ZEF Bonn
Zentrum für Entwicklungsforschung
Center for Development Research
Universität Bonn

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Number

64

Global Inventory of Wetlands and their Role in the Carbon Cycle

ZEF – Discussion Papers on Development Policy
Bonn, March 2003

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Sudip Mitra, Reiner Wassmann, Paul L.G. Vlek: Global Inventory of Wetlands and their Role in the Carbon Cycle. ZEF – Discussion Papers On Development Policy No. 64, Center for Development Research, Bonn, March 2003, pp. 44.

ISSN: 1436-9931

Published by:
Zentrum für Entwicklungsforschung (ZEF)
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Contents

List of Tables

List of Figures

Acknowledgement

The generous financial, technical, and administrative support extended to Mr. Sudip Mitra by the Zentrum für Entwicklungsforschung (ZEF), University of Bonn, is kindly acknowledged. Our sincere thanks go to Professor Daniel Hillel for his critical review of this discussion paper. Special thanks go to the timely assistance of Jan Friesen and Jens Liebe.

Abstract

Wetlands are among the most important natural resources on earth, as sources of biological, cultural and economic diversity. Conservation and management of wetlands have been identified as priority tasks for action in international conventions and regional policies, but extensive wetland area has been degraded in many developing countries. These continuing destruction demands to be restricted or at least slowed down. The primary objectives of this study were (i) assessing ecological functions and concepts for sustainable use of wetlands and (ii) compiling relevant information sources on geographic distribution of wetlands as well as their role in the global carbon budget.

Wetlands comprise a pivotal global carbon reservoir and can moreover sequester additional carbon from the atmosphere in form of soil organic matter. Pristine wetland soils are a source of the greenhouse gas methane, but – under improper management – these soils emit even larger quantities of the greenhouse gas carbon dioxide. The discussion on wetland protection measures is thwarted by uncertainties in the estimated carbon pool sizes and flux rates. On the global scale, the estimates on the carbon pool size vary from 200 to 530 Gt C while our own assessment (by incorporating global soil maps) clearly points towards the lower end of this range. Likewise, estimates of the carbon sequestration potential of wetlands vary between 80 to 230 Tg C/ yr. These discrepancies may in part be due to inherent problems in global land cover surveys, but diverging definitions of the ecosystem 'wetlands' (especially in dealing with peatlands) are further confounding an appraisal of global wetland resources.

Similar uncertainties as for the global estimates arise for the geographic distribution of wetlands as described in different data sources. The three published world maps on wetland resources only coincide in 20-30 % of the identified wetland area. Our compilation of data on quantity and distribution of the wetland carbon pool allows an identification of potential 'hot spots' of future emissions and could feed into development of research and conservation projects. There are many reasons in favor of protection or a 'wise use' of wetlands that maintains the basic features of the ecosystem. The significance of wetlands for the global carbon budget and thus, for climate change, is a crucial pro-conservation argument that has been substantiated in this study through findings from current research.

Kurzfassung

Feuchtgebiete gehören als Grundlage für biologische, kulturelle und wirtschaftliche Vielfalt zu den wichtigsten Ressourcen der Erde. Der Schutz und das Management von Feuchtgebieten sind als vorrangige Aufgaben in internationalen Konventionen und im Rahmen regionaler Entwicklungsprogramme definiert worden, jedoch findet in vielen Entwicklungsländern eine großflächige Degradation der Feuchtgebiete statt. Die anhaltende Zerstörung der natürlichen Feuchtgebiete ruft nach Maßnahmen zur Begrenzung oder zumindest Verlangsamung. Die vorrangigen Ziele der hier vorgelegten Studie sind (i) Bewertung der ökologischen Funktionen und nachhaltiger Nutzungskonzepte für Feuchtgebiete sowie (ii) Zusammenstellung von relevanten Informationsquellen über geographische Verteilung der Feuchtgebiete sowie deren Rolle im Kohlenstoffhaushalt.

Feuchtgebiete stellen einen der wichtigsten globalen Kohlenstoffspeicher dar und können zudem noch weiteren Kohlenstoff in Form von bodenorganischem Material binden. Andererseits sind die Böden natürlicher Feuchtgebiete eine Quelle des Treibhausgases Methan, wobei diese Böden jedoch bei unsachgemäßer Bewirtschaftung große Mengen des Treibhausgases CO_2 freisetzten. Die Diskussion um konkrete Schutzmaßnahmen für Feuchtgebiete wird durch Unsicherheiten bei der Abschätzung des Speichervermögens und der Flußraten für Kohlenstoff erschwert. Die Abschätzungen der globalen Kohlenstoffspeicherung in Feuchtgebieten schwanken zwischen 200 und 530 Gt C, wobei nach unserer eigenen Bewertung (unter Einbeziehung von globalen Bodenkarten) eher der untere Bereich dieser Schätzbreite zutreffen sollte. In ähnlicher Weise streuen auch die Abschätzungen der globalen Kohlenstoffbindung durch Feuchtgebiete zwischen 80 und 230 Tg C/ yr. Neben den inhärenten Problemen bei derartigen Abschätzungen im globalen Maßstab tragen unterschiedliche Definitionen des Ökosystems "Feuchtgebiet" (insbesondere bei der Behandlung von Torfböden) zu den großen Bandbreiten dieser Schätzung bei.

Auch hinsichtlich der geographischen Verteilung der Feuchtgebiete gibt es Diskrepanzen zwischen den verschiedenen Datenquellen. Die drei publizierten Weltkarten über Feuchtgebeite stimmen nur in 20-30 % der angegebenen Flächen mit Feuchtgebieten überein. Unsere Daten-Zusammenstellung über Menge und Verteilung der Kohlenstoffvorräte in Feuchtgebieten erlaubt die Bestimmung von potentiellen 'hot spots' der zukünftigen Emissionen und kann daher für die Entwicklung von Forschungs- und Schutzprojekten genutzt werden. Es gibt viele Gründe, für den Erhalt bzw. eine möglichst umweltverträgliche Nutzung von Feuchtgebieten einzutreten. Die Bedeutung der Feuchtgebiete für den globalen Kohlenstoffhaushalt und damit für globale Klimaänderungen ist hierbei ein ganz entscheidendes Argument, welches in dieser Studie mit konkreten Zahlen entsprechend dem aktuellen Forschungsstand belegt wurde.

1 Introduction

Ten years after 1992 Rio Earth Summit, the World Summit on Sustainable Development (WSSD) held in Johannesburg in 2002 was a major effort to focus the world's attention and direct action toward better implementation of Agenda 21. The WSSD 2002 brought together thousands of participants, including heads of states, national delegates and leaders from non-governmental organizations (NGOs), businesses and other major groups. This World Summit has correctly set the ground for the conservation and management of natural resources. Wetlands constitute important natural resources on earth and are sources of cultural, economic and biological diversity. This has been well recognised by various governments, scientists and policy makers (de Groot, 1992). Conservation and management of wetlands have been identified as a priority area for action in international conventions and regional policies. The Ramsar Convention, held in Iran in 1971 deals explicitly with wetland conservation is the oldest of the global intergovernmental environmental conventions. The Ramsar Convention on Wetlands provided the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources. There are presently 114 Contracting Parties to the Convention, with 977 wetlands sites, totalling 71 million hectares, designated for inclusion in the Ramsar List of Wetlands of International Importance.

Other conventions followed suit that directly or indirectly addressed the role of wetlands in the global environment from very different angles:

- Convention on Biological Diversity
- Convention on Migratory Species
- World Heritage Convention
- Convention to Combat Desertification (UNCCD) and
- UN Framework Convention on Climate Change (UNFCCC).

Despite these priorities and frameworks for action, however, many natural wetlands and the species, what depend on them continue to be threatened or degraded through a variety of human actions, both direct and indirect (Dugan, 1994). There is a strong need to increase awareness of the values of wetlands resources (Finlayson & van der Valk, 1995), especially among national and international decision-makers.

Wetlands can be found in all climate zones ranging from the tropics to the tundra regions (Antarctica is the only continent on Earth that has no wetlands). Although wetlands occupy only 4–6 percent of the Earth's land area (~530–570 Mha) (Matthews and Fung, 1987; Aselmann and Crutzen, 1989), they store a substantial amount of carbon. However, the actual quantity of carbon stored in wetlands can only be estimated within a broad range of uncertainty. Gorham (1995) for example, estimated that wetlands contain 350–535 Gt C, corresponding to 20–25 percent of the world's organic soil carbon. Irrespective of the precise quantities, these labile carbon reservoirs pose a major threat to an acceleration of the greenhouse effect (caused by a variety of anthropogenic sources) when released to the atmosphere.

Wetland destruction ultimately releases carbon to the atmosphere. Although the major cause for increasing CO_2 levels in the atmosphere is burning of fossil fuel, wetland destruction poses a potential threat for accelerating this greenhouse effect (Maltby et al., 1992). Undisturbed wetlands often function as active sinks of carbon, although they also emit the greenhouse gas methane in substantial quantities (Fung et al., 1991). A better understanding of the mechanisms responsible for the large fluctuations in wetland areas over the last glacial-interglacial cycle is necessary (Petit et al., 1999; Chappellaz et al., 1997).

Wetlands not only store water but also improve water quality, as shown, for example, by management action in the Chowilla floodplain in Australia (Phillips & Sharley, 1993). Wetlands can also be helpful in purifying wastewater from cities as observed, for another example in Calcutta, India (Ghosh, 1993). Maintaining the ecological role wetlands is an important step towards regulating the water management activities, which contribute to the GNP as well as the livelihood of local people.

There is no dearth of information about wetlands resources and their management, but that information is scattered in a variety of sources in incompatible formats. Hence it is difficult to obtain comprehensive and reliable information on the state and/or the management of global wetlands resources. The lack of accurate knowledge on the location, area, distribution and condition of wetlands makes it more difficult standardize a management plan or policy or to set management priorities. Because of uncertainties and lack of consensus regarding the purpose and use of wetlands inventories, the information available is too fragmented for broader uses or users. The scattered nature of wetlands inventories does not allow identifying the gaps that exist in the available inventories. An accurate assessment of the size and distribution of the global wetlands resources and the patterns of their change has become increasingly difficult to obtain (Finlayson & van der Valk, 1995).

The first objective of this study was assessing ecological functions and concepts for sustainable use of wetlands. This goal required a clarification of inherent problems in wetland definitions as well as a comprehensive overview on the role of wetlands in the environment. The second objective was compiling relevant information sources on both, geographic distribution of wetlands and their role in the global carbon budget.

PART A: CHARACTERIZATION OF GLOBAL WETLANDS RESOURCES

2 Definition and Classification of Wetlands

'Wetlands' is a generic term commonly used for habitats like marshes, swamps, bogs, fens, etc. Thus, this term is primarily descriptive of the overall condition of the land, but it has also been used with a variety of connotations depending on the discipline of the respective author and the context of the specific topic. For some, the term wetlands has been a euphemism for "swamp" and has therefore evoked negative feelings due to its usage in literature and everyday speech (National Research Council, 1995). Basically all concepts of wetlands imply the existence of a characteristic vegetation, which serve as a criterion for classifying a habitat as a wetland (Environment Protection Agency, 1993).

The term 'peatland' is often used as a synonym for wetlands, but this term has no consistent definition. The ambiguity in the concepts of peatland directly affects the varying estimates of soil organic carbon in wetlands soils. One common definition for peat is a pure organic layer at least 20 cm in thickness, and this definition was used in widely cited studies by Post et al., (1982) and Zinke et al., (1984). Quite another example is the study of Canadian peatland areas by Tarnocai (1980), who defined peatlands as having an organic matter layer greater than 40-cm, and mineral wetlands as having an organic matter layer of less than 40- cm. One of the most wide-ranging studies of northern peatlands was conducted by Gorham (1991), who used a minimum figure of 30-cm organic matter to distinguish between peat and non-peat. As yet, there is no sign of a true consensus among various investigators. Moreover, peatland concepts should distinguish latitudinal gradients in the properties of boreal, temperate and tropical peatlands. At present, the characterization of tropical peatlands is even less substantiated than for the others types (Walter, 1971; Radjagukuk, 1985).

2.1 Ramsar's Wetlands Definition

Wetlands have been defined variously in several countries by scientists and natural resource agencies interested in specific functions of wetlands, e.g. habitats for water birds, animals and potential land uses, etc. This profusion of definitions has prompted the Ramsar Convention (1971), an intergovernmental treaty on worldwide wetlands conservation, to work out an agreed definition as follows: Wetlands are "*areas of marsh, fen, peat land, or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish, or salty, including areas of marine water the depth of which at low tide does not exceed six meters".* In fact, the Ramsar definition goes beyond the areas actually considered as wetlands to "*incorporate riparian and coastal zones adjacent to wetlands"* and also efforts to capture *"islands or bodies of marine water deeper than 6 m at low tide lying within the wetlands*" as part of the wetland continuum (Ramsar Information Bureau, 1998).

This definition is very broad, extending both, area and water depth beyond the previous concepts of "deepwater habitats". The definition includes man-made wetlands such as Fish and shrimp ponds, farm ponds, irrigated agricultural land (e.g., rice paddies); saltpans, reservoirs, gravel pits, sewage farms, and canals (Ramsar Information Bureau, 1998). Though widely accepted in the political arena, the Ramsar definition has triggered some criticism of being too embracing.

A plethora of wetlands definitions has been developed based on different areas of expertise or interest – and it seems unlikely that these different wetlands concepts will ever be reconciled. Current wetlands definitions are largely based on biological principles, since professionals in wildlife biology and botany were among the first to recognize the values that wetlands in their unaltered state contribute to society (Tiner, 1999).

2.2 Wetlands Classification

A classification system is an essential prerequisite for obtaining an inventory (Finlayson and van der Valk, 1995) capable of encompassing the diversity of wetland types. Just as with wetlands definitions, various classification systems have been developed independently by different institutions and authors. The Ramsar Classification System for Wetlands Type (Ramsar Convention Bureau, 1997) has attained global dissemination and is used by over one hundred signatory countries to the Ramsar Convention. Despite this broad-scale application, its usefulness for inventory purposes appears limited (Costa et al., 1996).

2.2.1 Ramsar Classification of Wetlands Types

The Ramsar Classification of Wetlands Type currently in use was adopted by the Conference of the Parties in 1990. It divides wetlands into three main categories, namely: marine and coastal wetlands, inland wetlands, and man-made wetlands. The categories have further subdivisions, which give a total of 40 wetlands types. The Ramsar classification was initially developed as a simple tool for describing Ramsar sites. It also serves as a broad framework to aid rapid identification of the main wetlands habitats represented at each site, and to provide units for mapping and comparability of concepts and terms in national or regional wetlands inventories. It should be stressed that the Ramsar classification (Table 1) is suited for use at a broad domain of wetlands and it has always been recognized that more detailed but compatible systems may be needed at regional or national levels for complex integrated-planning activities.

Through the use of this broad classification system, and in conjunction with other data, the Convention can identify globally threatened wetlands types and types those are under-represented in the List of Wetlands of International Importance. This allows the opportunity to focus attention on those wetlands types and the threats they face.

Table 1: The Ramsar Convention's Wetlands Classification System

Marine and Coastal wetlands	Inland wetlands	Man-made/intensively farmed or grazed wetlands
A - Permanent shallow marine waters less than six meters deep at low tide; includes sea bays and straits.	*Tp - Permanent freshwater marshes/pools; ponds (below 8 ha), marshes and swamps on inorganic soils; with emergent vegetation water-logged for at least most of the growing season.*	*1 - Aquaculture (eg. fish/shrimp) ponds*
B - Marine subtidal aquatic beds; includes kelp beds, sea-grass beds, tropical marine meadows.		
C - Coral reefs.		*2 - Ponds; includes farm ponds, stock ponds, small tanks; (generally below 8 ha).*
D - Rocky marine shores; includes rocky offshore islands, sea cliffs.		
E - Sand, shingle or pebble shores; includes sand bars, spits and sandy islets; includes dune systems.	*Ts - Seasonal/intermittent freshwater marshes/pools on inorganic soil; includes sloughs, potholes, seasonally flooded meadows, sedge marshes.**	*3 - Irrigated land; includes irrigation channels and rice fields.*
F - Estuarine waters; permanent water of estuaries and estuarine systems of deltas.		
G - Intertidal mud, sand or salt flats.		
H – Salt marshes; includes salt meadows, saltings, raised salt marshes.	*U - Non-forested peatlands; includes shrub or open bogs, swamps, fens.*	*4 - Seasonally flooded agricultural land.*
I - Intertidal forested wetlands; includes mangrove swamps, nipa swamps and tidal freshwater swamp forests.	*Va - Alpine wetlands; includes alpine meadows, temporary waters from snowmelt.*	*5 - Salt exploitation sites; salt pans, salines, etc.*
J - Coastal brackish/saline lagoons; brackish to saline lagoons with at least one relatively narrow connection to the sea.		
K - Coastal freshwater lagoons; includes freshwater delta lagoons.	*Vt - Tundra wetlands; includes tundra pools, temporary waters from snowmelt.*	*6 - Water storage areas; reservoirs/barrages/dams /impoundments; (generally over 8 ha).*
L - Permanent inland deltas.		
M - Permanent rivers/streams/creeks; includes waterfalls.	*W - Shrub-dominated wetlands; Shrub swamps, shrub-dominated freshwater marsh, shrub carr, alder thicket; on inorganic soils.*	*7 - Excavations; gravel/brick/clay pits; borrow pits, mining pools.*
N - Seasonal/intermittent/irregular rivers/streams/creeks.		
O - Permanent freshwater lakes (over 8 ha); includes large oxbow lakes.	*Xf - Freshwater, tree-dominated wetlands; includes freshwater swamp forest, wooded swamps; on inorganic soils.*	*8 - Wastewater treatment areas; sewage farms, settling ponds, oxidation basins, etc.*
P - Seasonal/intermittent freshwater lakes (over 8 ha); includes floodplain lakes.		
Q – Permanent saline/brackish/alkaline lakes.		
R - Seasonal/intermittent saline/brackish/alkaline lakes.	*Xp - Forested peatlands; peatswamp forest.*	*9 - Canals and drainage channels, ditches.*
Sp - Permanent saline/brackish/alkaline marshes/pools.		
Ss - Seasonal/intermittent saline/brackish/alkaline marshes/pools.	*Y - Freshwater springs; oases.*	*0- No information*

2.2.2 The Cowardin System

The system successfully used by the United States National Wetlands Inventory for almost twenty years, known as the Cowardin System (Cowardin et al., 1979), is widely regarded as being one of the most comprehensive and versatile wetlands classification systems (Finlayson and van der Valk, 1995). More recently, the Cowardin system was refined to produce a Habitat Description System (Farinha et al., 1996) for application in an inventory of wetlands in the Mediterranean basin. The two most known and widely used wetlands classification systems are the Cowardin Classification System and the Ramsar Classification System:

The structure of the Cowardin System is quite different from almost all previous wetlands classification systems. This classification system is based on the determinants of wetlands diversity rather than the needs of a particular group of users. The Cowardin System is hierarchical and consists of several layers of detail for wetlands classification, including: a subsystem of water flow; classes of substrate types; subclasses of vegetation types and dominant species; as well as flooding regimes and salinity levels for each system. This system is appropriate for an ecologically based understanding of wetlands definition. The Cowardin System was designed for inventory purposes, and to be of equal use in decision-making involving wetlands conservation, management, and utilization. The following is a brief description of the major classes of wetlands under the Cowardian System.

<u>Marine</u>: Open ocean overlying the continental shelf and coastline exposed to waves and currents of the open ocean shoreward to (1) extreme high water of spring tides; (2) seaward limit of wetlands emergent plants, trees, or shrubs; or (3) the seaward limit of the Estuarine System, other than vegetation. Salinities exceed 30 parts per thousand.

<u>Estuarine</u>: Deepwater tidal habitats and adjacent tidal wetlands that are usually semi-enclosed by land but have open, partly obstructed, or sporadic access to the ocean, with ocean water at least occasionally diluted by freshwater runoff from the land. The upstream and landward limit is where ocean-derived salts measure less than .5 parts per thousand during the period of average annual low flow. The seaward limit is (1) an imaginary line closing the mouth of a river, bay, or sound; and (2) the seaward limit of wetlands emergent plants, shrubs, or trees when not included in (1).

<u>Riverine</u>: All wetlands and deepwater habitats contained within a channel except those wetlands (1) dominated by trees, shrubs, persistent emergent plants, and (2) which have habitats with ocean-derived salinities in excess of 0.5 parts per thousand.

<u>Lacustrine</u>: Wetlands and deepwater habitats (1) situated in a topographic depression or dammed river channel; (2) lacking trees, shrubs, persistent emergent plants with greater than

30% aerial coverage; and (3) whose total area exceeds 8 hectares (20 acres); or area less than 8 hectares if the boundary is active wave-formed or bedrock or if water depth in the deepest part of the basin exceeds 2 m (6.6 ft) at low water. Ocean-derived salinities are always less than 0.5 parts per thousand.

Palustrine: All nontidal wetlands dominated by trees, shrubs, persistent emergents, emergent mosses, or lichens, and all such tidal wetlands where ocean-derived salinities are below 0.5 ppt. This category also includes wetlands lacking such vegetation but with all of the following characteristics: (1) area less than 8 ha; (2) lacking an active wave-formed or bedrock boundary; (3) water depth in the deepest part of the basin less than 2 m (6.6 ft) at low water; and (4) ocean-derived salinities less than 0.5 parts per thousand. A palustrine system can exist directly adjacent to or within the lacustrine, riverine, or estuarine systems.

2.3 Carbon Cycling in Different Wetlands Classes

Wetlands are a major carbon sink (IPCC, 2001). While vegetation traps atmospheric CO_2 in wetlands and other ecosystems alike, the net-sink of wetlands is attributed to low decomposition rates in the anaerobic soils. Many riverine, estuarine, and coastal wetlands also trap large quantities of sediment from natural and anthropogenic watershed sources which adding to the carbon accumulation.

Carbon fluxes and pool sizes vary widely in different wetlands. Wetlands like coastal flats and playas have sparse vegetation, resulting in limited carbon turn-over; whereas salt marshes have high primary productivity matching tropical forests. Depending upon a variety of interrelated factors (such as temperature, water levels, flow of water and nutrients), the rate of decomposition varies within a wetlands area over time and space. Litter, peat, and carbon rich sediments may be quickly removed from some coastal wetlands by frequent coastal storms; flood flows and other physical processes. In contrast, organic matter in bogs may remain undisturbed for hundreds or thousands of years.

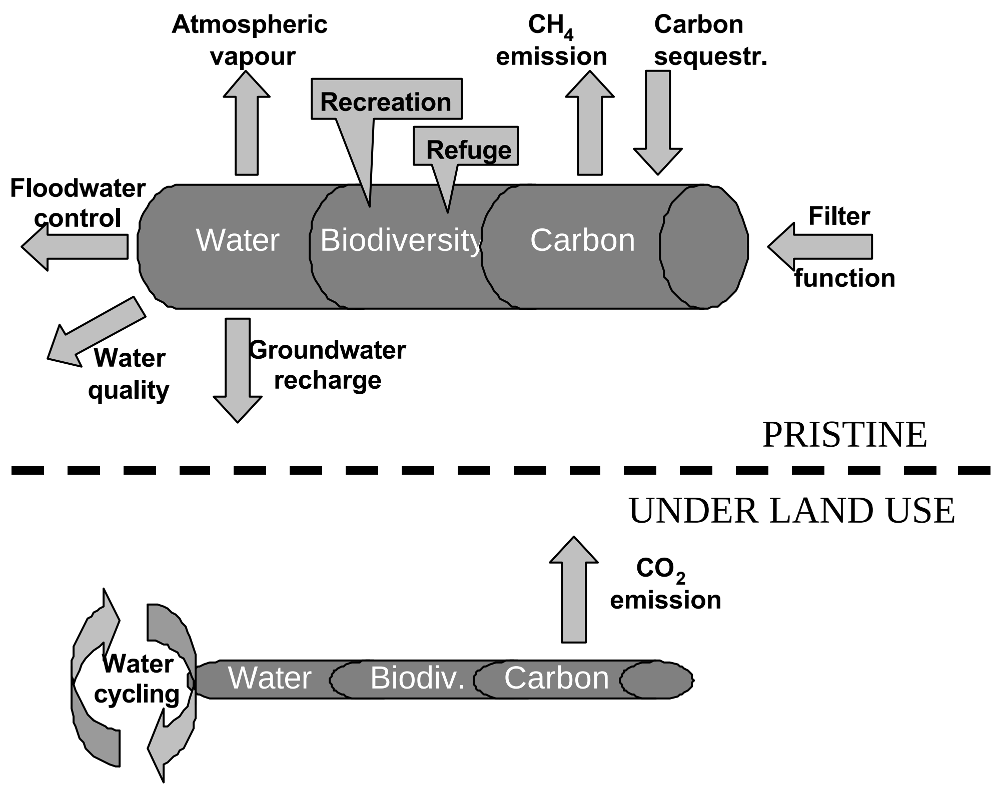
Various factors (viz. ground water levels, temperature, substrate availability, nutrient levels, and microbial populations) affect the decomposition rate and hence, carbon sequestration. Though wetlands are globally a major sink for carbon, releases of carbon dioxide may exceed photosynthesis in some circumstances. Moreover, wetlands emit large amounts of methane, an even more potent GHG than CO_2. Natural wetlands are the largest natural source of methane release to the atmosphere, accounting for ~ 20% of the current global emission of ~450-550 Tg (10^{12} g) (Khalil and Rasmussen, 1983; Fung et al., 1991; Houghton et al., 1996). An internal cycling could be observed in the carbon budget of wetlands. Larger amounts of methane are produced from the lower levels of peat (catotelm) while the upper levels (acrotelm) produce carbon dioxide and at least partially oxidize methane released from the lower levels (Kusler, 1999).

3. Functions and Values of Wetlands

People often view wetlands as wasteland. Wetlands are sometimes drained and filled for development; others are polluted from dumping. But ecologists and others are beginning to deliver the message that wetlands are some of the most biologically productive ecosystems on earth, (Tiner, 1989), comparable to rain forests and coral reefs. An immense variety of species of microbes, plants, insects, amphibians, reptiles, birds, fish, and mammals can be part of a wetlands ecosystem.

Although the terms 'function' and 'value' of wetlands are often used interchangeably, they connote different meanings. Wetlands ‘functions’ are the physical, chemical, and biological processes that characterize wetlands ecosystems (Figure 1). Wetlands ‘values’ are estimates, usually subjective, of worth, merit, quality, or importance (Richardson 1994). Wetlands values may be derived from outputs that can be consumed directly, such as food, recreation, or timber; indirect uses which arise from the functions occurring within the ecosystem, such as water quality and flood control; possible future direct outputs or indirect uses such as biodiversity or conserved habitats; and the knowledge that such habitats or species exist (Figure 1; known as existence value) (Serageldin, 1993). Costanza et al., (1997) estimated the total global value of services provided by coastal areas and wetlands ecosystems to be 15.5 trillion US$ per year, being 46% of the total value of services that global ecosystems are estimated to provide.

Figure 1: Schematic View of the Role of Wetlands in the Environment



3.1 Functions of Wetlands

3.1.1 Water Storage and Ground Water Recharge

The water storage capacity of wetlands can help to reduce peak water flows after a storm by slowing the movement of water into tributary streams, thus allowing potential floodwaters to reach rivers over a longer period of time. The extent of ground water recharge by a wetland depends upon soil, vegetation, site, perimeter-to-volume ratio, and water table gradient (Carter and Novitzki, 1988; Weller, 1981). Wetlands facilitate the flow of water between the ground-water system and the surface-water system.

3.1.2 Flood Control

Wetlands play a pivotal role in controlling floods. Wetlands help to lessen the impacts of flooding by absorbing water and reducing the speed at which floodwaters flow. Upstream wetlands can serve to store floodwaters temporarily and release them slowly downstream following their natural paths. If those pathways are altered or blocked, floodwaters may damage property and threaten public safety. Along part of the main stream of the Charles River in the USA, 3,800 hectares of wetlands have been valued at US$ 17 million per year, which is the estimated cost of flood damage that would result if they were drained (Ramsar, 2001). Flood protection may be especially important in urban settings and areas with steep slopes, overgrazing, or other land features that tend to increase storm water amounts and velocity. These functional values can provide economic benefits to downstream property owners (EPA, 2002). Without wetlands as a natural flood control mechanism, flooding can become more severe.

3.1.3 Shoreline Stabilization

The state of the physicochemical characteristics of a stream and other high quality waterways often depends on shoreline wetlands. By stabilizing soil, encouraging sediment deposition, and dampening the effects of wave action, the vegetation found in wetlands along the coast, around lakes and along the shorelines of rivers and streams helps to control erosion and hold sediment in place (Ramsar 2001).

3.1.4 Water Quality Control

Wetlands can improve water quality by removing pollutants from surface waters (Ramsar 2001). Three pollutant removal processes provided by wetlands are particularly important: sediment trapping, nutrient removal, and chemical detoxification (Department of Environmental Conservation, 1999).

3.1.5 Climate Effects

Apart from their effect on global climate (see chapter 9), wetlands also exert an impact on local/regional climate. Many wetlands return over two-thirds of their annual water inputs to the atmosphere through evapo-transpiration (Richardson and McCarthy 1994). The extreme temperature of the neighboring uplands might also be restrained by the presence of wetlands (Brinson 1993).

3.1.6 Community Structure and Wildlife Support

The wildlife community and the functioning of wetlands as suitable habitat are greatly affected by the shape and size of the wetlands (Kent 1994; Brinson 1993; Harris 1988). Shape is also important for the possibility of animal movement within the habitat and between habitats.

3.2 Values of Wetlands

3.2.1 Recreational and Aesthetic Value

Wetlands provide consumptive uses such as fishing and hunting; as well as non-consumptive uses such as swimming, boating, bird-watching, and hiking that do not remove or alter the wetlands resources. In addition to their recreational and aesthetic values, wetlands can also provide economic gains. Many wetlands are major attractions for tourism. Some of the finest wetlands are protected as National Parks, World Heritage Sites, Ramsar sites, or Biosphere Reserves. Many wetlands sites generate considerable income locally and nationally (Ramsar, 2001).

3.2.2 Water Supply and Quality

A major role is played by the wetlands in regulating the movement of water within watersheds as well as in the global water cycle (Richardson 1994; Mitsch and Gosselink, 1993). Wetlands play a key role in recharging the underground aquifers that store 97% of the world's unfrozen freshwater (Ramsar, 2001). To billions of people, groundwater is the only source of drinking water and for many a valuable source irrigation water. Groundwater recharge of up to 20% of wetlands volume per season has been observed (Weller, 1981). Several types of wetlands could be useful for their buffering capacity as an alternative to expensive technical measures for regulating the quantity of water flow. Various wetlands aquatic plants also act as purifiers that screen out several toxins and excess nutrients from the soils and water. Wetlands are immensely important in sustaining the quantity and the quality of water supplies.

3.2.3 Biodiversity Values

Wetlands are among the most productive ecosystems in the world (Mitsch and Gosselink, 1993). Wetland ecosystems include a wide diversity of species (McAllister et al., 1997). Even though only 1% of the Earth's surface is covered by the freshwater wetlands ecosystem, they hold more than 40% of the world's species, among which are 12% of all animal species (Ramsar, 2001). Wetlands provide habitat and nurture a plethora of varieties of plants, insects, amphibians, reptiles, birds, fish, microbes and other forms of wildlife. Flora and fauna available in various types of wetlands play a critical role in the pharmaceutical industry, as 80% of the world's population depend on traditional medicines for primary health care (Ramsar, 2001).

4. Wetlands Management and the Wise Use Concept

Degradation on a massive scale has already occurred in global wetlands ecosystems of immense importance. Measures must be taken to stop this progressive loss and degradation. Conservation measures must be initiated in making the wise use of wetlands and of the biological and economic wealth they support. The Ramsar Convention on Wetlands provides the framework for such action. In 1987, during the Ramsar meeting of the Conference of the Contracting Parties in Regina, the 'wise use' concept was defined as follows: "The wise use of wetlands is their sustainable utilization for the benefit of mankind in a way compatible with the maintenance of the natural properties of the ecosystem, and 'sustainable use' of a wetlands refers to the human use of a wetlands so that it may yield the greatest continuous benefit to the present generation while maintaining its potential to meet the needs and aspirations of future generations".

The main principle underlying the wise use concept is that the contracting parties should work towards the formulation of a national wetland policy and then try to integrate that in the national planning process. The guidelines to the wise use principle that member states ought to follow in the process of formulating their National Wetlands Policies include the following actions:

- to address legislation and government policies (such as a review and harmonization of existing legislation);
- to increase knowledge and awareness of wetlands and their values; to review the status of, and priorities for, wetlands; and
- to address problems at particular wetlands sites (Davis, 1994).

While countries like Australia, Canada and Uganda already have such policies in place, several others are in the process of formulating policies or have incorporated wetlands conservation concerns in National Biodiversity Strategies or in National Environmental Action Plans as measures to protect wetlands from degradation and/or loss. A proper integration of local and traditional agro-ecosystems addressing poor farmer's interests along with sustainable management of wetlands is the key for a successful wise use planning of wetlands. Cultural factors other than yields and economic profitability are equally important in determining the sustainable productivity of agricultural systems. A participatory approach bringing together all stakeholders is the key to successful wetland management.

More rapid dissemination of the available information on soil, plant, water and existing aquatic wetland communities could drastically reduce the risk of wetlands loss and lead to a more sustainable management plan. Geo-referenced (i.e. location-specific) data on topography, landform, soil, climate, water availability and use, water quality, land use and cover, arable land, land suitability, land productivity, population, incidence of diseases, infrastructure, land tenure, etc.– all these could assist in planning the wise use of wetlands. Remote sensing and GIS could be helpful in characterizing and mapping the changes in wetland use and its natural conditions. A precise appraisal of wetland resources and losses could be useful in devising risk-avoiding measures and in making wiser use of wetlands resources and maintaining its rich biological diversity. Effective cooperation in the assessment of wetlands use will only take place when the collated knowledge and information becomes accessible and usable for all stakeholders.

5. Wetlands Affected by Climate Change

The relationship between climate change and the conservation and wise use of wetlands is becoming increasingly important, yet not enough attention has been given to it by politicians and decision makers. The projected changes in climate are likely to affect the extent, distribution and nature of wetlands' functions significantly. The rise of nearly 0.6 degrees Celsius during the last century is quite small compared to the projected temperature rise of 1.4 – 5.8^{o}C over the next century (IPCC, 2001). Even the lower figure in that range would be more than double the increase of the last century. The upper-end projection of 5.8 degrees Celsius would be nearly 10 times as great (IPCC, 2001). The IPCC further projects that during this century sea level will rise from 0.1-0.9 m (IPCC,2001). Rise in sea level is likely to result in shifts in species compositions, a reduction of wetlands and productivity function (Warren and Niering, 1993). Increasing temperatures, changes in precipitation, and sea-level rise, are the main aspects of climate change that will affect wetlands distribution and function. At the same time, wetlands represent important carbon stores and contribute significantly to the global carbon cycle (Patterson, 1999). It has become necessary to consider how land use change and climate change may affect the role of wetlands in the global carbon cycle. Increases in temperature, sea-level rise, and changes in precipitation degrade the natural resources and services provide by the wetlands. The range of change in precipitation from pre-industrial levels is for example, estimated, for North America to be + /– 20% for precipitation, +/– 10% for evaporation and +/ – 50% for runoff (Frederick, 1997). The adaptation ability of wetlands ecosystems will be undoubtedly depend on the rate and extent of these changes.

High dependency on water levels makes wetlands specially vulnerable to changes in climatic conditions that affect water availability. Any changes in the hydrological cycle, rainfall pattern, and temperature will affect both surface and groundwater systems, domestic water supply, irrigation, hydropower generation, industrial use, navigation, and water-based tourism. It is projected that the demand for water will increase practically everywhere during the coming decades. However, climate change is expected to lead to a decrease in water availability, especially in arid and semi-arid areas. Wetlands play a pivotal role in recharging aquifers in the arid and semi arid regions of the world. For example, a dramatic decline in the surface of Chad Lake has been observed since 1960s as a result of less rainfall and discharge of water from Chari Rivers (Talling and Lamoalle, 1998). Impacts of climate change on wetlands are still poorly understood and are often not included in global models of climate change effects (Clair et al., 1998). The diverse nature of wetlands makes it all the more difficult to assess its relation to climate change more precisely. Increase in sea level might shift wetlands systems inland. The freshwater supplies from coastal wetlands might well be affected by the higher sea levels and the intrusion of salty water (Frederick, 1997).

Climate change may also affect the role of wetlands as a sources and sinks of greenhouse gases, which represent one of the most important feedback processes of climate change. Greenhouse gas emission and carbon sequestration in wetlands will be elaborated in chapter 9, which also addresses the possible impact of temperature on these processes. As a result of increased temperature, the permafrost might melt and ultimately lead to reduced carbon storage and sequestration by the wetlands. The uncertainty regarding the impact of climate change on carbon cycling in peatlands is considerable because of the spatial diversity, their different positions in the landscape, and the great variation within a single peatland (Moore et al., 1998).

PART B: WETLANDS AS GLOBAL CARBON RESERVOIRS

6. Wetlands Inventory: Relevant Databases

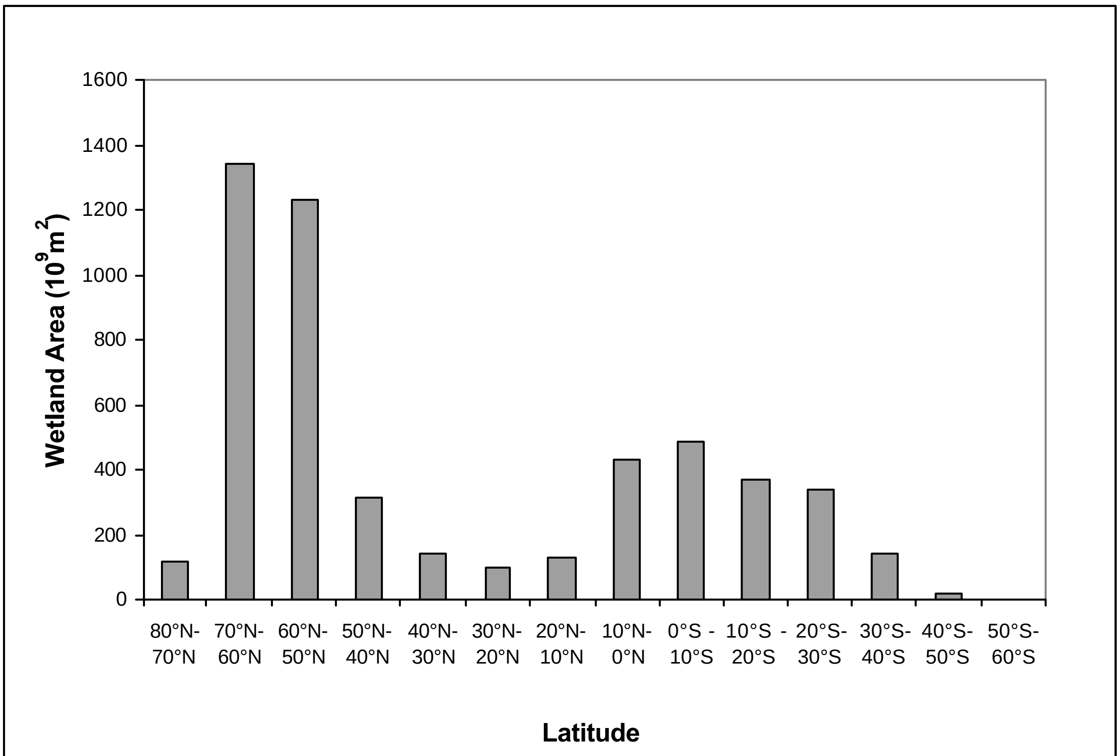
6.1 Global Wetlands Distribution

6.1.1 Matthews Natural Wetlands Database

E. Matthews from NASA/ Goddard Institute of Space Studies has produced (in part in collaboration with I. Fung) a series of files presenting the global coverage of wetlands (see http://www.giss.nasa.gov/data/landuse). These files were developed by combining vegetation, soil and inundation maps to show the distribution and environmental characteristics of naturally occurring wetlands (see Table 2). One of these maps is shown in Figure 2, displaying the geographical distribution of 5 wetlands classes; another wetlands attribute given in another file pertains to the fractional inundation of each wetlands pixel.

In the Matthews data base, about one –half of the total wetlands area lies between 50^o and 70^o N (Figure 2). This high latitude belt is characterized by peat-rich ecosystems such as bogs and fens (Figure 3). About 35% of the global wetlands area are broadly distributed in the latitudinal zone extending from 20^{o}N to 30^{o}S. This belt is co-dominated by forested and non-forested swamps and marshes, with a smaller contribution from alluvial or floodplain formations.

Figure 2: Latitudinal Distribution of Wetland Areas from Matthews Database



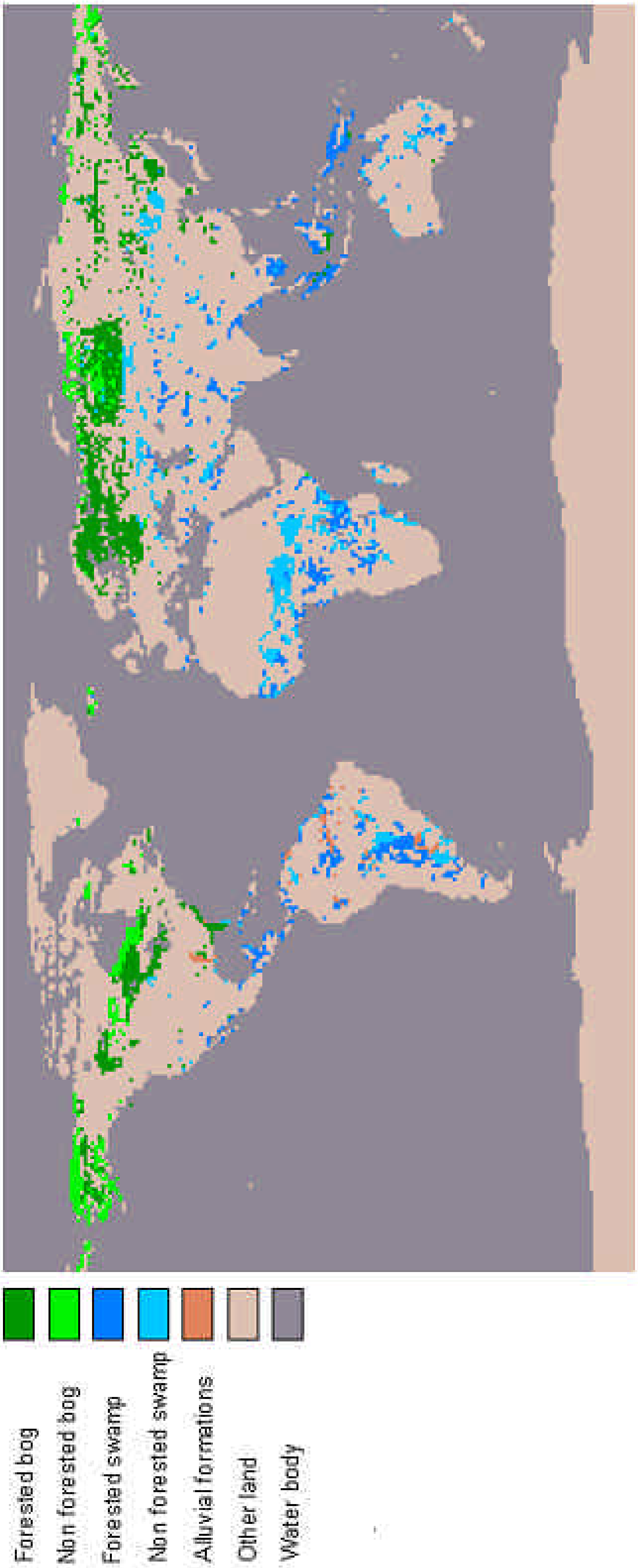


Figure 3: Global Distribution of Wetland Vegetation Types in Matthews and Fung's (1987) Database

Table 2: Characterization of Wetlands Databases

	Matthews and Fung	ISLSCP[1]	DIScover[2]	Ramsar
Resolution	1°	1°	1°	1°
Primary data sources	1) Vegetation: Unesco vegetation map, 2) Soil properties: Zobler (1986) 3) Inundation: Operational Navigation Charts	Published maps by J.G. Cogley (Trent University) providing areal coverage of different hydrological terrains (19 total)	1-km-resolution Advanced Very High Resolution Radiometer (AVHRR) data spanning April 1992 through March 1993	Geographical coordinates of 950 'Ramsar' wetlands
Attributes Given	a) Wetlands types (5 or 12 total) b) Percentage of cell area covered by wetlands	Percentage of cell area covered by wetlands	Land cover classes (17 total) incl. 'permanent wetlands'; percentage of cell area covered by wetlands	Name, date of designation, area (in hectares), percentage of cell area covered by wetlands, and geographical coordinates
Wetlands area (Mha)	520	467	127	(non-exhaustive)
Documentation	http://www.giss.nasa.gov/data/landuse	http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/ISLSCP/	http://edcdaac.usgs.gov/glcc/glcc.html http://ceos.cnes.fr:8100/cdrom-00b2/ceos1/casestud/igbp/wp193.htm	http://www.wetlands.org/RDB/global/Allsites.html

[1] ISLSCP = International Satellite Land Surface Climatology Project
[2] DIScover = The IGBP-DIS global 1 km land cover data set

6.1.2 The ISLSCP Database

The ISLSCP (International Satellite Land Surface Climatology Project) database was derived from hydrological maps compiled by by J.G. Cogley at Trent University. The Cogley data set provides global coverage (1^{o} resolution) of different hydrological terrains (19 total) and was used by Darras et al. (1999) for classifying wetlands into swamps, marshes, salt mashes, salt flats, and other wetlands. The wetlands area identified by ISLSCP is fairly homogeneously distributed over the continents with a higher concentration in Europe and Asia.

6.1.3 DISCover Database

IGBP/DIS (International Geosphere-Biosphere Programme/ Data Information System) has evaluated AVHRR (Advanced Very High Resolution Radiometer) data to compile a data base on global land cover. Thus, DIScover is a genuinely remote sensing data base whereas the other data bases were derived from maps as primary data sources (Table 2). Wetlands are determined as pixels with a permanent mixture of water and herbaceous or woody vegetation. Accordingly, seasonal wetlands are not represented in DISCover. DISCover database results in smaller wetlands areas than in Matthews and ISLSCP data, but classifies more coastal pixels as wetlands than does Matthews or ISLSCP.

6.1.4 Ramsar Database

Ramsar data base contains reliable information on those wetlands that fall under the Ramsar treaty. Even though this wetlands inventory is not meant to be exhaustive (neglecting non-protected wetlands), it can be used as ground truth for the validation of other databases. The data extractable for each site include area and geographical coordinates. Although many sites are located in Europe, Ramsar wetlands site areas are well distributed across different latitudes. Ramsar sites include seasonal wetlands (including agricultural lands) showing a geographic concentration in Asia or South America.

6.1.5 Comparison of Wetlands Databases

Figure 4 provides a synthesis of the global wetlands area given in the Matthews, ISLSCP and DISCover data bases (Ramsar was excluded from this comparison because its non-exhaustive nature). The DISCover estimate is significantly lower than the other two estimates corresponding to only 27% and 24% of the total global wetlands area estimated by Matthews and ISLSCP, respectively. The global estimates of Matthews and ISLSCP match reasonably well (+- 10%), but only 57% of the respective wetlands area were identified in the same geographical locations. Likewise, the wetlands areas identified by all three data bases correspond to approximately 25 % of each estimate (Figure 4). The percentage of area identified by one data base only was approximately 30 % (Matthews and ISLSCP) and 44 % (DISCover).

Darras et al (1999) compared the different data bases using Ramsar wetlands pixels as ground truth reference. Among the total wetlands areas described in the Ramsar data base, a large proportion (more than 30 %) is not identified by Matthews, ISLSCP or DISCover. Matthews's database showed the highest degree (45 %) of matching pixels with Ramsar followed by ISLSCP (26 %) and DISCover (5%). An analysis for different continents revealed that Matthews' database generally showed the best match (with the exception of North America); and that its data is especially accurate for Europe (Figure 5). This leads to the conclusions that Matthews' database is a fairly reliable – though not exhaustive– source for the geographical distribution of wetlands.

Figure 4: Areas of Common and Distinct Wetland Regions in Three Different Databases (Redrawn from Darras et al., 1999).

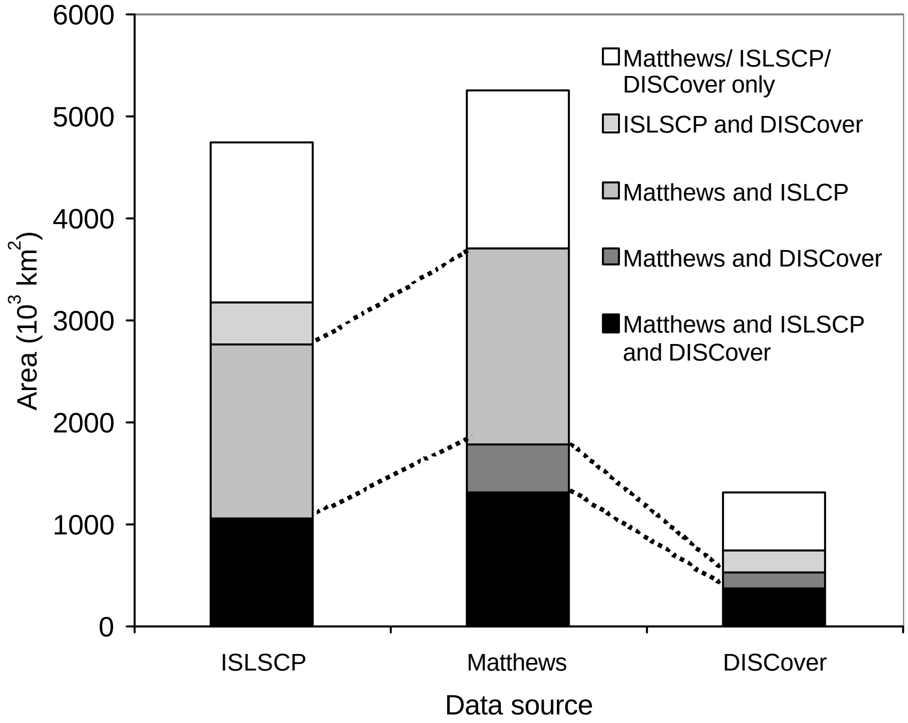
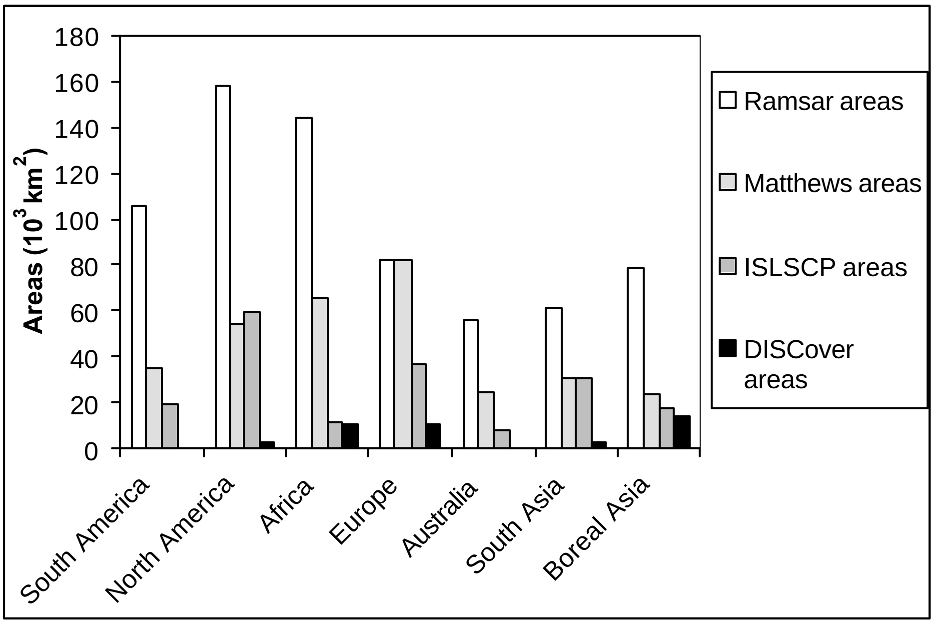


Figure 5: Ramsar Wetlands Area Identification by other Databases Distributed over Continents (from Darras et al., 1999)



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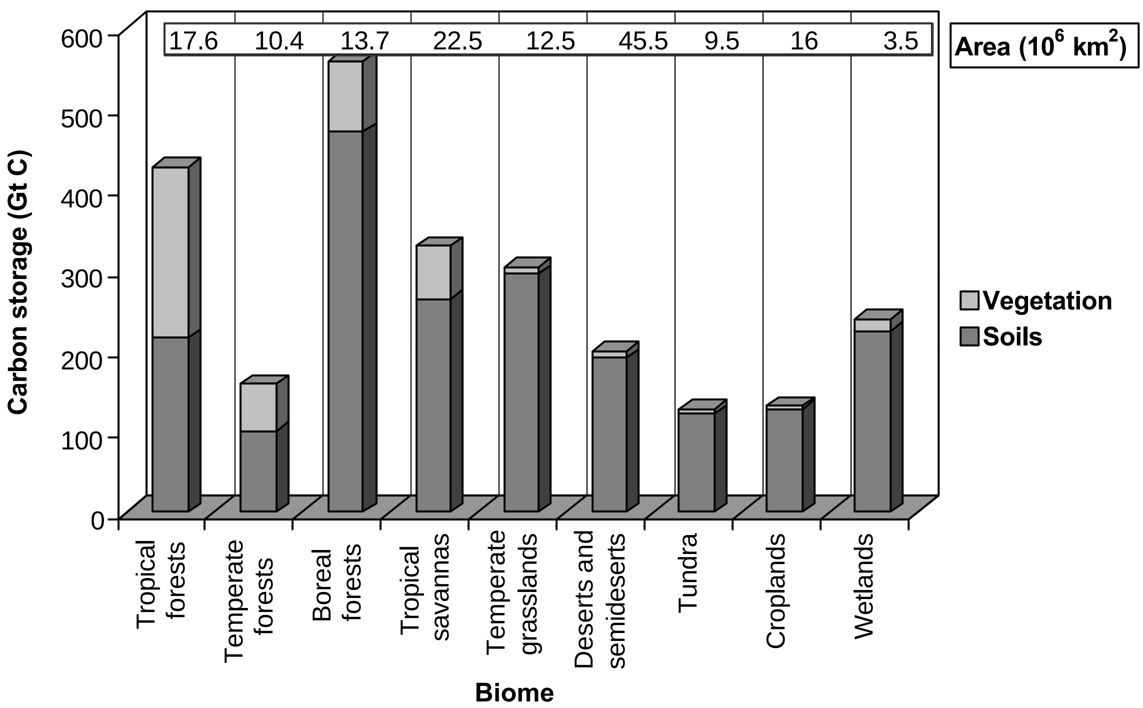
7. Soil Organic Carbon in Wetlands Soils

7.1. Previous Estimates

In Figure 6, estimated areas and carbon storage (Gt) values of global wetlands are set in comparison with other biomes. Deserts/ semi deserts are the biome with the largest area (45.5 10^6 km^2), but store only a relatively small amount of organic carbon. Boreal forests store the highest total amount of carbon (559 Gt), which is mainly attributed to the carbon pool in the soil (471 Gt). Tropical forests have the largest vegetation carbon pool (212 Gt), which makes this biome the second largest carbon pool in total. In comparison to other biomes, wetlands cover a smaller area but with relatively high carbon storage in it (240 Gt).

Figure 6: Soil Organic Carbon Storages and Areas of Different Global Biomes (Drawn with Data from WBGU, 1998).



However, the estimates of carbon in global wetlands show a very broad range of uncertainty from 202 to 377 Gt (Table 3). For comparison, these figures are substantially lower than estimated carbon pools in the atmosphere (720 Gt; Falkowski et al., 2000), but are in the same order of magnitude as the entire carbon fixed as oil (230 Gt C) or natural gas (140 Gt C). However, the inter-comparison of these estimates of the wetlands carbon pool is biased by various incongruities due to diverging definitions of wetlands/ peatlands (see chapter 2). These deviating wetlands concepts add to the inherent uncertainties attached to estimates of wetlands and of C stocks on regional as well as global scales.

Table 3: Estimated Areas and Soil Carbon Stocks of Wetlands

Reference	*Area (Mha)*	*Soil carbon density (t C/ha)*	*Global carbon store in soils (Gt C)*	*Remarks*
Sjörs et al., 1980	***--***	***--***	***300***	***Top 0-100 cm soil***
Post et al., 1982	***280***	***723***	*****	**** Corresponding. to 202 Gt C***
Buringh 1984	***120***	***375***	*****	***Only peatland acc. to USDA definition; * corr. to 45 Gt***
Adams et al., 1990	***n.d.***	***n.d.***	***202-377***	***For top 0-100 cm soil***
Maltby and Immirzi, 1993	***398***	********	***462***	***For 0-150 cm soil (Temperate +Tropical)***
Eswaran et al., 1993	***n.d.***	***n.d.***	***357***	***For top 0-100 cm soil***
Gorham, 1995	***n.d.***	***n.d.***	***350–535***	
Batjes, 1996	n.d	n.d	120	For top 0-30 cm soil
	n.d.	n.d.	330	For top 0-100 cm soil
WBGU 1998	350	642	225	For top 0-100 cm soil

* Not explicitly mentioned in the source; re-calculated in this report by multiplying given area and carbon density figures.

** Adjusted from Armentano and Menges (1986).

Post et al. (1982) reported that wetlands extend to only 280 Mha, and the average carbon density in wetlands is 723 t ha^{-1}. Estimates on carbon stored in wetlands are also affected by different definitions, i.e. peat lands are also classified in other ecosystem types such as boreal forest and tundra. Buringh (1984) classified histosols (peat soils) according to the USDA system (Soil Survey Staff 1975) resulting in only 120 Mha and carbon density 375 t ha^{-1} by considering the surface 33 cm only. Global figures on wetlands areas and their C storages not only conceal regional differences, but also different assumptions. Highly variable areal estimates of soil types and ecosystem type are among the many factors that give rise to disparate estimates of carbon quantities stored in peat (Table 3).

Superimposed on these uncertainties in areal extent are different figures on carbon content (per unit area) that are especially variable for peatland. In a peat soil carbon is present over the full depth of the deposit, the depth of which varies between a minimum of 30 cm and several meters. Gorham (1991) has suggested an average figure of 2.3 m for peatlands in Canada and 2.5 m for those in the Soviet Union, which together cover 269 Mha. In fact, particular peat deposits in various parts of the world may be significantly deeper.

Many studies express the carbon content of soils on a percentage (weight) basis, so it is difficult to derive the carbon storage (per unit area) if the depth of the organic layer is unspecified. In peat soils the carbon percentage usually does not change appreciably, and thus carbon densities (t C ha^{-1}) are a direct function of depth. In peatsoils the average carbon densities range between 600 and 1,500 tha^{-1} within the upper 1 m of the deposit (Armentano and Menges, 1986). On the basis of those carbon density statistics, the temperate peatlands C-store was estimated to be 256 Gt, and the tropical peatlands store waslike wise estimated at 19.3 Gt (Maltby and Immirzi, 1993). But this only accounts for peat to a depth of 1 meter. Adjusting the density to a depth of 1.5 m and using their own estimate for the temperate area (357 Mha), Maltby and Immirzi (1993) estimated that the temperate store alone could be as high as 392 Gt. The latter authors identified 41.5 Mha of peat lands in the tropical region. Applying a density value of 1687.5 tha^{-1} yields a further 70 Gt, which summed to the temperate store gives 462 Gt. Gorham's (1991) evaluation yielded 346 Mha or 86-90% of Maltby and Immirzi's (1993) global area. Gorham (1991) calculated the pool in boreal and sub arctic peat lands alone at 460 Gt. The carbon stored in peat could be 44-71% of the whole of the carbon held in the terrestrial biota (737 Gt) according to Matthews (1984).

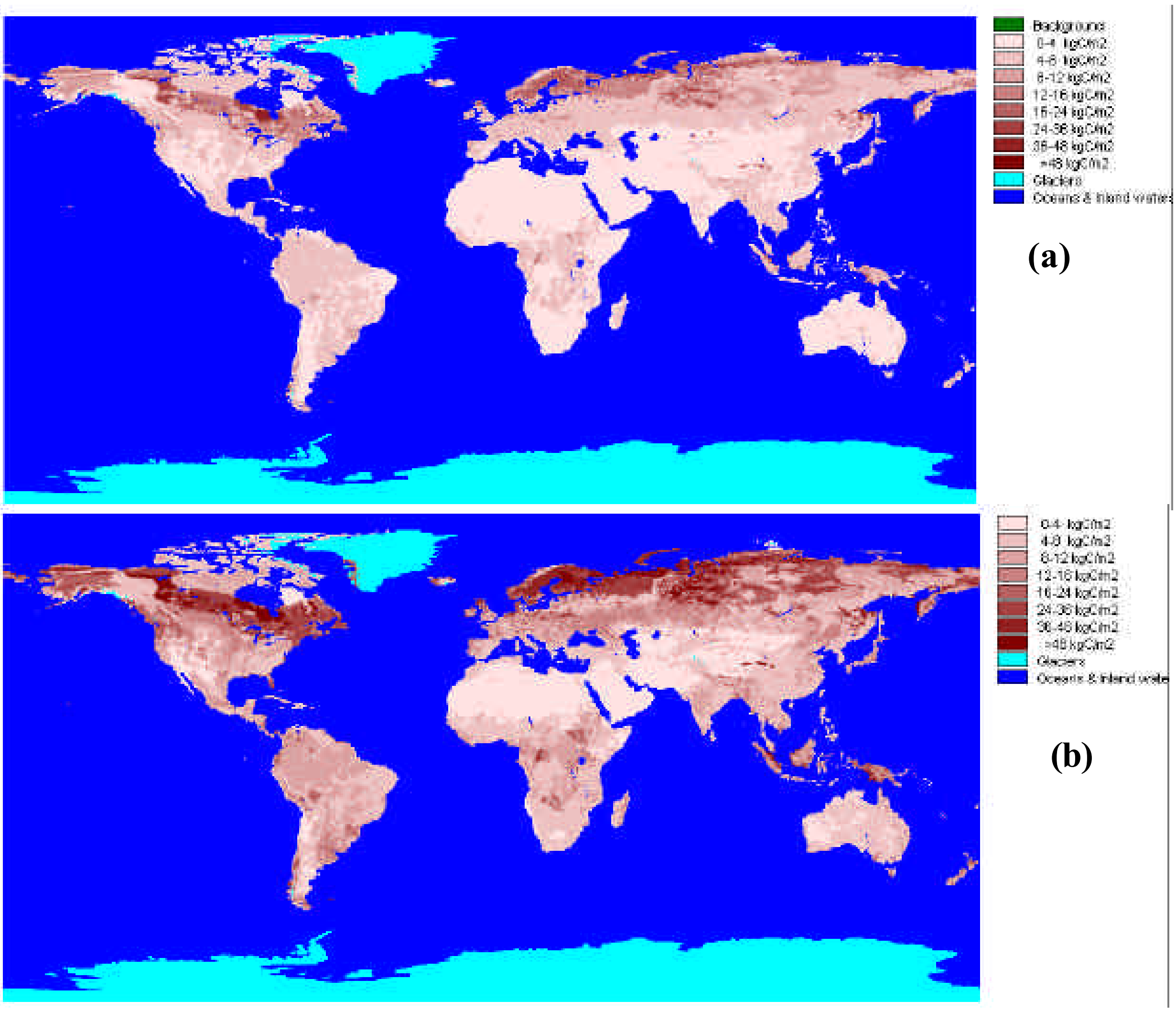
To ascertain consistency of these estimates ranging 200 to 530 Gt C, we have juxtaposed the Matthews data base (previously shown as the most reliable global wetland map) and the maps on global SOC distribution shown below (Batjes et al., 1996). The detailed results of this assessment are shown in Mitra et al. (submitted) and clearly point towards the lower end (rather than the higher end) of these SOC estimates for global wetlands. This finding is in line with the development of the scientific discussions as can be seen from the time series of estimates shown in Table 3.

7.2 ISRIC-WISE Soil Organic Carbon Data Base

ISRIC (International Soil Reference and Information Centre) has developed a uniform methodology for a global database of soil properties within the framework of WISE (World Inventory of Soil Emission Potentials), a project on World Inventory of Soil Emission Potentials (Batjes and Bridges, 1994; Batjes et al., 1995). The WISE database, which currently contains data for 4353 profiles, has been used to generate a series of uniform data sets of derived soil properties for each of the 106 soil units considered on the Soil Map of the World (FAO-UNESCO, 1974). The WISE data base excludes glaciers, oceans and inland waters. The highest soil organic carbon class (only existent in the 0-100 cm map) is >48 kg C/m^2.

These data sets were then linked to a ½ ° -resolution version of the edited and digital Soil Map of the World (FAO, 1995). As such, they can be used readily to generate thematic maps of soil properties for a range of studies of global environmental change (e.g. Knox et al., 2000). Figure 7a,b shows GIS raster images of soil organic carbon density (kg C m^{-2}) for 0-30 cm and 0-100 cm depths respectively, generated from these data files and used in this study. The raster data file is based on a 30 x 30 minute grid.

Figure 7a,b: Global Soil Organic Carbon Distribution in the Soils Layers of (a) 0-0.3m and (b) 0-1m (Batjes, 1996).



The juxtaposition of this soil map (Fig. 7b) with a global wetland map, namely the Matthews data base, allows a geographic description of the wetland SOC pool (Mitra et al., submitted):

Boreal/ temporal wetlands: The wetlands of Alaska have SOC contents of 10-30 kg C m^{-2} whereas other boreal wetlands, namely in the Canadian shield and the arctic circle in Eurasia, have in most cases SOC >30 kg C m^{-2}. The temperate zone has numerous regions with high wetland abundance, e.g. Eastern US and Eastern Europe, but SOC values in these wetlands rarely go beyond 20 kg C m^{-2}.

Tropical/ sub-tropical America: Carbon stocks are primarily located within two wetland continuums in South America, i.e. one longitudinal belt of wetlands along the Amazon and one latitudinal belt ranging from the Rio de la Plata estuary to Bolivia. The subtropical regions of the American continent contain pronounced hot spots of wetland carbon (Rio de la Plata plains, Florida) with SOC values >12 kg C m^{-2} that are characterized by high carbon concentrations in the lower soil layers.

Africa: Wetland carbon stocks are scattered over the entire equatorial belt of Africa, with carbon hot spots occurring mainly in inland valleys. SOC values in wetlands along the upper Nile, Congo and Zambesi rivers reach locally >16 kg C m^{-2}.

Tropical/ sub-tropical Asia: Wetland carbon stocks are concentrated in South-East Asian coastal areas. Wetlands in the Indonesian archipelago have the highest SOC values (in some cases > 30 kg C m^{-2}) of all tropical wetlands. With the exception of the Mekong Delta, the tropical and sub-tropical regions of continental Asia contain remarkably low wetland carbon stocks.

8. Greenhouse Gas Emissions and Carbon Sequestration

8.1 Sources and Sinks

The role of wetland-borne fluxes of carbon in the global carbon cycle is poorly understood, and more information is needed on different wetlands types and their functioning as both sources and sinks of greenhouse gases. Conceptually, wetlands may affect the atmospheric carbon cycle in four ways:

Firstly, many wetlands, particularly boreal and tropical peatlands, are highly labile carbon reservoirs. These wetlands may release carbon if water levels are lowered or land management practices result in oxidation of soils. Likewise, increasing temperatures could melt permafrost soils and subsequently emit methane hydrates entrapped by these wetlands.

Secondly, many wetlands may continue to sequester carbon from the atmosphere through photosynthesis by wetlands plants and subsequent carbon accumulation in the soil.

Thirdly, wetlands are intricately involved in horizontal carbon transport pathways between different ecosystems. Wetlands are prone to trap carbon-rich sediments from watershed sources, but may also release dissolved carbon through water flow into adjacent ecosystems. These horizontal transport pathways may affect both sequestration and emission rates of carbon.

Fourthly, wetland soils produce the greenhouse gas methane, which is regularly emitted to the atmosphere even in the absence of climate change.

The net carbon sequestering versus carbon release roles of wetlands are complex and change over time. Gradual net sequestration occurs over time for peatlands and certain other types of wetlands. Due to their anaerobic character and low nutrient availability, peatland carbon stocks increase continuously. Gorham (1991) estimates that bogs absorb globally about 0.1 Gt C yr^{-1}. Wojick (1999) gives a range for global C-sequestration in peatlands and other wetlands from 0.1 to 0.7 Gt C. In contrast, total carbon emissions from the conversion wetlands to agricultural land is estimated to range between 0.05 and 0.11 Gt C yr^{-1} (Maltby and Immirzy, 1993).

Comprehensive assessments of the source and sink potential of wetlands reclamation should include the net-emissions of carbon dioxide, methane and nitrous oxide (the latter being excluded in this study dealing with carbon compounds only). Wetlands are the largest source of methane due to a large area and anoxic conditions occurring in their flooded soils in combination with high rates of primary production (Bartlett and Harris, 1993). Recent estimates derived from inverse modeling of atmospheric methane distribution indicate a source strength of 145 ± 30 Tg CH_4 yr^{-1} (Lelieveld et al., 1998) corresponding to app. 25 % of all methane sources. Table 4 gives an overview of the various regional estimates of wetlands areas and the amount of methane (CH_4) emitted from them.

Table 4: Regional Wetlands Areas and Associated Methane Emissions from Various Studies

References	Tropical		Temperate		Boreal/Arctic		Global		Remarks
	Area Mha	**Emiss.** Tg CH_4 yr^{-1}	**Area** Mha	**Emiss.** Tg CH_4 yr^{-1}	**Area** Mha	**Emiss.** Tg CH_4 yr^{-1}	**Area** Mha	**Emiss.** Tg CH_4 yr^{-1}	
Aselmann & Crutzen, 1989	210	**45**	110	**11**	240	**25**	570	**80**	
Bartlett et al., 1990	200	**55**	60	**17**	270	**39**	530	**111**	
Fung et al., 1991	200	**71**	60	**12**	270	**32**	530	**115**	
Bartlett & Harriss, 1993	200	**66**	60	**5**	270	**34**	530	**105**	
Matthews and Fung, 1987	200	**34**	60	**1.2**	270	**65**	530	**111**	
Cao et al., 1996	200	**55.2**	60	**13.8**	270	**21.8**	530	**92**	Process model
Hein et al., 1997		**100**		**87**	-	**45**		**232 ±27**	Inverse modeling
Seiler & Conrad, 1987		**38 ±17**						**47 ±22**	
Khalil and Rasmussen, 1983		**90**		*		**66***		**156**	Peatlands only, *temperate included in boreal
Sebacher et al., 1996					450-900	**45-106**			Peatlands only
Crill et al., 1988					-	**72**			
Moore et al., 1990					150	**14-19**			Fens only
Ritter et al., 1992					730	**44**			Tundra only
Whalen & Reeburg, 1992					730	**14-42** [a] **26-78** [b] **24-67** [c] **69-135** [d]			Tundra only, estimates for 1987 [a], 1988 [b], 1989 [c], and 1990 [d]
Christensen et al., 1996						**20±13**			Tundra only
Reeburgh et al., 1998					730	**5.5-5.8**			Dry tundra only
Lelieveld et al., 1998								**145 ± 30**	Inverse modeling

Drainage of wetlands during conversion to agriculture or forestry generally results in a loss of carbon, as soil organic matter previously stored under anaerobic conditions is aerated and exposed to atmospheric oxygen. In many cases, the organic carbon stores that had accumulated slowly over centuries to millennia can be lost in days (in the case of burning) or over decades (IPCC 2001). Rates of carbon loss are often inferred from changes in the surface elevation of the peat layer. Careful analysis, however, shows that physical compaction of peat, if unaccounted for, may cause subsidence without carbon loss (Minkkinen and Laine, 1998). Loss of anaerobic conditions near the wetlands surfaces allows greater oxidation of produced methane. Drainage of wetlands decreases methane emissions to zero, in some cases even consuming small amounts of methane from the atmosphere. Roulet and Moore (1995) reported, however, that decreases in methane emission from the drained wetlands themselves might be offset (in some cases completely) by increased methane emissions from standing water in the ditches used to promote drainage.

Kasimir-Klemedtsson et al., (1997) examined the net effect of agricultural development on greenhouse gas (GHG) emissions from temperate wetlands in Europe. The conversion of bogs and fens to different cropping types led to five- to 23-fold increases in CO_2-equivalent emissions, with a large increase in CO_2 emissions dominating over a drop in CH_4 emissions. Increases in N_2O emissions have also been observed in drained organic soils (Kasimir-Klemedtsson et al., 1997), although few data are available.

Climate change is likely to affect the ability of wetlands to emit methane and to sequester carbon, but the results will vary for different wetlands types and are difficult to predict. Increased CO_2 in the atmosphere will result in higher primary productivity in most, if not all, wetlands. As for other biomes, this 'CO_2-fertilization' effect could enhance the standing stock of carbon in the ecosystem. On the other hand, wetlands rice fields have been shown to emit more methane under higher CO_2 exposure (Ziska et al., 2000), and it seems reasonable to assume a parallel trend for natural wetlands as well.

Increased temperatures may result in increased evapo-transpiration and may thus decrease ground-water and surface water levels in many wetlands. The combined effect of lower water levels and higher temperatures may stimulate decomposition and threaten the existence of many wetlands ecosystems. Sea-level rise may have equally negative effects on freshwater and coastal-zone ecosystems.

Probably the most drastic feed-back process of climate change may stem from the increase in boreal temperatures. The subsequent north-bound migration of the tundra wetlands ecosystems entails a thawing of permafrost wetlands. Permafrost presently covers approximately 25 percent of the earth's land area and contains vast amounts of biogenic methane that is trapped in shallow ice. A reduction in areal extent and depth of permafrost – or even a spatial shift – could lead to a sudden release of the greenhouse gas methane into the atmosphere. The current approximation of the amount of methane stored in permafrost is over 5,000 Tg in the ice portion alone (IPCC, 1992).

8.2 Net Balance of Greenhouse Gases

Derived from Table 4, average CH_4 emission rates for wetlands are in the order of 200 kg CH_4 ha^{-1} yr^{-1}. Given the higher global warming potential for CH_4, (i.e. the ability of one molecule CH_4 to trap heat exceeds that of CO_2 by a factor of 21 (IPCC 1998), this emission would compensate a carbon sequestration of 4.2 t CO_2 ha^{-1} yr^{-1}, corresponding to 1.5 t C ha^{-1} yr^{-1}. This value is slightly higher, but still in the same order of magnitude of what can be derived as average carbon sequestration. Based on the Wojick (1999) estimate of 0.1 to 0.7 Gt C yr^{-1} sequestered globally by wetlands, carbon sequestration per area is likely to be 0.2 to 1.4 t C ha^{-1} yr^{-1} (based on Matthews and Fung's global estimate of app. 500 Mha wetlands). Due to the counterbalancing of methane emission by carbon sequestration, pristine wetlands should be regarded as a relatively small net source of greenhouse gases.

When peatlands are drained, mineralization processes start immediately, and result in emissions ranging between 2.5 and 10 t C ha^{-1} yr^{-1} (Maltby and Immerzi, 1993). Mean carbon densities in wetland soils shown in Table 3 are in the range from 210 to 700 t C ha^{-1}; whereas the carbon pool in the vegetation mass is estimated to be in the order of 50 t C ha^{-1} (acc. to WBGU (1998)). The emission of the soil and vegetation carbon pools through wetland destruction would thus compensate for 175 to 500 years of methane emission from the same area (given the carbon equivalent of 1.5 t C ha^{-1} yr^{-1} for methane emission, see above). This computation does not take into account carbon sequestration that largely compensates the net emission of greenhouse gases from pristine wetlands. In turn, emission from the soil carbon pool through wetland destruction would account for several thousands of years of the net GHG emission of pristine wetlands. Subsequently, the role of wetlands in global climate change is mainly determined by the future development of wetland areas, whereas actual emissions from pristine wetlands (i.e. methane emission vs. carbon sequestration) play only a minor role.

It is yet uncertain if the conservation of wetlands will ever be fully integrated into international trading schemes of emission certificates as envisaged in the Kyoto Protocol. The Kyoto mechanisms were conceived to fund the mitigation of GHG sources, e.g. to introduce solar energy and to use fossil fuel consumption as a baseline to compute net emission savings. However, the Kyoto Protocol does not award the mere cessation of a GHG source such as deforestation, because it will be hard to justify the destruction of the natural resource base as a plausible and universally accepted baseline. The Kyoto mechanisms also apply to GHG sinks, regarded as a potential funding source for new and restored wetlands (Wylynko, 1999). However, the net sink capacity of new wetlands is thwarted by emissions of the GHG methane. Therefore, management strategies should primarily aim at increasing the carbon pool at given wetland area and thus, given methane emission. Even if trading of emission certificates may become an established pathway to fund restoration of degraded land, this mechanism can only be applied to those wetlands with high (vertical) carbon sequestration potential.

8.3 Management Strategies for Protecting Carbon Reservoirs and Carbon Sequestering Capabilities

Wetlands conservation and their sustainable use as natural habitats should be included in national and international management strategies that prevent destruction, degradation, fragmentation, and pollution of the natural resource base. Many other activities such as natural resources management, legal reforms and their implementation, advocacy, capacity building, education and public-awareness raising could greatly reinforce the wetland conservation effort. An additional mitigation strategy is the restoration of degraded wetlands and the creation of human-made wetlands ecosystems, which could augment some of the wetlands' environment functions (e.g. water quality improvement and flood control) (Kusler and Kentulla, 1990).

Enhancing carbon reserves in wetlands in the context of climate change is consistent with reducing greenhouse gas emissions from the wetlands and restoring their carbon reserves. Degradation of wetlands and disturbance of its anaerobic environment leads to a higher rate of decomposition of the large amount of carbon stored in it and thus augments greenhouse gas emissions to the atmosphere. Therefore, protecting the wetlands is a practical way of retaining the existing carbon reserves and thus avoiding emission of CO_2 and greenhouse gases. With the ever-increasing population pressure and elevated food demand, the global wetlands are under significant threats. Due to the changes in land use, over exploitation, drainage and several anthropogenic activities and natural processes the wetlands' physico-chemical as well as biological conditions are often disturbed, and these disturbances lead to rapid loss of carbon from organic soils.

Conservation of wetlands could be more effective if the climate change issues are also well controlled. An 'ecosystem approach'[1] to manage and conserve wetlands could be an efficient tool for the future conservation of wetlands. Proper education and dissemination of knowledge about the 'wise use' of wetlands is necessary to protect wetlands from further degradation and the loss of carbon stock from them to the atmosphere. Measures should be taken to stop the inflow of any organic residues from any source to the wetlands and to maintain the anaerobic condition of the soils. Wetlands have a large organic carbon stock, which could be preserved by proper conservation practices. Re-flooding of previously drained wetlands could lead to the sequestration of large amounts of CO_2 from the atmosphere (Batjes, 1999). If wetlands are not preserved or maintained properly, these ecsoystems could switch from being net sinks of carbon to becoming sources of greenhouse gases that accelerate climate change. More information on specific wetlands types and their role in regulating global climate (CO_2 sequestration vs. CH_4 emission) is needed to devise thorough management plans.

9. Conclusions and Recommendations

The ‘wise use’ concept of the Ramsar Convention on Wetlands and the idea of ‘sustainable use’ from the Rio Declaration on Environment and Development both advocated the same message of ‘good management’ by utilization of the available resources in ways that keeps them available for future generations. Chapter 10 of the Rio Declaration elucidated the issues and challenges, and the ways to tackle them. These principles are very much relevant to wetland management and conservation. There is a no doubt about the importance of wetlands in the life of humans and the ecosystems we thrive on. The plethora of wetland definitions and classification systems is an indication that how diversified and complex the wetland ecosystem is. Lack of consensus regarding a standard definition of wetland has caused much confusion and debate among the researchers and policy makers in distinguishing wetlands from other lands. There is a pressing need for a well-accepted standard definition of wetlands and of criteria for identifying wetlands of various types.

A broad consensus now exists that wetlands are important reservoirs of carbon in their above-ground biomass, litter, peats, soils and sediments. But there are wide variations whenever these reservoirs are quantified. This study examined those uncertainties. We believe a more restricted and location specific Ramsar definition of wetland could help to resolve the long-lasting uncertainties and the disagreements among scientists as well as policy makers.

This study on wetland areas and their organic C density distributions provides a clear picture of the range of organic C contents in the wetlands of particular geographical locations in the world. The joint display of global wetland resources and soil organic carbon may be useful in devising a long-term wetlands-conservation strategy. Estimating the net carbon sequestration potential of a wetland is difficult because the decomposition rate of organic matter, the prevalence of methanogenic microorganisms and the fluxes from the sediment are extremely complex and there are often gaps in relevant scientific knowledge. Our collated information on the wetlands area and density distribution of soil organic C in global wetlands could well be instrumental in determining efficient strategies related to carbon sequestration and greenhouse gas mitigation in wetland ecosystems.

The information base on the areal extent of wetlands has improved significantly over recent years, thanks mainly to new techniques in remote sensing and GIS. Simultaneously, the knowledge base on soil carbon stocks has been substantiated through rigorous efforts to compile global soil maps. This discussion paper confirms the global significance of wetland carbon storage. More than 100 Gt C in the soils alone is a sizable amount that could drastically increase the carbon stock in the atmosphere (currently app. 720 Gt C) when emitted through destruction of the wetland resources. Moreover, wetland ecosystems also store carbon in their vegetation (app. 15 Gt C; WBGU, 1998) that will be emitted concurrently.

The information on wetlands and soil organic carbon may be used to derive region-specific research and conservation projects on the hot-spots of carbon stocks. Knowledge of the location, distribution and character of natural resources, their values and uses, and the threats to them is an essential basis for environmentally sound development. Wetlands are crucial lands-cape elements, especially for hydrology and biodiversity. Moreover, wetlands represent one of the largest terrestrial reservoirs of carbon. Further destruction of wetlands would entail large emissions of the greenhouse gas carbon dioxide. There is broad agreement that certain types of wetlands contain large historic, reservoirs of carbon in the above-ground biomass, litter, peats, soils and sediments. It is also understood that land management practices such as drainage may cause the release at least a portion of the stored carbon. All that information is needed to better evaluate generically and in specific settings the roles of wetlands as carbon reservoirs, sources and sinks so as to guide protection, enhancement, and restoration efforts.

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