phenomena, when combined with ambient concentration distribution, can also serve to yield predicted fluxes in many environments which should agree with direct net flux measurements. The further development and use of a family of stable natural and artificial radioactive tracers for distinguishing the mechanisms and rates of wetland soil-atmospheric exchange is necessary.

3. Microbiological controls of trace gas generation and consumption:

The Global Biology Research Program Plan outlines general areas of research amenable to treatment via methods which emphasize a whole microbial community approach. Replacement of classical pure culture techniques by methods which maintain community structure are necessary to obtain rates and potential rates of microbial metabolism responsible for the generation of important gases. A thorough characterization of the chemical environment is essential to describe the microhabitat controlling the quantity and type of gas produced and the fate of gases after direct microbial release. Although the determination of the net flux of gases into the atmosphere is a major goal of the Global Biology Research Program, an increased understanding of the rates of gas production at the microbial level and control of these rates by the chemical environment will be essential for the calculation of accurate transfer factors for many compounds. Therefore, application of state-of-the art tracer methodology and new techniques devised to measure key microbial processes should be applied to wetland soils when required to elucidate observed fluxes.

Approaches which rely on a minimum of disturbance to natural gradients in microbial assemblages are necessary. Attempts should be made to fully utilize tracer methodology, whether it be radiotracer techniques, such as those perfected for sulfate reduction measurements (Jorgensen, 1978), or more indirect assessments of microbial community state, such as adenylate energy charge, thymidine incorporation, or perhaps enzyme activities (Hoppe, 1983; Karl and Holm-Hansen, 1978; Moriarty and Pollard, 1981). Assessment of microbial biomass via viable or direct counting techniques are discouraged in light of the process-oriented approach needed for studies of wetland biogeochemical cycles.

Significant controversy presently exists about the validity of results obtained from even the most simple field incubation procedures such as those developed for measuring microbial sulfate reduction to H_2S in anoxic environments using $^{35}SO_4$. Further field work, laboratory studies, and collaborative efforts between independent groups will be required to produce accurate rate data.

3.2.2. *Methanogenesis and sulfate-reduction interactions: a model for research in biogenic gas flux*.- Understanding the influence of microbial processes in wetlands on atmospheric chemistry is necessarily based on an interdisciplinary approach. The linkages between specific microbial processes and the chemical composition of the atmosphere are now clearly recognized for a number of gases produced in anaerobic environments but remain poorly quantified. As an example, we can briefly examine what is known about the processes of methane production and sulfate reduction.

Methane production and sulfate reduction are mutually exclusive processes in many organic-rich soils and sediments because of competition for the same substrates (Martens and Goldhaber, 1978). Not surprisingly, therefore, an understanding of the large-scale importance of methanogenesis necessitates an understanding of sulfur cycling as well. These competitive microbial interactions were only clearly recognized in the mid-1970's, along with the development of models, which explained the following observed vertical sequence of microbially mediated respiration reactions in sedimentary environments through which specific bacteria obtain energy for growth and maintenance (Claypool and Kaplan, 1974):

Reaction zone	Sediment depth sequence	Hydrogen acceptor	Reduced product
1. Aerobic respiration	Surface	O_2	H_2O
2. Nitrate reduction	↓	NO_3	NO_2, N_2O, N_2
3. MnO_2 reduction		MnO_2	Mn^{2+}
4. Fe_2O_3 reduction		Fe_2O_3	$Fe^{2=}$
5. Sulfate reduction		SO_4	H_2S
6. Methanogenesis	Depth	CH_3COOH	CH_4

This sequence of reactions appears to arise from competition in which specific symbiotic assemblages of organisms capable of greatest relative energy yield utilizing the available substrates and hydrogen acceptors dominate. Each "biogeochemical zone" is defined on the basis of either a unique dominant hydrogen acceptor (e.g., sulfate-reduction zone) or reduced end product (e.g., methanogenic zone). Because of the relatively high concentrations of dissolved oxygen and sulfate in marine waters, zones 1 and 5 in the preceding table are observed to dominate the high salinity end of estuaries, while zone 6 (methanogenesis) is observed to dominate the fresher upstream environments (Martens and Goldhaber, 1978). Vertical dimensions of the zones change in response to organic substrate supply, temperature, hydroperiod, and the extent of upstream sulfate-rich salt wedge incursion.

Techniques are currently being developed to accurately determine the gross rate of methanogenesis and the importance of specific methane precursors using radiocarbon-labeled tracers in soils and sediments. However, it should be emphasized that very little actual in situ rate results have been obtained, especially for wetland environments. Because sulfate-reducing bacteria compete with methanogens for key low-molecular-weight organic substrates such as acetate, an analysis of CH_4 and reduced sulfur gas fluxes to the atmosphere from wetland soils requires an understanding of subsurface metabolism within the soil column and thus requires cooperative efforts between scientists interested in atmospheric chemistry, microbial ecology, and transport phenomena. It should be possible to obtain measurements of net gas flux for important reduced compounds from a selected, extensive area of wetland. Such an experiment should be coordinated with remotely sensed data to demonstrate a capability for translating numerous ground-based flux measurements into a regional flux estimate for an important wetland area.

3.2.3 Scenarios for potential field experiments.- The workshop participants sought to identify several potential experimental scenarios which could lead to trace-gas flux results of interest on at least a regional scale. After considerable discussion, it was decided that a large-scale project involving multiple gas fluxes (i.e., more than 2-3 gases) at a large number of sites should await further development of gas concentration and flux measurement devices. The obvious gain from such experiments would be some immediate information concerning which gases were of special interest for lengthier quantitative studies. However, within the next few years we expect new analytical and field measurement advances (such as those achieved for CH_4 measurements as described above) to revolutionize our ability to conduct such multiple gas flux experiments efficiently.

Capabilities now exist for conducting a number of experiments which should produce gas flux results of immediate importance for quantifying the global methane budget and the influences of associated sulfur cycling on this budget. One such experiment involves a central emphasis on variations in gas production along wetland salinity gradients. Soil respiration processes in such organic-rich environments are typically dominated by sulfate reduction near the high-salinity mouth of the estuary and by methanogenesis upstream. While the distribution of these microbially mediated processes along the estuarine gradient has been documented (Martens and Goldhaber, 1978), there has been no direct effort made to examine their influence on variations in gas fluxes to the troposphere in spite of the obvious importance of estuaries as sites of biogeochemical cycling. In a recent publication on estuarine research, the National Research Council's Panel on Estuarine Research Perspectives (National Research Council, 1983) clearly pointed out both the importance and tractability of related estuarine research efforts during the next 10 years.

A second type of experimental project envisioned involves the determination of the integrated CH_4 gas flux from a relatively large wetland area. The project could rely heavily on existing expertise, techniques, and equipment allowing for significant progress within a period of 2 to 3 years. Completion of such an experiment would clearly demonstrate a capability for translating numerous ground-based flux measurements, coordinated with remote-sensing measurements, into a regional flux estimate for an important wetland area. The data would represent a significant contribution by Global Biology Program participants to the current understanding of biogeochemical cycling on a global scale.

With a small amount of technique refinement, similar experiments could be conducted examining fluxes of N_2, NO, and N_2O. Despite the lack of data in this area, wetlands are postulated to be major sites of nitrogen fixation (Capone and Carpenter, 1982) and denitrification (Kaplan et al., 1979). A relatively modest program of measurements in a variety of wetland types would be of great value in clarifying these speculative process rates.

3.2.4 Conclusions.- The development of a Global Biology Research Program within NASA represents an opportunity to aim a diverse group of scientists at the well-defined global-scale problems outlined in the Global Biology Research Program plan (Rambler, 1983). The wetlands working group concluded that NASA should support the application of existing techniques for measurement of net flux of reduced gases from wetland soils, the development of new measurement techniques, and studies of revelant processes of gas production and flux in representative sites. Cooperative efforts by successful research groups at regionally important sites should ultimately provide the interdisciplinary and quantitative approaches necessary for accurately assessing trace-gas fluxes on a global scale.

3.3 Research to Establish Transfer Functions

As discussed in section 2.3, the basis for modeling of global biogeochemical processes can only come from extrapolation of local measurements to regional and global scales, implying that the inventoried parameters such as hydrologic setting, climate, and vegetation type carry information regarding the rates of material cycling processes. There seems little doubt that these parameters are highly correlated with many of the biogeochemical processes underlying material fluxes, but the quantitative transfer functions between inventoried variables and actual flux rates are not available for most wetland processes of interest. A special class of research is therefore called for to identify critical parameters which can be inventoried, to relate them to measured flux rates and, if necessary, to develop inventory methods for important variables not accessible to available techniques. In some cases, transfer functions may fall naturally out of process-oriented research such as that described in the previous section. In other instances, specialized studies may be called for. As a start, it is useful to summarize the major inventoried parameters and their functional importance to material exchange mechanisms as follows:

1. Vegetation is a salient surface feature of wetland systems which is directly observed through remote sensing and is therefore likely to form the basis for any large-area inventory of wetland types. (See section 3.1.) The gross morphology of wetlands vegetation (trees, shrubs, grass, etc.) is easily identified using multispectral sensors and, with the exception of some forested systems, can be distinguished from that of adjacent, upland habitats. In general, any significant difference in a plant's gross morphology or leaf pigment composition will produce a

distinct multispectral "signature" which can be detected by a remote sensor. The use of these distinctions in the mapping of wetland systems is amply documented (e.g., Carter, 1978; Bartlett and Klemas, 1980). However, coastal wetlands have received the most attention, and more studies of applications to inland wetlands are needed.

Vegetation by itself, or in concert with physiographic setting, is often used to define a wetland habitat type. A first-order estimate of material flux rates may be possible based solely on habitat type, as, for example, in quantifying worldwide carbon fixation and storage by plants (Woodwell, 1980). Changes in the extent of these types, monitored through remote sensing, would then be correlated with changes in the global cycle of carbon (Woodwell, 1980). Characteristic rates of gas fluxes from various wetland types are beginning to appear as measurement technology becomes simpler and more portable (Sebacher and Harriss, 1982; DeLaune et al., 1983). Similarities in particulate and dissolved carbon, nitrogen and phosphorus fluxes for salt marshes described by numerous workers in widely varying locales have been noted (Nixon, 1980), indicating potential for first-order estimation of the impacts of this wetland type. While there are certainly other factors involved, it is increasingly clear that quantitative estimates of certain fluxes can now be made based on knowledge of the distribution of vegetation types and that the breadth and precision of these estimates are likely to increase with the passage of time.

Some important material exchanges may be tied directly, rather than by inference, to vegetation. There is evidence that estimates of plant biomass, and therefore of carbon and other nutrient storage, can be obtained from remote-sensor data (Tucker, 1979; Bartlett and Klemas, 1981; Hardisky et al., 1983). Hydrocarbon emissions from vegetation may be an important component of tropospheric trace-gas cycles and show promise of being assessed through remote sensing of vegetation distribution and biomass (Winer et al., 1982). Plants may also serve as conduits for gas flux from the soil (Dacey and Klug, 1979; Cicerone and Shetter, 1981). Further development of remote-sensing techniques for direct measurement of vegetative parameters such as biomass, leaf-area index, and physiological status should be a high priority for the Global Biology Program. (See section 3.1.4.)

2. Hydrology of wetland systems can be observed directy or inferred from knowledge of vegetation type. The distribution of vegetation species in a coastal wetland, for example, is correlated with the frequency and duration of tidal inundation (Chapman, 1974). The use of these relationships in remote-sensor inventories of tidal wetlands is common and widely accepted (e.g., Polis et al., 1974; Brown, 1977; Carter, 1978; Bartlett and Klemas, 1980). Direct sensing of the extent of inundation has also been carried out for wetland habitats having seasonal (as opposed to tidal) hydroperiods. Studies of the Okavango Swamp of south-central Africa (Hutton and Dincer, 1979) and of the Florida Everglades (Anderson and Higer, 1980; Rose and Rosendahl, 1983) have been reported. In forested habitats where the soil-water surface is obscured by a dense canopy, microwave systems should be useful in detecting inundation (MacDonald et al., 1980).

The significance of hydrology in biogeochemical cycling is multifaceted. Moving water carries materials in dissolved and particulate form, and the interactions of water with wetland systems can be studied using remote sensing (Butera, 1979). Inundation is also the primary factor producing saturated, anaerobic soil conditions responsible for the production of reduced gases. The characteristics and duration of inundation have been linked to reduced gas flux (CH_4) in both coastal (King and Wiebe, 1978) and inland (Harriss et al., 1982) wetland systems. Further documentation of hydrology-flux relationships in the field and development of improved sensing techniques for hydrologic parameters should be a significant component of the Global Biology Program.

3. Salinity is an important determinant of flux characteristics in estuarine wetlands (Martens and Goldhaber, 1978; DeLaune et al., 1983). Long-term, mean salinity distributions can be inferred from remote-sensing vegetative inventories (Butera, 1976). Passive microwave sensors have been used experimentally to measure the salinity of open waters directly (Kendall and Blanton, 1981).

4. Soil characteristics are important for models of material fluxes and can often be inferred from the distribution of wetland types. In many cases, however, field sampling of soils will be required to obtain critical soil parameters, as passive remote sensors cannot detect soil variables directly. Microwave sensor systems have been used to estimate soil moisture (Schmugge et al., 1980), and these techniques should be aggressively developed.

3.3.1 Modeling approach to transfer function studies.- As discussed in section 2.3, concepts of process-level and spatial modeling provide a useful approach to development of transfer functions. A wide variety of modeling techniques have been applied to ecological systems in general and to wetlands in particular. Several model types seem likely to be useful in addressing Global Biology Program goals, and these are described briefly as follows:

1. True Process models are concerned with specific cycling processes within wetlands. The projects outlined in section 3.2.1 are all candidates to produce models of this type. Few published examples exist for wetlands; however, diagenic models for the distribution of dissolved substances in pore waters, generally applied to marine sediments (e.g., Berner, 1975), could be applied to dissolved gases (e.g., CH_4, SO_4) in wetland sediments. If quantitative process simulation is not possible, a conceptual model may permit first-order estimates of cycling responses to environmental variables.

2. Point ecosystem models are spatially aggregated simulations of energy or elemental flows among biotic and abiotic components. The carbon model of a Georgia salt marsh (Wiegert et al., 1981) is a model of this type. Typically, processes transfer matter or energy from one compartment to another; thus, the process models described previously might be incorporated in differential equations used to simulate elemental flow in an ecosystem model. These models are usually site-specific, average descriptions of a homogeneous, small portion of a larger area.

3. Spatial models of processes on a regional scale incorporate some of the heterogeneity inherent in large ecosystems. The simplest spatial models partition the landscape into "cells", each with its own point model of ecosystem processes (e.g., CH_4 flux), and outputs from each cell model are summed with no interaction. By introducing transport models to link cells on a landscape, more complex spatial models are developed (Parker and Kadler, 1974; Kratz et al., 1979).

Clearly, spatial models can link wetland-atmosphere exchange processes to large-area inventories and thus have a major role to play in achieving Program goals. As suggested in section 3.2.3, the capabilities now exist to perform an integrated in situ measurement/process-model/geographic-information-system pilot experiment related to CH_4 flux. Figure 5 shows the interaction of a spatial data base with ground-based process measurements for such a pilot experiment. The data base contains geographically organized information on surface cover, inundation, salinity, etc. derived from remote-sensing inventory and/or other sources. Ground-based CH_4 flux measurements provide process-model equations and variable weights which are applied in the form of transfer functions to the spatial data and produce an estimate of total flux for the site of interest. Performing the analysis at temporal intervals appropriate to variability in the environmental parameters permits a time-integrated flux estimate to be made. The individual elements of the experiment are substantially in place (i.e., instrumentation for in situ CH_4 flux measurement, remote-sensing techniques for surface-cover inventory, geographic information system capable of incorporating both remote-sensor and ground-based information). Integrating these elements will test the capacity for developing quantitative transfer functions required for a spatial simulation of large-area biogenic gas flux.

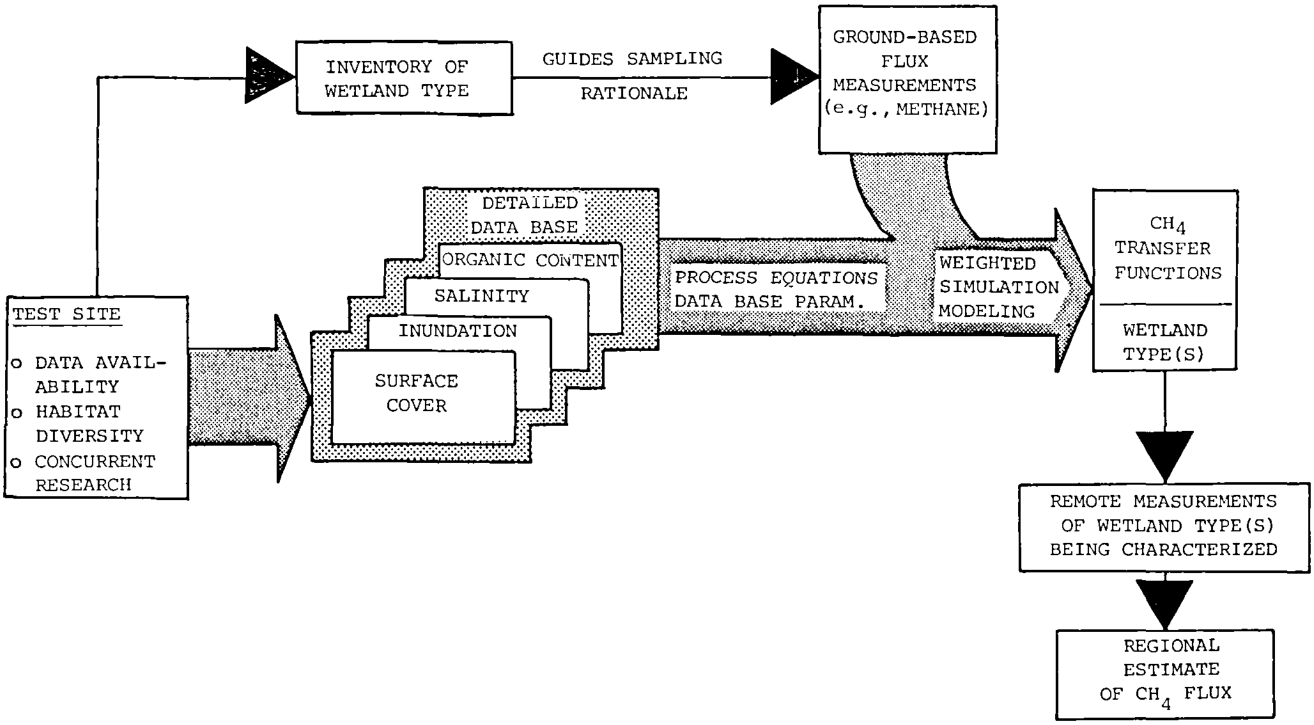


Figure 5.- Scenario for pilot experiment.

3.3.2 Conclusions.- Research in establishing transfer functions between inventoried parameters and wetland flux rates must be a high priority of the Global Biology Program. Development of conceptual, empirical, and mechanistic process-level models, and their incorporation into geographic-based data systems, will allow simulation of the effects of the spatial distribution of important variables on large-area biogeochemical cycling rates.

4. RECOMMENDATIONS

In summary, the working group on the role of wetlands in global biogeochemical cycles recommends the following:

1. Development of a geographic wetlands data base is vital to fulfilling Program goals. The data base should make extensive use of remote-sensing technology, especially as it can be applied to a large-area inventory of wetland cover types. The data base should also incorporate functional parameters which may or may not be accessible to remote sensing, and must allow easy access to and manipulation of all variables. Assessment of emerging remote-sensing technologies for gathering relevant data should continue.

2. Research in wetland-atmosphere exchange processes should be a significant component of the Global Biology Research Program. NASA stands in a unique position to contribute technology, expertise, and support to efforts to assess the fluxes of gas-phase carbon, nitrogen, and sulfur compounds across the wetland-atmosphere interface. Studies should include the development and implementation of techniques for direct measurement of net flux of gases in wetland environments and, where required, assessment of production and flux processes. Because of the embryonic status of this area of research, the probability of significant contributions resulting from NASA-supported studies is high.

3. Research in establishing transfer functions between inventoried parameters such as wetland type, climatic setting, etc. and estimates of actual rates of material exchange processes is a new and vital class of study required by program goals. The basis for assessment of global biogeochemical processes can only come from extrapolation of local measurements to regional and global scales - a task which must rely on modeling of flux rates based on major environmental variables accessible to remote sensing and included in large information systems. NASA is the most logical sponsor of the hybrid research programs required. Initial emphasis should be on field research combining process-oriented studies of material fluxes with quantitative evaluation of remote-sensing capabilities for making correlated measurements.

APPENDIX A

Participants

David Bartlett, Convenor
Mail Stop 483
NASA Langley Research Center
Hampton, VA 23665

David Brannon
NASA-NSTL-ERL
HA20
NSTL Station, MS 39529

M. Kristine Butera
Code EE-8
NASA Headquarters
Washington, DC 20546

David Dow
NASA-NSTL-ERL
HA20
NSTL Station, MS 39529

Patricia A. Flebbe
Institute of Ecology
University of Georgia
Athens, GA 30602

Michael Hardisky
College of Marine Studies
University of Delaware
Newark, DE 19716

Mark Hines
Jackson Estuarine Laboratory
University of New Hampshire
Durham NH 03824

Vytautas Klemas
College of Marine Studies
University of Delaware
Newark, DE 19716

Christopher Martens
Curriculum in Marine Sciences
12-5 Venable Hall 045A
University of North Carolina
Chapel Hill, NC 27514

Scott Nixon
Graduate School of Oceanography
University of Rhode Island
Kingston, RI 02881

William Odum
Department of Environmental
Sciences
University of Virginia
Charlottesville, VA 22903

Mitchell Rambler
Global Biology Program Manager
NASA
Life Sciences Division
600 Independence Avenue, SW
Code EBT-3
Washington, DC 20546

Daniel Sebacher
Mail Stop 483
NASA Langley Research Center
Hampton, VA 23665

APPENDIX B

Definitions of Wetland Classes

Criteria are based, in part, on Anderson et al., 1976; and Cowardin et al., 1979.

1. Forested Wetlands

1.1 Freshwater Swamps.- Wetlands whose vegetation is dominated by trees and large shrubs in which the water table is at or above the soil surface for significant periods during each year and in which water salinities do not exceed 0.5 ppt. Characterized by minimal surface water flows and surface drainage systems which are poorly defined or altogether absent.

1.2 Riverine Swamps.- Same as "Freshwater Swamps" except characterized by persistent measurable surface water flow and association with a riverine drainage system.

1.3 Mangroves.- Tropical coastal wetlands whose vegetation is dominated by any of several tree species commonly described as "mangroves".

2. Nonforested Wetlands

2.1 Tidal Salt Marshes.- Coastal wetlands exposed to periodic tidal inundation with waters exceeding 0.5 ppt salinity and dominated by emergent herbaceous plants such as grasses and rushes.

2.2 Tidal Fresh Marshes - Same as "Tidal Salt Marshes" except having water salinities below 0.5 ppt.

2.3 Freshwater Marshes.- Wetlands inundated with standing or riverine waters having salinities less than 0.5 ppt and dominated by emergent or floating herbaceous plants. Includes "bogs," "marshes," and "wet prairies."

2.4 Flooded Agricultural Systems.- Wetlands whose vegetation and inundation characteristics are controlled for the purposes of agriculture. Includes, but not limited to, cultivation of rice.

3. Wet Tundra

Treeless wetlands found above the latitudinal or altitudinal limit of boreal forests with standing water present during months with nonfreezing average temperature. Characterized by emergent sedges and rooted aquatic plants and by poorly drained, often glacially derived, soils.

REFERENCES

Anderson, D. C. and A. L. Higer, 1980. Water columns in the Florida Everglades from Landsat data. Open-File Rept., U.S. Geol. Survey.

Anderson, J. R., E. E. Hardy, J. T. Roach, and R. E. Witmer, 1976. A land use and land cover classification system for use with remote-sensor data. U.S. Geological Survey Professional Paper No. 964.

Atjay, G. L., P. Ketner, and P. Duvigneaud, 1979. Terrestrial primary production and phytomass. The Global Carbon Cycle, B. Bolin, E. T. Degens, S. Kempe, and P. Ketner, Eds., J. Wiley and Sons:129-181.

Bailey, R. G., 1978. Ecoregions of the United States. U.S. Forest Service, Intermountain Region, Ogden, Utah.

Barclay, L. A., 1978. An ecological characterization of the sea islands and coastal plain of South Carolina and Georgia. Coastal Zone '78. Am. Soc. of Civil Engineers, N.Y.:711-720.

Bartlett, D. S. and V. Klemas, 1980. Evaluation of remote-sensing techniques for surveying coastal wetlands. Report to Nat. Mar. Fisheries Serv. by Univ. of Delaware, Feb.

Bartlett, D. S. and V. Klemas, 1981. In situ spectral reflectance studies of tidal wetland grasses. Photogram. Eng. and Remote Sensing, 47(12):1695-1703.

Berner, R. A., 1975. Diagenic models of dissolved species in the interstitial waters of compacting sediments. American Journal of Science, 275:88-96.

Bolin, B., E. T. Degens, P. Duvigneaud, and S. Kempe, 1979. The global biogeochemical carbon cycle. The Global Carbon Cycle. B. Bolin, E. T. Degens, S. Kempe, and P. Ketner, Eds., J. Wiley and Sons:1-56.

Boon, J., 1975. Tidal discharge asymmetry in a salt marsh drainage system. Linnol. Oceanogr. 20:71-80.

Brooke, R. L. and G. A. Norcross, 1983. Seasat radar altimeter measurements over the Florida Everglades. NASA CR-156889.

Brown, W. W., 1977. Wetlands mapping in New Jersey and New York. Proc. Ann. Mtg., Am. Soc. Photogrammetry:381-395.

Bunnell, F. L. and P. Dowding, 1974. ABISKO - A generalized decomposition model for comparison between tundra sites. Soil Organisms and Decomposition in Tundra. A. J. Holding, O. W. Heal, S. F. McLean, Jr., and P. W. Flanagan, Eds., Tundra Biome Steering Committee, Stockholm, Sweden: 227-247.

Butera, M. K., 1978. A demonstration of wetland vegetation mapping in Florida from computer-processed satellite and aircraft multispectral scanner data. NASA-NSTL Rept. No. 168.

Butera, M. K., 1976. A technique developed for the determination of Louisiana marsh salinity zones from vegetation mapped by multispectral data: a comparison of results from satellite and aircraft data. NASA ERL Rept. No. 161, Johnson Space Center.

Butera, M. K., 1979. Computer-implemented remote-sensing techniques for measuring coastal productivity and nutrient transport systems. Proc. 5th W. T. Pecora Symp. on Remote Sensing. M. Deutsch et al., Eds., Am. Water Resour. Assoc.:522-532.

Butera, M. K. and J. A. Browder, 1983. Assessment of wetland productive capacity from a remote-sensing-based model-A NASA/NMFS joint research project. Presented at 1983 International Geoscience and Remote Sensing Symposium. Aug. 31-Sept. 2, 1983. San Francisco, CA.

Capone, D. C. and E. J. Carpenter, 1982. Nitrogen fixation in the marine environment. Science 217:1140-1142.

Carter, V., 1978. Coastal wetlands role of remote sensing. Coastal Zone 1978: Proc. Symp. on Technical, Environmental, Socioeconomic, and Regulatory Aspects of Coastal Zone Management. Am. Soc. Civil Eng.:1261-1283.

Chapman, V. J., 1974. Salt Marshes and Salt Deserts of the World, 2nd edit., Verlag Von J. Cramer, Bremerhauen, W. Germ.; 392 pp.

Cicerone, R. J. and J. D. Shetter, 1981. Sources of atmospheric methane: Measurements in rice paddies and a discussion. J. Geophys. Res. 86(c8):7203-7209.

Claypool, G. E. and I. R. Kaplan, 1974. The origin and distribution of methane in marine sediments. Natural Gases in Marine Sediments, I. R. Kaplan, Ed., Plenum Press, N.Y.:99-140.

Cowardin, L. M., V. Carter, F. C. Golet, and E. T. La Roe, 1979. Classification of wetlands and deepwater habitats of the United States. Fish and Wildlife Service 035-79/31.

Dacey, J. W. H. and M. J. Klug, 1979. Methane efflux from lake sediments through water lilies. Science 203:1253-1255.

DeLaune, R. D., C. J. Smith, and W. H. Patrick, Jr., 1983. Methane release from Gulf coast wetlands. Tellus 35B:8-15.

Denmead, O. T., 1979. Chamber systems for measuring nitrous oxide emission from soils in the field. Soil Sci. Am. J. 43:89-95.

Ehhalt, D. H. and D. Schmidt, 1978. Sources and sinks of atmospheric methane. Pageoph. 116:452-464.

Fefer, S. J., C. Laffin, L. Thornton, P. Schetting, and R. Brami, 1978. Marine coast characterization users guide. Contributed papers on coastal ecological characterization studies, J. B. Johnston and L. A. Barclay, Eds., U.S. Fish and Wildlife Service, FWS/OBS-77/37:46-66.

Finn, J. T., 1982. Digital vegetation mapping of Northeast coastal wetlands. Progress report to Nat. Mar. Fisheries Ser. by Univ. of Mass., Nov.

Gammon, P. T., W. G. Rohde, and V. Carter, 1979. Accuracy evaluation of Landsat digital classification of vegetation in the Great Dismal Swamp. 5th W. T. Pecora Symp. on Remote Sensing. Deutsch et al., Eds., Am. Water Resour. Assoc.:463-473.

Hanson, B. C. and R. K. Moore, 1976. Polarization and depression angle constraints in the utilization of SLAR for identifying and mapping surface water, marsh and wetlands. Proc. Fall Conv., Am. Soc. Photogrammetry:499-505.

Hardisky, M. A., R. M. Smart, and V. Klemas, 1983. Seasonal spectral characteristics and above ground biomass of the tidal marsh plant <u>Spartina alterniflora</u>. Photogram. Eng. and Remote Sensing 49(1):85-92.

Harriss, R. C., D. I. Sebacher, and F. P. Day, Jr., 1982. Methane flux in the Great Dismal Swamp. Nature 297:673-674.

Hoppe, H., 1983. Significance of exoenzymatic activities in the ecology of brackish water: Measurement by means of methylumbelliferyl-substrates. Mar. Ecol. Prog. Ser. 11:299-308.

Hutton, S. M. and T. Dincer, 1979. Using Landsat to study the Okavango Swamp, Botswuna. 5th W. T. Pecora Symp. on Remote Sensing. M. Deutsch et al., Eds., Am. Water Resour. Assoc.:512-519.

Jorgensen, B. B., 1978. A comparison of methods for the quantification of bacterial sulfate reduction in coastal marine sediments: I. Measurements with radiotracer techniques. Geomicrobiol. J. 1:11-27.

Kaplan, W., I. Valiela, and J. M. Teal, 1979. Denitrification in a salt marsh ecosystem Limnol. Oceanogr. 24(4):726-734.

Karl, D. M. and O. Holm-Hansen, 1978. Methodology and measurement of adenylate energy charge ratios in environmental samples. Mar. Biol.:48:185-198.

Kendall, B. M. and J. O. Blanton, 1981. Microwave radiometer measurement of tidally induced salinity changes off the Georgia coast. J. Geophys. Res. 86 (C7):6435-6441.

King, G. M. and W. J. Wiebe, 1978. Methane release from soils of a Georgia salt marsh. Geochim. Cosmochim. Acta (A2):343-348.

Kjerfve, B. J. and J. A. Proehl, 1979. Velocity variability in a cross-section of a well-mixed estuary. J. Mar. Res.:37:409-418.

Kratz, T. K., R. M. Friedman, and C. B. DeWitt 1979. A spatial simulation model of lake-edge wetland formation. IES Report 107. Institute for Environmental Studies, Univ. of Wisconsin-Madison.

Levine, J. S. and F. Allario, 1982. The global troposphere: biogeochemical cycles, chemistry, and remote sensing. Environmental Monitoring and Assessment 1:263-306.

MacDonald, H. C., W. P. Waite, and J. S. Demark, 1980. Use of Seasat satellite radar imagery for detection of standing water beneath forest vegetation. Proc. of the Fall Convention of Am. Soc. Photogram.

MacDonald, R. B. and F. G. Hall, 1980. Global crop forcasting. Science 280:670-679.

MacDonald, R. B., A. G. Houston, R. P. Heydorn, D. B. Botkin, J. E. Estes, and A. H. Strahler, 1981. Monitoring global vegetation. NASA TM-85166.

Martens, C. S. and M. B. Goldhaber, 1978. Early diagenesis in transitional sedimentary environments of the White Oak River Estuary, North Carolina. Limnol. Oceanogr. 23(3):428-441.

Matthias, A. D., D. N. Yorger, and R. S. Weinbeck, 1978. A numerical evaluation of chamber methods for determining gas fluxes. Geophys. Res. Let. (5):765-768.

McDonough, C., G. Dryden, T. Sofia, S. Wisotsky, and P. Howes, 1980. Pulsed laser mapping system for light aircraft. Proc. 14th Inter. Symp. On Remote Sensing of Environment, Environmental Research Inst. of Mich., Ann Arbor:1711-1720.

Mitsch, W. J., C. L. Dorge, and J. R. Wiemhoff, 1979. Ecosystem dynamics and a phosphorus budget of an alluvial cypress swamp in southern Illinois, Ecology 60:1116-1124.

Montanari, J. H. and J. E. Townsend, 1977. Status of the National Wetland Inventory. Trans. N. Am. Wildl. Nat. Resour. Conf. (42):66-72.

Moriarty, D. J. W. and P. C. Pollard, 1981. DNA synthesis as a measure of bacterial growth rates in seagrass sediments. Mar. Ecol. Prog. Ser., 5:151-156.

National Research Council, 1983. Fundamental Research On Estuaries: The Importance of An Interdisciplinary Approach, Nat. Acad. Press, Wash., DC.

National Aeronautics and Space Administration, 1983. Land-related global habitability science issues. TM-85841.

Nixon, S. W., 1980. Between coastal marshes and coastal waters - a review of twenty years of speculation and research on the rate of salt marshes in estuarine productivity. Estuarine and Wetland Processes With Emphasis on Modeling. Marine Science, P. Hamilton and K. B. Macdonald, Eds., Vol. 11, Plenum Press:437-525.

Parker, P. E. and R. H. Kadler, 1974. A dynamic ecosystem simulator. Am. Inst. Chem. Eng.; 78th Ann. Mtg., Paper No. 8C, Salt Lake City, UT.

Polis, D. F., M. Salter, and H. Lind, 1974. Hydrographic verification of wetland delineation by remote sensing. Photogram. Eng. 40(1):75-78.

Porter, K. and D. H. Volman, 1962. Flame ionization detection of carbon monoxide for gas chromatographic analysis. Anal. Chem. (34):748-749.

Rambler, M. B., Ed. 1983. Global Biology Research Program: Program Plan. NASA TM-85629.

Rose, P. W. and P. C. Rosendahl, 1983. Classification of Landsat data for hydrologic application, Everglades National Park. Photogram. Eng. and Remote Sensing 49(4):505-511.

Schmugge, T. J., T. J. Jackson, and H. L. McKim, 1980. Survey of methods for soil moisture determination. Water Resources Research 16(6):961-979.

Schwartzkopf, S. H., 1978. An open chamber technique for the measurement of carbon dioxide evolution from soils. Ecology 59:1062-1068.

Sebacher, D. I. and R. C. Harriss, 1980. A continuous sampling and analysis system for monitoring methane fluxes from soil and water surfaces to the atmosphere. Proc. 73rd Ann. Mtg. Air Pollution Control Assoc. Paper 80-39.4.

Sebacher, D. I. and R. C. Harriss, 1982. A system for measuring methane fluxes from inland and coastal wetland environments. J. Envir. Qual. 11:34-37.

Sebacher, D. I., R. C. Harriss, and K. B. Bartlett, 1983. Methane flux across the air-water interface: Air velocity effects. Tellus 35B:103-109.

Seiler, W. and R. Conrad, 1980. Field measurements of N_2O release rates from soils. Proc. 73rd Ann. Mtg. Air Pollution Control Assoc. Paper 80-39.7.

Seiler, W. and C. W. Junge, 1967. Entwicklung eines messverfahrens zur bestinmmung kleiner mengen kohlenoxid (CO). Meterol. Rdsch. 6:175-176.

Struve, H. and W. L. Kirk, 1980. Remote-sensing procedures for detecting and monitoring various activities regulated by the Mobile District. U.S. Army Engineer Waterways Experiment Sta., Tech. Rept. EL-80-1.

Tucker, C. J., 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sensing of Environment 8:127-150.

Waite, W. P., H. C. MacDonald, V. H. Kaupp, and J. S. Demarcke, 1981. Wetland mapping with imaging radar. Proc. Internatl. Geoscience and Remote Sensing Symp., IEEE-81CH1656-8:794-799.

Wiegert, R. G., R. R. Christian, and R. L. Wetzel, 1981. A model view of the marsh. The Ecology of a Salt Marsh, L. R. Pomeroy and R. G. Wiegert, Eds., Springer-Verlag, N.Y.:183-218.

Winer, A. M., M. C. Dodd, D. R. Fitz, P. R. Miller, E. R. Stephens, K. Neisess, M. Meyers, D. E. Brown, and C. W. Johnson, 1982. Assembling a vegetative hydrocarbon inventory for the California south coast air basin: Direct measurement of emission rates, leaf biomass and vegetative distribution. Air Pollution Control Assoc., Ann. Mtg. Paper 82-51-6.

Woodwell, G. M., Ed., 1980. Carbon dioxide effects research and assessment program: Measurement of changes in terrestrial carbon using remote sensing. U.S. Dept. of Energy, Conf. 7905176 UC-11.

1. Report No.
NASA CP-2316

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
GLOBAL BIOLOGY RESEARCH PROGRAM - BIOGEOCHEMICAL PROCESSES IN WETLANDS

5. Report Date
August 1984

6. Performing Organization Code
199-30-36-02

7. Author(s)
David S. Bartlett, Editor

8. Performing Organization Report No.
L-15791

9. Performing Organization Name and Address
NASA Langley Research Center
Hampton, VA 23665

10. Work Unit No.

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, DC 20546

13. Type of Report and Period Covered
Conference Publication

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report summarizes the results of a workshop examining potential NASA contributions to research on wetland processes as they relate to global biogeochemical cycles. The workshop participants concluded that NASA interests and expertise are well-suited to support: (1) Development of geographic wetlands data bases which utilize remotely sensed inventories and incorporate important parameters which may not be accessible through remote sensing. Digital data bases would make the best use of existing remote sensor data and would allow manipulation of large data sets. (2) Studies of wetland/atmosphere exchange processes. Studies should include the development and implementation of field techniques for direct measurement of net flux of gas-phase carbon, nitrogen, and sulfur compounds in wetland environments. Emphasis is placed on wetland production of biogenic gases, consumption of atmospheric CO_2, and storage of nutrients as biomass. (3) Research establishing transfer functions between inventoried data-base parameters and actual rates of material exchange for wetlands. Transfer functions provide the basis for extrapolation of local measurements to assess global biogeochemical cycling processes.

17. Key Words (Suggested by Author(s))
Biogeochemical cycles
Wetlands
Remote sensing
Biogenic gases
Carbon dioxide
Biomass
Global processes

18. Distribution Statement
Unclassified - Unlimited

Subject Category 51

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
44

22. Price
A03

For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1984

National Aeronautics and
Space Administration

Washington, D.C.
20546

Official Business
Penalty for Private Use, $300

THIRD-CLASS BULK RATE

Postage and Fees Paid
National Aeronautics and
Space Administration
NASA-451

U.S.MAIL

NASA

POSTMASTER: If Undeliverable (Section 158
Postal Manual) Do Not Return