An appraisal of global wetland area and its organic carbon stock

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Wetlands are among the most important natural resources on earth. They are the sources of cultural, economic and biological diversity. With their wealth of stored carbon, wetlands provide a potential sink for atmospheric carbon, but if not managed properly could become sources of greenhouse gases (GHGs) such as carbon dioxide and methane. Two important long-term uncertainties have initiated much debate in the scientific community. These are global wetland area and the amount of carbon stored in it. Compilation of relevant databases could be useful in setting up a long-term strategy for wetland conservation. It has been difficult to estimate the net carbon sequestration potential of a wetland, because the rate of decomposition of organic matter and the abundance of methanogenic micro-organisms and fluxes from the sediment are extremely complex, and there are often gaps in relevant scientific knowledge. The present discussion on density distribution of soil organic C in global wetlands could well be instrumental in formulating efficient strategies related to carbon sequestration and reduction of GHG emissions in wetland ecosystems. Effective assessment of wetlands will only take place when the available information becomes accessible and usable for all stakeholders.

TEN years after the 1992 Rio Earth Summit, the World Summit on Sustainable Development (WSSD) held at 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. Various governments, scientists and policy makers[1] have recognized the importance of the wetland as a natural resource on earth and a source of cultural, economic and biological diversity.

Conservation and management of wetlands have been identified as a priority area for action in international conventions and regional policies. The Ramsar Convention on wetlands held in Iran in 1971, which deals explicitly with wetland conservation, is the oldest of the global intergovernmental environmental conventions. The Convention provided the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources. There are presently 144 Contracting Parties to the Convention, with 1401 wetland sites, totalling 122.8 mha, designated for inclusion in the Ramsar List of Wetlands of International Importance.

Wetlands can be found in all climate zones ranging from the tropics to the tundra (Antarctica is the only continent on earth that has no wetlands). Although wetlands occupy only 4–6% of the earth's land area (~530–570 mha)[2,3], 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[4], for example, estimated that wetlands contain 350–535 Gt C, corresponding to 20–25% 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[5]. Undisturbed wetlands often function as active sinks of carbon, although they also emit the greenhouse gas (GHG) methane in substantial quantities[6]. A better understanding of the mechanisms responsible for the large fluctuations in wetland areas over the last glacial–interglacial cycle is necessary[7,8].

There is no dearth of information about wetland resources and their management, but that information is scattered in a variety of sources in incompatible formats. Hence it is

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difficult to obtain comprehensive and reliable information on the state and/or the management of global wetland resources. Lack of accurate knowledge on the location, area, distribution and condition of wetlands makes it more difficult to 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 wetland inventories does not allow identifying the gaps that exist in the available inventories. An accurate assessment of the size and distribution of the global wetland resources and the patterns of their change is difficult to obtain[9].

The objectives of this article are: (i) to provide a comprehensive overview on the role of wetlands in the environment; (ii) to elucidate the uncertainties in the estimation of wetland area and its soil organic carbon stock; and (iii) to collate information on different data sources of wetland area and soil organic carbon content.

Definition of wetland and peatland

There is a need to delineate the two terms 'wetland' and 'peatland', which will appear many times in this article. 'Wetland' 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. Basically all concepts of wetlands imply the existence of a characteristic vegetation, which serves as a criterion for classifying a habitat as a wetland[10].

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.*[11] and Zinke *et al.*[12]. Another example is the study of Canadian peatland areas by Tarnocai[13], 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[14], 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. The characterization of tropical peatlands is even less substantiated than for the others types[15,16].

In 1971, Ramsar Convention, an intergovernmental treaty on worldwide wetlands conservation, worked out a 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 6m at low tide lying within the wetlands' as part of the wetland continuum[17].

Functions and values of wetlands

People often view wetlands as wasteland. Wetlands are sometimes drained and filled for development; others are polluted from dumping of wastes from various sources (e.g. industry, agriculture, household, etc.). But ecologists and others are beginning to deliver the message that wetlands are some of the most biologically productive ecosystems on the earth[18], comparable to rainforests and coral reefs. An immense variety of species of microbes, plants, insects, amphibians, reptiles, birds, fish and mammals are part of a wetland ecosystem.

Although the terms 'function' and 'value' of wetlands are often used interchangeably, they connote different meanings. 'Functions' of wetlands are the physical, chemical and biological processes that characterize wetlands ecosystems (Figure 1). Costanza *et al.*[19] estimated the total global value of services provided by coastal areas and wetland ecosystems to be 15.5 trillion US$ per year, being 46% of the total value of services that global ecosystems are estimated to provide. The major functions of wetlands are water storage and groundwater recharge, flood control, shoreline stabilization, water quality control, moderating climate and community structure, biodiversity and wildlife support. Wetlands are immensely valuable in various aspects, viz. recreational and aesthetic value, supply and quality, biodiversity value, etc.

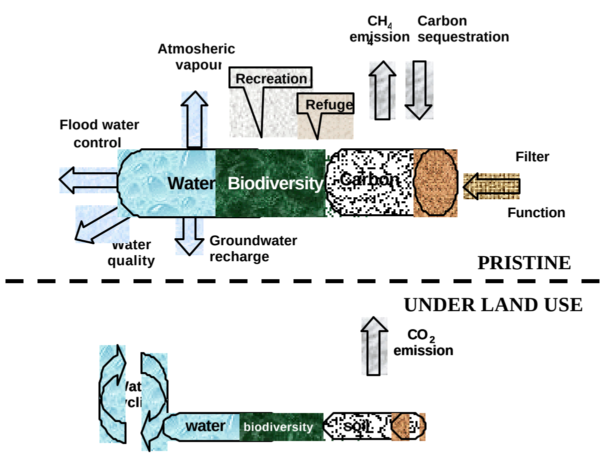

Figure 1. Role of wetlands in the environment.

Carbon cycling in different wetland classes

Wetlands are major carbon sinks[20]. While vegetation traps atmospheric CO_2 in wetlands and other ecosystems alike, the net-sink of wetlands is attributed to low decomposition rates in anaerobic soils. Many riverine, estuarine and coastal wetlands also trap large quantities of sediment from natural and anthropogenic watershed sources, 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 turnover; whereas salt marshes have high primary productivity matching tropical forests. Depending upon a variety of interrelated factors (such as temperature, water level, flow of water and nutrients), the rate of decomposition varies within a wetland 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. groundwater level, temperature, substrate availability, nutrient level, and microbial population) 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[6,21,22], accounting for ~20% of the current global emission of ~450–550 Tg (10^{12} g). 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[23].

Wetlands affected by climate change

The relationship between climate change and conservation and wise use of wetlands is becoming increasingly important; yet not enough attention has been given to it by politicians and decision makers. Wetlands play a pivotal role in recharging aquifers in the arid and semi-arid regions of the world. Impacts of climate change on wetlands are still poorly understood and are often not included in global models of climate-change effects[24]. The diverse nature of wetlands makes it all the more difficult to assess their relation to climate change more precisely. Increase in sea level might shift wetland systems inland. The freshwater supplies from coastal wetlands might well be affected by the higher sea levels and the intrusion of salty water[25]. The projected changes in climate are likely to affect the extent, distribution and nature of wetland functions significantly. The rise of nearly 0.6°C during the last century is quite small compared to the projected temperature rise of 1.4–5.8°C over the next century[20]. Even the lower figure in that range would be more than double the increase during the last century. The upper-end projection of 5.8°C would be nearly 10 times as great[20]. The IPCC (Intergovernmental Panel on Climate Change) further projects that during this century, the sea level will rise[20] from 0.1–0.9 m. Rise in sea level is likely to result in shift in species composition, a reduction of wetlands and productivity function[26]. Increasing temperatures, changes in precipitation, and sea-level rise are the main aspects of climate change that will affect distribution and function of wetlands. At the same time, wetlands represent important carbon stores and contribute significantly to the global carbon cycle[27]. It has become necessary to consider how landuse change and climate change may affect the role of wetlands in the global carbon cycle. Increase in temperature, sea-level rise and changes in precipitation degrade the natural resources and services provided 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[25]. The adaptation ability of wetland ecosystems to these climatic variabilities will undoubtedly depend on the rate and extent of these changes.

Climate change may also affect the role of wetlands as a source and sink of GHGs, which represent one of the most important feedback processes of climate change. As a result of increased temperature, the permafrost might melt and ultimately lead to reduced carbon storage and sequestration by the wetlands. 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 great variation within a single peatland[28].

Wetlands management and the wise-use concept

Degradation on a massive scale has already occurred in global wetland ecosystems. 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 that 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 wetlands refers to the human use of a wetland 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.
- To address problems at particular wetland sites[29].

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 through the media, press, and dialogue 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, landuse and cover, arable land, land suitability, land productivity, population, incidence of diseases, infrastructure, land tenure, etc. could assist in planning the wise use of wetlands. Remote sensing and GIS could be helpful in characterizing and mapping the changes in wetland landuse 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 wetland 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.

Wetlands inventory: relevant databases

Global wetlands distribution

Matthews natural wetlands database: E. Matthews, 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 (Table 1). One of these maps is shown in Figure 2, displaying the geographical distribution of five wetland classes.

In the Matthews database, about one half of the total wetland area lies between 50 and 70°N. This high-latitude belt is characterized by peat-rich ecosystems such as bogs and fens (Figure 2). About 35% of the global wetland area is broadly distributed in the latitudal zone extending from 20°N to 30°S. This belt is co-dominated by forested and nonforested swamps and marshes, with a smaller contribution from alluvial or floodplain formations.

The ISLSCP database: The ISLSCP (International Satellite Land Surface Climatology Project) database was derived from hydrological maps compiled by J. G. Cogley at Trent University. The Cogley dataset provides global coverage (1° resolution) of different hydrological terrains (19 total) and was used by Darras *et al*.[30] for classifying wetlands into swamps, marshes, salt mashes, salt flats, and other wetlands. The wetland area identified by ISLSCP is fairly homogeneously distributed over the continents, with a higher concentration in Europe and Asia.

DISCover database: IGBP/DIS (International Geosphere–Biosphere Programme/Data Information System) has evaluated AVHRR (Advanced Very High Resolution Radiometer) data to compile a database on global land cover. Thus, DIScover is a genuinely remote sensing database, whereas the other databases were derived from maps as primary data sources (Table 1). 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 wetland areas than in Matthews and ISLSCP data, but classifies more coastal pixels as wetlands than does Matthews or ISLSCP.

Ramsar database: Ramsar database contains reliable information on those wetland that fall under the Ramsar treaty. Even though this wetland 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 comprise seasonal wetlands (including agricultural lands) showing a geographic concentration in Asia or South America.

Comparison of wetland area databases: Figure 3 provides a synthesis of the global wetland areas given in the

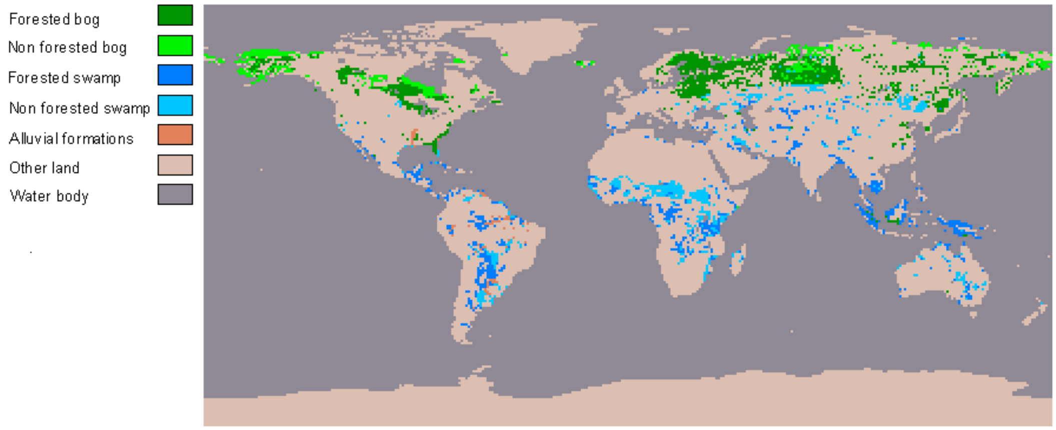

Figure 2. Global distribution of wetland vegetation types in Matthews and Fung's[2] database.

Table 1. Characterization of wetlands database

	Matthews and Fung	ISLSCP	DIScover	Ramsar
Resolution	1°	1°	1°	1°
Primary data sources	Vegetation: UNESCO vegetation map; Soil properties: 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	Wetland types (5 or 12 total) Percentage of cell area covered by wetlands	Percentage of cell area covered by wetlands	Land cover classes (17 total) including 'permanent wetlands'; percentage of cell area covered by wetlands	Name, date of designation, area (in ha), 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

ISLSCP, International Satellite Land Surface Climatology Project; DIScover, The IGBP–DIS global 1 km land cover dataset.

Matthews, ISLSCP and DISCover databases (Ramsar was excluded from this comparison because it is non-exhaustive in nature). The DISCover estimate is significantly lower than the other two estimates, corresponding to only 27 and 24% of the total global wetland areas estimated by Matthews and ISLSCP respectively. The global estimates of Matthews and ISLSCP match reasonably well (± 10%), but only 57% of the respective wetland area was identified in the same geographical locations. Likewise, the wetland areas identified by all three databases correspond to approximately 25% of each estimate (Figure 3). The percentage of area identified by one database only was approximately 30 (Matthews and ISLSCP) and 44 (DISCover).

Darras *et al.*[30] compared the different databases using Ramsar wetland pixels as ground-truth reference. Among the total wetland areas described in the Ramsar database, a large proportion (more than 30%) is not identified by Matthews, ISLSCP or DISCover. The Matthews 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 the Matthews database generally showed the best match (with the exception of North America); and that its data are especially accurate for Europe. This leads to the conclusion that the Matthews database is a fairly reliable – though not exhaustive – source for the geographical distribution of wetlands.

In another study on West Siberian wetlands, Takeuchia *et al.*[31] demonstrated that scaling techniques would provide a tool to extrapolate the local information from high spatial resolution data to larger scale using low spatial resolution data.

Soil organic carbon in wetland soils

In 1998, German Advisory Council on Global Change (WBGU)[32], estimated areas and carbon storage (Gt) for various biomes. Values of global wetlands are set in comparison with other biomes (Figure 4). Deserts/semi deserts are biomes 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).

However, estimates of carbon in global wetlands show a broad range of uncertainty from 202 to 535 Gt (Table 2). For comparison, these figures are substantially lower than estimated carbon pools in the atmosphere (720 Gt),[33] 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, inter-comparison of these estimates of the wetland carbon pool is biased by various incongruities due to diverging definitions of wetlands/peatlands. These deviating wetland concepts add to the inherent uncertainties attached to estimates of wetlands and of C stocks on regional as well as global scales.

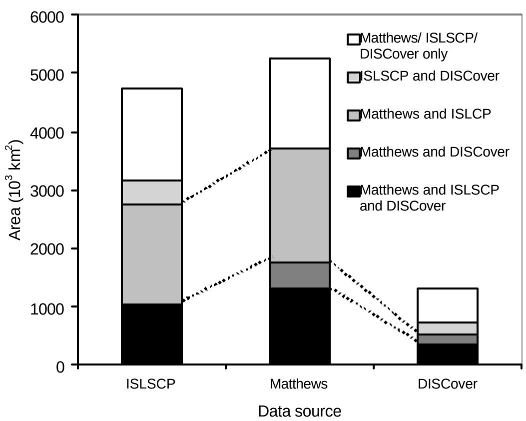

Figure 3. Areas of common and distinct wetland regions in three different databases (redrawn from Darras *et al.*[30]).

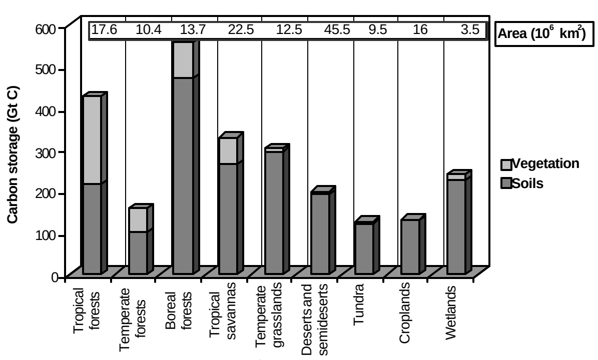

Figure 4. Soil organic carbon storage and area of different global biomes (drawn with data from WBGU[32]).

Post *et al.*[11] 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. peatlands are also classified in other ecosystem types such as boreal forest and tundra. Buringh[34] 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 wetland areas and their C storages not only conceal regional differences, but also different assumptions. Highly variable areal estimates of soil types and ecosystem types are among the many factors that give rise to disparate estimates of carbon quantities stored in peat (Table 2).

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 metres. Gorham[14] 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; thus 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 peat soils, the average carbon densities range between 600 and 1500 t ha^{-1} within the upper 1 m of the deposit[35]. On the basis of carbon density statistics, the C-store of temperate peatlands was estimated to be 256 Gt, and that of tropical peatlands[5] was likewise estimated at 19.3 Gt. This only accounts for peat to a depth of 1m. Adjusting the density to a depth of 1.5 m and using their own estimate for the temperate area (357 mha), Maltby and Immirzi[5] estimated that the temperate store alone could be as high as 392 Gt. The latter authors identified 41.5 mha of peatlands in the tropical region. Applying a density value of 1687.5 t ha^{-1} yields a further 70 Gt, which summed with the temperate store gives 462 Gt. The evaluation by Gorham[14] yielded 346 mha or 86–90% of the global area by Maltby and Immirzi[5]. Gorham[14] calculated the pool in boreal and subarctic peatlands alone at 460 Gt. The carbon stored in peat could be 44–71% of the whole carbon held in the terrestrial biota (737 Gt), according to Mathews[36].

Table 2. Estimated area and soil carbon stock of wetlands

Reference	Area (mha)	Soil carbon density (t C/ha)	Global carbon store in soils (Gt C)	Remarks
Sjörs *et al.*[52]	–	–	300	Top 0–100 cm soil
Post *et al.*[11]	280	723	*	*Corresponding to 202 Gt C
Buringh[34]	120	375	*	Only peatland according to USDA definition; *Corresponding to 45 Gt
Adams *et al.*[53]	n.d.	n.d.	202–377	For top 0–100 cm soil
Maltby and Immirzi[5]	398	(Adopted from Armentano and Menges[36])	462	For 150 cm depth of peat depth
Eswaran *et al.*[54]	n.d.	n.d.	357	For top 0–100 cm soil
Gorham[4]	n.d.	n.d.	350–535	
Batjes[55]	n.d.	n.d.	120	For top 0–30 cm soil
	n.d.	n.d.	330	For top 0–100 cm soil
WBGU[32]	350	642	225	For top 0–100 cm soil

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

Greenhouse gas emission and carbon sequestration

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 wetland types and their functioning as both sources and sinks of GHGs. Conceptually, wetlands may affect the atmospheric carbon cycle in four ways.

First, 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 wetland plants and subsequent carbon accumulation in the soil.

Thirdly, wetlands are intricately involved in horizontal carbon transport pathways among 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 GHG 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[14] estimates that bogs absorb globally about 0.1 Gt C yr^{-1}. Wojick[37] 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 of wetlands to agricultural lands is estimated[5] to range between 0.05 and 0.11 Gt C yr^{-1}. Cao *et al.*[38] used process-based ecosystem models to study the impact of climate change scenarios on methane emission from wetlands and found that global warming may produce higher methane emission; but this effect may be reversed by larger increases in temperature, due to the effect of soil moisture depletion.

Comprehensive assessments of the source and sink potential of wetland 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 emit more than 10% of the global source strength of methane as a result of the anoxic conditions occurring in their flooded soils and their high rates of primary production[39]. Nakano *et al.*[40] reported that fluxes from waterlogged sites in Siberian permafrost areas were much higher than the relatively dry sites where the fluxes were near zero and frequently negative. Temporal (intraseasonal and diurnal) variation in flux was larger at the waterlogged sites than at the dry sites. Table 3 gives an overview of the various regional estimates of wetland areas and the amount of methane emitted from them.

Drainage of wetlands during conversion to agriculture or forestry generally results in the 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[20]. 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[41]. Loss of anaerobic conditions near the wetland 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

Table 3. Regional wetland area and associated methane emission from various studies

	Tropical		Temperate		Boreal/arctic		Global		
Reference	Area (10^{12} m^2)	Emission (Tg yr^{-1})	Area (10^{12} m^2)	Emission (Tg yr^{-1})	Area (10^{12} m^2)	Emission (Tg yr^{-1})	Area (10^{12} m^2)	Emission (Tg yr^{-1})	Remarks
Aselmann and Crutzen[3]	2.1	45	1.1	11	2.4	25	5.7	80	
Bartlett *et al.*[56]	2.0	55	0.6	17	2.7	39	5.3	111	
Fung *et al.*[6]	2.0	71	0.6	12	2.7	32	5.3	115	
Bartlett and Harriss[39]	2.0	66	0.6	5	2.7	34	5.3	105	
Matthews and Fung[2]	2.0	34	0.6	1.2	2.7	65	5.3	111	
Cao *et al.*[57]	2.0	55.2	0.6	13.8	2.7	21.8	5.3	92	Process model
Hein *et al.*[58]		100		87	–	45		232 ± 27	Inverse model
Seiler and Conrad[59]		38 ± 17						47 ± 22	
Khalil and Rasmussen[21]		90		*		*66		156	Peatlands only; *Temperate included in boreal
Sebacher *et al.*[60]					4.5–9.0	45–106			Peatlands only
Crill *et al.*[61]					–	72			
Moore *et al.*[62]					1.5	14–19			Fens only
Ritter *et al.*[63]					7.3	44			Tundra only
Whalen and Reeburg[64]					7.3	14–42 **(1987)			Tundra only; **Estimates in different years
Whalen and Reeburg[64]					7.3	26–78 (1988)			
Whalen and Reeburg[64]					7.3	24–67 (1989)			
Whalen and Reeburg[64]					7.3	69–135 (1990)			
Christensen *et al.*[65]						20 ± 13			Tundra only
Reeburgh *et al.*[66]					7.3	5.5–5.8			Dry tundra only

and Moore[42] reported, however, that decreases in methane emission from the drained wetlands themselves may be offset (in some cases completely) by increased methane emissions from standing water in the ditches used to promote drainage.

Kasimir-Klemedtsson *et al.*[43] examined the net effect of agricultural development on 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[43], 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 wetland 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, wetland rice fields have been shown to emit more methane under higher CO_2 exposure[44], and it seems reasonable to assume a parallel trend for natural wetlands as well.

Increased temperatures may result in increased evapotranspiration and may thus decrease groundwater 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 feedback process of climate change may stem from the increase in boreal temperatures. The subsequent north-bound migration of the tundra wetland ecosystems entails a thawing of permafrost wetlands. Permafrost presently covers approximately 25% 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 methane into the atmosphere. The current approximation of the amount of methane stored in permafrost is over 5000 Tg in the ice portion alone[45]. Nakano *et al.*[40] reported that the parameter, centimetre-degrees, could be a good predictive indicator of methane emission from wetlands in permafrost areas.

Net balance of greenhouse gases

Derived from Table 3, 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 of CH_4 to trap heat exceeds that of CO_2 by a factor of 21)[46], 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 estimate by Wojick[37] 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 our global estimate of approx. 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 GHGs.

When peatlands are drained, mineralization processes start immediately and result in emissions[5] ranging between 2.5 and 10 t C ha^{-1} yr^{-1}. Mean carbon densities in wetland soils shown in Table 2 are in the range 210–700 t C ha^{-1}, whereas the carbon pool in the vegetation mass is estimated[32] to be in the order of 50 t C ha^{-1}. Emission of 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; as mentioned earlier). This computation does not take into account carbon sequestration that largely compensates the net emission of GHGs 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, eg. 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[47]. However, the net sink capacity of new wetlands is thwarted by emissions of methane. Therefore, management strategies should primarily aim at increasing the carbon pool at a given wetland area and thus a 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.

Management strategies for protecting carbon reservoirs and carbon sequestering capabilities

Conservation of wetlands 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 raising public awareness could greatly reinforce wetland conservation efforts. An additional mitigation strategy is the restoration of degraded wetlands and the creation of man-made wetland ecosystems, which could augment some of the environmental functions of wetlands (e.g. water quality improvement and flood control)[48].

Enhancing carbon reserves in wetlands in the context of climate change is consistent with reducing GHG emissions from the wetlands and restoring their carbon reserves. Degradation of wetlands and disturbances of their anaerobic environment lead to a higher rate of decomposition of the large amount of carbon stored in them and thus augment GHG 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 GHGs. With the ever-increasing population pressure and elevated food demand, the global wetlands are under significant threat. Due to the changes in land use, over exploitation, drainage and several anthropogenic activities and natural processes, the physico-chemical as well as biological conditions of wetlands 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' to manage and conserve wetlands could be an efficient tool for the future conservation of wetlands. (The ecosystem approach is a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way. It recognizes that humans, with their cultural diversity, are an integral component of ecosystems.) 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[49]. If wetlands are not preserved or maintained properly, these ecosystems could switch from being net sinks of carbon to becoming sources of GHGs that accelerate climate change. More information on specific wetland types and their role in regulating global climate (CO_2 sequestration vs CH_4 emission) is needed to devise thorough management plans.

National initiatives

In 1990, an inventory of the wetlands in India was carried out by the Ministry of Environment and Forests. According to this survey, about 4.1 mha is covered by wetlands of different categories. In addition, mangroves – coastal wetlands occupy an area[50] of about 6740 km^2. Realizing the importance of wetlands, the Ministry of Environment and Forests has taken several important steps for the conservation of wetlands, mangroves, and coral reefs in the country. The management and protection of mangroves and coral reefs have been taken into special consideration. A Coastal Regulation Zone Notification had been put forth in 1991, prohibiting development activities and disposal of wastes in the mangroves and coral reefs. Fifteen mangrove areas in the country have been identified for intensive conservation. Efforts have been initiated to establish Indian Coral Reef Monitoring Network to integrate various activities on coral reefs through national and international initiatives. Institutions of database networking, and capacity and training on coral reefs have been identified[51].

Conclusion 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 keep 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 relevant to wetland management and conservation. A broad consensus now exists that wetlands are important reservoirs of carbon in their above-ground biomass, litter, peat, soil and sediment. 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 wetlands could help resolve the long-lasting uncertainties and disagreements among scientists as well as policy makers.

Further destruction of wetlands would entail large emissions of carbon dioxide. There is broad agreement that certain types of wetlands contain large historic, reservoirs of carbon in the above-ground biomass, litter, peat, soil and sediment. It is also understood that land management practices such as drainage may cause the release of at least a portion of the stored carbon. 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.

1. de Groot, R. S., Functions of nature: evaluation of nature in environmental planning, management and decision making. *Wolters Noordhoff*, 1992, p. 315.
2. Matthews, E. and Fung, I., Methane emissions from natural wetlands: Global distribution, area and environmental characteristics of sources. *Global Biogeochem. Cycles*, 1987, **1**, 61–86.
3. Aselmann, I. and Crutzen, P. J., Global distribution of natural freshwater wetlands and rice paddies, their net primary productivity, seasonality and possible methane emissions. *J. Atmos. Chem.*, 1989, **8**, 307–358.
4. Gorham, E., In *Biotic Feedbacks in the Global Climatic System* (eds Woodwell, G. M. and MacKenzie, F. T.), Oxford University Press, New York, 1995, pp. 169–187.
5. Maltby, E. and Immirzi, C. P., Carbon dynamics in peatlands and other wetlands soils: regional and global perspectives. *Chemosphere*, 1993, **27**, 999–1023.
6. Fung, I., John, J., Lerner, J., Matthews, E., Prather, M., Steele, L. P. and Fraser, P. J., Three-dimensional model synthesis of the global methane cycle. *J. Geophys. Res.*, 1991, **96**, 13033–13065.
7. Petit, J. R. *et al*., Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature*, 1999, **399**, 429–436.
8. Chappellaz, J., Blunier, T., Dällenbach, A. Barnola, J.-M., Schwander, J., Raynaud, D. and Stauffer, B., Changes in the atmospheric CH_4 gradient between Greenland and Antarctica during the holocene. *J. Geophys. Res. D*, 1997, **102**, 15987–15997.
9. Finlayson, C. M. and van der Valk, A. G., Wetlands classification and inventory: A summary. *Vegetatio*, 1995, **11**, 185–192.
10. Environment Protection Agency, Guidance specifying management measures for sources of nonpoint pollution in coastal waters. http://www.epa.gov/OWOW/NPS/MMGI/, 1993.
11. Post, W. M., Emanuel, W. R., Zinke, P. J. and Stangenberger, A. G., Soil carbon pools and world life zones. *Nature*, 1982, **298**, 156–159.
12. Zinke, P. J., Stangenburger, A. G., Post, W. M., Emmanuel, W. R. and Olson, J. S., Worldwide organic soil carbon and nitrogen data. Environmental Sciences Division, Oak Ridge National Lab/US Department of Energy, 1984, Publication No. 2212.
13. Tarnocai, C., Canadian wetland registry. In Proceedings of a Workshop on Canadian Wetlands (eds Rubec, C. D. A. and Pollett, F. C.), Environ. Can., Ecol. Land Class. Series No. 12. Ottawa, 1980, pp. 9–21.
14. Gorham, E., Northern peatlands: Role in the carbon cycle and probable responses to climate warming. *Ecol. Appl.*, 1991, **1**, 182–195.
15. Walter, H., *Ecology of Tropical and Subtropical Vegetation*, Oliver & Boyd, Edinburgh, 1971.
16. Radjagukuk B., *Prospects of Peat Exploitation in Indonesia*, 1985, pp. 99–112.
17. Ramsar Information Bureau, Report of Allocations 1992–97, The Ramsar Convention, Small Grants Fund, Ramsar, Gland, Switzerland, 1998. http://www.iucn.org/themes/Ramsar.
18. Tiner, R. W., *Wetland Indicators: A Guide to Wetland Identification, Delineation, Classification, and Mapping*, CRC Press, LLC, USA, 1999.
19. Costanza, R. *et al*., The value of the world's ecosystem services and natural capital. *Nature*, 1997, **387**, 253–260.
20. IPCC, A special report of IPCC working group III: Summary for policymakers, emission scenarios (eds Nakiæenoviæ, N. *et al*.,), Cambridge University Press, Cambridge, 2001.
21. Khalil, M. A. K. and Rasmussen, R. J., Sources, sinks and seasonal cycles of atmospheric methane. *J. Geophys. Res*., 1983, **88**, 5131–5144.
22. Houghton, J. T., Meira Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A. and Maskell, K., *Climate Change 1995, The Science of Climate Change*, Cambridge University Press, Cambridge, UK, 1996.
23. Kusler, J. A., Carbon Cycle Implications Newsletter of the US National Assessment of the Potential Consequences of Climate Variability and Change. Institute for Wetlands Science and Public Policy, 1999.
24. Clair, T. A., Warner, B. G., Robarts, R., Murkin, H., Lilley, J., Mortsch, L. and Rubec, C., Canadian wetlands and climate change. In Canada Country Study: Climate impacts and adaptation. *Environ. Can*., 1998, **7**, 189–218.

25. Frederick, K., Water resources and climate change. *Climate Issues Brief No. 3. Resources For The Future*, Washington DC, 1997, p. 14.
26. Warren, R. S. and Niering, N. A., Vegetation change on a northeast tidal marsh: Interaction of sea level rise and marsh accretion. *Ecology*, 1993, **74**, 96–103.
27. Patterson, J., Wetlands and climate change. Feasibility investigation of giving credit for conserving wetlands as carbon sinks. Wetlands International Special, 1999.
28. Moore, T. R., Roulet, N. T. and Waddington, J. M., Uncertainty in predicting the effect of climatic change on the carbon cycling of the Canadian peatlands. *Climatic Change*, 1998, **40**, 229–245.
29. Davis, T. J., The Ramsar Convention Manual: A guide for the Convention on Wetlands of International Importance especially as waterfowl habitat, Ramsar Convention Bureau, Gland, Switzerland, 1994, p. 207.
30. Darras, S., Michou, M. and Sarrat, C., IGBP-DIS wetlands data initiative, a first step towards identifying a global delineation of wetlands. IGBP-DIS Working Paper, No. 19, 1999.
31. Takeuchia, W., Masayuki, T. and Yoshifumi, Y., Estimation of methane emission from West Siberian wetland by scaling technique between NOAA AVHRR and SPOT HRV. *Remote Sensing Environ.*, 2003, **85**, 21–29.
32. WBGU, Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen: Die Anrechnung biologischer Quellen und Senken im Kyoto-Protokoll: Fortschritt oder Rückschlag für den globalen Umweltschutz. Sondergutachten 1998, Bremerhaven, Germany, p. 76 (available in English).
33. Falkowski, P. *et al*., The global carbon cycle: A test of our knowledge of earth as a system. *Science*, 2000, **290**, 291–296.
34. Buringh, P., Organic carbon in soils of the world. In *The Role of Terrestrial Vegetation in the Global Carbon Cycle. Measurement by Remote Sensing* (ed. Wondwell, G. M.), SCOPE 23, 1984, pp. 91–109.
35. Armentano, T. V. and Menges, E. S., Patterns in the change of carbon balance of organic soil wetlands of the temperature zone. *J. Ecol.*, 1986, **74**, 755–774
36. Matthews, E., Vegetation, land-use and seasonal albedo data sets: Documentation of archived data sets. NASA Technical Memorandum, No. 86107 (original not seen), 1984.
37. Wojick, D. E., Carbon storage in soils: The ultimate no-regrets policy? A report to greening earth society, 1999 http://www.greeningearthsociety.org/pdf/carbon.pdf
38. Cao, M., Gregson, K. and Marshall, S., Global methane emission from wetlands and its sensitivity to climate change. *Atmos. Environ.*, 1998, **32**, 3293–3299.
39. Bartlett, K. B. and Harris, R. C., Review and assessment of methane emissions from wetlands. *Chemosphere*, 1993, **26**, 261–320.
40. Nakano, T., Kuniyoshi, S. and Fukuda, M., Temporal variation in methane emission from tundra wetlands in a permafrost area, northeastern Siberia. *Atmos. Environ.*, 2000, **34**, 1205–1213.
41. Minkkinen, K. and Laine, J., Long term effect of forest drainage on the peat carbon stores of pine mires in Finland. *Can. J. For. Res.*, 1998, **28**, 1267–1275.
42. Roulet, N. T. and Moore, T. R., The effect of forestry drainage practices on the emission of methane from northern peatlands. *Can. J. For. Res.*, 1995, **25**, 491–499.
43. Kasimir-Klemedtsson, L., Berglund, K., Martikainen, P., Silvola, J. and Oenema. O., Greenhouse gas emissions from farmed organic soils: a review. *Soil Use Manage.*, 1997, **13**, 245–250.
44. Ziska, L. H. and Caulfield, F. A., Rising CO_2 and pollen production of common ragweed (*Ambrosia artemisiifolia*), a known allergy-inducing species: Implications for public health. *Aust. J. Plant Physiol.*, 2000, **27**, 893–898.
45. IPCC, Climate Change 1992 – The Supplementary Report to the IPCC Scientific Assessment (eds Houghton, J. T., Callander, B. A. and Varney, S. K.), Cambridge University Press, UK, 1992, p. 205.
46. IPCC, In Proceedings of the International Professional Communication Conference, Tech. Pap., Québec City, Canada, 23–25 September 1998, volume 2, IEEE Professional Communication Society, 1998.
47. Wylynko, D., Prairie wetlands and carbon sequestration – Assessing sinks under the Kyoto Protocol, International Institute for Sustainable Development, Winnipeg, Canada, 1999, p. 45.
48. Kusler, J. A. and Kentulla, M. E., *Wetlands Creation and Restoration: The Status of the Science*, Island Press, Washington DC, 1990.
49. Batjes, N. H., Management options for reducing CO_2-concentrations in the atmosphere by increasing the carbon sequestration in soil. ISRIC Technical Paper 30, Wageningen, The Netherlands, 1999.
50. Biswas, D. K. and Trisal, C. L., Indo-British Workshop on Biodiversity, 1993, pp. 47–70.
51. Anon., Fish collection database of the Natural History Museum, London (formerly British Museum of Natural History), 1999.
52. Sjörs, H., Peat on earth: multiple use or conservation? *Ambio*, 1980, **9**, 303–308.
53. Adams, J. M., Faure, H., Faure-Denard, L., McGlade, M. and Woodward, F. I., Increases in terrestrial carbon storage from the Last Glacial Maximum to the Present. *Nature*, 1990, **348**, 711–714.
54. Eswaran, H., Van den Berg, E. and Reich, P., Organic carbon in soils of the world. *J. Soil Sci. Soc. Am.*, 1993, **57**, 192–194.
55. Batjes, N. H., Total carbon and nitrogen in the soils of the world. *Eur. J. Soil Sci*., 1996, **47**, 151–163.
56. Bartlett, K. B., Crill, P. M., Bonassi, J. A., Richey, J. E. and Harriss, R. C., Methane flux from the Amazon River floodplain: emissions during rising water. *J. Geophys. Res*., 1990, **97**, 16773–16788.
57. Cao, M., Marshall, S. and Gregson, K., Global carbon exchange and methane emissions from natural wetlands: application of a process-based model. *J. Geophys. Res*., 1996, **101**, 14399–14414.
58. Hein, R., Crutzen, P. J. and Heimann, M., An inverse modeling approach to investigate the global atmospheric methane cycle. *Global Biogeochem. Cycles*, 1997, **11**, 43–76.
59. Seiler, W. and Conrad, R., Contribution of tropical ecosystems to the global budgets of trace gases, especially CH_4, H_2, CO, and N_2O. In *The Geophysiology of Amazonia* (ed. Dickinson, R. E.), John Wiley, New York, 1987, pp. 133–162.
60. Sebacher, D. I., Harriss, R. C., Bartlett, K. B., Sebacher, S. M. and Grice, S. S., Atmospheric methane sources: Alaskan tundra bogs, an alpine fen, and a subarctic boreal marsh. *Tellus*, 1986, **38**, 1–10.
61. Crill, P. M. *et al.*, Methane fluxes from Minnesota peatlands. *Global Biogeochem. Cycles*, 1988, **2**, 371–384.
62. Moore, T. R., Roulet, N. T. and Knowles, R., Spatial and temporal variations of methane flux from subarctic/northern boreal fens. *Global Biogeochem. Cycles*, 1990, **4**, 29–46.
63. Ritter, J. A. *et al*., Airborne flux measurements of tree species in an artic boundary layer. *J. Geophys. Res*., 1992, **97**, 16601–16625.
64. Whalen, S. C. and Reeburgh, W. S., Interannual variations in tundra methane emission: A 4-year time-series at fixed sites. *Global Biogeochem. Cycles*, 1992, **6**, 139–159.
65. Christensen, J. H., Christensen, O. B., Lopez, P., van Meijgaard, E. and Botzet, M., The HIRHAM4 Regional Atmospheric Climate Model. DMI Scientific Report, DMI, Copenhagen, 1996, vol. 96, p. 51.
66. Reeburgh, W. S., Kling, J. Y., Regli, S. K., King, G. W., Auerbach, N. A. and Walker, D. A., A CH_4 emissions estimate for the Kuparuk River Basin, Alaska. *J. Geophys. Res*., 1998, **103**, 29005–29013.

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