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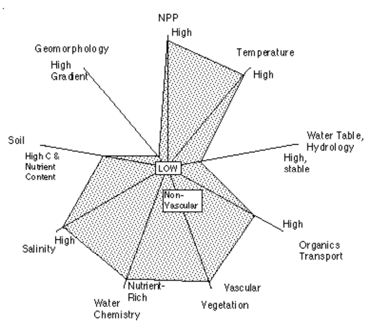

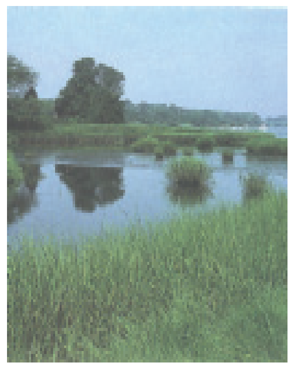

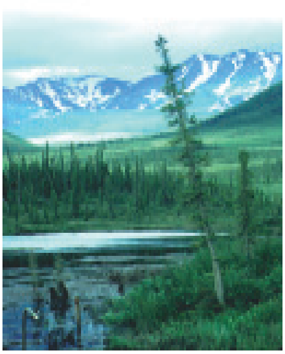

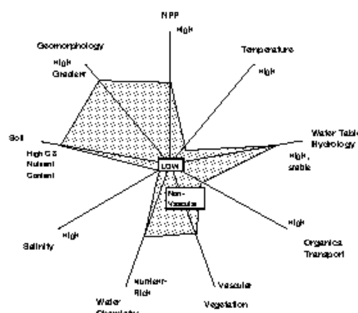

Global Wetland Distribution and Functional Characterization: Trace Gases and the Hydrologic Cycle

Workshop Report

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Global Wetland Distribution and Functional Characterization: Trace Gases and the Hydrologic Cycle

Report from the Joint GAIM, BAHC, IGBP-DIS, IGAC, and LUCC Workshop Santa Barbara, CA, USA, 16–20 May 1996

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Workshop Report

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Cover Illustration: Two wetlands of contrasting characteristics, with corresponding 9-dimensional parameterization. (Salt marsh photo from Connecticut Department of Conservation; USA; Alpine wetland photo from Patrick Crill; Parameterization by Dork Sahagian)

Layout and Technical Editing: Lisa Wanrooy-Cronqvist

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Participants in the IGBP Wetlands Workshop, 16–20 May 1996.
Standing from left to right: Dork Sahagian, Brad Newton, Leal Mertes, Charon Birkett, Kevin Rogers, Tom Dunne, John Melack, Jeff Chanton, Laura Hess, Leslie Morrissey, Louise Fresco, Elaine Matthews, Ron Sass, Yoshifumi Yasuoka, Max Finlayson, Wolfgang Junk, Victor Klemas, Reyaldo Victoria, Misauki Tamura, Nigel Roulet, Suzanne Sippel, and Mats Nilsson. Seated from right to left: Brij Gopal and the late Ted Hollis (with official wetland rubber boots). Not photographed: Ichtiaque Rasool and Jack Estes.

Abstract

The IGBP Wetlands workshop (Santa Barbara, CA, USA,16–20 May 1996) was held for the purpose of identifying data and research needs for characterizing wetlands in terms of their role in biogeochemical and hydrologic cycles. Wetlands cover only about 1% of the Earth's surface, yet are responsible for a much greater proportion of biogeochemical fluxes between the land surface, the atmosphere and hydrologic systems. They play a particularly important function in processing methane, carbon dioxide, nitrogen, and sulphur as well as in sequestering carbon. Considerable progress has been made in the past 10 years regarding wetlands and methane: a global digital dataset of wetlands (Matthews and Fung 1987) was produced and global observations of methane have been combined with global three-dimensional atmospheric modelling (Fung *et al.* 1991) to constrain modelled fluxes of methane from high-latitude wetlands. Furthermore, significant advances have been made in understanding the biogeochemical processes that control fluxes of methane and other trace gases. The progress has made clear that present wetland classification schemes do not accurately reflect their roles in these processes because they have been based on wetland attributes such as dominant plant types which do not reflect differences in the functions of wetlands regarding biogeochemical cycles. Further, traditional wetland classifications cannot be distinguished on the basis of global remotely sensed observations. Consequently, it has been impossible to accurately quantify the distribution of key fluxes on the basis of observed land cover.

We have developed a wetland parameterization scheme based on observable quantities to better incorporate wetlands into global land surface characterization schemes so that the relation between land cover and biogeochemical fluxes can be more accurately determined. An improved understanding of this relation will make it possible to better use observed or historical changes in land cover to infer changes in biogeochemical fluxes, including the cycles of gases such as methane and carbon dioxide which affect the radiative balance of the atmosphere.

The initial nine parameters proposed by the participants at the wetlands workshop as important for characterizing the role of wetlands in biogeochemical cycling of trace substances are: hydrology, temperature, primary production, vegetation, soil type, salinity, chemical information, transport of organics and sediment, and topography/geomorphology. When plotted in a 9-space defined by the wetland parameters, wetlands which define similar curves will function similarly in terms of biogeochemical fluxes, regardless of location. While the proposed functional param-

eters are not entirely independent of each other, they represent a complete set which can be obtained on the basis of existing or presently possible observations. These parameters may be refined subsequently in future research to establish a robust set of orthogonal parameters. Some of these functional parameters are typical also of the non-wetland land surface, and may be part of a larger dataset when wetlands are included in global land cover maps.

With the functional parameterization developed at the wetlands workshop, it will be possible to subdivide wetlands into functional types in land cover and biome maps so that the maps will bear on the global distribution and change (both natural and anthropogenic) of biogeochemical cycling. The latter will be an important element in prognostic biogeochemical models as they are developed.

Introduction

Global Analysis, Interpretation, and Modelling (GAIM), in conjunction with Biospheric Aspects of the Hydrological Cycle (BAHC), Data and Information System (IGBP-DIS), the International Global Atmospheric Project (IGAC), and Land Use/ Cover Change (LUCC), held a joint workshop for the purpose of advancing the state of knowledge regarding the distribution of wetlands as well as developing a functional wetland characterization scheme on a global basis. The purpose of the workshop was to establish a functional parameterization of wetlands directed toward integrating wetland trace gas, hydrologic, nutrient, and other fluxes into regional and global biogeochemical models more effectively than presently possible. Wetland scientists from every continent and various disciplines related to wetlands gathered and formulated a nine-parameter functional n-space into which all wetlands can be plotted. The formulation was developed jointly by field ecologists and scientists with remote sensing expertise to define functions and determine the types of data sets which could be brought to bear on the problem of discrimination between wetlands with different sets of parametric values. The initial nine parameters proposed by workshop participants were: primary production, temperature, hydrology, transport of organics and sediment, vegetation, chemical information, salinity, soil types and topography/geomorphology. These may be refined in future research to establish a robust set of orthogonal parameters. This report describes the conclusions drawn at the Wetland Workshop. In many cases, it raises more questions than it answers. The intent is to chart a course for future wetlands research within the context of IGBP so that the important role played by wetlands in global biogeochemical cycles can be accurately incorporated into global terrestrial ecosystem models.

Wetlands have been defined in various ways. At the workshop, we developed a working definition of wetlands as: **"An area in which: (a) the water table is at or near the soil surface for a significant part of the growing season; and (b) soils are covered by active vegetation (during the period of water saturation)"**. The extent of wetlands is uncertain because it is difficult to identify and classify wetlands on a global scale. In addition, the areal extent of wetlands is being modified as a result of land-use changes, so that once a globally consistent classification scheme is established, the areal distribution must be monitored and recompiled periodically. The global areal extent of wetlands has been estimated as 5.3 x 1012 m^2 (Matthews and Fung 1987) or 8.6 x 1012 m^2 (Mitchell 1990), but these figures are uncertain. While relatively small compared to ocean, savannah, or forest area, wetlands are biogeochemically active because of their high productivity and redox gradients. In particular, wetlands are major natural sources of reduced gases such as methane and sulphur compounds, and can have high rates of denitrification and nitrogen fixation.

In the past, wetlands have been classified in various ways on the basis of hydrology, geomorphology, and vegetation. However, for the purpose of understanding the effects of wetlands on global biogeochemical cycles, it is necessary to devise a functional characterization of wetlands, so that distributions of wetlands can be included on this basis into global biogeochemical models. This way, general land cover maps can include different functional types of wetlands so that biogeochemical interpretations can be made for these areas as they are for "dry land" areas. The primary missions of the IGBP Wetlands Workshop was to develop a scheme for functional characterization of wetlands and to evaluate applications of remote sensing to studies of wetlands biogeochemistry.

The timing and extent of flooding is a key environmental factor controlling ecological processes in wetlands. Flooding brings nutrients and creates the physical environment required by the plants and microbes. Hence, modifications to wetland hydrology severely disrupt their function. The US and Europe have drained and converted wetlands extensively (Mitchell 1990, Mitsch and Gosselink 1986). Land-use changes in developing countries are increasingly eliminating wetlands on a global basis. Moreover, given the expected increase in human population (mostly in developing regions) the pressure to convert wetlands for agriculture to meet growing food requirements is expected to increase even further.

Wetland Processes

Wetland functions are defined as processes and manifestations of processes occurring in wetlands. Most functions fall within three categories: hydrologic; biogeochemical and maintenance of habitat and food webs. Hydrologic functions include long and short-term surface water storage, and the maintenance of high water tables. Such functions reduce the amplitude of flooding peaks downstream, maintain base flow rates by buffering flow distributions and maintain the hydrophilic community and habitat. Biogeochemical functions include the transformation and cycling of elements, retention and removal of dissolved substances from surface waters, and accumulation of peats and inorganic sediments. These functions retain nutrients and other elements, improve water quality, and affect aquatic and atmospheric chemistry. Respiration of organic matter (OM) occurs and results in the reduction of electron acceptors alternative to O2, most significantly involving nitrate, sulphate, iron, and organic matter (to produce methane). Wetlands act as sediment sinks, particularly in floodplains. Habitat and food web support includes maintenance of wetland plant communities which provide food and habitat for waterfowl and other animals, thus maintaining diversity.

Wetlands are among Earth's most productive systems. The productivity of many wetland plants (*e.g., Spartina, Phragmites, Typha, Cyperus papyrus*) is as great as the most hearty agricultural crops (Mitsch and Gosselink 1993). Wetlands fix and store organic matter, and can release dissolved and particulate organic carbon (DOC and

POC) to adjacent aquatic environments or those downstream (Nixon 1980). Several studies have detailed these processes in salt marsh wetlands (Chalmers *et al.* 1985, Valiela *et al.* 1978, Woodwell *et al.* 1977). Results from these studies have been equivocal; it has been difficult to prove conclusively that export of organic carbon in large amounts is a general characteristic of salt marshes.

The situation may be different for alluvial wetlands. The Apalachicola River, Florida, USA, supports a largely undisturbed forested wetland on its floodplain and a highly productive estuary at its mouth, the Apalachicola Bay (Leitman *et al.* 1984). The system contains one of the largest floodplain wetlands preserved in the Continental USA. A flux of 35000 metric tons of organic carbon derived from leaf litter to the estuary during spring flooding has been documented (Livingston 1984). Wetland productivity fuels secondary production as organisms graze within the wetland. Primary production in wetlands is exported to fuel secondary production in estuaries. The importance of terrestrial input to the estuary has been underscored by Meeter *et al.* (1979) who found that the productivity of the estuary depends upon both annual pulses of detritus and the large scale import of detritus during 5 to 7 year pulses of increased river flow (Mattraw and Elder 1984). Increased river flow has been linked to increased crab and oyster catch in the estuary (Wilbur 1992, 1994).

In the large river systems of South America, primary production by algae and vascular plants in the floodplain wetlands supports food webs in the floodplain lakes and the river channel (Forsberg *et al.* 1993, Hamilton *et al.* 1992), and these food webs include fishes consumed by local human populations. The floodplains both produce and degrade large quantities of organic matter (Junk *et al.* 1989), but the variable water levels favour floating and emergent vascular plants, and hence the biological metabolism beneath the water surface is generally strongly heterotrophic. Depletion of dissolved O_2 in the floodplain waters is commonly observed, and can be particularly acute when the rising rivers first inundate the previously dry floodplain. Such an event has been described in the Pantanal wetland, in which the entire Paraguay River channel became anoxic for 6 weeks at rising water due to rapid rates of decomposition in adjacent floodplain areas (Hamilton *et al.* 1997).

Microbial oxidation of organic materials in wetlands and the resultant reduction of electron acceptors including and alternative to O_2 results in transformations of nitrate, sulphate, iron, and carbon which are significant in wetlands. The importance of these electron acceptors varies with soil depth and has been found to vary along a salinity gradient (Martens and Goldhaber 1978). In a New England salt marsh O_2 uptake at the sediment surface was found to integrate both aerobic and anaerobic metabolism. Annual estimates of O_2 uptake agree with those for CO_2 production. While almost 50% of below ground carbon remineralization proceeded by sulphate reduction in this marsh, the produced sulphide must have been nearly quantitatively oxidized at the soil-water interface or in the rhizosphere (Howes *et al.* 1984). The importance of sulphate reduction to carbon remineralization in salt marsh sediments has also been documented (Howarth and Giblin 1983, 1984).

Recent reviews of the biogenic sulphur cycle include Bates *et al.* (1992) and Saltzman and Cooper (1989). Howarth and Giblin (1983) have reviewed wetland sulphur cycling. Dimethyl sulphide (DMS) and hydrogen sulphide (H_2S) dominate gas emissions from marshes and tidal mud flats, although methyl mercaptan, carbonyl sulphide (COS), carbon disulphide (CS_2) and dimethyl disulphide (DMDS) are also emitted (Cooper *et al.* 1987, Hines *et al.* 1993). Fluxes of S gases from coastal wetlands are 10–100 times higher than sulphur fluxes from the ocean, but their areal extent is limited. DMS flux is related to plant physiological processes, while H_2S flux is related to sediment chemistry. Positive relationships between *Spartina alterniflora* (live aboveground and root) biomass and DMS emission have been observed (Morrison and Hines 1990). DMS is a degradation product of the osmoregulant dimethylsulphonio-propionate (DSMP) (Dacey and Blough 1987) which is found in the tissues of *Spartina alterniflora, Spartina anglica* and *Zostera marina* (Dacey and Blough 1987). DMS fluxes have been found to be substantially higher in *Spartina alterniflora* than in plants which do not contain DMSP (*e.g., Spartina patens, Juncus roemerianus, Distichlis spicata, Avicennia germinans, Batis maritima,* and *Cladium jamaicense*) (Cooper *et al.* 1987, Morrison and Hines 1990). Enhancement of DMS emission and production has been observed with plant ingestion by animals (Hines *et al.* 1993). Information on sulphur emissions from freshwater wetlands has been reviewed by Hines *et al.* (1993).

Denitrification can be a significant sink for nitrogen in wetlands. Generally it is coupled with nitrification of ammonia so a complex zonation of oxygenated and suboxic micro-environments is required. The oxidized rhizosphere of aquatic plants can be an ideal environment for this coupling (Reddy *et al.* 1989). Several studies have evaluated the importance of denitrification in wetlands (Groffman *et al.* 1992, Whitney *et al.* 1981, Zanner and Bloom 1995).

The importance of iron reduction as an agent of carbon remineralization has been reviewed by Lovley (1995). In a recent study of a southeastern US freshwater wetland, Fe(III) oxide reduction accounted for 65% of total carbon metabolism in rhizosphere sediment incubations, compared to 22% for methanogenesis (Roden and Wetzel 1996). Salt marsh soils may contain high iron concentrations which may be cycled rapidly by sulphate reduction and sediment oxidation on annual and episodic time scales (Kostka and Luther 1995). The presence of abundant iron oxide can inhibit methane production in wetlands and rice fields (Roden and Wetzel 1996).

Methane production is the terminal process of organic carbon remineralization in anoxic soils and sediments and occurs when there is a high input of labile organic matter in the absence of oxygen and alternative electron acceptors such as sulphate. Acetate fermentation and CO_2 reduction are the dominant methane production mechanisms although methane can also be produced from methyl amines, methanol, and formaldehyde. Wetlands and rice fields are two of the largest sources of methane to the atmosphere (Bartlett and Harriss 1993) due to the anoxic conditions occurring in their flooded soils and their high primary production. Together rice fields and wetlands make up about 40% of the methane input to the troposphere. Excellent reviews of methane emissions from global wetlands may be found in Bartlett and Harriss (1993) and Matthews (1993). The importance of northern wetlands in releasing methane to the atmosphere is still somewhat uncertain. Crill (1996) divided the world's wetlands into four major latitudinal zones, tropical (0–20°) temperate (20–45°) boreal (45–65°) and arctic (>65°) and calculated that more than half of the yearly emission of methane comes from boreal wetlands. Bartlett and Harriss (1993) estimated that 60% of the methane input to the atmosphere from wetlands was from tropical regions while only 35% was from wetlands north of 45°. Initial high estimates of the importance of boreal wetlands were made based upon elevated methane emission rates observed in Minnesota (USA) peatlands (Crill *et al.*

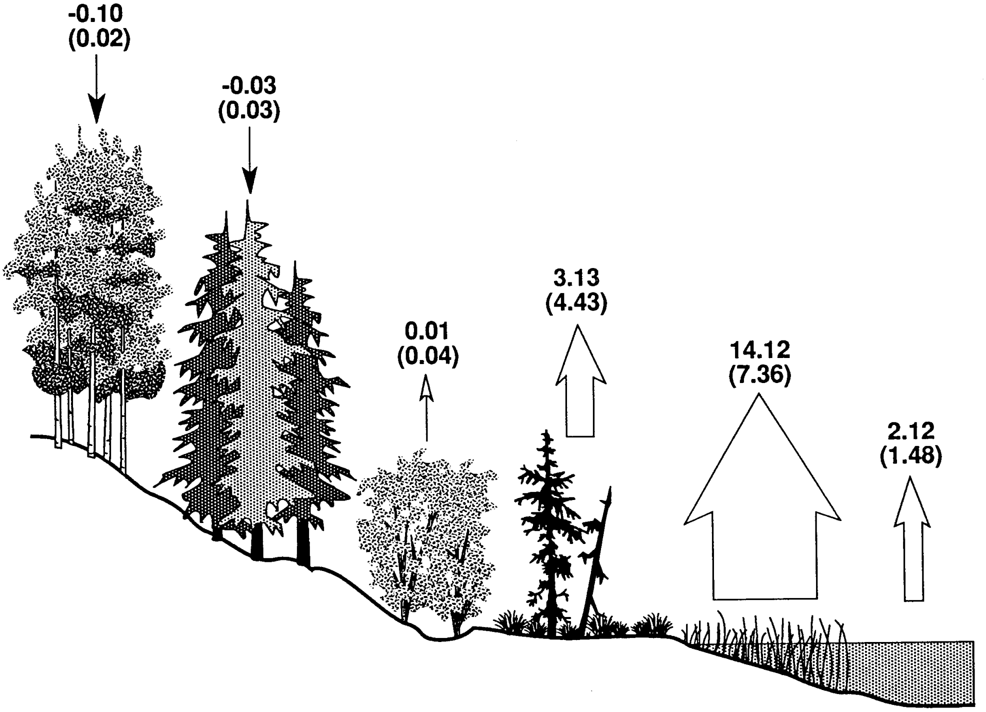
1992, Dise 1993). Rates in Minnesota apparently are 5–15 times higher than those reported for nearby Canadian peatlands of the Hudson Bay lowlands (Klinger *et al.* 1994, Moore and Knowles 1990). The Hudson Bay data caused revision downward in the importance of northern wetlands in supplying methane to the atmosphere and focused attention to the tropics. More recent data collected suggests that the Hudson Bay lowland data may be more atypical of northern wetlands than are the Minnesota peatlands.

Wetland plants, including rice, serve to enhance methane emission by serving as conduits for gas exchange (Holzapfel-Pschorn *et al.* 1986) and through the production of root exudates and above and belowground litter. Linkages between vegetation biomass and net ecosystem production and methane emission within and across wetlands have been observed (Aselmann and Crutzen 1989, Sass *et al.* 1990). Mid-season methane exchange rates for boreal communities (Figure 1) can vary by several orders of magnitude representing both consumption and emission (Morrissey *et al.* 1994). Methane consumption is characteristic of the forested uplands while open water bodies and herbaceous wetlands, in particular, act as key sources of methane. Black spruce forests, bogs and riparian shrublands can act as sources or sinks depending on the saturation of the underlying sediments. Important factors controlling methane production are salinity (Bartlett *et al.* 1987), fertilization of rice field soil, water level (Roulet *et al.* 1992, Sass *et al.* 1992), temperature (Crill 1996), soil properties (Sass *et al.* 1994), light (King 1990) and methane oxidation both at the soil water interface and in the rhizosphere (King 1994). Some of the controls on methane emissions from wetlands have been modelled and validated with observational data (Walter *et al.* 1996). Comprehensive studies of several years duration (Moore and Knowles 1990, Whalen and Reeburgh 1992) have led to the conclusion that many of the factors influencing methane emission are not entirely independent and that integrating parameters or variables are required.

Wetlands play an important role in carbon and nitrogen storage (Roulet *et al.* 1993). The ability of a wetland ecosystem to store carbon is related to hydrology and oscillation of the water table, geomorphology and climatic setting. The hydrology of a wetland system controls the oxidation/reduction potential of the system. A stable water table leads to anoxic (reducing) conditions and the production of methane. A highly variable water table however, allows deposited organic material to be oxidized, and thus would not promote accumulation within the system. Geomorphology determines both hydrologic regime as well as deposition of sediments and organic matter. In systems with a significant gradient, the flow of water and sediments through the system would not promote significant accumulation of organic matter, but in systems with low gradients, it is possible for accumulation, reduction of carbon and other elements. The climatic conditions of a wetland determine the seasonality of hydrology, net primary productivity (NPP), chemical activity, and availability and deposition of organic matter.

Figure 1

Methane exchange rates (mg CH_4 m^{-2} hr^{-1}) from boreal vegetation communities along an idealized elevation gradient; mean values (+/- standard deviation). Classes represent deciduous forest, coniferous forest, riparian tall shrubs, bogs, fens, and open water. (From Morrissey *et al.* 1994).



Anthropogenic Factors

The areal extent of wetlands is subject to change as a result of both natural and anthropogenic factors. The conversion of wetlands for agriculture and urban development leads to major changes in hydrology, vegetation, soil characteristics, and concomitant biogeochemical cycles. Wetland areas are influenced both by on-site factors (*e.g.*, impoundments and drainage) and by off-site or upland areas where clearing may lead to enhanced run-off, erosion, sedimentation, and accumulation of organic and inorganic solutes and particulates. From the perspective of land use, wetlands are important as a direct source of food and various other products (*e.g.*, lumber), grazing grounds, and drinking and irrigation water sources. Uplands surrounding wetlands need to be taken into account because of their controls on hydrology and nutrient supply which affect wetlands. Conversely, the landward encroachment of coastal wetlands resulting from recent and future sea level rise may threaten developed and agricultural coastal regions.

One could argue that the single most important factor affecting wetland distribution changes in the future will be demographic pressure, and related agricultural and urban land use. This factor may well dwarf some of the expected changes in sea level, temperature and CO_2 concentration variations associated with possible climate changes.

In estimates of the extent and distribution of wetlands, confusion results in cases where man has altered either the hydrology or organic/inorganic flux. These changes lead to the transformation of wetlands with concomitant effects on biogeochemical cycles. Human intervention may have four major effects on hydrologic fluxes:

1. Total drainage and transformation of wetlands into grasslands and/or dry cropland and urbanization. Hence the area is technically excluded from wetland inventories. It is necessary to determine the areal extent of altered wetlands so that the influence of human activity can be assessed.

2. Partial water management for the purpose of reducing the frequency and extent of flooding (*e.g.*, seasonal dikes, lowering of water table) either for fishing or agricultural purposes. By definition, these areas remain wetlands, but effects on biogeochemical cycles depend strongly upon flooding regime as well as additions of organic and inorganic carbon. In addition, carbon can be removed in massive quantities through grazing and peat harvesting.

3. Total hydrologic control for the purpose of rice production. This leads to changes in the fluxes of methane, CO_2, N, P, K, S, *etc.*

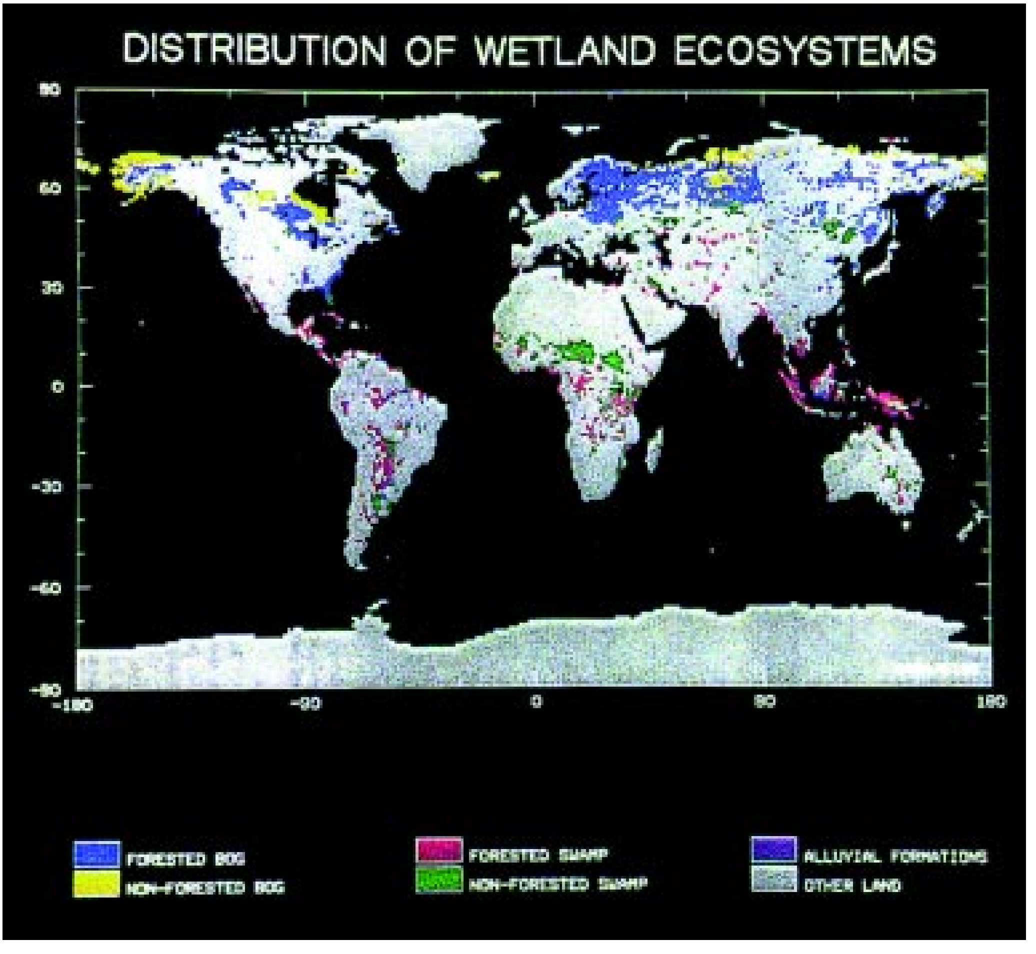
4. Grazing without hydrologic control resulting in changes in vegetation and consequent changes in elemental balances. The area remains a wetland, but is functionally altered.

Present Status of Wetland Distribution and Classification

Detailed maps of wetlands are available for the USA and Europe and regional maps are available for most of the world. However, these maps are almost always static and based on floristics rather than function. It would be beneficial to establish current and ongoing monitoring of wetland extent and flooding, with classification based on biogeochemical function. Such information is now obtainable with remote sensing in conjunction with regional data on soils, climate, and vegetation. While some studies are addressing the global effect of atmospheric exchange of trace gases from wetlands (Aselmann and Crutzen 1989), most have been concerned with wetlands at a local level (Frolking and Crill 1994). A global compilation (Matthews and Fung 1987) of wetland extent divided into five ecosystems is illustrated in Figure 2.

Figure 2

(From Matthews and Fung 1987).



New Data Availability

Newly available remotely sensed data provides the opportunity for major advances in the classification and determination of the distribution of wetlands. Passive and active microwave remote sensing provides the capability of mapping inundation extent seasonally to monitor natural and anthropogenic (agricultural) variations (Turner *et al.* 1994). These are critical data because in many regions, the amplitude of natural seasonal variations are equal to or greater than the anthropogenic modifications.

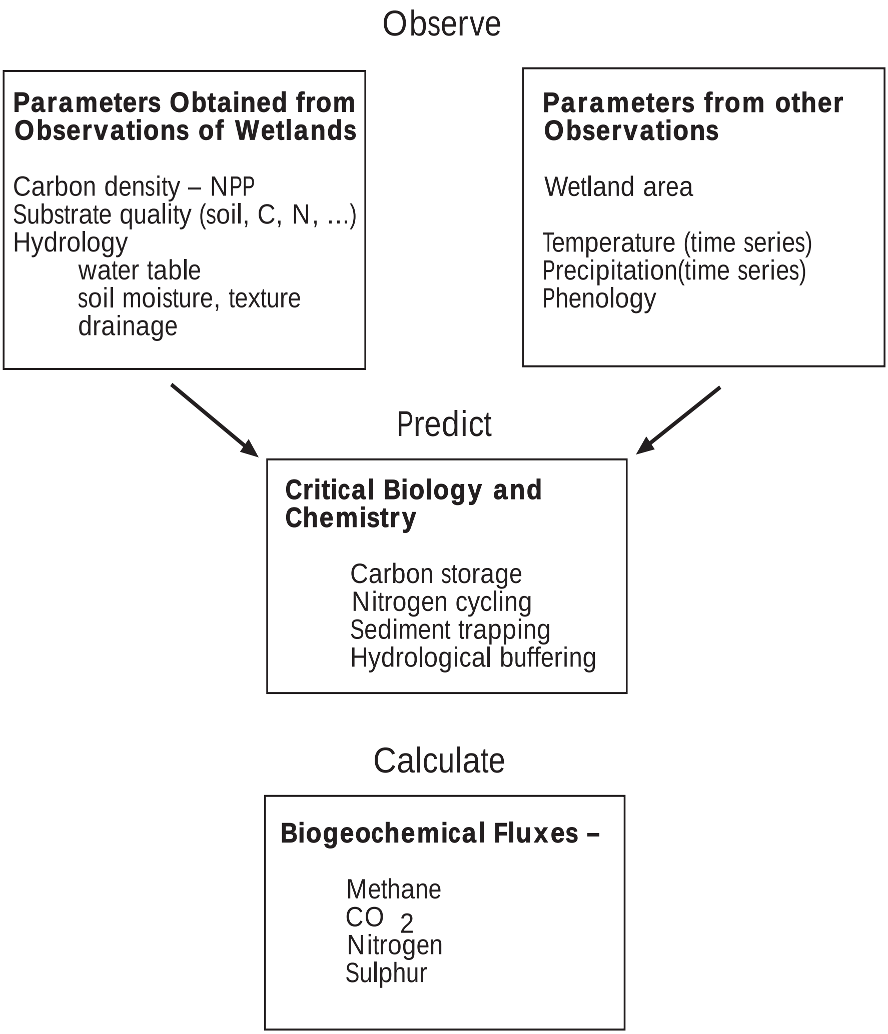
IGBP-DIS has identified several key data needs for global biogeochemical models, including land cover, fire data, soils, NPP-related data (Photosynthetically Active Radiation [PAR], Normalized Difference Vegetation Index [NDVI], *etc.*), topography, past vegetation types and distribution, and wetlands. While progress has been made in each of the other areas, there have been no significant advances to date in developing the datasets necessary for functional characterization and determination of the distribution of wetlands, in part because there has not yet been a functional parameterization scheme. The scheme emerging from the wetlands workshop has led to the identification of important data gaps which can now begin to be addressed by IGBP-DIS.

Present land cover maps do not agree in the amount or distribution of vegetation types. In the new 1-km global land cover product, there is no separation of wetlands into functional types, and thus it will be difficult to use the new product for determining trace gas and hydrologic fluxes from and through wetlands of different types. Toward that end, the experience gained in the development of the new land cover product can be helpful in developing a scheme for wetland functional classification. For example, it has been revealed that it is important to devise a validation methodology during the development of any classification scheme. Without a clearly defined system for testing the wetlands functional parameterization scheme, it will not be possible to assess its reliability for application to wetlands where only limited observational data are available. Consequently, the functional parameterization scheme developed at the wetlands workshop is based on the ability to validate each class on the basis of site-based observational data, which provide a test not only of the validity of the functional parameterization, but also of the completeness of parameters.

Once the existing wetlands data were reviewed at the Wetlands Workshop with the identification of data gaps, appropriate techniques were evaluated for generating new datasets to meet the identified needs. These techniques include the use of remotely sensed data which can provide a synoptic perspective. There have been several remote sensing studies on characterizing various types of wetlands at differing scales using airborne and space borne systems (see following section on "Remote Sensing"). Most of these studies have been at a local scale using airborne systems. The challenge facing the workshop participants was to identify those techniques that can be applied to regional and global scales, yet provide the type and level of detail and information needed to compile and maintain an evolving wetland distribution inventory based on functional parameterization. Currently available optical and microwave systems were evaluated with respect to suitability of their spatial and temporal resolutions for generating new improved regional and global datasets on wetland extent and seasonality. A suite of different techniques and sensing systems is needed to capture the necessary information. As part of its focus, the workshop reviewed the current state of remote sensing science on wetlands detection and monitoring and the feasibility of generating the necessary data. Combinations of ground-based measurements and remote sensing were also considered (Figure 3). Once the appropriate techniques were identified, implementation plans were developed toward the generation of these new datasets. IGBP-DIS has a clear role to play in the coordination of the development of the datasets.

Figure 3

Observations from ground-based studies within wetlands as well as remote observations must be combined to provide the necessary biological and chemical information for calculations of CH_4, CO_2, N, and S fluxes from wetlands. (From Sahagian, unpublished).



Remote Sensing

There are several observational tools available for wetlands studies. These tools make it possible to observe a large number of land surface characteristics which bear on wetlands. Each measurement can be assessed on the basis of present reliability and capabilities, in addition to potential for future utilization.

For the purpose of global biogeochemical models, it is necessary to determine the functional distribution of wetlands globally. While this has been hampered by a lack of wetland functional characterization, it has also been delayed by the inability of ground-based observations to be concatenated on a world-wide basis. Consequently, remotely sensed data which are sensitive to differences between functionally contrasting wetlands must be brought to bear on the problem. Tools for the generation of such data are now emerging.

The availability of spaceborne remote sensing tools provides a unique opportunity to study dynamic wetland processes worldwide and through time. Optical, microwave, and thermal sensors provide new and promising capabilities for mapping the type and distribution of wetlands and the temporal distribution of inundation. An evaluation of the utility of each of these categories of sensors for detecting and monitoring wetland parameters has been completed. Evaluations were based on the advantages and limitations of each of the systems and whether successes were proven in selected sites or globally, and on identifying sensors with a high potential for success but in need of further research.

To evaluate the utility of present and future sensors, we grouped them into six categories: optical coarse resolution; optical fine resolution; optical hyperspectral sensors; passive microwave; active microwave; and microwave altimetry. The utility of the various sensors, however, was balanced by the feasibility of data acquisition. For example, optical sensors may have frequent temporal resolution but the actual acquisition over a particular site may be quite limited due to cloud cover. In contrast, since microwave data is not limited by cloud cover, actual acquisition frequency is nearly the same as temporal frequency of collection. Optical data are also limited in the detection of surface characteristics (*e.g.*, inundation) below a forest canopy because optical wavelengths reflect off the top of the canopy. Hyperspectral data have considerable potential for distinguishing many wetland parameters, however, the high cost of data acquisition makes this source of data limited in global applications. The availability of algorithms is often correlated with the time since launch of a sensor. Sensors like Advanced Very High Resolution Radiometer (AVHRR) that have been in existence for years have had strong technical development while new sensors are without the necessary proven algorithms. Other issues relevant to a particular sensor system such as sensor calibration, atmospheric attenuation, infrastructure support for collection, archives, and distribution (*i.e.,* data availability) are discussed below.

Optical Coarse Spatial Resolution Sensors

AVHRR is currently an operational sensor representative of optical coarse spatial resolution systems. It has been used successfully for measuring vegetation, land cover, sea surface temperature, and cloud coverage. The advantage of AVHRR is its high temporal frequency of observation (global coverage generally twice per day) and multiple wavelengths in the visible, near-infrared and thermal portions of the spectrum.

The presence and absence of inundation can be monitored with AVHRR in some situations. However, observation is often hindered by clouds and tree canopies masking the underlying flooding at the surface. Open water can readily be delineated because it is usually more persistent than inundation, so the effect of cloud cover is less serious. Snow cover can be differentiated from cloud and other land cover types using AVHRR bands 1, 3, and 4 (Xu *et al.* 1993). Estimation of APAR (absorbed photosynthetically active radiation) on a global basis is still a subject to be studied, although some efforts have been made to obtain global distribution of APAR by combining AVHRR and Nimbus-7 Total Ozone Mapping Spectrometer (TOMS) data (Dye and Goward 1993). It is difficult to estimate soil moisture in wetland areas, although the drainage network for large, extensive regions can be delineated giving a clue as to the nature and extent of wetlands.

Land cover and land use information can be derived from AVHRR. The NDVI derived from AVHRR is useful to distinguish between vegetated and non-vegetated lands. It can also be applied to roughly separate woody vegetation from non-woody vegetation. More detailed classification of vegetation (*e.g.,* distinction between trees and bushes) is difficult with coarse spatial resolution data. While biomass above ground surface is qualitatively related to NDVI, additional research is needed to obtain a quantitative relationship. Land use within a watershed can also be roughly determined. Deforestation can be monitored by using AVHRR bands 1, 2, and 3 (Shimabukuro *et al.* 1994). Fires can be detected by band 3 imagery and fire scars can be observed by use of multiple-season NDVI composite data.

Optical Fine Resolution Sensors

Under this heading we are including satellite sensors in the optical wavelength region which have fine spatial resolution, *i.e.*, 5–100 m (Table 1). Thus, the sensors that were primarily considered are: SPOT; Landsat MultiSpectral Scanner (MSS), Thematic Mapper (TM), Enhanced Thematic Mapper (ETM); Linear Imaging Self-Scanning System (LISS-I and LISS II) on Indian Remote Sensing Satellite (IRS-1A and IRS-1B), respectively; and Advanced Visible and Infrared Imaging Spectrometer (AVNIR) on Advanced Earth Observing Satellite (ADEOS). Most of these sensors are multispectral scanners having spectral bands within the range from 0.4–2.4 mm. The history, development and applications of satellite multispectral sensors are reviewed in the Handbook of Remote Sensing (Colwell 1983).

High resolution, multispectral scanners have been used effectively to map the more static features of watersheds and floodplains, especially the land cover and vegetation. Due to their large, uniform stands, salt marshes have been mapped with considerable accuracy (Kiraly *et al.* 1990). Forested swamp species are more difficult to discriminate, since in the visible bands upland and wetland forests have similar spectral signatures. These sensors have also been employed successfully to monitor biomass changes and stress in Spartina marshes (Gross *et al.* 1990). However, the infrequent temporal coverage combined with obstruction by cloud cover makes the sensors less suitable for observing the more dynamic features of wetlands and floodplains. For instance, to monitor tidal or seasonal wetland inundation one would have to supplement these sensors with many field observations or other satellite sensors which provide more frequent coverage such as Synthetic Aperture Radar (SAR). The most effective approach for observing wetlands and their inundation should combine optical multispectral data with SAR and microwave altimetry data.

Multispectral visible infrared sensors have also been used to discriminate different water types and provide approximate water quality evaluations. Suspended sediment plumes and approximate sediment concentrations have been mapped with Landsat and SPOT data (Mertes *et al.* 1993). Chlorophyll concentrations are more difficult to determine, but phytoplankton blooms and high concentrations of chlorophyll have been mapped by Landsat TM and SPOT (Abbott *et al.* 1994). Estuarine waters containing high concentrations of dissolved organics (*e.g.*, humic acids) have been identified with remote sensors but measurements of their actual concentrations are not yet reliable.

Optical multispectral sensors on satellites can make a major contribution to wetland studies, especially if they are used in relatively cloud-free areas (or periods) or in conjunction with active microwave sensors, such as SAR. Optical multispectral sensors would be more useful for wetland studies if it were not for the problems of cloud obscuration and inability to penetrate tree canopies to observe inundation levels, soil conditions, *etc*.

Table 1

Characteristics of High Spatial Resolution Spaceborne Remote Sensing Systems.

System	Spatial Resolution (m)	Temporal Coverage (days)	Swath Width (km)	Spectral Bands (bands and range in μm)
Landsat MSS	80	16	185	4 bands - 0.5- 1.1
Landsat TM	30	16	185	6 bands - 0.45-2.35
SPOT	20 (colour) 10 (pan)	26 (nadir) 2-3 (off-nadir)	60	3 bands - 0.5- 0.89 1 band - 0.51-0.73
IRS/LISS I	73	22	148	4 bands - 0.45-0.86
IRS/LISS II	36.5	22	145 (2 cameras)	4 bands - 0.45-0.86
ADEOS/AVNIR	16 (colour) 8 (pan)	41 (nadir) (More frequent due to +/- cross-track pointing)	80 80	4 bands - 0.42-0.89

Optical Hyperspectral Sensors

Hyperspectral or imaging spectrometers provide remotely sensed data in narrow spectral bandwidths (≤10 mm wide), covering the visible to near infrared portion of the spectrum (0.3–2.5 mm) and sometimes into the thermal region (7.5–12.5 mm). Their fine spectral resolution enables absorption and reflection features associated with vegetation and substratum structural and biochemical properties to be established. Commercial and scientific hyperspectral sensors operate from airborne platforms with pixel sizes ranging from 2–20 m, and swath sizes from 1–11 km. Several of the scientific sensors such as the National Aeronautics and Space Administration (NASA)'s Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) serve as test beds for spaceborne sensors due to be launched within the next five years. Spaceborne imaging spectrometers will provide global hyperspectral coverage at 30 m and 250–500 m pixel sizes (Earth Observing System (EOS) – moderate resolution imaging spectrometer), including visible, near to short infrared and thermal infrared bands.

Acquisition hyperspectral data is costly and is only in a developmental stage for application to wetland environments. These costs and limitations include: passive nature of hyperspectral sensors restricting applications in cloudy environments; current predominance of airborne sensors; and lack of applications in all global wetland environments to establish links with relevant ecological variables. Specific attention has, however, been paid to extensive development and testing of sensor calibration and atmospheric correction algorithms. Algorithms for processing hyperspectral data employ spectral unmixing to estimate fractional composition of scene elements in each pixel, spectral curve matching or manipulation to discriminate scene elements, and empirical or deterministic models to estimate structural on biochemical properties. In each case the results can be used to map spatial variation in surface cover, structural and biochemical properties. Models linking hyperspectral data to biophysical variables need to be applied and validated in wetlands using appropriate methods.

The use of hyperspectral data for discriminating between vascular and non-vascular plants, trees and shrubs, and mosses, is based on the assumption that differences in their structural, biochemical and function attributes produce significantly different spectral responses. Spectral mixture analysis of hyperspectral image data using field-based spectra for each plant type can be used to identify the fraction of each pixel occupied by vascular or non-vascular plants (Roberts *et al.* 1993). A similar approach may also be taken to determine the fraction of trees and shrubs in a pixel based on proportions of non-photosynthetic vegetation and canopy shade spectra. Fraction images representing per-pixel dominance for each plant type may then be classified to produce a map of plant type distribution. Additional structural variables (*e.g.*, Leaf Area Index [LAI]) and biochemical variables (*e.g.*, chlorophyll) have also been derived from hyperspectral data and may be used to determine tree or shrub type and presence/proportion of moss within a pixel. The large number of spectral bands enables optimization of individual bands and algebraic combinations (spectral vegetation indices) for a specific environment and variable requirements, *e.g.*, vascular and non-vascular discrimination in subtidal and intertidal areas. There have been only a few published reports on application of hyperspectral data for monitoring different wetland environments (*e.g.*, Gross and Klemas 1986).

Hyperspectral image data have also been used to provide estimates for different levels of phytoplankton and chlorophyll in the water column and on its surface. Its advantage over broad band multispectral data has been the ability to select optimal bands to estimate and map concentration levels of both phytoplankton and chlorophyll (Vane and Goetz 1993). The very fine spectral resolution enables distinct variations in absorption bands associated with chlorophyll and ancillary pigments to be detected and used to estimate concentrations (Melack and Gastil 1994). As with spectral unmixing and estimates of biochemical properties, field based spectra are required for calibration. Applications of hyperspectral data to estimate chlorophyll and phytoplankton levels have been reported for offshore, nearshore and lacustrine water bodies, with no published work in coastal and inland wetlands.

Use of larger pixel sizes, improved detector technology (increasing signal:noise) and completion of baseline evaluations of the utility of hyperspectral data in wetland environments will provide a basis for their use in determining the variables discussed above.

Passive Microwave

Passive satellite-mounted microwave sensors offer a unique opportunity to monitor inundation patterns in large remote wetlands. A global record of passive microwave observations from satellites is available from 1979 to the present. The Scanning Multichannel Microwave Radiometer (SMMR) was operated on board the Nimbus-7 satellite from 1979–1987, with global coverage every six days. The Special Sensor Microwave/Imager (SSM/I) replaced SMMR in 1987 and continues today with three-day global coverage. These microwave emission measurements include both vertical and horizontal polarizations and four frequencies. For wetland studies, the two highest frequencies, 37 GHz (SMMR and SSM/I) and 85.5 GHz (SSM/I only), are the most useful because they offer the best spatial resolution (*ca.* 30 and 15 km, respectively). Passive microwave emission measurements are expressed as brightness temperatures in Kelvins, and the difference between the two polarizations may be referred to as DT. The principal advantages of the passive microwave observations are their frequent global coverage and their ability to reveal certain characteristics of the land surface beneath cloud cover and vegetation. The coarse spatial resolution may be an advantage for global studies because it reduces the data volume, but it is often a limitation for studies of specific sites.

SMMR observations of the 37 GHz DT have been analyzed to determine spatial and temporal patterns of inundation in the extensive floodplains of the Amazon River (Sippel *et al.* 1994) and the Pantanal wetland (Hamilton *et al.* 1996) (Figure 4) of South America. Calm water surfaces result in a strongly polarized emission at 37 GHz (SMMR DT *ca.* 60 K), although this is attenuated to varying degrees by overlying vegetation. In the absence of flooding, the dense vegetation and relatively level terrain of the South American lowlands present a stable background of depolarized microwave emission (SMMR DT averaging *ca.* 4 K). Fluctuations in the extent of inundation can be quantified if the DT is raised sufficiently above background. Inundation area is estimated from the DT by mixing models that incorporate the microwave emission characteristics of the major landscape units (Sippel *et al.* 1994), which are best determined empirically for a particular region. A similar approach can be adopted for the SSM/I data, yielding a longer time series. The prospects are good for application of passive microwave remote sensing to monitor inundation in the other major wetlands of South America, including the Orinoco Llanos of Venezuela and the Llanos de Mojos of the upper Madeira River basin in Bolivia.

The utility of passive microwave remote sensing to monitor inundation in other wetlands of the world has yet to be investigated. The coarse spatial resolution limits the application of the technique to large wetlands, or to regions where the cumulative area of smaller wetlands comprises a significant proportion of the landscape. Surface roughness, exposed soil and rock, seasonal vegetation changes, and seasonal snow cover can affect DT, and these factors may have to be accounted for to quantify the variability in flooded area using microwave emission.

There have been many investigations of the potential use of passive microwave remote sensing to quantify surface soil moisture and precipitation rates over land, both of which are variables of potential interest for wetland monitoring. Soil moisture studies have focused on arid and semi-arid regions where bare soils dominate, or in agricultural areas. Jackson and Schmugge (1991) discussed the effects of vegetation on the microwave emission from soils and concluded that there is little chance of reliably estimating soil moisture under forest or shrub canopies, which attenuate the emission from the soil surface. In addition, the lowest frequency available for satellite data is 19.4 GHz, where emission represents less than 1 cm of soil depth, and the satellite measurements have a spatial resolution of about 50 km. Estimation of precipitation over land appears feasible using currently available satellite data, although bare soil, snow, and ice may present problems. The precipitation algorithms require further development. Precipitation estimates by remote sensing would be most valuable for the more remote wetland regions where ground-based monitoring is often inadequate.

Active Microwave

Because of their ability to detect flooding beneath vegetation and to penetrate cloud cover, synthetic aperture radar (SAR) sensors are well suited to monitoring many types of wetlands. Multi-frequency, multi-polarization SAR data have been available for several years from airborne systems, and from space with the 1994 shuttle-based Spaceborne Imaging Radar - C (SIR-C) mission (Table 2). Although satellite SAR sensors are currently limited to single-frequency systems, combining data from different SAR satellites approximates a space-based multi-frequency capability. High accuracy has been achieved using European Remote Sensing Satellite / Japanese Earth Resources Satellite (ERS-1/JERS-1) composites for land-cover classification (Dobson *et al.* 1996). Because the difference in backscattering between flooded and non-flooded vegetation is generally greater at HH than VV polarization, the combination of RADARSAT and JERS-1 is preferable for inundation monitoring. With the exception of RADARSAT's ScanSAR mode, the 5–25 m spatial resolution of current SAR sensors is best suited to regional (as well as local) studies. It is feasible to image even very large regions at two different seasons, as is being done for the Amazon basin using JERS-1. Smaller regions can be imaged by satellite on a nearly monthly basis. Using the RADARSAT ScanSAR mode, frequent coverage (every one to four days) is possible for large regions.

Figure 4

Comparison of the SMMR 37 GHz DT (solid lines) over the Pantanal wetland and a nearby upland area during 1979–1987, plotted together with stage (dashed line) of the principal river at the floodplain site. This clearly illustrates that the seasonal cycles in DT over the floodplain are driven by inundation. (From Hamilton *et al.* 1996).

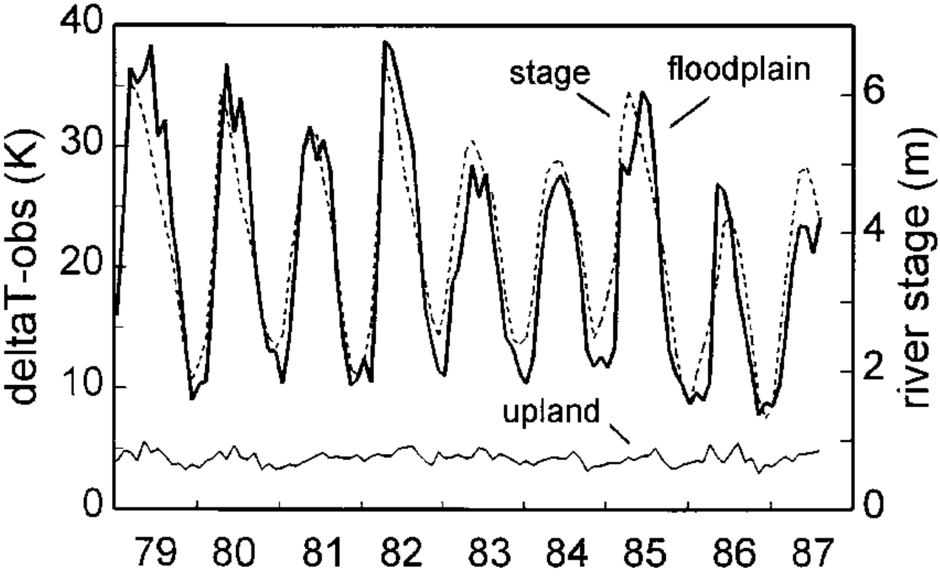


Table 2

Active Microwave Platforms.

PLATFORM	SATELLITE			SPACE SHUTTLE		AIRCRAFT
Sensor	ERS-1/2	RADARSAT	JERS-1	SIR-C	X-SAR	Airborne SARs
Radar band	C	C	L	C,L	X	C,L,P
Polarization	VV	HH	HH	HH,VV,HV	VV	HH,VV,HV
Resolution (m)	25	10-100	18	25	25	5-10
Swath width (km)	100	50-500	75	15-40	15-40	12.5
Repeat cycle (days)	35	1-24	44	*	*	< 1
Incidence angle	23	20-50	35	20-50	20-50	15-60
Launched	1991	1995	1992	1994	1994	1988

* 11-day missions flown in April and October 1994

Since smooth water surfaces spectrally reflect SAR pulses away from the sensor, open water surfaces are accurately delineated with any of the systems in Table 2; the principal source of error is non-specular returns caused by wave-induced surface roughness. Mapping of open water area of rivers and lakes has been demonstrated for the Amazon River (Sippel *et al.* 1992) and the Mississippi River (Brakenridge *et al.* 1994). Algorithms for deriving water depth or discharge based on time-series of SAR-derived inundation are in the developmental stage and may require supplemental stage data. Smith *et al.* (1997) have used ERS-1 data to estimate river discharge based on channel width for large braided rivers in Alaska and British Columbia.

When specular reflections from an underlying water surface interact with vegetation via double-bounce or multiple scattering, backscattering is enhanced. SIR-C data has been used to delineate flooded and nonflooded vegetation and open water on a reach of the Amazon floodplain with accuracy greater than 90%, and to quantify the change in inundated area accompanying a change in river stage (Hess *et al.* 1995). LHH was found optimal for separating flooded from nonflooded forests, CHH for inundated *vs.* upland grasses, and LHV for woody vs. nonwoody vegetation. Many studies have found similar increases in L-band returns from flooded forests, even for open stands. For herbaceous vegetation, enhancement due to flooding does not occur in some cases; Pope *et al.* (1996) found SIR-C backscattering from Yucatan marshes increased due to flooding at both CHH and LHH for tall, dense stands but decreased for short sparse stands. Returns from rice fields can vary with factors such as row orientation and spacing. CVV returns from flooded rice fields vary with LAI, but the relationship is not monotonic.

Algorithms for SAR-based biomass estimation, while promising, are at present largely site-specific. Limitations include signal saturation at biomass levels that include a significant percentage of the world's forests, and inability to separate soil moisture and biomass contributions to backscattering for non-closed canopy stands. However, mapping into more general regrowth categories (suitable for watershed characterization) has given good results even for tropical forests, especially when SAR and optical imagery are combined (Rignot *et al.* 1997). Recent clearings are distinguishable from forest at LHH during the dry season, but LHV is necessary to distinguish clearings as regrowth proceeds. The biomass saturation point is higher at the longer P-band wavelength, which is limited to airborne systems. For regions where accurate topographic data is unavailable, elevation data generated using SAR interferometry can be used for watershed delineation. Repeat-pass interferometry is limited by signal decorrelation over forests at C-band but maybe not at L-band.

While most efforts have focused on lower-frequency (L-band) SARs to detect flooded forests, higher-frequency systems have been shown to be able to detect flooded forest canopies when no leaves are present (Ustin *et al.* 1991), to monitor levels of tidal inundation under vegetation in salt water marshes, and to monitor levels of inundation in tundra regions (Morrissey *et al.* 1994). In addition, SAR data acquisition is not limited by extensive cloud cover, low solar zenith angles, or darkness, which itself can limit the use of optical data. With the launch of ERS-1/2, the acquisition of SAR time series has provided the basis for seasonal studies of dynamic wetland processes (Morrissey *et al.* 1996).

SAR has proven useful in delineating inundation, a key indicator of the anaerobic conditions necessary for methane production. Backscatter from ERS-1 SAR acquired over Barrow, Alaska in 1991 is related to the position of the local water table and thus to methane exchange rates (Figure 5) (Morrissey *et al.* 1994). Backscatter from non-inundated sites was low, that from herbaceous inundated sites was high, and that from sites with the water table at the surface was intermediate, mirroring methane exchange rates for the region. The capability to differentiate wetlands (i.e. methane source areas) and non-wetlands with SAR is further enhanced by the availability of time series ERS-1 SAR data (Morrissey *et al.* 1996). Seasonal changes in backscatter for northern wetlands and non-wetlands are shown in Figure 6. Under an extended period of freezing temperatures in the winter of 1992, radar returns for wetland and non-wetland did not differ significantly. Following snowmelt in the spring, backscatter for wetlands was consistently higher than that from non-wetlands. With the onset of colder temperatures and decreasing daylight in late summer, backscatter for both wetlands and non-wetlands decreased dramatically with freezing.

Satellite Radar Altimetry

Satellite radar altimeters allow measurement of topographic height and roughness. For height measurements, their operation is based on observing the delay time between transmitted and reflected microwave pulses. Each altimeter produces height values along the satellite ground track, at spatial distances ranging from 335 m (ERS-1) to 670 m (Seasat/Geosat). The heights are average values within a footprint, whose diameter can range from hundreds of metres to several kilometres, depending on the roughness of the terrain. Originally, altimeters were designed for ocean applications, but some recent designs (ERS-1, ERS-2, and Ocean Topography Experiment [TOPEX/POSEIDON]) allow good tracking over wetland regimes (Figure 7).

Satellite radar altimeters measure surface topography. This allows two wetland parameters to be obtained: (i) a measure of surface height change, or if the wetland undergoes an absolute dry period, the change in depth of inundation; and (ii) the construction of a local digital elevation model. The many advantages of altimeters include: (i) they have day/night and all-weather operation; and (ii) their surface heights are determined with respect to one single reference datum. They can provide information where ground data is lacking due to the inaccessible nature of the wetland environment. However, the accuracy of the elevation changes are primarily dependent on knowledge of the satellite orbit. The spatial and temporal resolution of the data is dependent on the orbit of the satellite, the complexity of the surface topography, and the tracking mechanism of the altimeter.

Although basic altimetry techniques have been validated (Birkett 1995), most research has been based on case studies, such as the Amazon and the Sudd, with elevation change accuracy better than 10 cm rms. Considering IGBP aims, access should be allowed to all altimeter datasets, and individual altimeter assessments over a variety of wetlands should be performed on a global scale.

Figure 5

ERS-1 SAR backscatter and methane exchange rates in relation to the position of the local water table in herbaceous Arctic tundra. (From Morrisey *et al.* 1994).

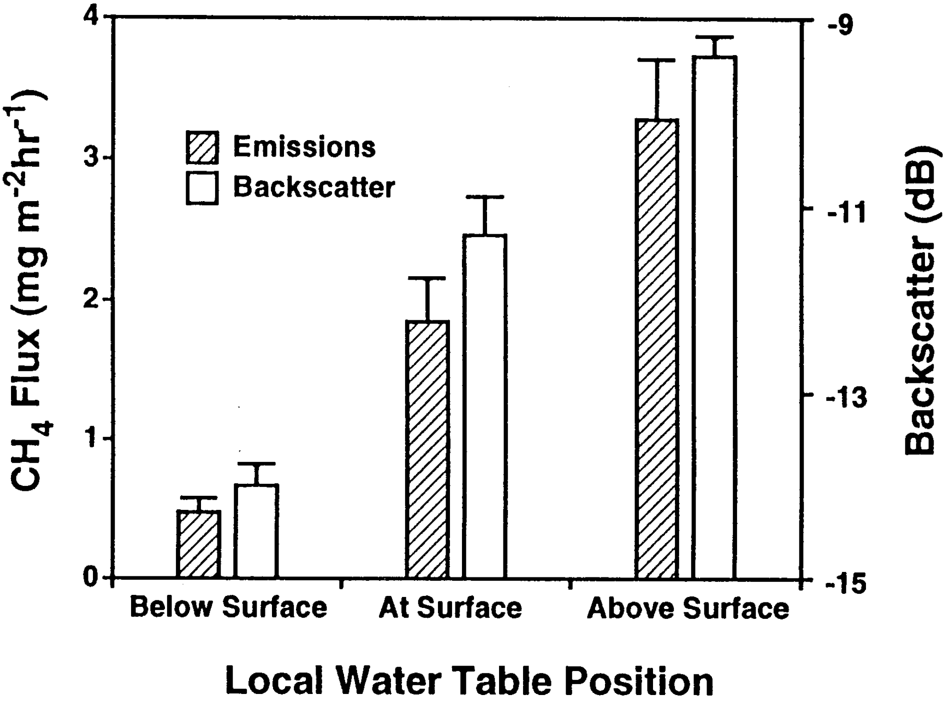


Figure 6

Seasonal variation in ERS-1 SAR backscatter from wetlands and non-wetlands for data collected over Barrow, Alaska (mean ± standard error). (From Morrisey *et al.* 1994).

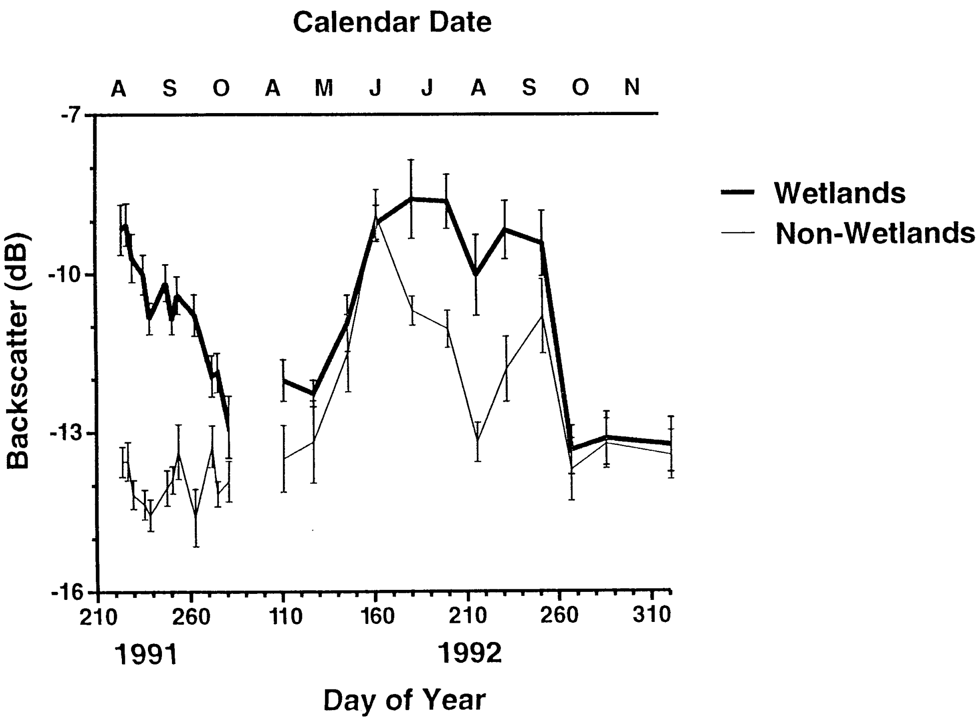
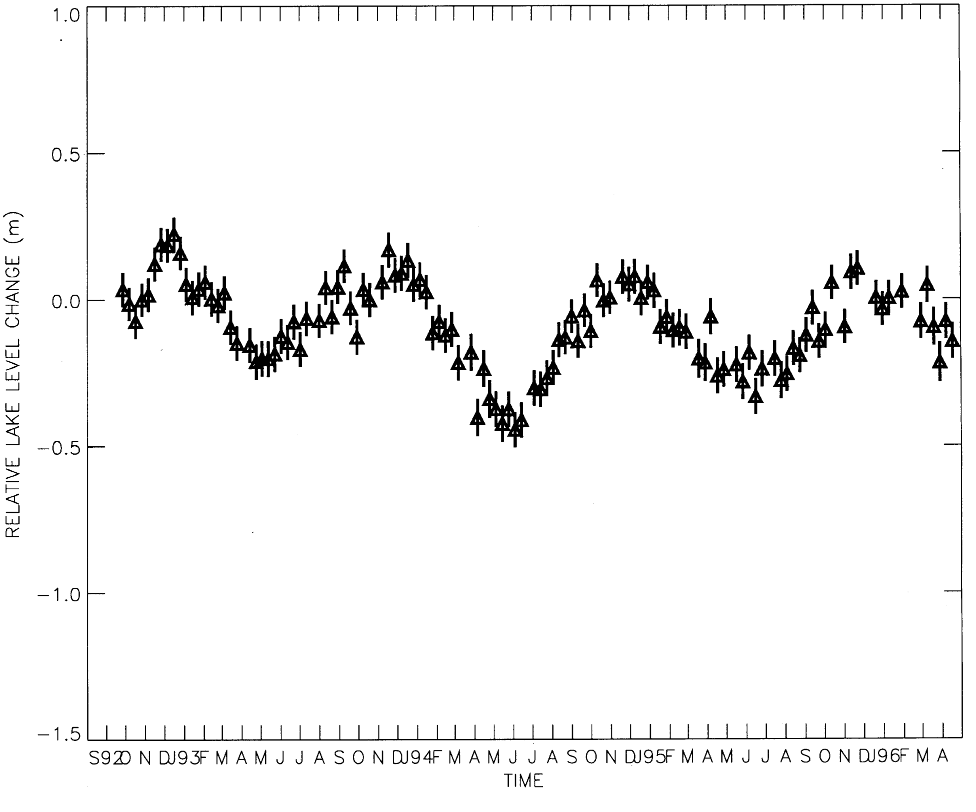


Figure 7

Variation of surface height for a TOPEX/POSEIDON pass across the Sudd marshes for the time period 1992–1995. Accuracy is 5 cm rms. (From Birkett 1995).



Conceptual Framework

Wetland Functional Parameterization

There are several major biogeochemical constituents which are controlled by processes which occur in wetlands. These materials include CO_2, methane, nitrogen, DMS, and sulphur, among others, in addition to water. Of these, four have been chosen as the basis for developing a functional classification for wetlands. These include methane, nitrogen, sulphur and carbon dioxide. The flux of each of these is determined by several processes which act in all wetlands systems to varying degrees. The nine primary deterministic parameters have been formulated so as to represent all important biogeochemical functions of wetland ecosystems, and represent the minimum number of necessary observational schemes. While the nine parameters are not completely independent of one another, they can be measured using existing facilities and described with existing types of data. With future data acquisition, a set of truly orthogonal parameters may be developed.

We propose a single conceptual model to encompass wetland function and category rather than a series of models in a number of wetland categories. This involves an interactive classification scheme where one queries functionally based modelled or measured input parameters which could be displayed as map contours. If, for example, one is interested in methane, the interaction of the input parameters could yield methane emission contours. Wetland functions (listed below) would be output responses determined by the nine input parameters (listed below). To validate the model, predicted function values can be compared with those determined observationally.

Wetland Functions

1. Methane production
2. Carbon accumulation or export
3. Denitrification/N burial
4. Sulphur cycling – DMS, H_2S production

Input Parameters

Description of Wetland Functions:

1. Primary Production
2. Temperature
3. Water table and hydrology
4. Transport of organics and sediment into and out of the wetland (including fertilizers)
5. Vegetation or lack thereof, type and morphology if present
6. Chemical information about organic materials (lignin, N content, DOC quantity, chlorophyll)
7. Salinity
8. Soil nutrient status
9. Topography/geomorphology

The challenge to the wetlands research community is to develop algorithms to relate the nine input parameters to the four wetland functions so that a model can be constructed to enable predictions, and also to test models by direct observation.

In this section, focusing on methane emission, we illustrate the details of each of the nine functional parameters which control wetland processes.

1. Primary Production

Net Primary Production (NPP) is the difference between the amount of carbon incorporated into plant tissue and the amount of carbon respired by the plant itself. Net Ecosystem Productivity (NEP) is a measure of the production of the total ecosystem and is equivalent to NPP minus soil microbial respiration. Since the four identified wetland functions are associated with organic matter decomposition or preservation, organic matter production should be a driving force. Aselmann and Crutzen (1989) estimated methane emissions by assuming that the methane flux/NPP ratio was 0.02–0.07, but concluded that the approach was limited by a lack of concurrent net primary production and methane emission measurements. Whiting and Chanton (1993) undertook a study to remedy the situation and reported that the net primary production of a flooded wetland is a major integrating parameter useful for predicting methane emission. This powerful variable incorporates many environmental factors, substrate production being one of the more important. Linear correlations have been observed between methane emission and ecosystem production within and across wetlands (Chanton *et al.* 1997) and suggest that methane emission is about 3% of NEP. However, most of these measurements were conducted in flooded wetlands to eliminate the variable of water table oscillation (see Hydrology, below). A lowered water table would increase CO_2 emissions while concurrently decreasing methane emissions (Funk *et al.* 1994). The dataset is further limited in that only warm season measurements have been reported. Annual measurements of NEP and CH_4 emission are currently being conducted in Alberta (Canada) by a team headed by; G. Whiting, T. Popp, and J. Chanton; and in Manitoba (Canada) by a team led by P. Crill, T. Moore, and N. Roulet.

2. Temperature

Temperature controls the rate of all processes, and in temperate and boreal regions freezing can arrest biogeochemical cycling seasonally. The preservation of organic matter in soils is inversely related to temperature. Numerous seasonal studies of methane flux in northern wetlands have found correlations between methane flux and temperature (Frolking and Crill 1994), and in temperate systems (Kelley *et al.* 1995). However, as pointed out by Frolking and Crill (1994), as temperature changes, other variables are also changing (for example rising temperature, falling water table and increasing plant production). The direct response of methanogenesis to temperature change has been shown in laboratory studies to have Q_{10} values ranging from 2.5–3.5 (Conrad 1989). Correlations of seasonal emission and temperature measurements from field studies have often resulted in Q_{10} values which are significantly higher (Bubier *et al.* 1995a). The higher field determinations could be due to changes in production associated with increased sunlight. In tropical wetlands, temperature is a less important variable relative to water table variation.

3. Hydrology

Hydrology is critical in the function (and very definition) of a wetland. Key parameters that control hydrology are geomorphology, flooding, precipitation and evapotranspiration. Generally peatlands and temperate wetlands become drier in the warmer late summer, which has the effect of depressing methane emissions (Happell *et al.* 1994). Inter-season variations in CH_4 emission are controlled by water table variation in wetland tundra sites (Christensen 1993) as well as for boreal sites (Bubier *et al.* 1995a). In tropical systems, changing hydrography results in wide ranges in methane emission and may also cause variations in methane transport pathways. When water levels fall, the decreasing hydrostatic pressure results in increasing frequency of bubble ablution relative to other gas transport modes (Chanton *et al.* 1989).

On the basis of hydrology, there are two categories of wetlands:

A. Wetlands with Stable Water Tables

While the water table may move up and down relative to soil surface, these wetlands are always wet below the surface. Such wetlands have certain characteristics including:

- Reducing environment
- Little or no sediment input
- Soil formation is autochthonous
- Peat formation (net carbon sinks).

They can occur in northern climates (*e.g.*, fens, bogs), subtropical environments (*e.g.*, everglades), or tropical environments (*e.g.*, papyrus swamps). In these hydrologic environments both CO_2 uptake and methane emission are important.

B. Ephemeral Wetlands

These wetland periodically dry out and include floodplains and savannas. The inundation characteristics and their consequences for tropical wetlands have been termed the flood pulse concept (Junk *et al.* 1989). The pulse flood is coupled with an edge effect which extends a "moving littoral" or migrating aquatic/terrestrial transition zone. This moving littoral zone may prevent prolonged stagnation and allows rapid cycling of organic matter and nutrients resulting in higher productivity than might be found in permanent water bodies. These wetlands have short-term accumulation of organic carbon but during drier periods this organic matter is decomposed, driving the cycles of S, Fe, N, and CH_4. In this case, methane production is important but carbon deposition is not. The production of N_2O is a key feature of fluctuating moisture.

4. Organic Matter and Sediment Transport

Sediment and organic matter are transported in and out of a wetland by various processes including water flow, fire, grazing, and harvesting. These processes determine the availability and residence time of the organic material to be processed (*e.g.*, methane production or nitrogen cycling), and in addition to primary production/ decomposition may be an important source or sink term for an ecosystem.

5. Vegetation

Vegetation is grouped in terms of vascular or non-vascular (*e.g.*, Bryophytes and *Sphagnum*), which affects both the sites of production of organic matter and gas transport modes. Organic matter which has been produced by non-vascular plants must pass through a zone of aerobic decay as it transits to the methane production zone. Vascular plants are rooted in the methane production zone and their below-ground production and root exudation occurs within the methane production zone, so there is more labile substrate input to methanogens (Whiting and Chanton 1993). When this effect is added to the vascular plant conduit effect through hollow air-filled stems, it further compounds the dominant role of vascular plants in enhancing methane emission, as vascular plants transport methane and thus by-pass the oxidizing environment at the water-soil or water-air interface (Happell *et al.* 1994). Different plant types have differing potentials to transport methane depending upon their epidermal layers or their modes of gas transport (Chanton and Smith 1993). Bubier *et al.* (1995a) have found sedge and tree cover correlated with high and low methane emission, respectively. Shrub cover was of less predictive value. Bubier *et al.* (1995b) address the utility of *Sphagnum* as an indicator of methane emission.

6. Chemistry

Chemical information regarding the lability of organic materials (lignin, N content, DOC quantity, chlorophyll, *etc.*) is important in determining the conditions for reactions involved in methanogenesis, N cycling, *etc.* Changes in nutrient status may affect root biomass. In seeking additional nutrients, plants may trigger excess root production, leading to more exudation, resulting in more methane production.

7. Salinity

Salinity strongly controls the type of bacterial activity within a wetland and thus the production of methane, carbon accumulation, and S and N cycling. Marine waters carry abundant sulphate, which serves as an electron acceptor which suppresses methane production (Bartlett *et al.* 1987). DMS is a degradation product of the osmoregulant dimethylsulphonio-proprionate (DMSP) (Dacey and Blough 1987) which is found in the tissues of *Spartina alterniflora*, *Spartina anglica*, and *Zostera marina* (Dacey *et al.* 1987). DMS fluxes have been found to be substantially higher in *Spartina alterniflora* than in plants which do not contain DMSP, *e.g.*, *Spartina patens, Juncus roemerianus, Distichlis spicata, Avicennia germinans, Batis maritima,* and *Cladium jamaicense* (Morrison and Hines 1990).

8. Soils

The type of soil present in a wetland can be characterized by texture, C content, and nutrient status. These factors will provide feedbacks to the parameters listed above. Soil carbon content will control the redox state of the soil, which will determine the electron acceptors utilized (Patrick and Reddy 1976). Nutrient status will affect the ratio of belowground to aboveground production.

9. Topography/Geomorphology

The surface topography and geomorphologic structure of the regions surrounding the wetland controls the large-scale hydrologic behaviour as well as vegetation characteristics. Underlying topography may be important as well and may influence wetland development by providing groundwater. The current topographic maps of the world tend to have contour intervals (often 5–30 m) that are too course for effective use in wetland studies. The present digital terrain models of the world tend to have a vertical resolution which is equivalent to some of the coarsest maps and so are judged to be inappropriate for wetlands work. The significance of micro-topography and the very low slopes found in wetlands at the regional scale are such that a vertical discrimination of better than 1 m and ideally 3–5 cm is needed.

Evaluation of Available Data and Functional Classification Scheme

The functional parameterization described in the previous section is based on parameters whose values can be quantifiable, either by direct measurement, proxy or modelling (Table 3). With values for each parameter, it is possible to assign a position in parametric 9-space for an individual wetland.

There are several impediments to parameter assessment:

Wetland Extent and Distribution (Classification and Definition)

The information base is inadequate (*i.e.*, missing data, poor data, and poorly disseminated datasets). Compilations have been constrained by lack of agreement on definition and classification. We need to compare and relate the functional parameterization to widely used biodiversity or conservation oriented classifications which are usually hierarchical.

Uneven Spatial and Temporal Data Coverage

Available information is biased to the northern boreal and temperate zones, being generally sparser for tropical and southern subtropical and temperate zones. Spatial and temporal aspects need further investigation (*e.g.*, periodicity of inundation: permanent; seasonal; intermittent; and episodic).

Variable Data Availability and Quality for Various Constituents (Methane, CO_2, *etc.*)

Primary data requirements are generally the same for all biogeochemical processes being considered, but information is not uniformly available (Table 4).

Soils Information

Global compilations of soils information are generally poor or misleading from the standpoint of wetland functionality.

Hydrological Data

Hydrological data are poor except for a few very well-studied wetland sites.

Anthropogenic Influences
The history of anthropogenic influences through land-use changes, water works and other activities are not well quantified. This should be incorporated as part of a general 200 year land-use database

Parameters
There are various types of measurable information necessary for assessment of each of the nine functional parameters. The most important of these are highlighted below. (Within each, the most critical measurements are underlined):

NPP
Biomass (above- and belowground), litterfall (leaf and wood), PAR, Soil/water respiration

Hydrology
Flow, position of water surface, periodicity (tides, seasonal, *etc.*), areal extent, phase (solid, liquid), precipitation, evapotranspiration, infiltration (and subsurface flow)

Organic Transport
Grazing, harvesting, fire, waterborne processes, airborne processes, decomposition, dry deposition, erosion

Vegetation
Functional groups (*e.g.*, periphyton, phytoplankton, hydrophytes, shrubs, herbs, trees, sedges, grasses, bryophytes, legumes), morphology or physiognomy, phenology

Water Chemistry
Nutrients (N,C,S), dissolved oxygen (with water temperature), redox potential, metals (Fe, Mn), temperature

Salinity
Salinity or conductivity (with water temperature)

Soils
Texture, nutrient status (C,N,S,P,K), organic content, moisture, depth of bacteriological active soil, cation exchange

Geomorphology
Channel and basin size, distribution, form, slope.

The highest data priorities related to the above information have been identified as:

- Wetland inventory (underpinned by a suitable parameterized classification), with emphasis on bolstering tropical and southern hemisphere data.
- Hydrological data
- Soils.

Table 3

Temperature (atmospheric), wind speed, relative humidity.

PARAMETER	WANT FOR	HOW OBTAINED	NEED
NPP (input of C)	Atmospheric input	NPP models and measurements plus wetland distribution	Measurements (validation) nutrients (in/out) in soils
Temperature (rate of decomposition, methanogenesis, oxidation)	Soil temperature Water temperature and depth	Soil Vegetation Atmosphere Transfer (SVATs) SVATs	Soils (+ Σ and atmospheric corrections – skin T)
Hydrology - static - pulsed	Water table Areal extent of water table	SVATs SVATs and flood routing	Vegetation type, soils- from climate models. Vegetation type, flooded area from: (i) altimetry from active and passive microwave) (ii) DEMs
Organic/inorganic transport	Water flow	Hydrological models existing data	
Vegetation	Classification (process group), temporal % Δ Vascular, non-vascular, woody, non-woody, phytoplankton	RS sampling, mapping existing information	% of vegetation cover
Hydrological and chemical information	Water chemistry (DOC, N, pCO_2, S, POC)	Field measurements	
Salinity	Fresh/saline	Location (coasts, *etc.*) conductivity	
Soil	Carbon content; nutrient status; texture; location of wetland based on soil data	Observations, correlate with soil type (C, texture)	Soil distribution
Topography/ geomorphology	Slopes within wetlands as well as in surrounding uplands	Correlate area in-undated from SMMR/ SAR with computed volume of H_2O storage in wetlands	

Table 4

Parameters and our ability to measure them with remote sensing.

Various methods of measurement of wetland parameters (first column and subparameters). Optical-coarse, optical-fine, passive microwave, microwave-altimetry, active microwave, optical-hyperspectral, thermal. a= highly reliable; b= moderately reliable; c= potential (needs further development).

			Optical / C	Optical / F	Micro-Pass	Micro-altim	Micro-active	Optical / H	Thermal
NPP									
	biomass		c	c			c	c	
	PAR		c						
TEMP.									
	soil								c
	water								b
HYDROL.									
	inundation								
		depth-inun.				b	c		
		depth- w tab					c		
		pres/abs	c	c	b		b		c
	open water		b	b			a		
	phase						b		
ORGANIC TRANSPORT									

			Optical / C	Optical / F	Micro-Pass	Micro-altim	Micro-active	Optical / H	Thermal
VEGETAT.									
	veg./non veg.		a	b			a		
	vascul/non						c	c	
	woody/non		b	b			b		
		tree/shrub	c	c			c	c	
	moss			c				c	
	phytoplankt							c	
WATER CHEMISTRY									
	chlorophyl								
	N content								
SALINITY									
SOIL					c				
	land use								
		watershed	b	b			c		
		rice		b			b	c	
	deforest.		b	b			a		
		fire scars	b	b			c		
	snow cover		a	b					
GEOMORPH.									
	drainage net		b	b			a		
	topography			b			b		

Understanding Wetland Processes: A Set of Research Priorities

Wetland extent

The largest gap in wetland characterization is the size of wetlands themselves, both in space and time. The level of flooding and the areal extent of wetlands is the largest uncertainty in applying models of wetland function to models of the global system. Both the temporal and areal extent of wetland flooding should be characterized in terms of ha-days. An additional factor is the phasing of flooding (*i.e.*, continuous or intermittent). These issues are not adequately addressed in present land cover compilations and terrestrial ecosystem models.

Soil characterization

Existing databases should be assessed for adequacy regarding wetland soils. Critical aspects are organic content and texture (sand, silt, and clay content).

Correlative studies

Most models run on correlations so additional studies are required to better define the relationships between the processes of interest and the input parameters. Correlations which make use of variables which can be remotely sensed are the most useful. For example, Bubier *et al.* (1995a) explored the correlation between vegetation and methane emission. Tree and sedge cover were good indicators of low and high flux, respectively. Bryophytes also are generally indicative of low emissions but may release DMS.

Mechanistic Studies

A detailed understanding of wetland systems is necessary in addition to field measurements for model validation and more data to correlate the nine parameters to the four functions. Mechanistic studies are required so that the correlations described above are not misapplied. For example, Q_{10} published for methane to temperature ranges from 1.6–20. However Q_{10} values over 3 or 4 are probably not physiologically meaningful in terms of microbial physiology. Most likely the high observed Q_{10} correlations are due to simultaneous changes in temperature and substrate availability (Whiting and Chanton 1993) and changes in substrate availability coincident with temperature increase are being mistaken for a temperature response.

Another example is the relationship between NPP and CH_4 emission. Mechanistic studies are required to reveal the details of this correlation which could be used to enable prediction of the timing of the relationship between these parameters. If NPP increased in one year, would methane emission increase in the same year, or some number of years later? Additionally, mechanistic studies will yield understanding to allow for hypothesis development in terms of the response of wetlands to changing climatic conditions (Dacey *et al.* 1994).

Isotopic studies (*e.g.*, ^{13}C, ^{14}C, ^{15}N, and ^{34}S) are useful for elucidating the mechanisms of the biogeochemical cycles. For example, ^{13}C studies of soil organic matter are necessary to elucidate carbon cycling in C-3 and C-4 plants. These studies have been useful for determining the effects of land-use change from forest to grassland or forest to pasture (Trumbore *et al*. 1995). Additionally, methane ^{13}C increases by 15% going down the Amazon basin, possibly due to the increase in C-4 plants (Devol *et al*. 1990). The C-3 or C-4 nature of the original plant material can have a dramatic effect on methane carbon isotopic composition (Chanton and Smith 1993).

Vegetation Scheme

Various systems for organizing vegetation should be evaluated for their relationships to the functions of interest and for their accessibility to determination by remote sensing. Categorization might vary between woody (shrub or tree) or non-woody (sedge) or non-vascular (phytoplankton or moss). This scheme should be refined and compared to other floristic schemes. This may help test if the functional groups used are correct as well as the relative extent of the different functional groups.

Model Development

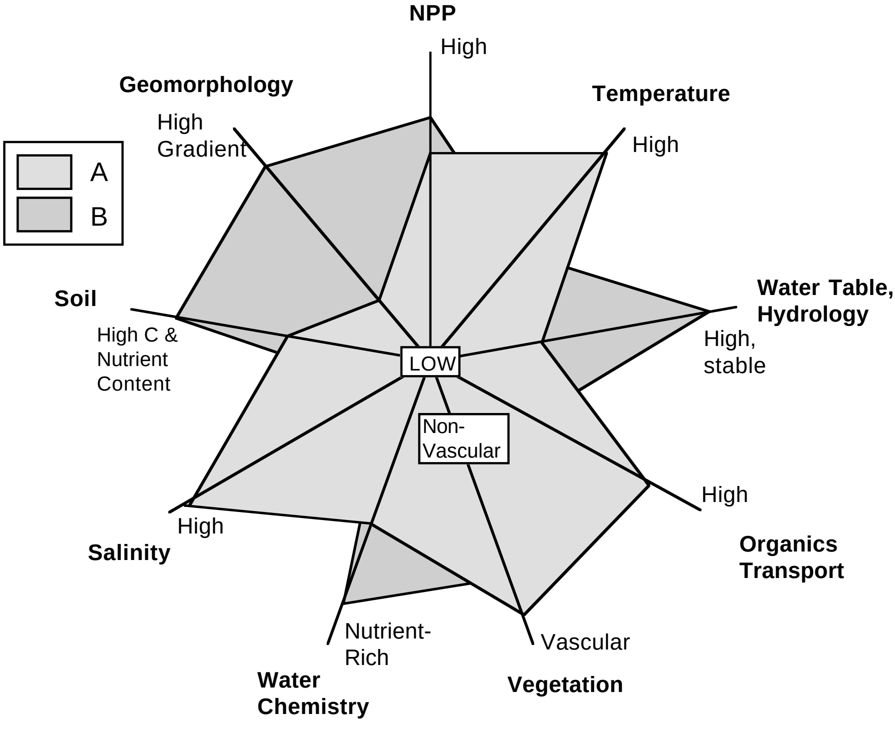
A comprehensive model needs to be developed that accommodates all types of wetlands, including rice fields and natural wetlands, bogs, fens, flooded forest, marsh, etc. We have suggested a 9-dimensional model with a descriptive component and a process component. The relationship between the nine functional parameters; (j) and important wetland processes; (i) (*e.g*., methanogenesis, carbon accumulation, *etc*.) can be formulated as:

$$Fi = f(Pj).$$

On a 9-dimensional graph with orthogonal axes defined by the nine functional parameters, any wetland ecosystem will correspond to a certain 9 dimensional volume. The 9-space can be represented on paper as done in Figure 8. Any wetland that described the same shape in parametric 9-space will have the same functional characteristics, and can be mapped and inventoried accordingly. This is analogous to principal component or cluster analysis.

Figure 8

Graphical representation (2-D) of 9-dimensional parameter space for wetland parameterization scheme. Two wetland functional types are shown. Type A has high salinity, high proportion of vascular plants, high temperature, *etc.* Type B has low salinity, high gradient in surrounding regions, high soil carbon and nutrient content, *etc*. Any wetlands with similar shapes on this 9-dimensional representation are postulated to have the same set of functional processes (controlling CH_4, CO_2, N, S) regardless of where they are found. However, wetlands with different shapes on this representation can also share the same functions with appropriate trade-offs between the various parameters. The quantitative relationships (Pj) between the effects of the nine parameters have not yet been established, and represent a primary research goal in future investigations of wetland processes. (From Sahagian, unpublished).



Models: Existing Examples

Model for Methane Emissions from Rice Fields

Two semi-empirical process models for methane emissions from rice fields have been published (Cao *et al.* 1995, Ding and Wang 1996). Cao *et al.* (1995) have developed calculated methane emissions based on supplies of carbon substrate for methanogens by rice primary production and soil organic matter degradation, environmental factors, and a postulated balance between methane production and consumption by methanotrophic oxidation. Ding and Wang (1996) base their model calculations on climate conditions, field water management, organic fertilizers and soil types. Huang, Sass, and Fisher (personal communication) have an unpublished model of six years of experimental data that is based on soil texture, cultivar type, rice primary production, water management, and organic additions. They are attempting to incorporate their model into a general rice crop model developed in China (Gao *et al.* 1992).

Conceptual models for a rice agroecosystem model thus can be viewed to have as major components of the system a crop growth module and a soil biogeochemistry module. The drivers for the system would include organic carbon inputs, soil texture, soil water and temperature, land use and agricultural management practices. The most common management practices are flood irrigation, soil cultivation, addition of organic matter, inorganic fertilizer addition, cultivar type, and crop rotation systems. The model needs to simulate the biogeochemistry dynamics and crop growth for the year round crop rotation system in order to predict annual fluxes of N_2O, CO_2, and CH_4 and crop yields.

The soil biogeochemical processes to be simulated include: (i) CH_4 production and consumption; (ii) denitrification and nitrification: N_2O and N_2 gas fluxes; (iii) nutrient mineralization; and (iv) soil organic matter dynamics. The biogeochemistry modules need to respond to changes in soil water status which range from anaerobic soil flooding, drying and rewetting, and aerobic non-flooded conditions. The crop growth module needs to simulate growth of rice and crops grown in rotation with rice and respond to the dominate agricultural management practices such as cultivation, water management and fertilizer additions. Modules have already been developed to simulate the different soil biogeochemistry and plant growth processes. However, we are not aware of an existing agroecosystem models which includes all of the processes needed for a complete rice agroecosystem model.

The major drivers to the system include canopy temperature, air temperature, rainfall, soil water status (flooding), land use and agricultural management practices. Remote sensing data can be used to determine land use, canopy temperature, and soil water status and have the potential to give some information about the spatial extent of different agricultural management practices. Precipitation and air temperature data can be measured using data from ground stations, while agricultural management practices can be determined using surveys of farming practices in the different rice growing regions of the world.

An agroecosystem model can be used to simulate annual gas fluxes of N_2O, CO_2, and CH_4 and crop yield. The models may be applied for all of the different agricultural management practices and land uses in a region and the results summed to get regional trace gas fluxes and crop yields. Databased estimates of trace gas fluxes and crop yields may also be independently derived by using empirical models and regional databases of the driving variables and agricultural management practices. Country wide or global estimates of trace gas and crop yield may then be derived by summing regional estimates that come from field data integration and model results.

Modelling Nitrification, Denitrification, and Fermentation Under Anaerobic Conditions

Modelling the nitrogen cycle involves a number of factors separate from those which control carbon, and others which are linked to carbon. As an example of models which treat N, DNDC (DeNitrification DeComposition) is a process-oriented simulation model of soil carbon and nitrogen biogeochemistry (Li *et al.* 1996). It predicts N_2O, NO, N_2, and CH_4 emissions under anaerobic conditions based on simulating soil temperature, Eh, pH, organic matter decomposition, and plant growth. The model predicts emissions of CO_2, N_2O, NO, CH_4, and NH_3 from agricultural lands under various farming practices including tillage, fertilization, manure application, irrigation, flooding, and weeding. The model has been validated against field measurements at more than forty sites across climate zones and soil types worldwide.

As a biogeochemical model, DNDC simulates soil C and N biochemical and geochemical processes driven by climate, soil properties, and farming management. Trace gas emission is part of the simulated products. DNDC contains five interacting submodels. The thermal-hydraulic submodel uses soil physical properties, air temperature, precipitation, irrigation, and flooding data to calculate soil temperature and moisture profiles and soil water fluxes through time. The plant growth submodel calculates daily water and N uptake by plants, LAI and plant biomass development, and litter deposition. The decomposition submodel calculates daily decomposition, nitrification, ammonia volatilization, and soil microbial respiration. The denitrification submodel calculates hourly denitrification rates and NO, N_2O, and N_2 production under anaerobic conditions. The fermentation submodel calculates soil Eh dynamics and CH_4 production, oxidation, ebullition and plant transport under long-term submerged conditions.

In DNDC, soil Eh is calculated based on the duration of saturated time period. When a rainfall or irrigation event occurs, a certain amount of surface layers will be set as saturated for a short term according to the duration of the rainfall or irrigation. Soil Eh value in the saturated layers will decrease from 600 mv (a normal value under aerobic conditions) to 200–500 mv. In this case, the denitrification submodel will be started to calculate N_2O, NO, and N_2 production. If a soil is flooded for several days or longer, the Eh value will further decrease because of depletion of oxides in the soil. DNDC regulates the Eh decrease rate for each layer based on its depth, temperature and organic matter content, as well as flooding duration and plant (*e.g.*, rice) aerenchyma development. If Eh is lower than -150 mv, CH_4 will be produced in the layer. The oxidation rate is regulated by the Eh value at the layer. CH_4 is allowed to diffuse between layers based on the concentration gradients. CH_4 is emitted from the soil into the atmosphere through two mechanisms: plant transport and ebullition. The plant submodel calculates rice growth and development of roots and aerenchyma. The calculated results will be fed into this fermentation submodel to regulate soil available C and plant transport rates.

In DNDC, nitrification rate is regulated by soil temperature, Eh, pH, organic matter content, and ammonium concentration. Under short- or long-term anaerobic conditions, decomposition and nitrification routines work continuously such that their rates vary according to the change in soil Eh and other conditions. Under submerged conditions, nitrification slows down because of the low Eh. Ammonium produced from either fertilizer or organic matter only slightly converts to nitrate. DNDC predicts that denitrification occurs quickly during the first few days after flooding, but subsequently decreases to a low level during the rest of time of inundation. Fertilization does not significantly increase denitrification unless the fertilizer is nitrate. The predicted results are consistent with the field measurements.

The DNDC model is being used for regional estimates of soil trace gas emissions from agricultural lands. Trace gas emissions and crop yield are the two relevant aspects related to soil biogeochemistry. DNDC predicts interrelations among trace gas production, soil fertility, crop yield, and ground water contamination under various management scenarios.

Implementation Plans for Future Wetlands Research in the Context of Functional Parameterization Scheme (1998–2002)

Global Inventories of Wetland Area

In order to quantitatively assess the spatial distribution of the various types of wetlands on a functional basis, it will be necessary to compile wetland inventories from wetland sites. There is information available from all regions, but coverage is poor in intermittent wetlands. Information is more comprehensive for permanently inundated wetlands.

Wetland areas are often underestimated. Some estimates of areal extent have been estimated by groups with narrow topical interest (*e.g.*, water fowl). Some of the major gaps, including the Siberian wetlands, are mainly due to lack of access. Wetlands in forested areas are difficult to determine, especially in those areas where the water table is below the surface. In pulsed (riverine or periodic rainfall) systems, wetlands are also underestimated. A partial compilation of wetland inventories can be found on the GAIM website at http://gaim.unh.edu and will be updated as new inventories are created and existing ones are expanded. It is our hope to eventually have a global inventory based on wetland functional parameterization.

Current estimates of the global extent of wetlands involve either the compilation of anecdotal information from interviews or questionnaires or more systematic planimetry of areas identified as swamps on worldwide Operational Navigation Charts (ONC). In the late 1980s, more complete inventories became available for North America, but the best global database is that of Matthews and Fung (1987). More recent mapping of wetlands is driven by national agencies, with NGOs generally ahead of national governments in extending the identification of wetlands. There is not yet any global assessment of the seasonal variation in the extent of wetlands. Furthermore, remote sensing has not been systematically applied to the problem of identifying the global extent and distribution of wetlands.

The national inventories are usually conducted for resource management or conservation, rather than for global change research, and consequently they identify only the portion of wetlands that are occupied by some particular type of surface such as wildfowl habitat. Thus, to greater or lesser degree they (and the aforementioned regional surveys) underestimate the inundatable area that is of interest to biogeochemists. Thus, there is a need to intensify national wetland inventories in various parts of the world and to integrate them into regional and global calculations.

Another general feature of the national inventories is that successive national surveys increase both the number and the cumulative area of wetlands identified. In many countries the state of practice in countrywide wetland mapping involves planimetry of wetland symbols on the best available topographic maps, which are usually 1:50,000 scale. There is usually little redefinition of the area of a specific wetland once it has been identified; the growth in the cumulative area results mainly from the identification of more wetlands, because each survey builds on previous inventories. Thus, for each repeatedly surveyed nation or region one can draw a curve of the number of wetlands identified against cumulative area of wetlands, and because the largest are usually identified first followed by successively smaller and more ephemeral wetlands, the curve is convex upward and asymptotically approaches the maximum extent that is relevant to global change research (Figure 9). On such a curve, one could estimate whether a particular national inventory is high or low on the curve. Such an estimate indicates roughly the degree to which current calculations need to be adjusted, and the magnitude of the improvement to be reaped from intensifying national inventories.

A survey of physiographic and climatic conditions suggests that the continental area with the largest extent and duration of inundation are North America, Northern Eurasia, South America, and South and East Asia. Of these, the North American inventory is high on the above-mentioned curve and South America is currently being inventoried with passive and active microwave satellite imagery that will identify the large wetlands of the Orinoco, Amazon, and Pantanal basins. A conspicuous gap in knowledge exists in the arc of South and East Asia that extends from the Indo-Gangetic lowland to the Huang He delta. This situation suggests the value of a rapid refinement of wetland inventories in that region could be accomplished through a programme of digitizing areas indicating swamp symbols on 1:250,000-scale topographic maps and then digitizing the same wetlands on a small sample of larger-scale maps (such as 1:50,000 or 1:25,000) in order to calculate conversion factors by which to translate the coarser-resolution estimates to a "probable maximum" wetland area. The project for Asia might be organized through some regional or global agency with the work for each country being done by local experts, with the quality control, gap-filling, data integration, and time schedule being driven by the coordinating agency. The same strategy could fruitfully be explored for African wetlands.

It should be emphasized that such an inventory is of extent and (regional) position only. There is a large gap between such an inventory of extent and an inventory of the variables which are required for functional modelling of wetland production (*e.g.*, methane production, carbon storage, *etc.*). For these purposes, parametric data will be required (*e.g.*, temperature, NPP, soils, *etc.*) to be combined with information on the spatial extent of wetlands around the globe. Once the global wetland data have been compiled digitally, it would be possible to overlay various data fields (*e.g.*, air temperature and NPP over area of inundation during wet season, *etc.*).

Global biogeochemical cycling in wetlands has a major influence on methane production, carbon storage/release, denitrification, and sulphur cycling, each of which must be accounted for in a model of wetland function (Figure 10). In the case of each of these processes, its global significance is determined from a simple equation:

Area of Wetland x Process Rate = Global Rate.

The rate of each of the processes, but especially methane production and denitrification, is crucially dependent upon periodically flooded areas. Therefore it is necessary that global wetland extent be expressed in two categories:

- Permanently flooded
- Periodically flooded: seasonally or episodically.

The current efforts at global land cover mapping treat only permanent wetland area. Consequently, in future initiatives to assess wetland area in various functional categories particular effort needs to be focused on the seasonally and episodically inundated areas. In such initiatives, <u>wetland extent should be expressed in terms of hectare-days</u> (or equivalent units). This will allow for a spatial as well as temporal analysis of biogeochemical functioning. It will be necessary to construct a relationship for a range of test sites around the world. The aim will be to determine the relationship between the area of wetland identified and the number of wetland sites listed as the sophistication and cost of the methodology is increased (Figure 9).

An intersection of this inventory work with those who model wetland biogeochemistry will permit a determination of the point where additional effort at wetland identification does not significantly affect the estimates of rates of global biogeochemical processes.

Figure 9

Area of wetlands in a given region. (From Sahagian, unpublished).

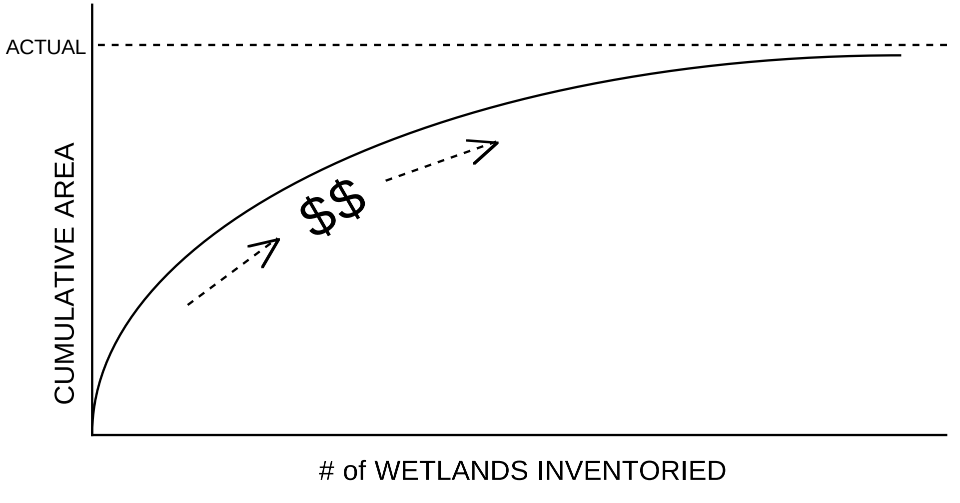
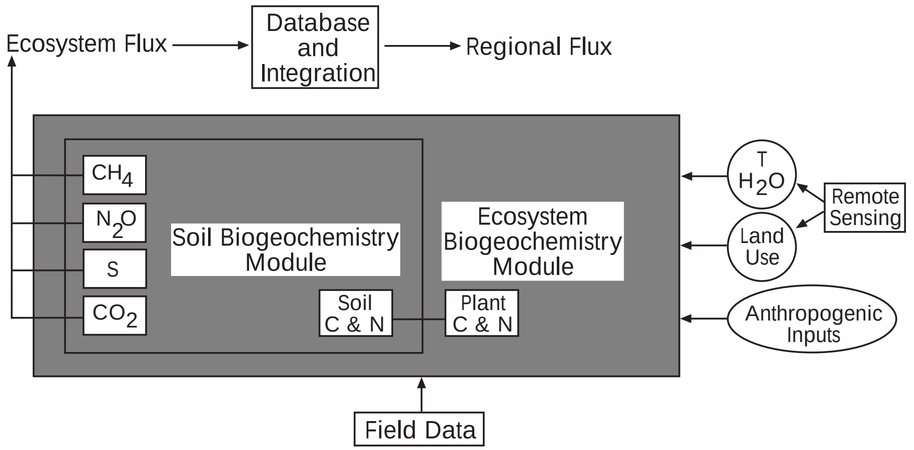


Figure 10

Simplified diagram of a model for wetland function. Hydrology is inherent throughout. (From Sass, unpublished).



A complete wetlands inventory could be compiled using the following types of information:

1. Ramsar Convention database
2. Global/Continental scale inventories
3. National inventories
4. ONC charts
5. Swamp marks on local topographic maps of 1;250,000 scale
6. Swamp marks on local topographic maps of 1:50,000 scale
7. AVHRR type RS data classified using expert local knowledge
8. AVHRR type RS data classified using about four types of swamp marks from local 1:100,000 maps
9. Passive microwave of surface flooded area when the wetlands are dry
10. Passive microwave of surface flooded area when the wetlands are wet
11. Active microwave estimate of surface flooded area when the wetlands are dry
12. Active microwave estimate of surface flooded area when the wetlands are wet
13. Optical (TM probably) classified with local knowledge input
14. Optical (TM probably) classified using the digitized swamp marks only
15. (a) hybrid of AVHRR and TM
    (b) passive microwave and TM
    (c) active microwave and TM.

While these present and potential sources of information may lead to a snapshot of the present extent of wetlands, it will be necessary to develop a long-term strategy for global monitoring of changes in wetland extent, distribution and functionality.

Case Study Approach

Specific wetlands sites can be analyzed as an aid to discussion of the data needed for global parameterization of wetlands and the means by which they could be collected. Two contrasting regions are used as examples of a case study approach.

Amazon (Tropical Riverine)

There are five priority strands of data that are needed for biogeochemical estimates for the Amazon Basin: potentially flooded area, month by month inundation, river channel flow, temperature and vegetation. The other variables (NPP, soil, salinity, chemistry, organic transport) seem to be of lesser importance or are deemed to be very difficult to assess.

Potentially flooded areas cannot be assessed from existing topographic maps. The Radar of the Brazilian Amazon (RADAM) mapping exercise used land systems mapping techniques coupled with X band radar imagery to determine the topographic limits of the floodplains and wetlands.

Monthly inundated area can be determined at present on a 1 degree grid cell basis by use of passive microwave sensors. In the near future RADARSAT (Canadian) imagery will probably permit mapping on a 100 m x 100 m scale. However, the impact of the tree canopy on this system has yet to be determined.

Traditional hydrological data are available from five main channel gauging points with reliable data for 25 years. A 100 year record of riverflow exists for Manaus. In addition there are around 100 gauging sites of generally lesser quality on the major tributaries. There are around 400 rain gauges operating in the basin.

The traditional hydrological data can be linked with the short month by month inundation record and the potentially floodable area to provide an estimate of the area of inundation for each month during the last 100 years.

Temperature is available from 12 reliable stations measuring air temperature across the Amazon Basin. Since temperature is a conservative parameter in this region, these few stations will probably give an adequate representation of this variable over the basin. Surface temperature should soon be available from thermal infra-red remote sensing methods.

Mapping of vegetation from optical and SAR remote sensing methods is probably the most effective method available.

The newly established Large-scale Biosphere-Atmosphere program in the Amazon (LBA) will include a long term measurements programme which could be used for model validation and to determine the response of a model to changing conditions. The emission model could also feed into an atmospheric chemistry model which could be checked against atmospheric concentrations. Validation at the local level could be conducted by comparing the model output with field measurements. Validation at the global scale could be conducted by putting the emission model into a methane atmospheric chemistry model and comparing its output with measured concentrations of methane in the atmosphere.

Hudson Bay Lowland (Polar Non-Riverine)

Four parameters are central to the estimation of biogeochemical cycling in this area: position of the water table; vegetation; NPP; and temperature.

Maximum wetland extent can be determined by active microwave sensing systems on satellites operating at the end of the snowmelt period when almost the entire bog system is inundated.

Position of the water table is the crucial variable in determining methane production as well as other biogeochemical cycles. The essential classes for the first cut analysis are where the water is above the surface, at the surface or below the surface. Active microwave sensors can assess the situations where the water is at or above the surface. The area of bog where the water is below the surface will have to be determined as the difference between the maximum area and the areas with water at or above the surface.

Vegetation needs to be classified into bryophyte/macrophyte and no vegetation (open water) categories. The best method for determining these distinctions is aerial photographic analysis, but optical remote sensing may be feasible.

Modelling

One of the primary purposes of developing a wetland functional parameterization scheme is to be better able to constrain the role of wetlands in the global biogeochemical system as modelled by terrestrial ecosystem models of various types. Such models can use wetland functional class as a refinement of biomes as input data. Whereas there is no biome distribution scheme which is universally adopted by all modelling groups, the wetlands functional characterization scheme will provide a common subset of data for this particularly important source and flux of methane and other biogeochemically active materials.

In addition, it will be important to incorporate wetland function into terrestrial ecosystem models to better capture the wetland internal functions and their interactions with the larger terrestrial ecosystem. For example, NPP is one of the major output results of many ecosystem models. However, the NPP of wetlands is an important function upon which the functional classification is based. Consequently, it will not be possible to use the gross output of ecosystem models to calculate NPP within wetlands for the purpose of wetland classification. Rather, it will be necessary to incorporate wetland processes within the larger ecosystem models and simultaneously calculate NPP for wetlands (for classification subroutines) and develop wetland functional distribution for the purpose of biogeochemical fluxes.

Appendix I

Selected Site Studies

Methane Emissions from Texas Rice Fields, USA

Ronald L. Sass and Frank M. Fisher

Research has been conducted over the period from 1989 to 1996 to describe as fully as possible various factors that influence methane production and emission from rice fields in the Texas Gulf Coast area (USA) near 94°30'W, 30°N. Rice represents the main agricultural activity in this area which has an annual growing season of approximately 275 days and only 15 days with temperatures below 0°C. Annual rainfall averages 1340 mm, of which about 50% (122 mm month^{-1}) occurs during the rice-growing season in April through September. Soybeans are generally rotated with rice. Native vegetation is coastal prairie. Most studies were done on one of three clay soils: Beaumont clay (an Entic Pelludert); Lake Charles clay (a Typic Pelludert which is slightly less acid and stronger in structure); and Bernard-Morey (a fine clayey silty loam thermic Vertic Ochraqualf). All three soils have poor internal and surface drainage with percolation rates less than 0.5 mm day^{-1} after initial saturation. In addition, some comparison studies were done on a Katy-Crowley soil association (Alfisols), a fine sandy loam west of Houston, Texas. These four soils are representative of the majority of the rice growing areas of the Texas Gulf Coast. To date, full seasonal field production and emission datasets have been collected utilizing thirty-six different experimental conditions.

Diurnal variations in methane emission were observed in the field to be largely due to temperature variation and observed daily cycles in methane emission levels can be explained by the daily cycle in soil temperature (Sass *et al*. 1991a). The response of methane emission to soil temperature change is rapid and consequently no phase difference is observed between the temporal course of the soil temperature and that of methane emission.

The temperature dependence of methane production observed in anaerobic soil incubations show the same Arrhenius dependence (same activation energy) as the field emission data, indicating that the limiting step that determines the rate of methane emission is the same as that for methane production (Sass *et al*. 1991b). It was concluded from these experiments that the majority of the methane emission to the atmosphere was via the rice plant and took place rapidly after being produced. Furthermore, in these dense clays with low porosity and percolation rates, only minor build-up of methane in the pore water has been observed (<400 μM) and methane emission by ebullition or bulk diffusion has been observed to be minimal.

Although daily variations in methane emission were strongly temperature dependent, seasonal variations in methane production and emission followed plant development with no apparent temperature dependence (Sass *et al*. 1992). From negligible values at permanent flood, methane emission generally rose during the vegetative phase. Emission peaked at panicle differentiation during a period of rapid root development, probably due to increased carbon loss from the rapidly growing root tips. Emission obtained a relatively constant value during the reproductive stage, decreasing during late grain filling. During the period from permanent flood to past the end of the reproductive stage (65–75 days), methane emission correlated with aboveground biomass. Prior to the end of the flooded season, an emission peak was generally observed. This late season increase in emission was attributed to an increase in soil carbon substrate due to leaf and root senescence and methane emission increases while live biomass decreases. The addition of readily degradable carbon such as rice grass or straw before planting resulted in an increased early season methane emission as the straw decomposed. In a soil of given clay content, methane production correlated with the local root biomass (Sass *et al*. 1990). In the early season, production was concentrated near the base of the rice plants. As the season progressed and the root system extended deeper and laterally farther from the base of the plant, methane production in these regions increased along with root biomass.

By varying planting date during the same season, three different fields, both with and without incorporated straw, were subject to different climate variables, including integrated solar radiation (Sass *et al*. 1991b). Seasonal emission rates of methane and amount of rice grain yield from individual fields were positively correlated with accumulated solar radiation for both straw-incorporated and control plots. Linear regression analyses of these data show the following: A 1% increase in accumulative solar radiation is accompanied by a 1.1% increase in methane emission and a 1% increase in rice grain yield. In the presence of incorporated straw, a 1% increase in solar radiation is accompanied by a 1.7% increase in methane emission and a 2.2% increase in rice grain yield. However, straw incorporation resulted in an overall decrease in grain yield and an overall increase in methane emission. It is hypothesized that solar radiation and hence photosynthetic activity of the rice plant correlates with methane production and grain yield through partitioning of non-structural carbohydrates to the root system and grain panicle. If photosynthates are available to form root exudates, then the amount of plant derived substrate available for methanogenesis is directly associated with solar radiation. If straw incorporation affects root respiration in such a way as to cause additional root carbohydrate fermentation or loss, then the partitioning of photosynthates may be altered from grain formation to increased root exudation and subsequent methane production and emission.

Emission data obtained between 1989 and 1992 were collected from fields composed of three different soils: Beaumont; Lake Charles; and Bernard-Morey. Averages of the seasonal methane emission values obtained from each soil show a strong linear correlation with the percent sand in the soil. In ten experimental sites established along a transect through a field containing a soil sand-clay-silt gradient ranging from 15% to 35% sand (Sass *et al*. 1994), methane emission was positively correlated with sand content and negatively with clay content.

Four water management schedules were investigated: normal permanent flood (46 days post planting to harvest drain); normal permanent flood with a mid-season drainage aeration (six days immediately following panicle differentiation); normal flood with multiple drainage aeration of 2–3 days each; and late flood (76 days post planting) (Sass *et al*. 1992). Methane emission rates varied markedly with water regime. Periodic drainage of irrigated rice fields results in a significant decrease in methane emissions. A single mid-seasonal drain reduced methane emission by approximately 50% compared to a normal water management schedule (4.86 g m^{-2} compared to 9.27 g m^{-2}). A short period of drainage (two days) approximately every three weeks during the growing season can reduce seasonal methane emissions from irrigated rice fields to an insignificant amount (<1 g m^{-2}). Methane emission may be reduced to near zero values by field draining while methane production and oxidation values remain high. In the normally treated field, methane oxidation increases as the season progresses and may account for as much as 81% of the methane produced. In the fields with late flooding and with a mid-season drain, methane oxidation was as high as 94% of the methane produced. Periodic short periods of water drainage do not appear to reduce rice grain yield. However, delaying initial flooding for too long a period may result in a delayed but intensified pattern of methane emission and a significant loss of rice grain yield.

Straw incorporation influences methane emission in two ways depending on the amount of straw added, either by increased methane emission only during the 2–3 week period following permanent flooding or by increased methane emission throughout the flooded season. When straw incorporation causes an increase in methane emission over the whole season, rice grain yield decreases proportionately. Over a three year period the degree of seasonal methane emission from a specific field was lowest when the field had remained fallow for an extended period before planting, intermediate in following years when only the roots and low stubble from the previous year was tilled into the soil, and highest when additional straw was added prior to planting. An increase in methane emission with additional straw amendments depended on the method of incorporation. The lowest increase occurred when the straw was tilled into the field before the winter season. This treatment gave the maximum time for aerobic decomposition before rice planting. Higher increases in methane emission were observed when the straw was tilled into the field immediately before planting and when the rice stubble from the previous year was not tilled. The highest increase in emission was observed when the applied straw was partially burned.

Additional studies indicate that the choice of rice cultivar has a substantial effect on the amount of methane emitted to the atmosphere during the growing season. Ten rice cultivars appropriate to temperate and sub-tropical irrigated rice fields have been investigated. The seasonal methane emission rates from these cultivars varied from 17.95 to 41.05 gm CH_4 m^{-2}, or by a factor of 2.3.

An Inter-Regional Trans-Asia Research Programme on Methane Emission from Rice Fields - International Rice Research Institute, Los Baños, the Philippines

Reiner Wassmann

Specific Goals of the Project

1. Characterization and quantification of methane emission from major wetland rice ecosystems. These data are required to improve the base for reliable estimates of source strengths at regional and global scales.

2. Identification of current rice technologies that promote or mitigate methane emission in major rice ecosystems. The above flux measurements will encompass comparative studies of various fertilizer treatments, water regimes and cultivars with respect to the impact on methane emission.

3. Evaluate processes that control methane emission in the field. Effects of soil temperature, soil redox potential, soil acidity, and soil conductivity will be recorded and soils classified according to methane production potential.

4. Develop technically and socioeconomically feasible strategies to mitigate methane emission from rice cultivation which maintain or enhance rice productivity and production in sustainable rice systems.

5. Develop research capacities in national agricultural research systems that can significantly contribute to clarify crucial issues in methane emission from rice paddies. Special emphasis should be given to investigate the specific features of the regional rice cultivation, *e.g.*, to screen abundant soil types of the region regarding the methane production potential or to screen rice cultivars regarding the gas transfer capacity.

Participating Organizations

CHINA (Beijing)	Institute of Crop Breeding and Cultivation (CBC), Beijing
CHINA (Beijing)	China National Rice Research Institute (CNRRI), Hangzhou
INDIA	Central Rice Research Institute (CRRI), Cuttack
INDIA	Indian Agricultural Research Institute (IARI), New Delhi
INDONESIA	Central Research Institute for Food Crops (CRIFC)
PHILIPPINES	Philippine Rice Research Institute (PhilRice)
THAILAND	Rice Research Center, Prachinburi.

The Programme

The overall objective of this programme is to establish, in collaboration with national programs in major rice growing countries, the technological resources and training necessary to obtain reliable data about the scale and control mechanisms of methane emission of major rice ecosystems and to foster sustainable rice productivity and production by developing methane mitigating technologies that are technically and socioeconomically feasible. Because of priorities and a lack of technology, national agricultural research scientists (NARS) of rice growing developing countries in Asia have not generally had the facilities to establish and conduct intensive research on methane emissions from rice fields. On the other hand, the International Rice Research Institute (IRRI) research and training activities over the past several decades have contributed greatly to gains in rice grain production efficiency and sustainability and have strengthened the capacity of NARS rice research programs through well established collaborative programs. In the recent past, IRRI has also developed world prominence in the technology and science of trace gas research. Because of their technological advantage in this and other areas of rice research, because of their long established collaborative ties with NARS in Asia, and because of their distinguished record in the management of large multinational research programs, IRRI is uniquely suited to initiate and carry out this important project and, in fact, may be the only organization equipped to do so.

Greenhouse Gas Emissions in India: Methane from Rice Fields - National Physical Laboratory, New Delhi, India

A.P. Mitra

This programme is an ongoing campaign organized and coordinated by the National Physical Laboratory and utilizes researchers in 16 organizations spanning India, including the various laboratories of the Council of Scientific and Industrial Research (CSIR), agricultural universities and institutes. A measurement campaign was launched in 1991 and continues to date. Seasonal methane emissions at specific sites are extrapolated to give state/regional emissions based on agricultural categories: rain-fed water-logged; deep-water; irrigated; and upland rice. These are combined to assess the total methane emission from rice fields of all of India. In addition to recording seasonal methane emissions, data were collected on areal extent of rice fields in each category, paddy biomass, soil type and condition, pH of the soil and surface water, soil and ambient temperature, fertilizers used and organic carbon inputs. Field measurements collected in selected rice-growing areas of India resulted in an estimate of 3 Tg $year^{-1}$ for all of India. This figure is considerably lower than had been previously expected.

Methane Emission in Rice Based Cropping Systems - India Central Rice Research Institute, Cuttrack, India

T.K. Adhaya

This study was carried out partly under the national CH_4 campaign organized in India by the National Physical Laboratory, New Delhi. It is concerned with field measurements of methane in irrigated flooded rice fields at the Central Rice Research Institute, Cuttack. Observed methane emissions are significantly higher than values reported for irrigated rice in the national CH_4 campaign, but indicate that methane emissions from alluvial soil, as used in this study, are considerably lower than the predicted estimates of the United States Environmental Protection Agency published in 1990.

Experiments have been carried out to study the effect of varietal variation on methane efflux from flooded rice paddies using ten established rice varieties. Data was collected during both wet and dry season. Methane emissions were compared with rice grain yield results and with effects of added phosphate. Highest methane emission was noted under conditions of zero added phosphate. In studying this effect it was found that the phosphate fertilizer commonly used by farmers contained high amounts of sulphate and subsequent incubation studies with added sulphate verified a sulphate inhibition of methanogenic bacteria. There was a wide variation among different varieties with mean methane emissions ranging from 3.20 mg CH_4 m^{-2} hr^{-1} in cultivar CR-674^{-1} to 10.68 mg CH_4 m^{-2} hr^{-1} in cultivar Rasi. Other variables were studied: percent area of air space in the stem of different rice varieties; mean grain yield; redox potential in the rhizosphere; and Naphthylamine oxidize activity. Only root oxidation activity indicated any significant relationship with methane emission.

Other field studies are investigating the effect of mode of planting, *i.e.*, direct seeded and transplanting, the effect of plant spacing, and methane emission from wild forms of the rice species *Oryza*.

Future research plans include studies of the effect of water management treatment on methane emission, *i.e.*, irrigation vs. rain-fed and thereby intermittent flooding and the effects of organic fertilizer treatment such as green manure, composted straw and azolla. At this site, automated equipment is in place but is not fully operational. It is apparent in discussions with scientists that their research priorities are to investigate methane emission as it is affected by the various cropping systems in eastern India. In future years this group will also investigate the effects of soil types and farming practices on methane emission in other parts of India.

India Agricultural Research Institute, New Delhi, India

M.C. Jain

Seasonal data are being obtained from plots utilizing three different rice cultivars employing intermittent flooding in which the plots were allowed to evaporate, dry and then reflooded. This is consistent with local farming practices. In addition, a continuously irrigated control plot was employed. Methane emission was found to be very low in all cases, possibly due to very low carbon content in these soils, water treatment and use of only mineral fertilizer. Interesting data were obtained on the relationship between acetate as a methanogenic substrate and the formation of methane in the incubation experiments. Future work will concentrate on process level studies and possible companion measurements of nitrous oxide emission. These studies will be part of the national CH_4 campaign organized in India by the National Physical Laboratory, New Delhi.

Report on Greenhouse Gas Inventory Studies - Chinese Academy of Science, China (Beijing)

Wang Ming Xing

China is conducting considerable work on greenhouse emissions and sinks. Three emission inventories have been formulated by three donor projects: the Asian Development Bank, the World Bank project "National Response Strategy for Global Climate Change: China" and the China Science and Technology Commission-Environment. The Asian Development Bank project divides the Chinese rice cultivation areas into five regions: South China; Central China; Middle and lower reaches of the Yanqzi River; Southwest China; and North China. Considering the cultivation type in various regions, it assesses the methane emission range from Chinese rice fields. The emission coefficients originate from available measurement results in China. From these measurements it is apparent that methane emissions from Chinese rice fields are affected by many factors. The key factors identified are soil type (including soil physics and chemistry), water level and its history in the growing season, soil temperature, fertilizer application, cultivation and agricultural practice. At present there are insufficient data to incorporate all of these factors. Continued experimental data are being collected to investigate the effects of these factors on the level of methane emission from rice fields.

Over the seven year period 1988–1995, a considerable number of investigations on methane emissions from Chinese rice fields have been reported. A total of 73 different seasonal emission values have been published from six area locations. Of these measurements, over half are from the Beijing area, reflecting the large concentration of research scientists in that area as opposed to the rest of the country. Data from the other five locations are each the results of a particular research group. Reported seasonal methane emission from the Beijing area range from 1.1 to 176.5 gm m^{-2} $crop^{-1}$. The average emission value reported for Beijing is 49.1 gm m^{-2} $crop^{-1}$ with a standard deviation from this average of 49.3 gm m^{-2} $crop^{-1}$. Data from other areas also range widely. Several reasons for such a large range of values are apparent from the table and from experience: (i) there is an inter-annual variation that can be attributed to weather and other annually changing factors; (ii) within an individual area there are different cropping schedules resulting in different planting times (early, mid season, late), different field rotation schedules and different rotational crops; (iii) even within the same area and particularly between areas, there are a variety of different water management practices; (iv) there are different cropping times, in part due to different seasons, climate, cultivars, *etc;* (v) a large number of different fertilizer treatments have been reported, reflecting the many different practices of local farmers; and (vi) all of the above variables affect emissions from different areas of such a large region as China. Continued experimental data are being collected to investigate the effects of these and other factors on the level of methane emission from Chinese rice fields.

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List of Acronyms

ABLE	Arctic Boundary Layer Expedition
ACE	Aerosol Characterization Experiment (IGAC)
ADEOS	Advanced Earth Observing Satellite
AGCM	Atmospheric General Circulation Model
APAR	Absorbed Photosynthetically Active Radiation
ATM	Atmospheric Transport Model
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible and Infrared Imaging Spectrometer
AVNIR	Advanced Visible and Near Infrared Radiometer
BAHC	Biospheric Aspects of the Hydrological Cycle (IGBP)
BATGE	Biosphere-Atmosphere Trace Gas Exchange in the Tropics (IGBP)
BOREAS	Boreal Ecosystems Atmosphere Study (BAHC/GEWEX)
CACGP	Commission on Atmospheric Chemistry and Global Pollution (IAMAS)
CARBICE	Carbon Dioxide Intercalibration Experiment
CEOS	Committee for Earth Observation Satellites
CSIR	Council of Scientific and Industrial Research (South Africa)
CZCS	Coastal Zone Colour Scanner
DAAC	Distributed Active Archive Center
DGVM	Dynamic Global Vegetation Model
(IGBP-) DIS	Data and Information System (IGBP)
DMS	dimethylsulphide
DMSP	dimethylsulphonio-proprionate
DMDS	Dimethyl disulphide

DNDC	Denitrification decomposition
DOC	Dissolved Organic Carbon
DOLY	Dynamic Global Phytogeography Model
ECHIVAL	European International Project on Climate and Hydrological Interactions between Vegetation, Atmosphere and Land Surfaces European Climate and Hydrological Project on Interactions between Vegetation, Atmosphere, and Land ?
ENSO	El Niño - Southern Oscillation
EOS	Earth Observing System (NASA, USA)
ESA	European Space Agency
ETM	Enhanced Thematic Mapper
FACE	Free-Air CO_2 Enrichment
FAO	Food and Agriculture Organization (UN)
GAIM	Global Analysis, Interpretation and Modelling (IGBP)
GCM	General Circulation Model ?
GCTE	Global Change and Terrestrial Ecosystems (IGBP)
GEIA	Global Emissions Inventory Activity (IGAC)
GEWEX	Global Energy and Water Cycle Experiment (WCRP)
GIS	Geographical Information System
GLOBEC	Global Ocean Ecosystems Dynamics (IGBP/IOC/SCOR)
GLOCARB	Global Tropospheric Carbon Dioxide Network (IGAC)
GLOCHEM	Global Atmospheric Chemical Survey (IGAC)
HESS	High Latitude Ecosystems as Sources and Sinks of Trace Gases (IGAC)
IASC	International Arctic Science Committee
ICSU	International Council of Scientific Unions
IGAC	International Global Atmospheric Chemistry Project (IGBP/CACGP)
IGBP	International Geosphere-Biosphere Programme (ICSU)
IGFA	International Group of Funding Agencies for Global Change Research
IHDP	International Human Dimensions Programme on Global Environmental Change (ICSU/ISSC)
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change (WMO/UNEP)
IRRI	International Rice Research Institute

IRS	Indian Remote Sensing Satellite
ISLSCP	International Satellite Land Surface Climatology Project (WCRP)
JERS	Japanese Earth Resources Satellite
JGOFS	Joint Global Ocean Flux Study (IGBP/SCOR)
LAI	Leaf Area Index
LAMBADA	Large Scale Atmospheric Moisture Balance of Amazona using Data Assimilation
Landsat	Land Remote-Sensing Satellite (USA)
LBA	Large-scale Biosphere-Atmosphere Experiment in Amazonia
LISS	Linear Imaging Self-Scanning System
LOICZ	Land-Ocean Interactions in the Coastal Zone (IGBP)
LUCC	Land Use/Cover Change (IGBP/IHDP)
MEHALICE	Methane and Halocarbons Intercalibration Experiment (IGAC)
MILOX	Mid-Latitude Ecosystems as Sources and Sinks for Atmospheric Oxidants (IGAC)
MSS	MultiSpectral Scanner
NARS	National Agricultural Research Scientists
NASA	National Aeronautics and Space Administration (USA)
NDVI	Normalized Difference Vegetation Index
NEP	Net Ecosystem Productivity
NGO	Non-Governmental Organization
NOAA	National Oceanic and Atmospheric Administration (USA)
NOMHICE	Non-Methane Hydrocarbon Intercomparison Experiment (IGAC)
NPP	Net Primary Productivity
OM	Organic Matter
ONC	Operational Navigation Charts
PAGES	Past Global Changes (IGBP)
PANASH	Palaeoclimates of the Northern and Southern Hemispheres (PAGES)
PAR	Photosynthetically Active Radiation
PILPS	Project for Intercomparison of Landsurface Parameterization Schemes (WCRP)
POC	Particulate Organic Carbon

RADAM	Radar of the Brazilian Amazon
RICE	Rice Cultivation and Trace Gas Exchange (IGAC) Regional Interactions of Climate and Ecosystems (GAIM)
SAR	Synthetic Aperture Radar
SeaWiFS	Sea-viewing Wide-field-of-view-Sensor
SIR-C	Spaceborne Imaging Radar - C
SMMR	Scanning Multichannel Microwave Radiometer
SSM/I	Special Sensor Microwave/Imager
START	Global Change System for Analysis, Research, and Training (IGBP/IHDP/WCRP)
SVAT	Soil-Vegetation Atmosphere Transfer (Model)
TEM	Terrestrial Ecosystem Model
TM	Thematic Mapper
TOMS	Total Ozone Mapping Spectrometer
TOPEX/POSEIDON	Ocean Topography Experiment (USA/France)
TRAGEX	Trace Gas Exchange: Mid-Latitude Terrestrial Ecosystems and Atmosphere (IGAC)
UNESCO	United Nations Educational, Scientific and Cultural Organization
WCRP	World Climate Research Programme (ICSU/IOC/WMO)

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Report Nos. 12-19 are available in limited numbers.

No. 20*
Improved Global Data for Land Applications: A Proposal for a New High Resolution Data Set, Report of the Land Cover Working Group of IGBP-DIS. Edited by J.R. Townshend (1992). IGBP Secretariat, Stockholm, 75 pp.
This report outlines a proposal to produce a global data set at a spatial resolution of 1 km derived from the Advanced Very High Resolution Radiometer primarily for land applications. It defines the characteristics of the data set to meet a number of requirements of IGBP's science plan and outlines how it could be created. It presents the scientific requirements for a 1 km data set, the types and uses of AVHRR data, characteristics of a global 1 km data set, procedures, availability of current AVHRR 1 km data, and the management needs.

No. 21*
Global Change and Terrestrial Ecosystems: The Operational Plan. Edited by W.L. Steffen, B.H. Walker, J.I. Ingram and G.W. Koch (1992). IGBP Secretariat, Stockholm, 97 pp.
The objectives of GCTE are: to predict the effects of changes in climate, atmospheric composition, and land use on terrestrial ecosystems, including agricultural and production forest systems, and to determine how these effects lead to feedbacks to the atmosphere and the physical climate system. The research plan is divided into four foci: ecosystem physiology, change in ecosystem structure, global change impact on agriculture and forestry, and global change and ecological complexity. Research strategies are presented.

No. 22
Report from the START Regional Meeting for Southeast Asia. Arranged by The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP), in collaboration with Human Dimensions of Global Environmental Change (HDGEC) Programme (1992). IGBP Secretariat, Stockholm, 114 pp.
The report presents general recommendations on global change research in the region, thematic studies relating to IGBP Core Project science programmes, global change research in studies of eight countries in the area, and conclusions from working groups on the participation of the region in research under the five established IGBP Core Projects and the related HDGEC programme.

No. 23
Joint Global Ocean Flux Study: Implementation Plan. Jointly published with the Scientific Committee on Oceanic Research (SCOR) (1992). IGBP Secretariat, Stockholm, 78 pp. (JGOFS Report No. 9)
The Report describes how the aims of JGOFS are being, and will be, achieved through global synthesis, large scale surveys, process studies, time series studies, investigations of the sedimentary record and continental margin boundary fluxes, and the JGOFS data management system.

No. 24
Relating Land use and Global Land-Cover Change: A Proposal for an IGBP-HDP Core Project. A report from the IGBP/HDP Working Group on Land-Use/Land-Cover Change. Edited by B.L. Turner, R. H. Moss, and D.L. Skole (1993). IGBP Secretariat, Stockholm, 65 pp. (Human Dimensions of Global Environmental Change Programme, HDP Report No. 5).
The report presents the main findings of the joint Working Group of the IGBP and the International Social Science Council on Land-Use/Land-Cover Change; it describes the research questions defined by the group and identifies the next steps needed to address the human causes of global land-cover change and to understand its overall importance. It calls for the development of a system to classify land-cover changes according to the socioeconomic driving forces. The knowledge gained will be used to develop a global land-use and land-cover change model that can be linked to other global environmental models.

No. 25
Land-Ocean Interactions in the Coastal Zone (LOICZ) Science Plan. Edited by P.M. Holligan and H. de Boois, with the assistance of members of the LOICZ Core Project Planning Committee (1993). IGBP Secretariat, Stockholm, 50 pp.
The report describes the new IGBP Core Project, giving the scientific background and objectives, and the four research foci. These are: the effects of global change (land and freshwater use, climate) on fluxes of materials in the coastal zone; coastal biogeomorphology and sea-level rise; carbon fluxes and trace gas emissions on the coastal zone; economic and social impacts of global change on coastal systems. The LOICZ project framework includes data synthesis and modelling, and implementation plans cover research priorities and the establishment of a Core Project office in the Netherlands.

No. 26*

Towards a Global Terrestrial Observing System (GTOS): Detecting and Monitoring Change in Terrestrial Ecosystems. Report of the Fontainebleau Workshop. Edited by O.W. Heal, J.-C. Menaut and W.L. Steffen (1993). Paris: MAB, 71 pp. (UNESCO Man and the Biosphere Digest 14).

The Fontainebleau Workshop, July 1992, defined a strategy to initiate a global terrestrial monitoring system for the IGBP project on Global Change and Terrestrial Ecosystems, the French Observatory for the Sahara and the Sahel, and the UNESCO Man and the Biosphere programme, in combination with other existing and planned monitoring programmes. The report reviews existing organisations and networks, and drafts an operational plan.

No. 27*

Biospheric Aspects of the Hydrological Cycle. The Operational Plan. Edited by BAHC Core Project Office, Berlin (1993). IGBP Secretariat, Stockholm, 103 pp.

A presentation of the mandate, scope, principal subjects and structure of the BAHC research plan is followed by a full description of the four BAHC Foci: 1) Development, testing and validation of 1-dimensional soil-vegetation-atmosphere transfer (SVAT) models; 2) Regional-scale studies of land-surface properties and fluxes; 3) Diversity of biosphere-hydrosphere interactions; 4) The Weather Generator Project.

No. 28*

The IGBP in Action: The Work Plan 1994-1998. 1994. IGBP Secretariat, Stockholm, 151 pp.

This Report provides an overview of the global change research to be carried out under the aegis of the International Geosphere-Biosphere Programme over the next five years. It represents a follow-up to IGBP Report No. 12 (1990) that described the basic structure of the global change research programme, the scientific rationale for its component Core Projects and proposals for their development. The IGBP Core Projects and Framework Activities present their aims and work programme in an up-to-date synthesis of their science, operational and implementation plans.

No. 29

Africa and Global Change. A Report from a Meeting at Niamey, Niger, 23-27 November, 1992. (1994). IGBP Secretariat, Stockholm. (English and French under the same cover) 55 pp.

A summary is given of the conference arranged by the Global Change System for Analysis, Research and Training (START) on behalf of the IGBP, the Human Dimensions of Global Environmental Change Programme (HDP), and the Joint Research Centre of the Commission of the European Communities (CEC) that describe the global change scientific research situation in Africa today.

No. 30

IGBP Global Modelling and Data Activities, 1994-1998. Strategy and Implementation Plans for Global Analysis, Interpretation and Modelling (GAIM) and the IGBP Data and Information System (IGBP-DIS) (1994). IGBP Secretariat, Stockholm, 86 pp.
This report sets out the goals and directions for GAIM and IGBP-DIS over the next five years, expanding on the recent overview of their activities within IGBP Report 28 (1994). It describes the work within IGBP-DIS directed at the assembly of global databases of land surface characteristics, and within GAIM, directed at modelling the global carbon cycle and climate-vegetation interaction.

No. 31

African Savannas and the Global Atmosphere. Research Agenda. Report of a joint IGBP/START/IGAC/GCTE/GAIM/DIS Workshop on African Savannas, Land use and Global Change: Interactions of Climate, Productivity and Emissions, 1-5 June 1993, Victoria Falls, Zimbabwe. Edited by C. Justice, B. Scholes and P. Frost (1994). IGBP Secretariat, Stockholm, 53 pp.
The workshop focused on interactions between African savannas and the global atmosphere, specifically addressing land-atmosphere interactions, with emphasis on sources and sinks of trace gases and aerosol particles. The report discusses the ecology of African savannas, the research issues related to carbon sequestration, ongoing and proposed activities, and gives a research agenda.

No. 32

International Global Atmospheric Chemistry (IGAC) Project. The Operational Plan. 1994. IGBP Secretariat, Stockholm, 134 pp.
The goals of IGAC are to: develop a fundamental understanding of the processes that determine atmospheric composition; understand the interactions between atmospheric chemical composition and biospheric and climatic processes, and predict the impact of natural and anthropogenic forcings on the chemical composition of the atmosphere. The Operational Plan outlines the organisation of the project. The plan describes the seven Foci, their related Activities and Tasks, including for each the scientific rationale, the goals, strategies.

No. 33

Land-Ocean Interactions in the Coastal Zone. Implementation Plan. Edited by J.C. Pernetta and J.D. Milliman (1995). IGBP Secretariat, Stockholm, 215 pp.
LOICZ is that component of the IGBP which focuses on the area of the Earth's surface where land, ocean and atmosphere meet and interact. The implementation plan describes the research , its activities and tasks, and the management and implementation requirements to achieve LOICZ 's science goals. These are, to determine at regional and global scales: the nature of these dynamic interactions, how changes in various compartments of the Earth system are affecting coastal zones and altering their role in global cycles, to assess how future changes in these areas will affect their use by people, and to provide a sound scientific basis for future integrated management of coastal areas on a sustainable basis.

No. 34

BAHC-IGAC-GCTE Science Task Team. Report of First Meeting. Massachusetts Institute of Technology, Cambridge, Massachusetts, USA, 10-12 January, 1994 (1995). IGBP Secretariat, Stockholm, 45 pp.
The Science Task Team discussed and developed recommendations for multi-Core Project collaboration within the IGBP under three headings: process studies in terrestrial environments, integrated modelling efforts, and partnership with developing country scientists. Three interrelated themes considered under process studies are: transects and large-scale land surface experiments, fire, and wetlands. Methods for implementation and projects are identified.

No. 35

Land-Use and Land-Cover Change. Science/Research Plan. Edited by B.L. Turner II, D. Skole, S. Sanderson, G. Fischer, L. Fresco and R. Leemans (1995). IGBP Secretariat, Stockholm, HDP Secretariat, Geneva, (IGBP Report 35/HDP Report 7) 132 pp.
The Science/Research Plan presents land-use and land-cover change and ties it to the overarching themes of global change. It briefly outlines what is currently known and what knowledge will be necessary to address the problem in the context of the broad agendas of IGBP and HDP. The three foci address by the plan are: (i) land-use dynamics, land-cover dynamics - comparative case study analysis, (ii) land-cover dynamics - direct observation and diagnostic models, and (iii) regional and global models - framework for integrative assessments.

No. 36

The IGBP Terrestrial Transects: Science Plan. Edited by G.W. Koch, R.J. Scholes, W.L. Steffen, P.M. Vitousek and B.H. Walker (1995). IGBP Secretariat, Stockholm, 53. pp. Also available in Chinese.
The IGBP Terrestrial Transects are a set of integrated global change studies consisting of distributed observational studies and manipulative experiments coupled with modelling and synthesis activities. The transects are organised geographically, along existing gradients of underlying global change parameters, such as temperature, precipitation, and land use. The initial transects are located in four key regions, where the proposed transects contribute to the global change studies planned in each region.

No. 37

IGBP Northern Eurasia Study: Prospectus for an Integrated Global Change Research Project. Edited by W.L. Steffen and A.Z. Shvidenko (1996). IGBP Secretariat, Stockholm, 95 pp. Also available in Russian.
This report was prepared by scientists representing BAHC, IGAC, and GCTE. It is a prospectus for an integrated hydrological, atmospheric chemical, biogeochemical and ecological global change study in the tundra/boreal region of Northern Eurasia. The unifying theme of the IGBP Northern Eurasia Study is the terrestrial carbon cycle and its controlling factors. Its most important overall objective is to determine how these will alter under the rapidly changing environmental conditions.

No. 38
Natural Disturbances and Human Land Use in Dynamic Global Vegetation Models. A report of a workshop co-convened by the GAIM, GCTE, LUCC, and IGBP-DIS Programme Elements of the IGBP. Edited by F.I. Woodward and W.L. Steffen (1997). IGBP Secretariat, Stockholm, 49 pp.
This report summarises the findings and recommendations of an International Geosphere-Biosphere Programme (IGBP) Workshop which aimed to develop an approach to modelling landscape-scale disturbances in the context of global vegetation change.

No. 39
Modelling the Transport and Transformation of Terrestrial Materials to Freshwater and Coastal Ecosystems. A workshop report and recommendations for IGBP Inter-Programme Element Collaboration. Edited by C.J. Vörosmarty, R. Wasson and J. Richey (1997). IGBP Secretariat, Stockholm, 84 pp.
This report is the major product of a three-day workshop entitled: "Modelling the Delivery of Terrestrial Materials to Freshwater and Coastal Ecosystems" held in Durham, NH, USA from 5-7 December 1994.

No. 40
Global Ocean Ecosystem Dynamics. Science Plan. Final editing by: R. Harris and the members of the GLOBEC Scientific Steering Committee (SSC) (1997). IGBP Secretariat, Stockholm, 83 pp.
Based on a draft plan written by the SCOR/IOC SSC for GLOBEC in 1994. That plan was itself based on a number of scientific reports generated by GLOBEC working groups and on discussions at the GLOBEC Strategic Planning Conference (Paris, July 1994). This document was presented to the Executive Committee of the Scientific Committee on Ocean Research (SC-SCOR) for approval (Cape Town, November 14-16 1995), and was approved by the SC-IGBP at their meeting in Beijing in October 1995. The members of the SCOR/IGBP CPPC were: B.J. Rothschild (Chair), R. Muench (Chief Editor), J. Field, B. Moore, J. Steele, J.-O. Strömberg, and T. Sugimoto.

No. 41
Causes and Consequences of Land Use and Land Cover Change in Central African Miombo Ecosystems: Strategy for an IGBP LUCC Miombo Network. Workshop Report. Edited by P.V. Desanker, P.G.H. Frost, C.O. Justice and R.J. Scholes (1997). IGBP Secretariat, Stockholm, 109 pp
This report describes a science and implementation plan for the Miombo Network Initiative, developed at an IGBP intercore-project workshop in Malawi in December 1995 and further refined during the LUCC Open Science Meeting in January, 1996.

No. 42
The Kalahari Transect: Research on Global Change and Sustainable Development in Southern Africa. Workshop Report. Edited by R.J. Scholes and D.B. Parsons with contributions from A. Kamuhuza, G. Davis, R. Ringrose, J. Gambiza, and E. Chileshe (1997). IGBP Secretariat, Stockholm, 61 pp
This report is the basis for the proposed Kalahari Transect proposed as one of the IGBPs Mega Transects.

No. 43

Predicting Global Change Impacts on Mountain Hydrology and Ecology: Integrated Catchment Hydrology/Altitudinal Gradient Studies. Workshop Report. Edited by A. Becker and H. Bugmann (1997). IGBP Secretariat, Stockholm, 61 pp.
This report is the result of a workshop on IGBP mountain research issues held in Kathmandu, Nepal, from 30 March to 2 April 1996.

No. 44

START Implementation Plan, 1997-2002. Edited by R. Fuchs, H. Virji, and C. Flemming (1998). IGBP Secretariat, Stockholm, 80 pp.
This report describes the Implementation of START (Global Change System for Analysis, Research and Training). START involves the establishment of a system of regional networks with particular emphasis on the developing regions. The primary mission of these networks is: (i) to conduct research on regional aspects of global change; (ii) to assess the impacts of the regional findings; and (iii) to provide regionally important integrated and evaluated information to policy-makers and governments. START's overall objective is to build, through regional research activities, a world-wide indigenous capacity to tackle the scientific and policy aspects of environmental changes and sustainable development.

No. 45

Past Global Changes (PAGES): Implementation Plan. Edited by F. Oldfield (1998). IGBP Secretariat, Stockholm, 236 pp.
This report summarizes progress made thus far by the Past Global Changes (PAGES) programme element of the IGBP. The document also outlines the implementation plans for most of the Foci, Activities and Tasks currently within the PAGES remit. The plan first introduces the scope and rationale of PAGES science and explains how PAGES is organized structually and scientifically to achieve its goals.

No. 46

Global Wetland Distribution and Functional Characterization: Trace Gases and the Hydrologic Cycle. Report from the joint GAIM/IGBP-DIS/IGAC/LUCC workshop. Edited by D. Sahagian and H. Melack (1998). IGBP Secretariat, Stockholm.
The IGBP Core Projects BAHC, LUCC and IGAC, in conjunction with Framework Activities GAIM and IGBP-DIS held a joint workshop to identify data and research needs for characterizing wetlands in terms of their role in biogeochemical and hydrologic cycles.

Book of Abstracts

Book of Abstracts. Natural and Anthropogenic Changes: Impacts on Global Biogeochemical Cycles. Asian Change in the Context of Global Change. Beijing, 23-25 October, 1995. IGBP Secretariat, Stockholm, 107 pp.
This book of abstracts is a result of materials presented at the scientific symposium held in conjunction with the Fourth Scientific Advisory Council for the IGBP (SAC) held in Beijing, 23-25 October, 1995.

IGBP Booklet*

A Study of Global Change (1989). Edited by IGBP Secretariat, Stockholm, 9pp.

Global Change: Reducing Uncertainties
Prepared by P. Williamson, with editorial assistance from the Scientific Committee for the IGBP (June, 1992; reprint August 1993), IGBP Secretariat, Stockholm, 40 pp.

IGBP Directory
IGBP Directory. No. 1, February 1994. Edited by IGBP Secretariat, Stockholm
IGBP Directory. No. 2, October 1995. Edited by IGBP Secretariat, Stockholm
IGBP Directory Update: 1996, April 1996. Edited by IGBP Secretariat, Stockholm
IGBP Directory 1997, February 1997. Edited by IGBP Secretariat, Stockholm
IGBP Directory 1998, February 1998. Edited by IGBP Secretariat, Stockholm

IGBP NewsLetter
Global Change NewsLetter. Quarterly, No. 1, 1989. Edited by IGBP Secretariat, Stockholm (latest issue No. 34, June 1998)

IGBP Science No. 1
The Terrestrial Biosphere and Global Change: Implications for Natural and Managed Ecosystems. A Synthesis of GCTE and Related Research. Edited by B. Walker and W. Steffen (1997). IGBP Secretariat, Stockholm, 31 pages.
This executive summary presents the major findings of the synthesis of the first six years of the Global Change and Terrestrial Ecosystem (GCTE) Core Project of the IGBP. It begins by identifying the major components and drivers of global change. It then outlines the important ecosystem interactions with global change, focusing on the functioning of ecosystems and the structure and composition of vegetation. The executive summary then discusses the implications of these ecosystem interactions with global change in terms of impacts in three key areas: managed production systems, biodiversity and the terrestrial carbon cycle. The full synthesis results and conclusions, with a complete reference list, are presented as a volume in the IGBP Book Series No. 4, published by Cambridge University Press (Walker *et al.* (In Press). Here key references only are included.