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Global Distribution of Natural Freshwater Wetlands and Rice Paddies, their Net Primary Productivity, Seasonality and Possible Methane Emissions

I. ASELMANN and P. J. CRUTZEN
Max-Planck-Institute for Chemistry, Division of Atmospheric Chemistry, PO Box 3060, D-6500 Mainz, F.R. Germany

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Abstract. A global data set on the geographic distribution and seasonality of freshwater wetlands and rice paddies has been compiled, comprising information at a spatial resolution of 2.5° by latitude and 5° by longitude. Global coverage of these wetlands total 5.7×10^6 km^2 and 1.3×10^6 km^2, respectively. Natural wetlands have been grouped into six categories following common terminology, i.e. bog, fen, swamp, marsh, floodplain, and shallow lake. Net primary productivity (NPP) of natural wetlands is estimated to be in the range of $4\text{–}9 \times 10^{15}$ g dry matter per year. Rice paddies have an NPP of about 1.4×10^{15} g y^{-1}. Extrapolation of measured CH_4 emissions in individual ecosystems lead to global methane emission estimates of 40–160 Teragram (1 Tg $= 10^{12}$ g) from natural wetlands and 60–140 Tg from rice paddies per year. The mean emission of 170–200 Tg may come in about equal proportions from natural wetlands and paddies. Major source regions are located in the subtropics between 20 and 30° N, the tropics between 0 and 10° S, and the temperate-boreal region between 50 and 70° N. Emissions are highly seasonal, maximizing during summer in both hemispheres. The wide range of possible CH_4 emissions shows the large uncertainties associated with the extrapolation of measured flux rates to global scale. More investigations into ecophysiological principals of methane emissions is warranted to arrive at better source estimates.

Key words. Wetlands, bog, fen, swamp, marsh, floodplain, lake, rice paddy, net primary productivity (NPP), distribution, seasonality, methane emissions.

1. Introduction

Methane is a significant 'greenhouse gas' and is of fundamental importance in atmospheric photochemistry, as it regulates the formation of ozone (O_3) and hydroxyl (OH), which are responsible for the breakdown of most gases that are emitted into the atmosphere by natural and anthropogenic processes (Levy, 1971; McConnell *et al.*, 1971; Crutzen, 1973). The methane load of the atmosphere has been increasing for the past three centuries from about 0.7 to 1.7 parts per million by volume (ppmv) with accelerating speed during the past decades (Craig and Chou, 1982; Rasmussen and Khalil, 1984; WMO, 1985; Khalil and Rasmussen, 1987). The current rate of increase is around 1% per year, adding some 40–50 Teragram (1 Tg $= 10^{12}$ g) to the atmosphere. The increase in the atmospheric methane load can be attributed both to increasing production from biogenic and abiotic sources at the Earth's surface and to a decrease of the abundance of OH radicals, the major sink for methane in the atmosphere. Atmospheric increase, destruction through OH and microbial consumption at the Earth's surface require CH_4 sources totalling some 400–600 Tg annually (WMO, 1985; Cicerone and Oremland, 1988). The most important methane sources are enteric fermentation in ruminants, anaerobic decay of organic matter in rice paddies, natural wetlands and landfills, coal mining, natural gas production and distribution, oil exploration and production, and biomass burning. Although the total CH_4 source is fairly well established, the distribution among the individual sources is far less certain. For instance, for natural wetlands source estimates in the past ranged between 13 and 300 Tg (e.g. Ehhalt, 1974; Baker-Blocker *et al.*, 1977; Seiler, 1984), but newer estimates indicate a range of 100 to 150 Tg (Matthews and Fung, 1987). Recent investigations by Manning *et al.* (1989) and Wahlen *et al.* (1989, and private communication) have indicated that 20–30% of the methane could be abiotic. In 1988, Cicerone and Oremland made a comprehensive overview of the atmospheric methane budget. This study will concentrate on natural wetlands and rice paddies whose source strengths are still largely uncertain.

Frequently cited estimates of global wetland areas range between 2 and 3.6×10^6 km^2 (Lieth, 1975; Whittaker and Likens, 1975; Ajtay *et al.*, 1979). The first two of these studies only consider swamps and marshes, whereas Ajtay *et al.* (1979) also include an estimated peatland area of 1.6×10^6 km^2 in tundra regions. Yet, according to other studies, the area of peatlands alone ranges from 2.3×10^6 km^2 to about 4×10^6 km^2 (Bazilevich *et al.*, 1971; Moore and Bellamy, 1974; Kivinen and Pakarinen, 1981). Esser (1984), based on Schmithüsen's atlas of potential natural vegetation ('Atlas zur Biogeographie', 1976) arrives at 4.4×10^6 km^2 for the global area of freshwater wetlands. Of these, only 0.6×10^6 km^2 are classified as bogs and other cold temperate or boreal peatlands. Matthews and Fung (1987) published a compilation of wetlands from three independent data sets on vegetation, soil, and inundation. Their global estimate for wetland areas is 5.3×10^6 km^2, of which 2.6×10^6 km^2 are classified as forested or nonforested bogs mostly in latitudes north of 50° N. These numbers show that, due to different classification, the distribution and extent of wetlands are subject to rather high uncertainties. In Section 2 and 3 of this paper, we present a data set on freshwater wetlands that is designed specifically for methane emission studies. It is compiled from published information and various maps and is spatially resolved on a 2.5° latitude by 5° longitude grid. It includes information on seasonality brought about by flooding and freezing. We consider seasonal and permanent freshwater ecosystems, either peatforming or not, that are likely to exhibit anoxic conditions when waterlogged or inundated, and are thus likely to produce methane. Saltwater wetlands are excluded as their methane production is usually insignificant (Bartlett *et al.*, 1985b). In addition to natural wetlands, we compiled a data set at the same grid resolution for rice paddies. The data set described here uses different information from Matthews and Fung's (1987) compilation. Our data are basically drawn from regional wetland surveys and monographs, while Matthews and Fung's study is based on a combination of global sets of maps on soils, vegetation, and inundation. Both compilations also differ in their wetland classification. In Section 5 of this paper we derive estimates on net primary productivity of wetlands and use this information to estimate ranges of CH_4 emissions. These are compared to emission estimates derived from measured flux rates presented in Section 6.

2. Terminology and Sources of Information

The starting point for our investigation has been the book by Gore (1983) on mires. This volume describes most of the World's regions with extended wetlands (i.e. Canada, the U.S.A., Brasil, Scandinavia, the British Isles, the U.S.S.R., Australasia, Western Malaysia, and Africa). Wetlands in the remaining regions were deduced for this study from various maps. The classification of wetlands for each region in the data set follows those used in the sources. This allows flexible grouping of specific types into broader categories, which may have similar methane emission rates.

In total, 45 different freshwater wetland types are distinguished, which we grouped into six categories (Zoltai and Pollett, 1983): bogs, fens, swamps, marshes, floodplains, and shallow lakes.

Bogs (raised bogs) are peat producing wetlands in moist climates, where organic material has accumulated over long periods. Their main feature is ombrotrophy, which means that water and nutrient input into the system is entirely through precipitation. There is no mineral input through soil water as the system, during peat formation, has risen above the land surface. Bogs are thus extremely acid and nutrient deficient. Typically, the major vegetation component is sphagnum moss but others may be dominant in the tropics and the Southern Hemisphere.

Fens are peat producing wetlands which are influenced by soil nutrients from water flowing through the system. They are commonly less acid than bogs and may even be alkaline. The vegetation consists of grasses or sedges in community with mosses. Nevertheless, other plants may occur. Due to the better nutritional status in comparison to bogs, fens are commonly more prolific, given the same climatic conditions. The largest areas are to be found in boreal and tundra regions including the area of permafrost in the extreme north.

Swamps are forested freshwater wetlands on waterlogged or inundated soils, where little or no peat accumulation takes place. This definition follows North American terminology. In other parts of the world, the term is not restricted to forested wetlands, but may also apply to herbaceous communities such as papyrus swamps in Africa, which we classified as marsh.

Marshes are herbaceous mires with vegetation commonly dominated by grasses, sedges or reeds. They are subject to gravitational waterlevels and they may be either permanent or seasonal wetlands. Salt marshes are excluded from this category, because they do not produce significant fluxes of methane. Whenever the vegetation type is not documented, the distinction between marshes and swamps becomes arbitrary.

Floodplains are periodically flooded areas along rivers or lakes. They show considerable variation in vegetation cover. Seasonally flooded savannas of Africa and South America, usually comprised of a mixture of grass and trees, constitute the major wetland type in this category.

Shallow lakes denote open water bodies of a few meters depth, which are likely to emit methane through the watercolumn to the atmosphere. This category is only considered for Europe, Africa, and South America. In cool temperate and arctic regions they are included in bogs, fens, and marshes, often composed of a mosaic of mire vegetation and open waters.

It is recognized, that the above grouping of a large variety of wetlands into only six categories, contrasts to the partly very detailed classifications available for certain regions. However, differences in terminology and data accuracy for different regions hamper a more detailed distinction.

Swamps, marshes and floodplains may exhibit substantial seasonality, a fact that is important for methane studies as it determines the length of the CH_4-productive period. Whether a wetland is seasonally or permanently waterlogged was deduced from the literature. In many cases, wetlands were cited as seasonal but time and duration of inundation was not given. In such cases, the time of inundation was determined from hydrological and meteorological records. For this, data on the high-water period of the major rivers were taken from Degens (1982) and Degens *et al.* (1983, 1985), while for catchment areas with no hydrological data available, the wet season was infered from rainfall data (Müller, 1983). However, for swamps, information on the seasonal status was not always available and these areas were classified as swamps with unknown seasonality. The duration of the inundation periods in the data set is generally expressed in units of months. Next, we present estimates of the coverage of wetland types in the world on a regional basis and summarize the information in Table I.

3. Geographical Distribution of Wetlands

Canada: The distribution of wetlands has been digitized from the 'National Atlas of Canada' (1986) by following the subdivision of wetland regions and types in Zoltai and Pollett (1983). In total, Canada has about 1.27×10^6 km^2 of wetlands of which bogs and fens constitute 95%.

U.S.A.: In the U.S. (contiguous states) extension, distribution, and classification of mires were taken from Shaw and Fredine (1956), who give an area of

Table I. Global wetland areas [in 10^3 km^2]

Region		Bogs		Fens		Swamps		Marshes		Floodplains		Lakes		Total
U.S.S.R.	max:	917	(6-9)	531	(7-8)	25	(4-10)	39	(4-11)	–	–	–	–	1512
	min:	0	(12-3)	0	(12-2)	0	(12-2)	0	(1-2)	–	–	–	–	
Europe	max:	54	(5-9)	93	(5-9)	1	(1-12)	4	(4-11)	1	(4-6)	1	(4-11)	154
	min:	25	(1-2)	7	(2)	–	–	1	(1)	0	(7-3)	<1	(12-2)	
Near East	max:	–	–	–	–	–	–	8	(1-12)	–	–	–	–	8
	min:	–	–	–	–	–	–	–	–	–	–	–	–	–
Far East	max:	–	–	–	–	11	(1-12)	–	–	–	–	–	–	11
	min:	–	–	–	–	–	–	–	–	–	–	–	–	
China	max:	11	(4-10)	–	–	3	(3-11)	18	(4-10)	–	–	–	–	32
	min:	0	(11-3)	–	–	2	(12-2)	0	(11-3)	–	–	–	–	
S.E. Asia	max:	197	(1-12)	–	–	44	(1-12)	–	–	–	–	–	–	241
	min:	–	–	–	–	–	–	–	–	–	–	–	–	
Aust./N.Z.	max:	2	(1-12)	3	(1-12)	1	(1-12)	–	–	9	(1-3)	–	–	15
	min:	–	–	–	–	–	–	–	–	0	(4-12)	–	–	
Africa	max:	–	–	–	–	85	(1-12)	57	(4-7)	174	(8)	39	(1-12)	355
	min:	–	–	–	–	–	–	49	(9-3)	7	(11)	–	–	
Alaska	max:	?	–	400	–	?	–	?	–	?	–	?	–	(325)
	min:	?	–	250	–	?	–	?	–	?	–	?	–	
Canada	max:	673	(6-9)	531	(7-8)	14	(4-10)	44	(4-10)	–	–	6	(4-10)	1268
	min:	3	(1)	<1	(1)	<1	(1)	<1	(1)	–	–	0	(11-3)	
U.S.A.	max:	13	(4-10)	–	–	80	(4-10)	40	(4-10)	95	(3)	–	–	228
	min:	11	(12-2)	–	–	52	(1)	27	(1)	0	(7-11)	–	–	
Cen. America	max:	–	–	–	–	15	(1-12)	2	(1-12)	1	(8-10)	–	–	18
	min:	–	–	–	–	–	–	–	–	0	(11-7)	–	–	
S. America	max:	–	–	–	–	851	(4)	62	(6-8)	543	(3)	68	(1-12)	1524
	min:	–	–	–	–	534	(10)	54	(9-5)	29	(6)	–	–	
Total		1867		1483		1130		274		823		114		5691

0.23×10^6 km^2 of freshwater wetlands. It would appear, however, that this estimate is somewhat out of date, as additional drainage of wetlands has taken place. Nevertheless, Hofstetter (1983) in his recent chapter on mires in the U.S., employs these data unaltered. The distribution of the various wetland types and their seasonal wetland status was determined from the major migration routes of water fowl. Within these regions, mires were distributed according to map diagrams given in Shaw and Fredine (1956). Fen is not a common term in the U.S. and fens are often included in bogs, comprising all types of 'mossy' peatlands.

South America: Descriptions and estimates of wetlands in the Amazon region and northern South America have been supplied by Junk (1989). About 0.3×10^6 km^2 of floodplains, called Várzea and Igapó, occur along the Amazon and its tributaries. The geographical distribution of the Várzea and Igapó areas was obtained from the 'Atlas zur Biogeographie' and from a map in Junk (1989). The waterlevel of the main rivers follows a monomodal floodpattern with decreasing amplitude from the upper Amazon to the delta. Maximum waterlevel occurs in May–June and the entire flood period normally lasts from April to September, although there is a large variation from year to year. At high water, the floodplains consist of 60% open water body, about 30% flooded forests, and some 10% aquatic macrophytes (Junk, 1985). As waters recede, large areas of the floodplains become dry. At low water, some 40% are covered by herbaceous plant communities, about 30% remain as lakes and river channels, the rest is forest. These are, of course, approximate mean numbers which change from place to place (Junk, 1985). However, we assume 30% shallow lakes and 70% of seasonal swamps within the floodplain, while recognizing that interactions between inundation and wetland status are quite complicated. For the Peruvian part of the Amazon system, we followed the description and map in Salo *et al.* (1986). Furthermore, Junk (1989) estimates that up to another 1×10^6 km^2 of small river and stream floodplains may occur on *terra firma* within the Amazon basin, mainly in regions of rain forests. This estimate is based on soil maps of the vicinity of Manaus and subsequent extrapolation to entire Amazonia. As the streams rise instantaneously after heavy rains, these floodplains exhibit polymodal flood patterns. Tentatively, we estimate that there are some 0.5×10^6 km^2 of small river floodplain, which we distributed as forested swamps onto the grid areas for the Amazon lowland. Both large and small river floodplains according to this estimate, account for more than 30% of the Amazon lowland. The distribution of wetlands in the Orinoco basin, in the Magdalena region, and other wetland areas north of the Amazon follows that of Junk (1989).

Information about wetlands for regions south of the Amazon catchment area are scarce and only qualitative descriptions exist (e.g. Pisano, 1983; Walter, 1973). We used 'The Great Geographical Atlas' (1982), the 'Atlas zur Biogeographie' (1976), and the 'World Atlas of Agriculture' (1969) and compared land use, natural vegetation and inundated areas to deduce the wetland areas, particularly within the Pantanal and the floodplains along the Rio Parana drainage system. Salt pans or halophytic wetlands were excluded. In total, we estimate a wetland area of 1.52×10^6 km^2 in South America.

U.S.S.R.: Classification, distribution and extent of wetlands in the U.S.S.R. follows information by Botch and Masing (1983, and personal communication, 1986). Wetlands are estimated to cover some 1.5×10^6 km^2. Of these, the European part and western Siberia are well documented, but information deteriorates towards the north-eastern parts of Siberia. We substracted the better documented wetlands in the European part and in western Siberia (Vasyuganye bogs, Walter (1977)) from the total of 1.5×10^6 km^2 and distributed the remaining areas according to 'The World Atlas' (1969) onto the 2.5° × 5° grid. The division into wetland types follows Botch and Masing (1983). In total, 65 000 km^2 were classified as swamps and marshes and 1.45×10^6 km^2 as bogs and fens.

Europe: The extent and distribution of wetlands in Europe were deduced from various surveys. For Sweden, we used the 'Atlas över Sverige' (Map on Peatlands), which was kindly provided to us by Prof. H. Sjörs. The wetlands deduced from the map cover 14.6% of the country in agreement with the estimate of 14–16% by Sjörs (1983). The breakdown of wetlands into different mire types in each grid follows the descriptions by Sjörs (1983). In Finland, approximately 104 000 km^2 or *ca.* 30% of the total land were once covered by virgin mires, of which about 55 000 km^2 have been reclaimed, mainly for forestry (Ruuhijärvi, 1983). The distribution of the remaining virgin wetlands (47 500 km^2) among the various types were deduced from maps in Ruuhijärvi (1983). Wetlands on Iceland (mostly fen) are estimated to cover about 10 000 km^2 (Gore, 1983). Great Britain and Ireland have almost 25 000 km^2 of bogs and fens (Taylor, 1983). This excludes reclaimed areas that have been drained for forestry or peat industry. The distribution of the wetland types in the data set follows the maps given by Taylor (1983).

Virgin peatlands and other types of freshwater wetlands in Central Europe have almost all been drained and turned into agricultural land and forests. In Poland, more than 90% of the once existing mire area of *ca.* 15 000 km^2 has been exploited (Gore, 1983). Some wetland areas still exist in southern Europe, in France and Rumania. In total, we deduced 6 700 km^2 of various wetland types on mainland Europe (excluding the U.S.S.R.) from descriptions by Gore (1983).

Africa: African wetlands and their geographical distribution have been described by Thompson and Hamilton (1983) with revision by Howard-Williams and Thompson (1985). The latter publication includes a list of the main drainage systems of the continent and their wetland regions giving information on location, seasonality, and wetland status. These data, in conjunction with maps provided by the same authors, allowed the derivation of a geographical distribution of wetlands onto the 2.5° × 5° grid scheme. For the Okavango delta, data from satellite remote sensing on the permanent and seasonal status of the swamps were used (Hutton and Dincer, 1979). We have broken down some areas of shallow lakes quoted by Howard-Williams and Thompson into 10% marsh and 90% water body (shallow lakes). In total, Africa has an estimated wetland area of 356 000 km^2, both permanent and seasonal.

South East Asia: For Indonesia, Papua New Guinea, and Malaysia we used the data by Anderson (1983). According to this author, peatlands in Malaysia and Indonesia (excluding West Irian) occupy some $0.18–0.19 \times 10^6$ km^2 with the major portion on Sumatra and Kalimantan. These wetlands are mostly forested peat plateaus, resembling temperate bogs in their ombrotrophy. Extensive wetlands occur also on Papua New Guinea, but no estimate is given by Anderson. We used 'The Great Geographical Atlas', the 'Atlas zur Biogeographie', the 'World Atlas of Agriculture' and supplementary information from Walter (1973) to deduce a swamp and bog area of 69 000 km^2 on the island. Altogether we estimate the area of forested peat bogs and swamps in Indonesia, Papua New Guinea, and Malaysia at 200 000 and 44 000 km^2, respectively. No specification of types and seasonality was available for the swamps.

Australia and New Zealand: Information on virgin mires in Australia was deduced from the 'Atlas of Australian Resources, Natural Vegetation' (1976) and from Campbell (1983). Freshwater wetlands occur as marshy floodplains and forested swamps on the north coast and as sedgeland on Tasmania. As in other parts of the world, large areas of wetlands have been converted to agriculture. These and ephemeral floodplains, so-called channel countries (Carnahan, 1976, and personal communication, 1986), in the inner and south-easterly regions of Australia have been excluded. Also, in New Zealand considerable areas of wetlands have been reclaimed for agricultural purposes and the present area of unmodified peatlands is assessed to be 1400–1660 km^2, mostly Restiad bogs (Davoren, 1978; McCraw, 1979).

Other parts of the world: Wetlands in the regions considered so far constitute the major fraction of the global wetland inventory. In addition, it is necessary to consider further regions for which no information is available in the literature. These regions are China, the Near East (Iran, Iraq), the Far East with India and Bangladesh, South East Asia (Birma, Cambodia, Vietnam), Central America, and Alaska for which we give estimates deduced from physical atlasses, land use maps ('World Atlas of Agriculture') and vegetation maps ('Atlas zur Biogeographie').

For China, we deduced a wetland area of 31 000 km^2 in the extreme north-east of the country, which agrees well with the estimated 34 800 km^2 of virgin peatlands given by Kivinen and Pakarinen (1981). Yet, due to lack of information, the categorization of wetland types remains rather difficult. This also applies to the estimated wetland area in the Far East (10 700 km^2) along the main rivers and in the large river deltas, where rice cultivation is extensive and where paddies mix with natural wetlands. Our estimates for the Near East (8000 km^2 of marsh) and for Central America (17 500 km^2) are also tentative, since no explicit descriptions of wetlands in these regions are available. However, the major problem remains with Alaska for which all surveyed maps most probably underestimate the wetland area. For instance, 'The Great Geographical Atlas' shows wetlands for only about 55 000 km^2, whereas according to Dachnowski-Stokes (1941, cited by Hofstetter, 1983), wetlands (bogs and marshes or fens) cover some 445 000 km^2 or 29% of the land surface. This is more than the entire lowland plains in this state. Peat deposits are estimated to be even more widespread (494 000 km^2; Kivinen and Pakarinen, 1981). This estimate is based on soil survey data by the USDA and includes 114 000 km^2 of true peat deposits (Histosols) and 380 000 km^2 of organic tundra soil on permafrost. As these soil types, in particular the latter, are likely not all methane producing, we estimate that mires in Alaska cover an area of 250 000–400 000 km^2, mostly fens and bogs. For the following methane calculations we assume an area of 325 000 km^2.

In summary, we arrive at a global wetland area of 5.7×10^6 km^2 (c.f. Table I). The most widespread wetland category is bogs covering 1.9×10^6 km^2, followed by fens and swamps contributing about 1.5×10^6 km^2 and 1.1×10^6 km^2, respectively. Floodplains add another 0.8×10^6 km^2, whereas marshes and lakes contribute only 7% to the total. Seasonal swamps, marshes, and floodplains together cover about 1.2×10^6 km^2, of which 0.8×10^6 km^2 are seasonal floodplains mainly in South America and Africa. Wetlands, with no defined inundation period, or unknown seasonality, add up to 0.7×10^6 km^2, the major fraction of this stems from small river floodplains in the Amazon basin. Truly permanent swamps, marshes and floodplains only sum up to 0.3×10^6 km^2. The duration of flooding, in the case of seasonal floodplains, is between 2 and 6 months with a mean of 3.5 months, whereas seasonal swamps and marshes on average are wet for about 5 months. The seasonality of the areas in Table I is expressed by the maximum and minimum extent of wetlands, followed by the months (in parenthesis), denoting the frost free or flooding period. For example, all bogs in the U.S.S.R. are dormant due to frost between December and March, whereas all areas are active between June and September.

The distribution of the wetlands along 10° latitude belts is displayed in Figure 1a, and Figure 1b depicts the monthly active wetland area along the 10° latitude regions. The largest areas occur between 50° and 70° N, comprised of bogs and fens primarily in Alaska, Canada, and the U.S.S.R. Second in importance is the tropical belt between 10° N and 20° S with major contributions from the Amazon region, from South-East Asia and Africa. Figures 2a–g depict the geographic distributions of the wetland categories. The numbers denote the area of wetlands expressed in percent fraction of the grids. The grid areas (in km^2) are given in the right-hand column, while the first column and top and bottom row denote the latitudes and longitudes of the grid centers. Major regions of peatlands (bogs and fens) are found in Canada along the south-west coast of Hudson Bay and also in Scandinavia, as fens in the north and as bogs in the south. In the U.S.S.R., the largest bog region is found in the West Siberian lowland around the

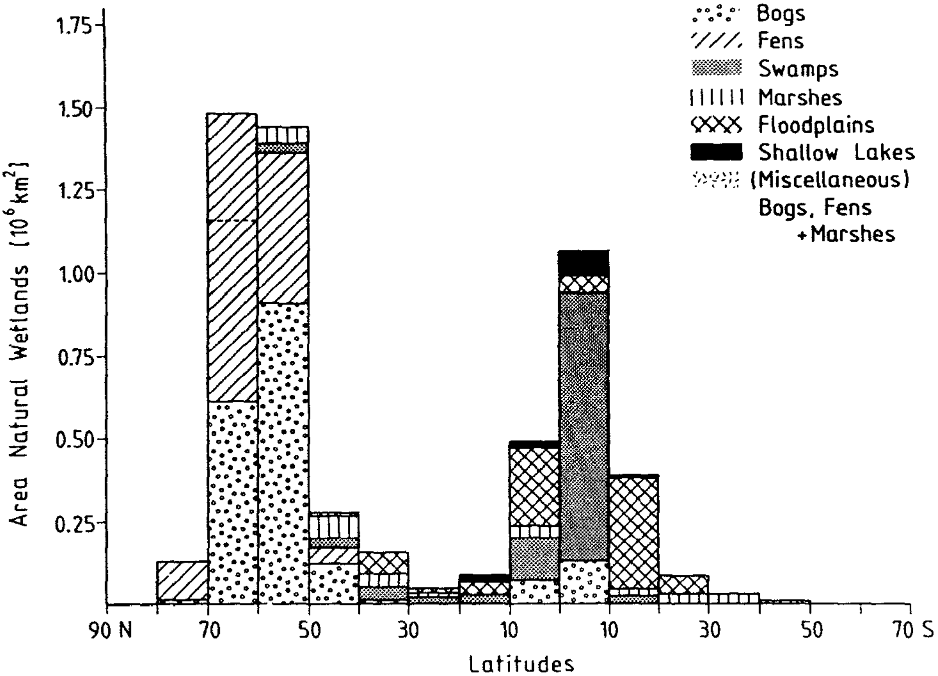

Fig. 1a. Distribution of natural wetlands along 10° latitudinal belts.

Vasyuganye bogs, whereas fens are more dominant in the eastern part of the country. Tropical forested peat bogs are concentrated on the island of New Guinea, Borneo, and Sumatra. Swamps and floodplains are located primarily in temperate and tropical regions. The largest swamps and floodplains occur in the Amazon region, in southern Brasil and Argentina and on the African peneplain.

Other compilations comparable to our data set are less detailed with respect to wetlands (excluding Matthews and Fung, 1987) as they emphasie vegetation classification based on climate and plant form (Esser, 1984), on soil and climate (Bazilevich *et al.*, 1971), or on phytomass (Olson *et al.*, 1985). Due to these authors' specific interests, they do not always distinguish between 'wet' and 'dry' lands. For example, the bog area given by Bazilevich *et al.* (1971) is 3.2×10^6 km^2, of which only 2×10^6 km^2 can be classified as true bogs. The same mixing of wetlands and nonwetlands is apparent in their swamp category, leading to a total estimate of 11.2×10^6 km^2 in their compilation.

Esser's (1984) estimate of total freshwater wetlands (4.4×10^6 km^2) is closer to the estimate in the present study (5.7×10^6 km^2). Due to a different classification, the total wetland area in his compilation consists primarily of swamps and floodplains each contributing about 1.9×10^6 km^2.

Olson *et al.* (1985) have published a digital data set of major world ecosystem complexes that include two broad categories; cool mires (peatlands) and warm

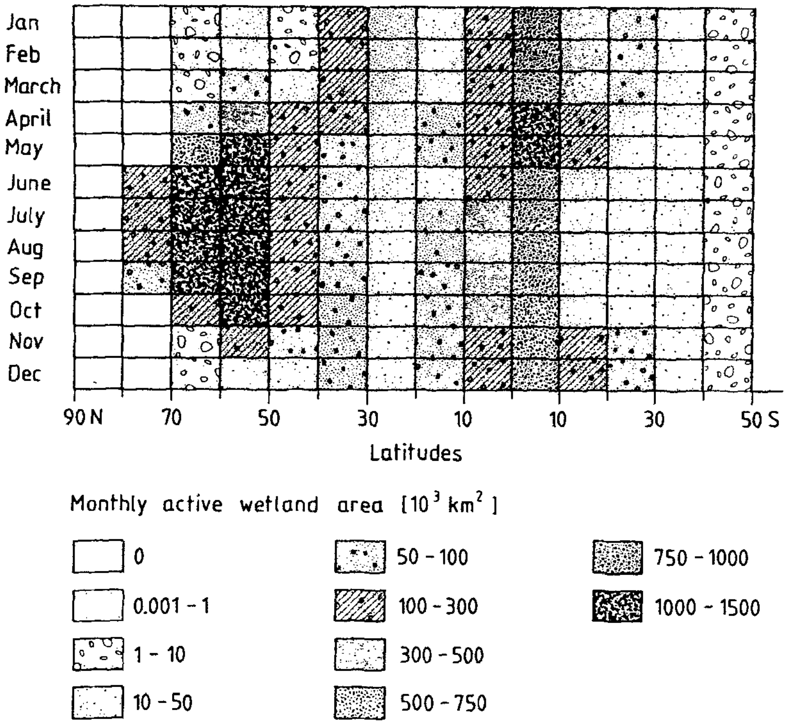

Fig. 1b. The monthly active wetland area (either frost free or inundated) for 10° latitude belts in correspondence to Figure 1a.

wetlands (swamps and marshes), covering areas of about 10^6 km^2 and 1.6×10^6 km^2, respectively. These are distributed within the major wetland regions in Canada and the U.S.S.R., southern South America, Africa, and Malaya. These low figures can be explained by the relatively few areas shown for Alaska, the Amazon basin and for East Siberia.

Comparison with the compilation by Matthews and Fung: The only wetland survey that is as extensive as ours has recently been published by Matthews and Fung (1987). They compiled a data set on wetlands with a 1° × 1° spatial resolution, combining three independent digital data bases for soils (FAO soil maps), vegetation (based on the UNESCO classification scheme, Matthews, 1983), and inundation (Operational Navigation Charts for Pilots (ONC-maps)). Their approach leads to different degrees of confidence, being highest when all three sources indicate wetlands for a given grid element and lowest when only one source reports wetlands. Whenever at least one source map showed mires, Matthews and Fung computed these according to the fraction of inundated area in the navigation charts. According to the authors, the approach also identifies small and scattered mires that are missed when vegetation alone is taken as the sole source of information.

East	2.5		12.5		22.5		32.5		42.5		52.5		62.5		72.5		82.5		92.5		102.5		112.5		122.5		132.5		142.5		152.5		162.5		172.5		
88.75																																					3300
86.25																																					10100
83.75																																					16800
81.25												—																									23500
78.75			—	—																	—																30100
76.25													—	—							—	—	—														36700
73.75												—		2.3		2.3		2.3	2.3	18.1	2.3	6.7		6.7	4.4	22.5			—								43200
71.25														4.4	9.5	11.7	4.4	—	11.7	2.2	2.2	—	—	—	—	2.2	—	24.8	24.8	27.2	11.7	24.8					49600
68.75				—	13.5	12.5	—	6.8			6.8	8.9	6.8	2.3	2.3	6.8	4.5	2.3	—	—	—	—	—	4.5	11.3	—	8.9	—	—	11.3	24.8	38.4	8.9	11.3	20.2	8.9	56000
66.25				9.2	17.6	20.9	29.9	15.0	18.0	53.1	48.2	48.2	4.5	6.8	2.3	37.4	6.3	6.6	—	—	—	—	6.8	47.3	20.3	—	—	—	—	13.5	13.5	—	—	6.8	11.3	15.8	62200
63.75			6.0	17.6	9.3	14.6	17.7	19.2	20.2	4.5	11.3	11.3	11.7	18.9	29.5	44.2	2.1	29.5	—	—	—	—	2.2	11.3	24.7	11.3	—	6.7	—	—	—	—	2.2	4.5	15.8	27.1	68300
61.25		—	13.0	5.2	4.0	2.7	7.3	18.0	6.7	4.4	4.4	2.3	14.7	27.3	40.0	31.6	37.9	25.2	—	—	—	—	2.3	4.4	—	—	—	—	—	—	—		13.5	4.4	—		74300
58.75		—	7.2	2.8	2.2	4.5	20.3	15.7	2.2	9.0	2.2	—	25.3	35.8	52.6	45.1	35.8	46.3	—	—	—	—	—	—	—	—	—	—	2.2	4.5	4.5	4.5	2.2				80100
56.25			8.0	1.6	4.7	3.5	4.5	3.5	8.2	5.2	—	—	—	6.8	22.5	51.9	49.7	4.5	—	—	—	—	—	—	—	—	—	—				20.3	—				85800
53.75			—	0.1	1.5	—	—	—	7.7	—	—	—	—	—	—	—	2.3	—	—	—	—	—	—	—	—	15.8	11.3	13.5	2.3			6.8					91300
51.25		—	—	—	9.8	40.1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	11.3	6.7	13.5	6.7			2.3					96700
48.75	—	—	—	0.3	—	1.3	—	—	—	—	2.3	—	—	—	—	—	—	—	—	—	—	—	—	2.9	3.4	4.4	16.2	22.6	2.3								101900
46.25	—	0.1	—	0.9	0.7	—	—	4.5	—	—	4.5	—	0.9	0.7	0.5	0.9	—	—	—	—	—	—	—	1.0	4.1	—	7.5	—	2.2								106800
43.75	0.7	—	—	—	—	0.6			—	—	—	2.0	—	0.8	4.5	0.1	—	—	—	—	—	—	0.7	0.3	4.5	—	—		—								111600
41.25	—				—	—	—		—	—		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—											116100
38.75					—	—	—	—	—	—		—	—	—	—	—	—	—	—	—	—	—	—	0.6		—											120500
36.25	—	0.6						—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		—		—									124600
33.75	—	—						—	—	0.2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1.4												128500
31.25	—	—	—		—	—		—	—	5.9	—	—	—	—	—	—	—	—	—	—	—	—	—	—													132100
28.75	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—													135500
26.25	—	—	—	—	—	—	—	—	—	—		—	—	—	—	—	—	—	—	—	—	—	—	—													138600
23.75	—	—	—	—	—	—	—		—	—	—	—			—	—	—	2.1	0.9	—	—	—	—	—													141400
21.25	—	—	—	—	—	—	—		—	—	—	—				—	—		—	—	—	—															144000
18.75	—	—	—	—	—	—	—	—	—	—	—					—	—			—	—																146300
16.25	—	—	—	—	—	—	—	—		—	—					—			0.1	0.5	—																148300
13.75	0.9	—	9.2	—	—	—	—	—		—						—					—	0.6			—												150100
11.25	3.2	—	—	4.1	—	—	—	2.3	—							—						2.6			—												151500
8.75	—	5.2	0.1	—	—	—	57.6	0.3	—	—						—						0.4															152700
6.25	0.6	—	—	—	—	—	9.1	1.2	—	—											0.7			0.4													153600
3.75			4.3	—	—	—	8.4	—	—	—										2.0	3.1		4.8	3.0													154200
1.25			—	19.4	—	—	3.6	0.1	—												25.1		4.5	3.4													154500
-1.25		2.6	0.3	12.0	—	—	4.9	0.1													23.2		5.2	4.9	—		3.2	3.5									154500
-3.75			—	0.2	—	—	—	—													13.2		17.7		—			4.2	9.2								154200
-6.25				—	—	—	4.8	—														—						16.3	1.6	—							153600
-8.75				—	—	13.8	1.5	5.7																—				6.5	—	—							152700
-11.25				—	—	—	9.2	—																			0.4	0.7	—								151500
-13.75				—	2.8	1.9	—	0.4																			5.6		—								150100
-16.25			—	—	—	4.0	—	1.4		0.9																—	—	—	—								148300
-18.75			—	—	9.0	—	—			—															—	—	—	—	—								146300
-21.25				—	0.6	—	—			—														—	—	—	—	—	—	—							144000
-23.75				—	—	—	—			—														—	—	—	—	—	—	—							141400
-26.25				—	—	—	0.1																	—	—	—	—	—	—	—	—						138600
-28.75				—	—	—	—																	—	—	—	—	—	—	—	—						135500
-31.25					—	—																		—	—	—	—	—	—	—	—						132100
-33.75					—																			—	—				—	—							128500
-36.25																													—	—							124600
-38.75																																				0.4	120500
-41.25																														2.8					—		116100
-43.75																																			—		111600
-46.25																																		1.1			106800
-48.75																																					101900
		7.5		17.5		27.5		37.5		47.5		57.5		67.5		77.5		87.5		97.5		107.5		117.5		127.5		137.5		147.5		157.5		167.5		177.5	

Natural Wetlands

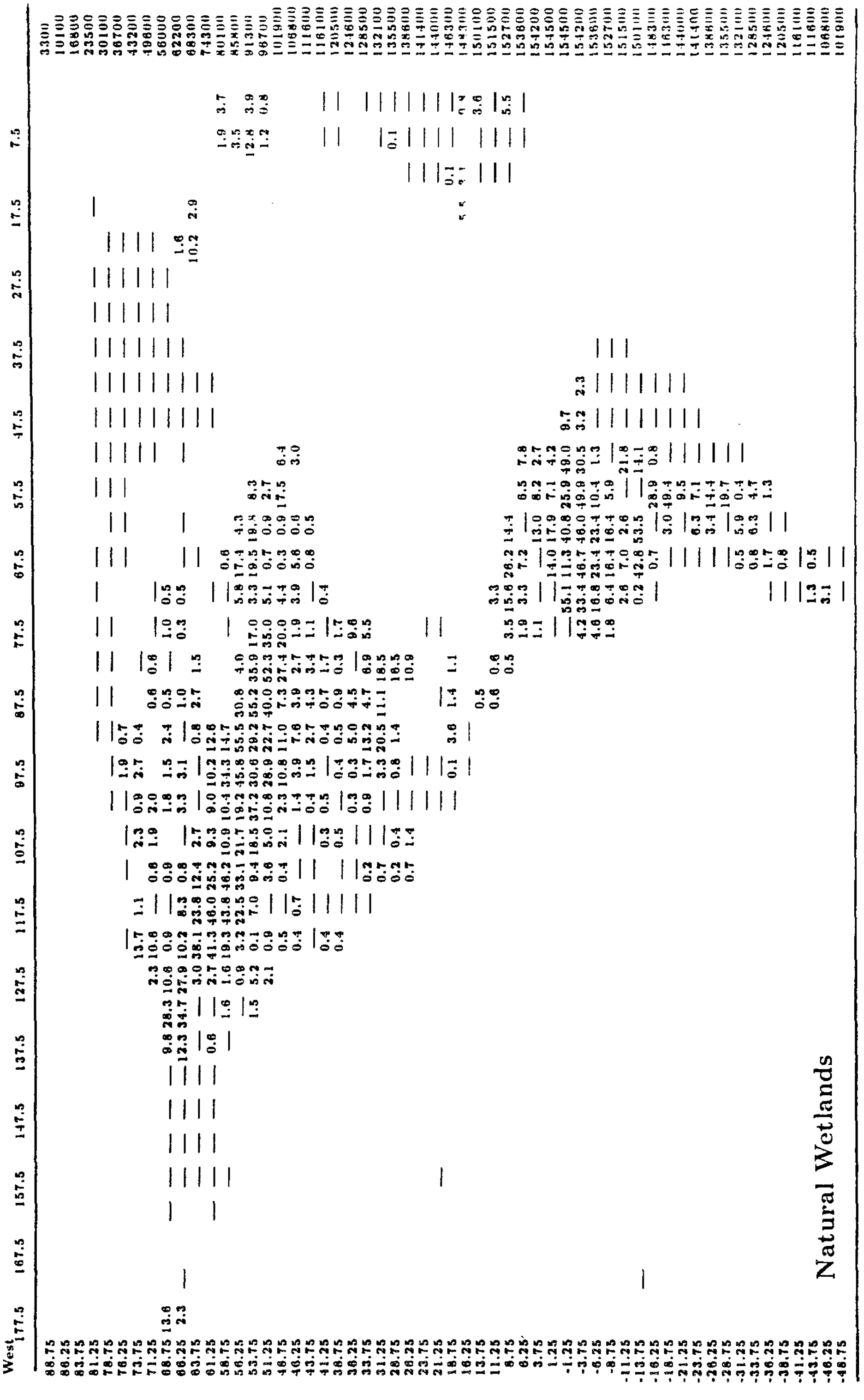

Fig. 2a. Distribution of all wetland categories.

Fig. 2a–g. Distribution of natural wetlands. Numbers denote the percentages of the 2.5° latitude by 5° longitude grids that are covered by wetlands. To convert to areas these percentages should be multiplied by the total area of a grid given in the right hand column in km^2. Left hand column and top and bottom row denote the center coordinates of the grids.

Bogs

East	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	62.5	67.5	72.5	77.5	82.5	87.5	92.5	97.5	102.5	107.5	112.5	117.5	122.5	127.5	132.5	137.5	142.5	147.5	152.5	157.5	162.5	167.5	172.5	177.5	
88.75																																					3300
86.25																																					10100
83.75																																					16800
81.25												—																									23500
78.75			—	—																	—																30100
76.25													—	—							—	—	—														36700
73.75												—						—	—	—	1.2	1.2							—								43200
71.25														—	—		—	—	2.2	1.1	1.1	—	—	—	—	—	—	—	—	4.5	3.6	12.4					49600
68.75				—	—	3.6	—	—			1.2	4.5	3.4	1.2	1.2	3.4	2.2	2.3	—	—	—	—	—	2.2	5.6	—	—	—	—	—	—	—	—	5.6	4.5	4.5	56000
66.25				—	—	—	6.0	3.0	9.5	42.4	32.8	9.6	2.7	6.8	2.3	31.1	6.3	6.6	—	—	—	—	—	20.3	10.1	—	—	—	—	—	—	—	—	—	—	—	62200
63.75			0.6	—	3.7	—	4.6	16.5	17.0	3.6	9.0	9.0	11.7	18.9	29.5	44.2	2.1	29.5	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	68300
61.25		—	6.5	3.6	4.0	2.7	5.3	17.1	5.4	3.6	3.6	1.8	14.7	27.3	40.0	31.6	37.9	25.2	—	—	—	—	—	—	—	—	—	—	—	—	—			—	—		74300
58.75		—	5.0	2.2	1.5	3.0	20.3	15.7	2.2	6.0	1.8	—	25.3	35.8	52.6	45.1	35.8	46.3	—	—	—	—	—	—	—	—	—	—				4.5	2.2				80100
56.25			5.6	1.1	3.3	3.5	4.5	2.3	5.7	3.2	—	—	—	6.8	22.5	42.4	49.7	4.5	—	—	—	—	—	—	—	—	—	—				20.3	—				85800
53.75			—	—	—	—	—	—	5.4	—	—	—	—	—	—	—	0.9	—	—	—	—	—	—	—	—	—	—	4.5	2.3			6.8					91300
51.25		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	11.3	6.7			2.3					96700
48.75	—	—	—	0.1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2.3	16.2	22.6	2.3								101900
46.25	—	0.1	—	—	—	—	—		—	—		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	7.5	—	—								106800
43.75	—	—	—	—	—	—			—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2.2	—	—		—								111600
41.25	—				—	—	—		—	—		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—											116100
38.75					—	—	—	—	—	—		—	—	—	—	—	—	—	—	—	—	—	—	—		—											120500
36.25	—	—						—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		—		—									124600
33.75	—	—						—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—													128500
31.25	—	—	—		—	—		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—													132100
28.75	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—													135500
26.25	—	—	—	—	—	—	—	—	—	—		—	—	—	—	—	—	—	—	—	—	—	—	—													138600
23.75	—	—	—	—	—	—	—		—	—	—	—			—	—	—	—	—	—	—	—	—	—													141400
21.25	—	—	—	—	—	—	—		—	—	—	—				—	—		—	—	—	—															144000
18.75	—	—	—	—	—	—	—	—	—	—	—					—	—			—	—																146300
16.25	—	—	—	—	—	—	—	—		—	—					—					—																148300
13.75	—	—	—	—	—	—	—	—		—						—					—	—			—												150100
11.25	—	—	—	—	—	—	—	—	—							—						—			—												151500
8.75	—	—	—	—	—	—	—	—	—	—						—																					152700
6.25		—	—	—	—	—	—	—	—	—											0.7			0.4													153600
3.75			—	—	—	—	—	—	—	—										2.0	3.1		4.8	3.0													154200
1.25			—	—	—	—	—	—	—												25.1		4.5	3.4													154500
-1.25			—	—	—	—		—													23.2		5.2	4.9	—		—										154500
-3.75			—	—	—	—	—	—													13.2		17.7		—			—	—								154200
-6.25				—	—	—	—	—														—						16.3	—	—							153600
-8.75				—	—	—	—	—																—					—	—							152700
-11.25				—	—	—	—	—																					—								151500
-13.75				—	—	—	—	—																			—		—								150100
-16.25			—	—	—	—	—	—		—																—	—	—	—								148300
-18.75			—	—	—	—	—			—															—	—	—	—	—								146300
-21.25				—	—	—	—			—														—	—	—	—	—	—	—							144000
-23.75				—	—	—	—			—														—	—	—	—	—	—	—							141400
-26.25				—	—	—	—																	—	—	—	—	—	—	—	—						138600
-28.75				—	—	—	—																	—	—	—	—	—	—	—	—						135500
-31.25					—	—																		—	—	—	—	—	—	—	—						132100
-33.75					—																			—	—				—	—							128500
-36.25																													—	—							124600
-38.75																																				0.4	120500
-41.25																														—					—		116100
-43.75																																			—		111600
-46.25																																		1.1			106800
-48.75																																					101900

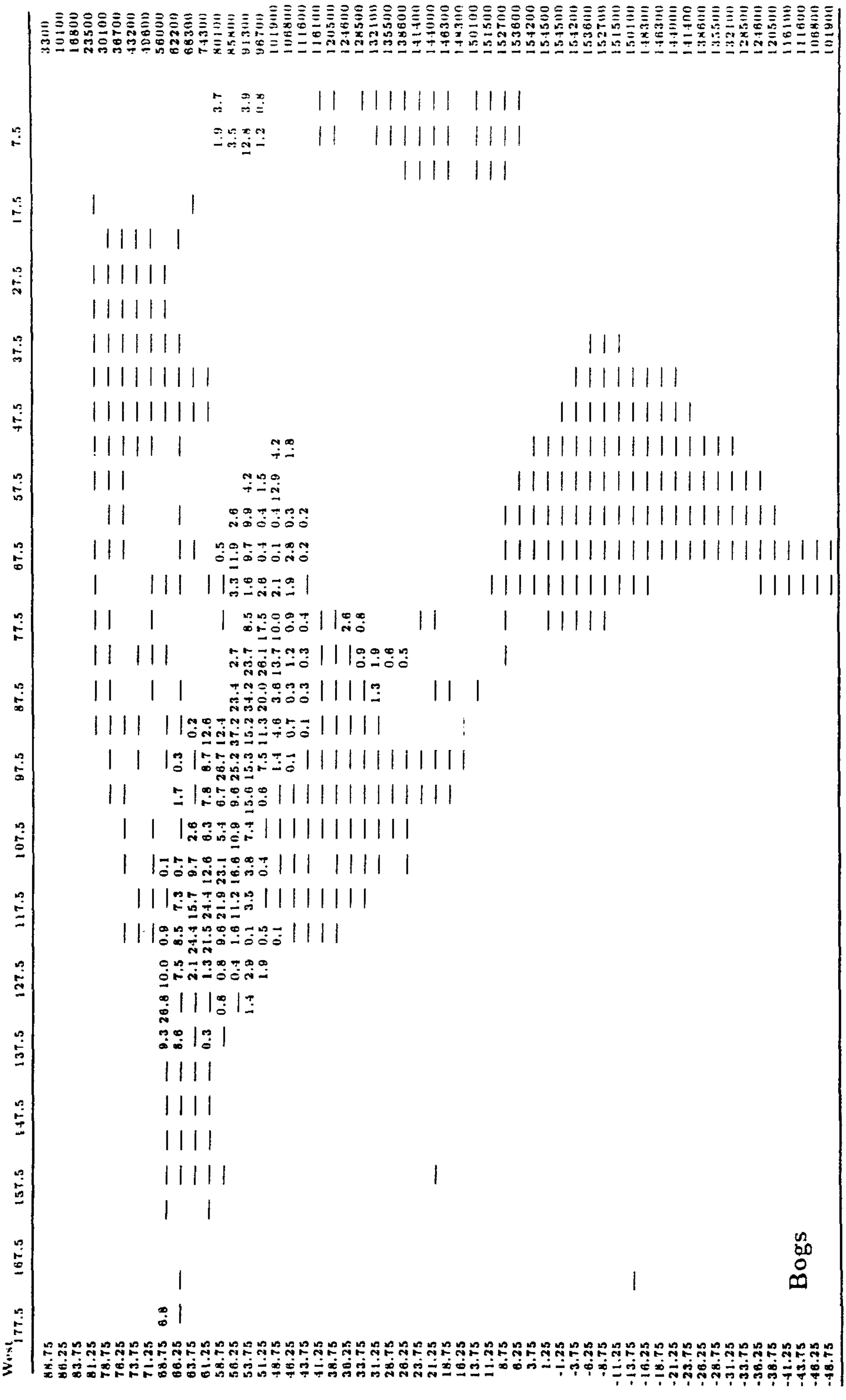

Fig. 2b.

Fig. 2b–g. Distribution of individual wetland categories.

Fens

East	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	62.5	67.5	72.5	77.5	82.5	87.5	92.5	97.5	102.5	107.5	112.5	117.5	122.5	127.5	132.5	137.5	142.5	147.5	152.5	157.5	162.5	167.5	172.5	177.5	
88.75																																					3300
86.25																																					10100
83.75																																					16800
81.25												—																									23500
78.75			—	—																	—																30100
76.25													—	—							—	—	—														36700
73.75												—		2.3		2.3		2.3	2.3	18.1	1.2	5.6		6.7	4.4	22.5			—								43200
71.25														4.4	9.5	11.7	4.4	—	9.5	1.1	1.1	—	—	—	—	2.2	—	24.8	24.8	22.7	8.1	12.4					49600
68.75				—	13.5	8.9	—	6.8			5.6	4.5	3.4	1.2	1.2	3.4	2.2	—	—	—	—	—	—	2.2	5.6	—	8.0	—	—	11.3	24.8	38.4	8.9	5.6	15.7	4.5	56000
66.25				9.2	17.6	20.9	23.9	12.0	8.6	10.7	15.4	38.6	1.8	—	—	6.3	—	—	—	—	—	—	6.8	27.0	10.1	—	—	—	—	13.5	13.5	—	—	6.8	11.3	15.8	62200
63.75			5.4	17.6	5.6	14.6	13.1	2.7	3.2	0.9	2.3	2.3	—	—	—	—	—	—	—	—	—	—	2.2	11.3	24.7	11.3	—	6.7	—	—	—	—	2.2	4.5	15.8	27.1	68300
61.25		—	6.5	1.6	—	—	2.0	0.9	1.3	0.9	0.9	0.5	—	—	—	—	—	—	—	—	—	—	2.3	4.4	—	—	—	—	—	—	—		13.5	4.4	—		74300
58.75		—	2.2	0.6	0.7	1.5	—	—	—	—	0.4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2.2	4.5	4.5		—				80100
56.25			2.4	0.5	1.4	—	—	—	—	—	—	—	—	—	—	9.4	—	—	—	—	—	—	—	—	—	—	—	—				—	—				85800
53.75			—	0.1	0.7	—	—	—	—	—	—	—	—	—	—	—	1.4	—	—	—	—	—	—	—	—	15.8	11.3	9.0				—					91300
51.25		—	—	—	3.4	13.4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	11.3	8.7	2.3	—			—					96700
48.75	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—								101900
46.25	—	—	—	—	—	—	—		—	—		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2.2								106800
43.75	—	—	—	—	—	—			—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		—								111600
41.25	—				—	—	—		—	—		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—											116100
38.75					—	—	—	—	—	—		—	—	—	—	—	—	—	—	—	—	—	—	—		—											120500
36.25	—	—						—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		—		—									124600
33.75	—	—						—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—													128500
31.25	—	—	—		—	—		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—													132100
28.75	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—													135500
26.25	—	—	—	—	—	—	—	—	—	—		—	—	—	—	—	—	—	—	—	—	—	—	—													138600
23.75	—	—	—	—	—	—	—		—	—	—	—			—	—	—	—	—	—	—	—	—	—													141400
21.25	—	—	—	—	—	—	—		—	—	—	—				—	—		—	—	—	—															144000
18.75	—	—	—	—	—	—	—	—	—	—	—					—	—			—	—																146300
16.25	—	—	—	—	—	—	—	—		—	—					—																					148300
13.75	—	—	—	—	—	—	—	—		—						—					—	—			—												150100
11.25	—	—	—	—	—	—	—	—	—							—						—			—												151500
8.75	—	—	—	—	—	—	—	—	—	—						—																					152700
6.25		—	—	—	—	—	—	—	—	—														—													153600
3.75			—	—	—	—	—	—	—	—										—	—			—													154200
1.25			—	—	—	—	—	—	—												—		—	—													154500
-1.25			—	—	—	—		—													—		—		—		—										154500
-3.75			—	—	—	—	—	—																	—			—	—								154200
-6.25				—	—	—	—	—														—							—	—							153600
-8.75				—	—	—	—	—																—					—	—							152700
-11.25				—	—	—	—	—																					—								151500
-13.75				—	—	—	—	—																			—		—								150100
-16.25			—	—	—	—	—	—		—																—	—	—	—								148300
-18.75			—	—	—	—	—			—															—	—	—	—	—								146300
-21.25				—	—	—	—			—														—	—	—	—	—	—	—							144000
-23.75				—	—	—	—			—														—	—	—	—	—	—	—							141400
-26.25				—	—	—	—																	—	—	—	—	—	—	—	—						138600
-28.75				—	—	—	—																	—	—	—	—	—	—	—	—						135500
-31.25					—	—																		—	—	—	—	—	—	—	—						132100
-33.75					—																			—	—				—	—							128500
-36.25																													—	—							124600
-38.75																																				—	120500
-41.25																														2.8					—		116100
-43.75																																			—		111600
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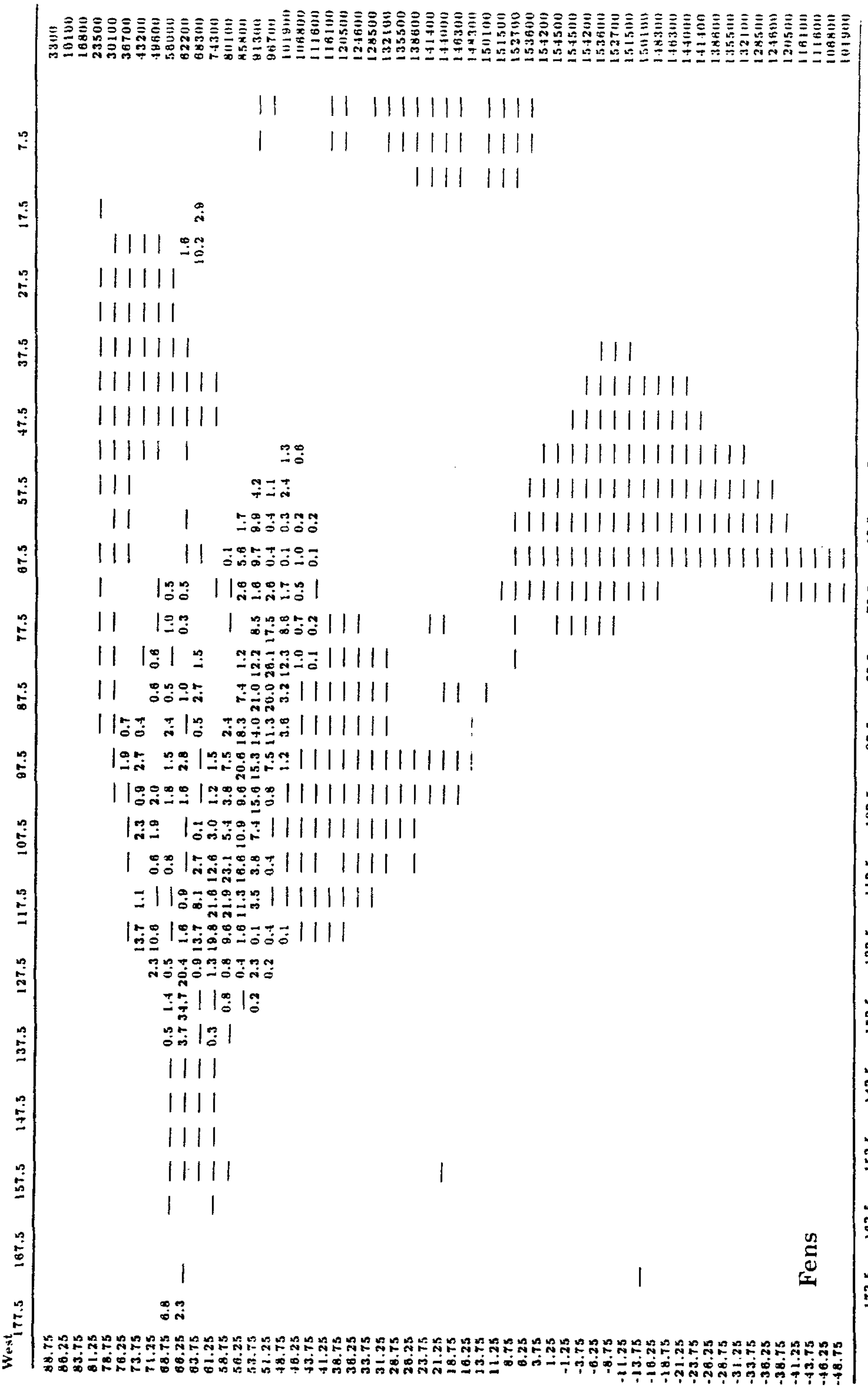
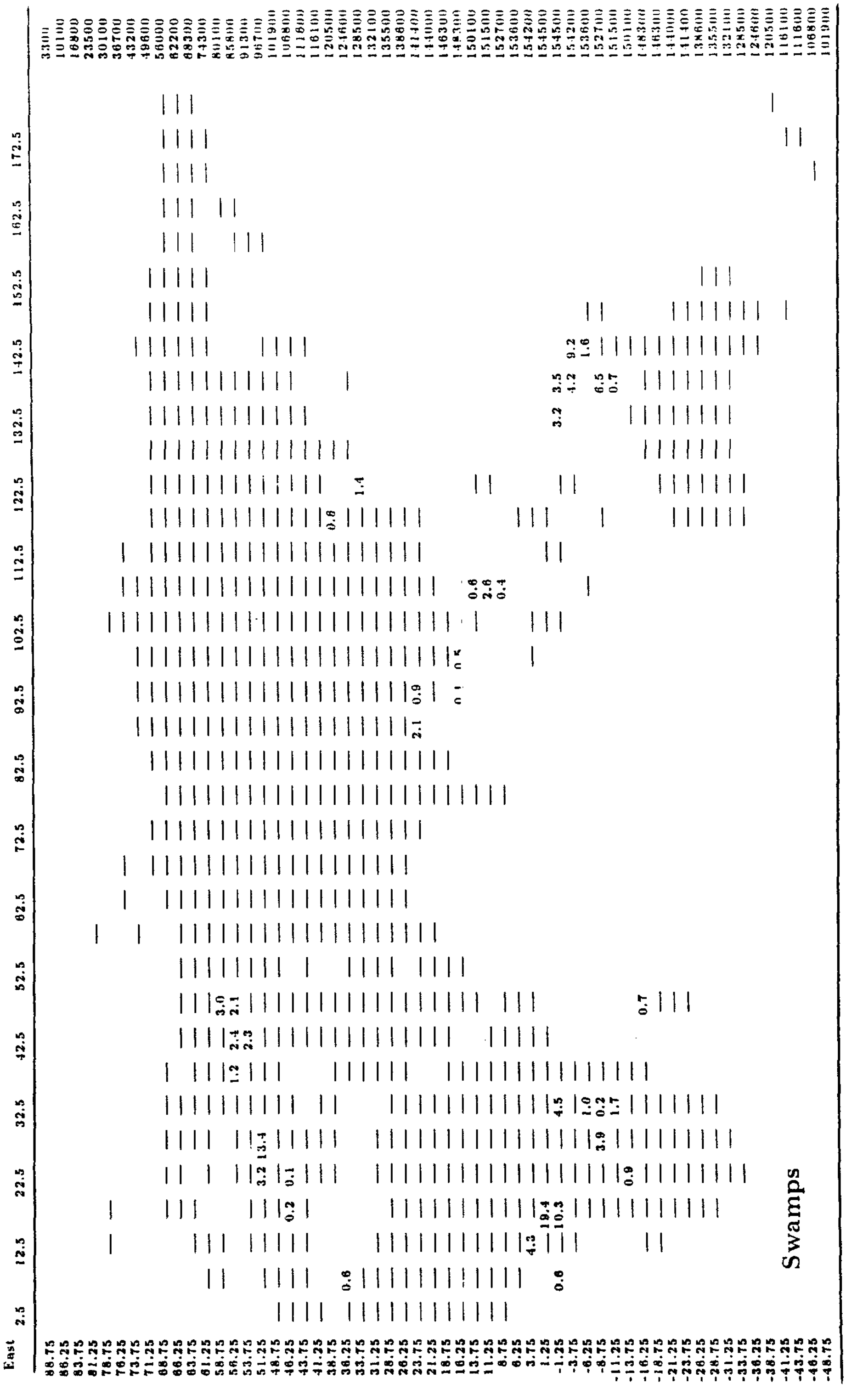


Fig. 2c.


Swamps
East
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12.5
22.5
32.5
42.5
52.5
62.5
72.5
82.5
92.5
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112.5
122.5
132.5
142.5
152.5
162.5
172.5
7.5
17.5
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57.5
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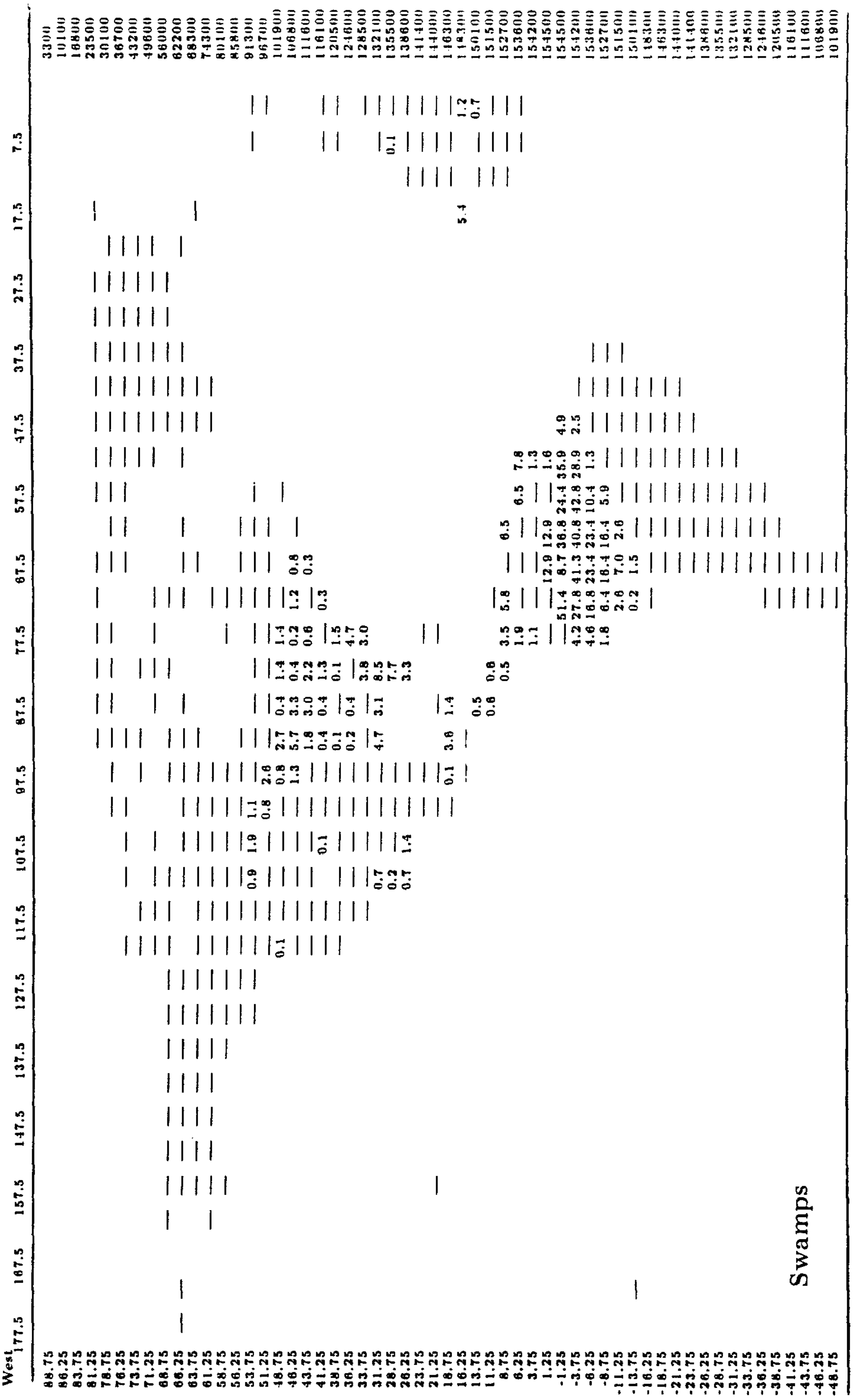
167.5
177.5


West
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157.5
147.5
137.5
127.5
117.5
107.5
97.5
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57.5
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37.5
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62.5
72.5
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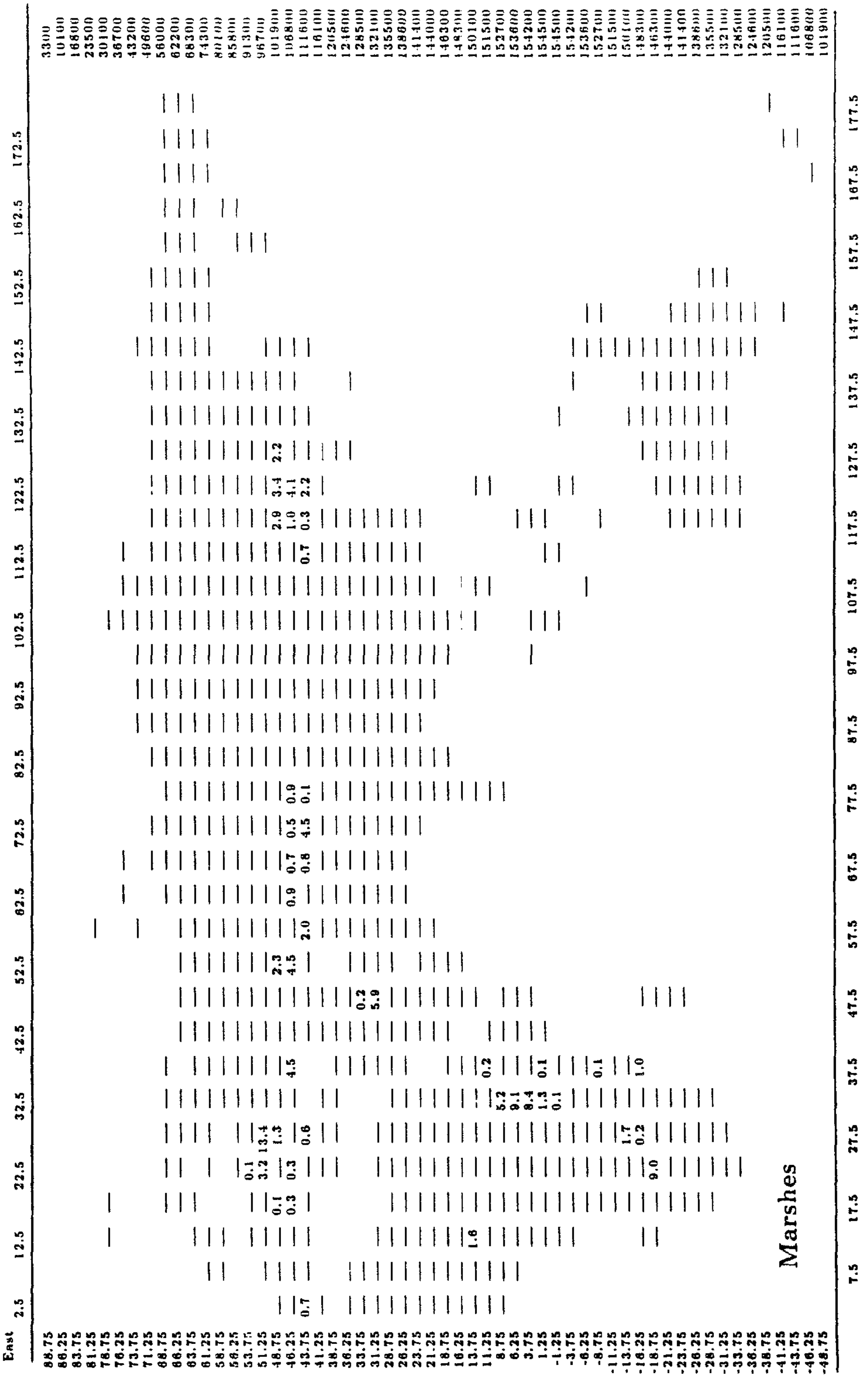
132.5
142.5
152.5
162.5
172.5
Swamps

Fig. 2d.


Marshes
East
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112.5
122.5
132.5
142.5
152.5
162.5
172.5
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47.5
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177.5

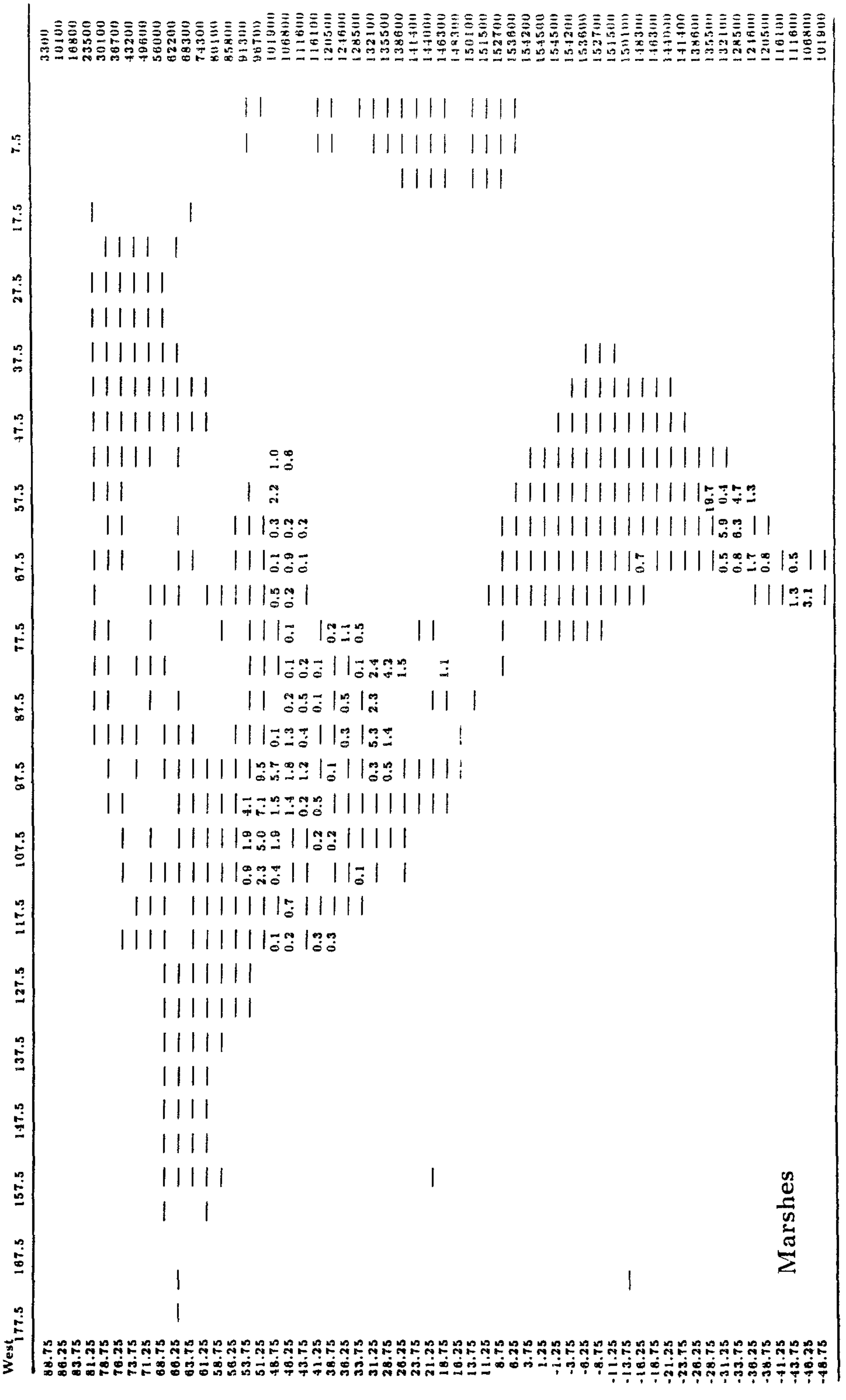
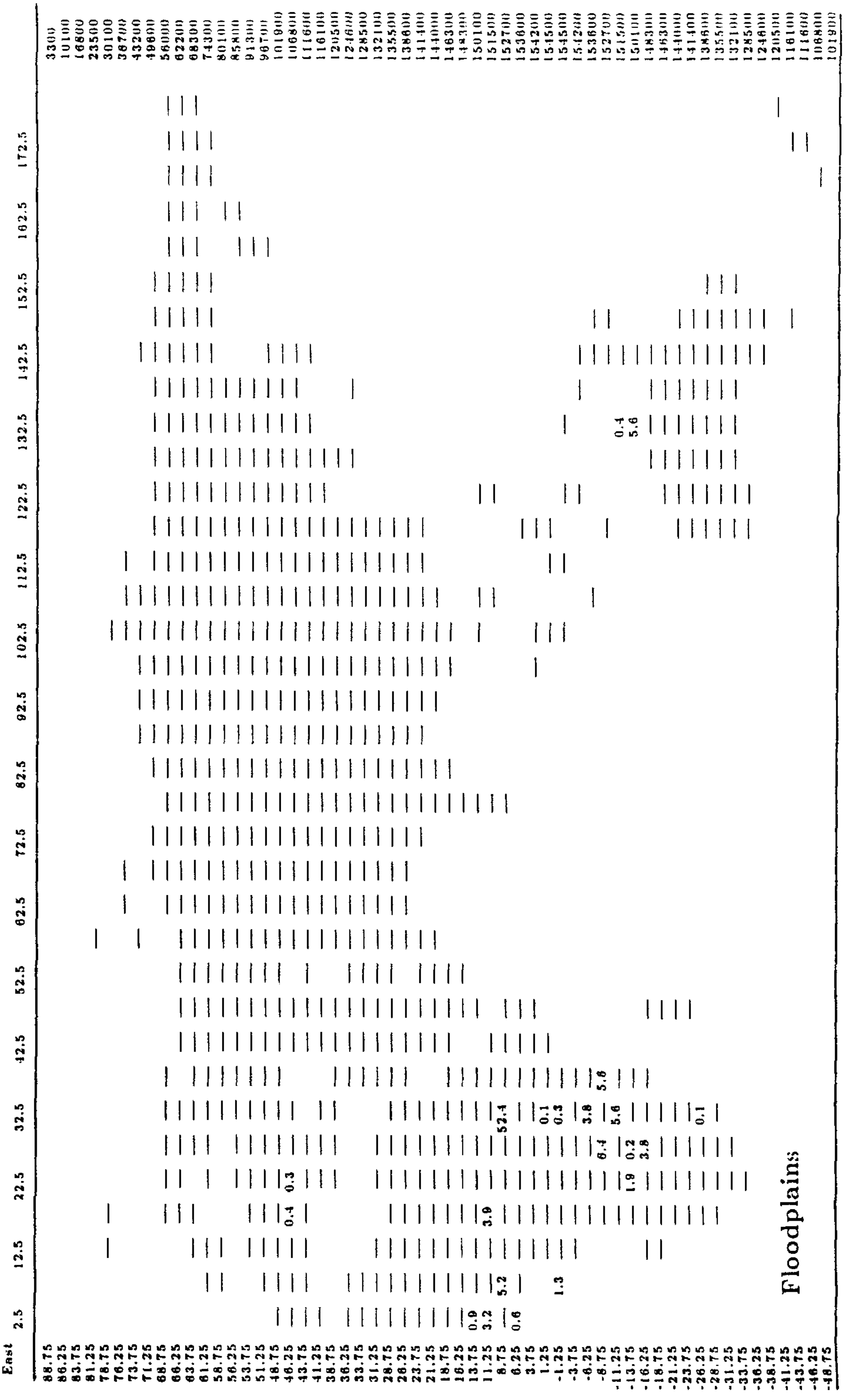


Fig. 2e.


Floodplains
East
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22.5
32.5
42.5
52.5
62.5
72.5
82.5
92.5
102.5
112.5
122.5
132.5
142.5
152.5
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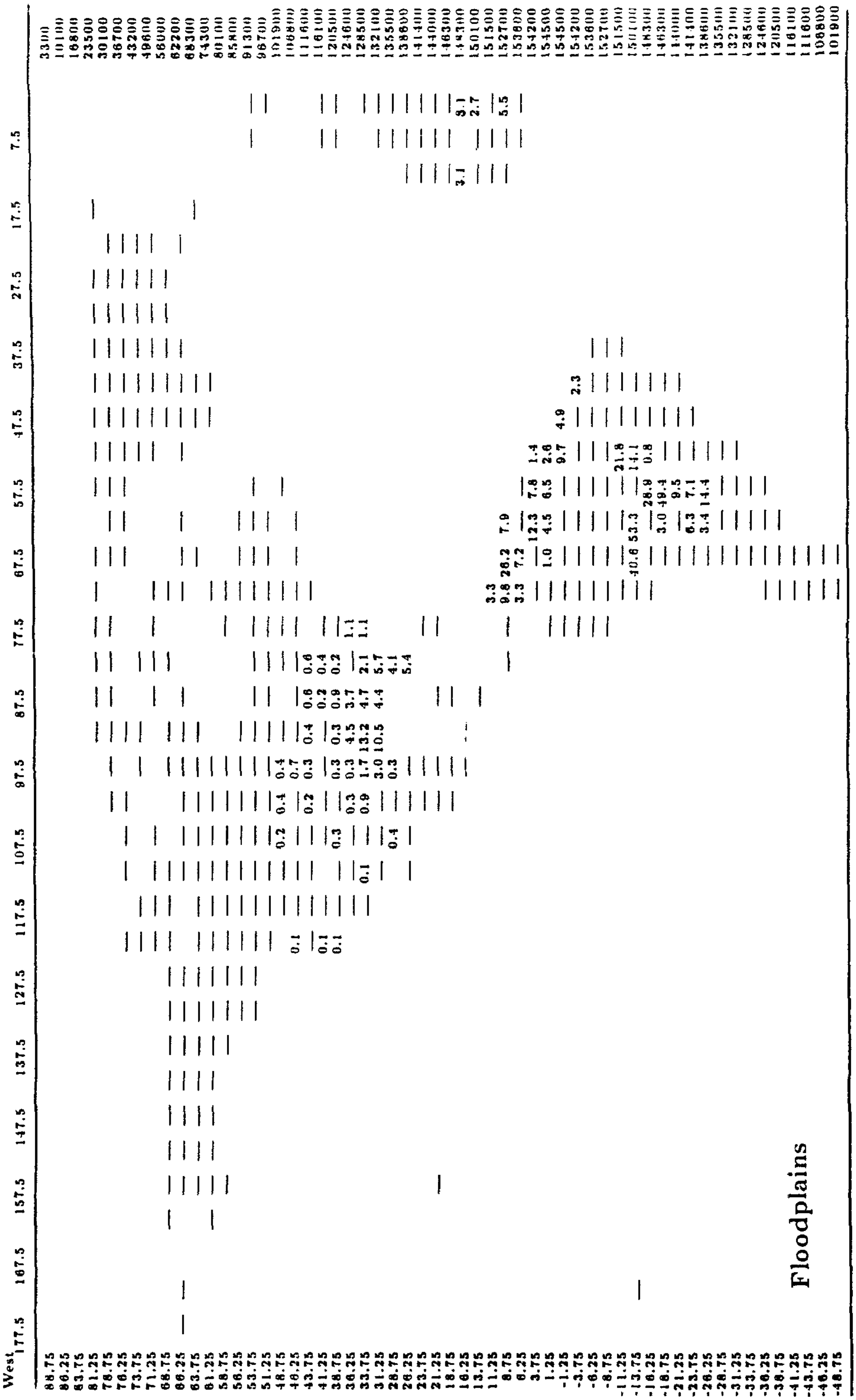
Floodplains
West
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167.5
157.5
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137.5
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77.5
67.5
57.5
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112.5
102.5
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52.5
42.5
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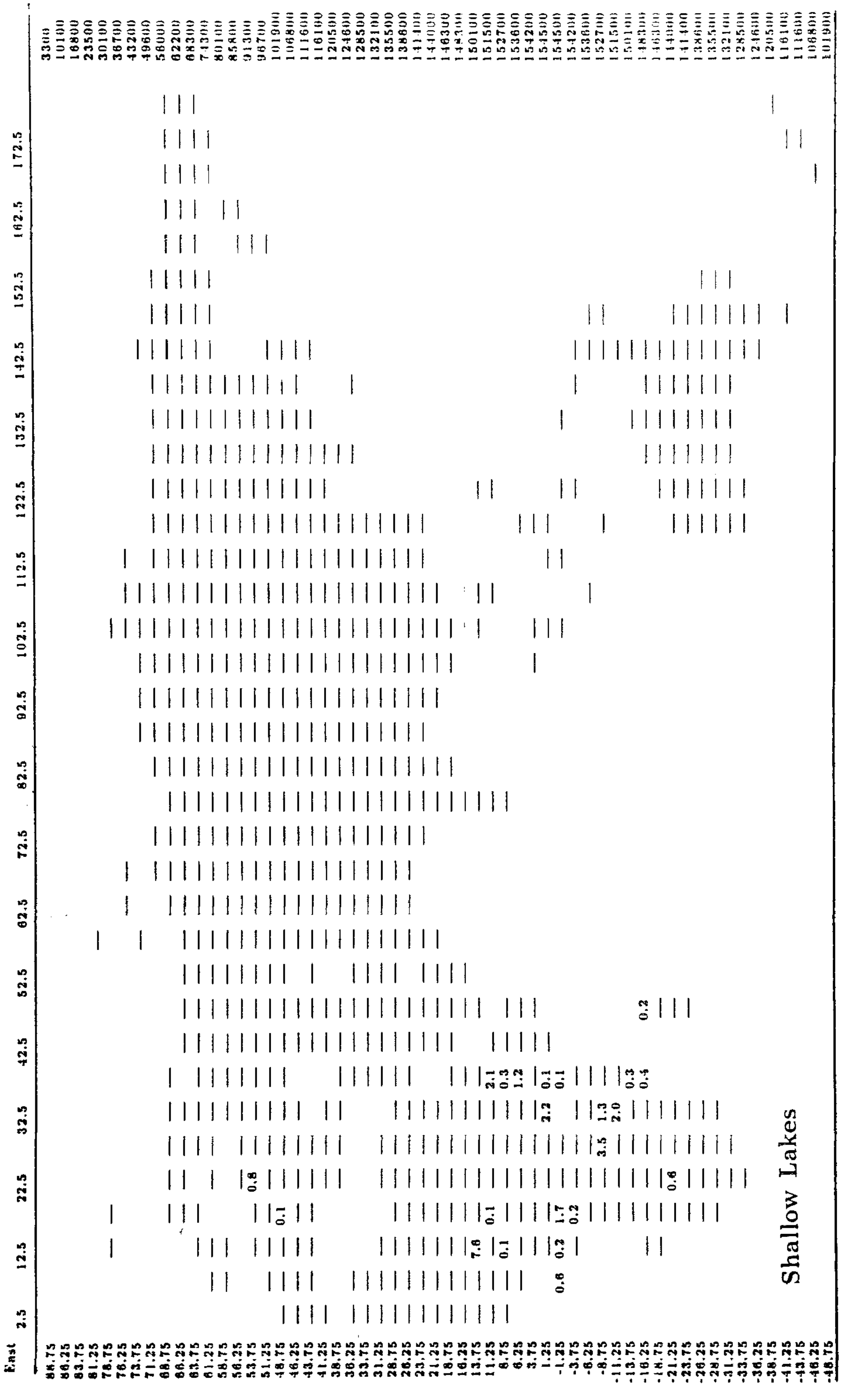
22.5
12.5
2.5

Fig. 2f.


Shallow Lakes
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12.5
22.5
32.5
42.5
52.5
62.5
72.5
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112.5
122.5
132.5
142.5
152.5
162.5
172.5
7.5
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37.5
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67.5
77.5
87.5
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107.5
117.5
127.5
137.5
147.5
157.5
167.5
177.5
88.75
86.25
83.75
81.25
78.75
76.25
73.75
71.25
68.75
66.25
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28.75
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56000
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68300
74300
80100
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91300
96700
101900
106800
111600
116100
120500
124600
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132100
135500
138600
141400
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144000
141400
138600
135500
132100
128500
124600
120500
116100
111600
106800
101900
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0.8
7.6
0.1
0.1
2.1
0.3
1.2
0.1
0.1
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1.7
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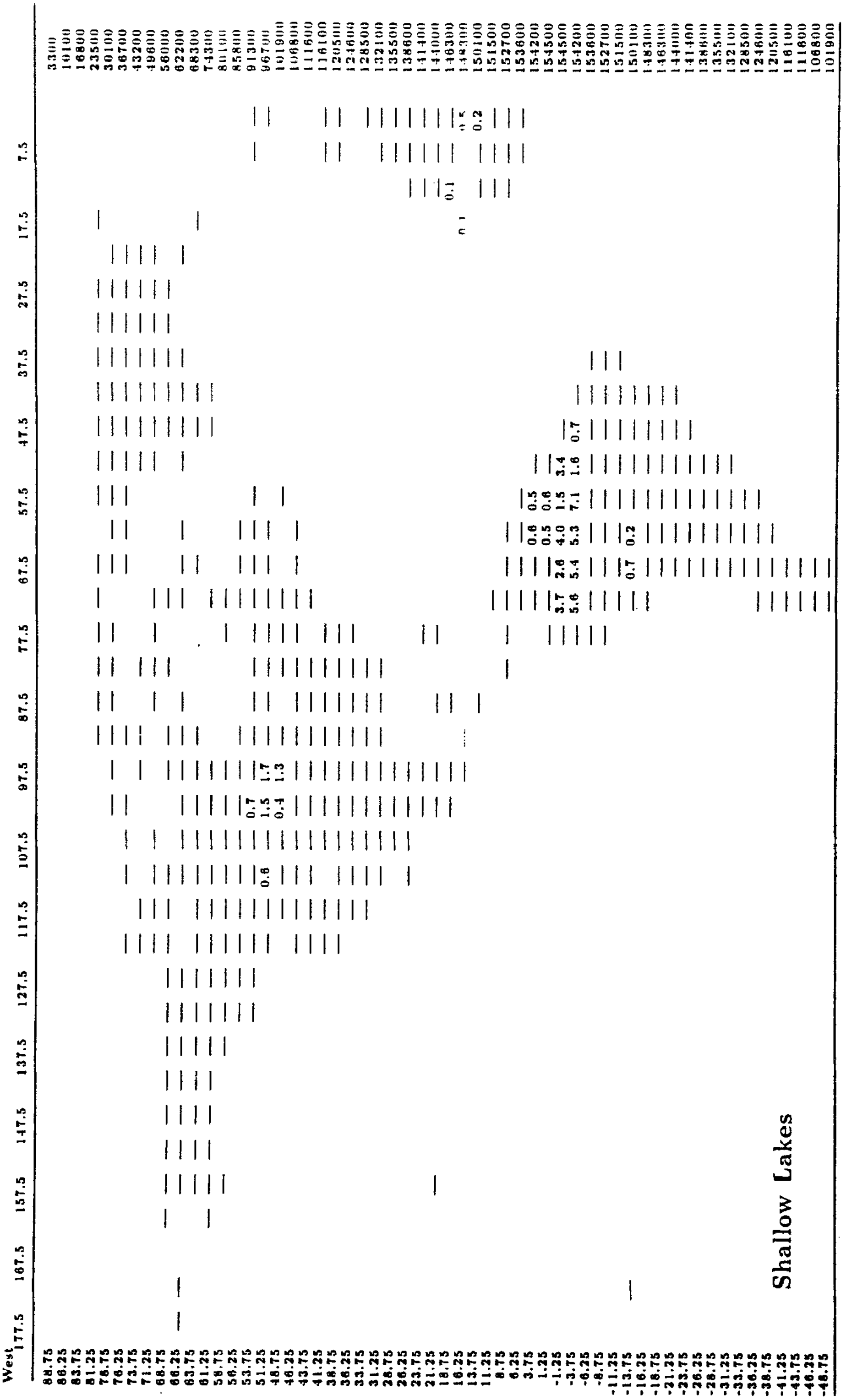
West
177.5
167.5
157.5
147.5
137.5
127.5
117.5
107.5
97.5
87.5
77.5
67.5
57.5
47.5
37.5
27.5
17.5
7.5
172.5
162.5
152.5
142.5
132.5
122.5
112.5
102.5
92.5
82.5
72.5
62.5
52.5
42.5
32.5
22.5
12.5
2.5
Shallow Lakes

Fig. 2g.

By comparing the latitudinal distribution of wetlands in the two data sets we address the likely strengths and weaknesses in the two approaches.

Table II shows the latitudinal belts, where the main differences between the two studies occur. These are apparent between latitudes 50–70° N including the major peatland areas of Alaska, Canada, the U.S.S.R. and Scandinavia. The present study reveals an area of 2.9×10^6 km^2 with about equal contribution from both latitude belts. For the same latitudes, Matthews and Fung show 2.6×10^6 km^2 with the higher portion between 60–70° N. The difficulties associated with the Alaska data are probably not the cause of our higher number, as Matthews and Fung show wetlands in this region for almost every grid point, indicating an estimated area of some 350 000 km^2 in their data set. Major differences are apparent in Canada between 60–70° N where Matthews and Fung show only few wetlands, whereas our data set yields a wetland area of 190 000 km^2. In eastern Europe and the U.S.S.R. within 60–70° N, the wetland estimates in both compilations coincide, although Matthews and Fung show scattered wetlands in East Siberia not depicted here. For wetlands between 50–60° N in regions east of Hudson Bay and for Great Britain and Ireland, most of the grid points in Matthews and Fung show no wetlands but they do in East Siberia. Their total wetland estimate for this belt is 210 000 km^2 less than ours.

Matthews and Fung show numerous scattered wetlands in Central Asia between 30–50° N in arid areas which, according to FAO soil maps (FAO-UNESCO, 1978), are partly salt influenced, nonfreshwater wetlands, which have been excluded from out data set. This may explain our lower number of 43 000 km^2 for latitudes 40–50° N. However, wetlands in the United States are more frequent in our data set when compared to Matthews and Fung.

Further south, between 10–30° N, the Matthews and Fung data set depicts higher values, probably partly due to regions, which we did not consider, i.e. salty marshlands on the Arabic Peninsular, or the north-east coast of India. Other wetland estimates in Central America and Africa at these latitudes generally coincide in both compilations.

Better agreement is found between 0–10° N, covering Venezuela, Columbia, Central Africa with the Zaire-Congo basin, and northern Indonesia. However, major differences exist for regions south of the Equator, primarily due to the large area of small river floodplains in the Amazon basin, which we have considered as forested swamps.

Estimates between latitudes 10–20° S agree well within the two data sets but disagree much for latitudes south of 20° S, where the estimate by Matthews and Fung is 250 000 km^2 higher than ours. Although occurrence of wetlands in both data sets generally coincide in southern South America and southern Africa for these latitudes, they do not for Australia. Matthews and Fung show wetlands in central and south-eastern Australia which we have disregarded. According to Carnahan (1976), extended floodplains in inner Australia (channel countries) are ephemeral, flooded only once in several years, while others have mostly

Table II. Comparison of estimated wetland areas with results of Matthews and Fung (1987) along 10° latitude belts [in 10^3 km^2]

Latitudes	80–90N	70–80N	60–70N	50–60N	40–50N	30–40N	20–30N	10–20N	0–10N	0–10S	10–20S	20–30S	30–40S	40–50S
Matthews and Fung	–	122	1355	1235	319	128	94	276	431	484	360	333	132	3
This study	–	130	1481	1445	276	156	49	85	488	1062	393	85	29	10
Difference	–	8	126	210	–43	28	–45	–191	57	578	33	–248	–103	7

been converted to agricultural land. We counted only Arafura swamps and floodplains on the northern coast and fens on Tasmania, which might explain the difference in figures for latitudes south of 20° S. In short, the data set presented here generally gives somewhat higher values for the Northern Hemisphere and, with the exception of the Amazon basin, lower values for the Southern Hemisphere than the compilation by Matthews and Fung.

Weaknesses in our data set arise from the fact that sources and quality of information are inhomogenous, being weak especially for Alaska, nontropical South America, Central America, and the large delta regions in Asia. Furthermore, our data set is presented with a coarser resolution when compared to Matthews and Fung's compilation and disregards numerous small wetlands particularly in Central Asia. Yet, if the FAO soil map is consulted, it appears that in arid regions and at some coastlines the ONC-maps used by Matthews and Fung (1987) do not distinguish between brackish or salt water and truly freshwater wetlands. This distinction is, however, crucial for methane emission studies. Further, raised peat bogs not documented in the ONC-maps, for example in Canada, Ireland, or Great Britain may imply an underestimation of these wetlands in the Matthews and Fung data set.

In general, the distinction of high northern latitude wetlands from nonwetland areas may be difficult when prevailing wet summer conditions in nonwetland areas may be difficult when variable wet summer conditions in noncircumpolar tundra region as a whole is methane emitting, as assumed by Whalen and Reeburgh (1988), then Matthews and Fung's and our data set would substantially underestimate high northern wetland areas. New studies on tundra environments and methane flux characteristics may lead to revised classification and distribution of high northern wetlands in the future.

Despite these uncertainties and differences in the extent of wetlands within latitudinal belts, both wetland compilations indicate a much larger potential reservoir of methane producing anoxic environments globally than previously assumed in methane studies.

4. Geographical Distribution of Rice Paddies

The present data set is supplemented by a compilation of rice paddy areas, which are also important sources of methane (Koyama, 1963; Ehhalt and Schmidt, 1978; Seiler *et al.*, 1984; Holzapfel-Pschorn and Seiler, 1986). For this purpose, we used a compilation by J. Richards (in Darmstädter *et al.*, 1987), which gives the area of rice paddies country by country. For the two major rice growing nations, India and China, a regional subdivision is given. Richards' compilation also includes information on the cultivation periods and on cropping indices. The data identify the areas harvested, e.g. if a country's cropping index is 2, the harvested area is twice the physical rice paddy area, with the cultivation periods given in units of months. The areas were distributed onto the 2.5° × 5° grid using the 'World Atlas of Agriculture'.

Rice is grown in many fashions, but one may basically distinguish between three major types of cultivation, i.e. dry land rice, rain fed rice, and irrigated rice cultivation (Huke, 1980). Only the two latter types are of interest for methane studies, as the soils of dry land rice do not promote methane production. According to Huke (1980), the dry land rice area makes up about 20% of the total cultivated rice area in India, but less in the surrounding countries, for example, 11% in Bangladesh, 7% in Sri Lanka, 5% in Nepal and Bhutan. As the compilation by Richards does not distinguish between dry and wet rice, we are only able to reduce the areas of dry rice in South Asia by referring to Huke (1980). No correction can be made for the other major countries in Asia due to a lack of information. Consequently, the potential CH_4-producing area of rice paddies may be overestimated by some 10%. However, as we will see later, the CH_4 production rates are significantly less certain. The estimated global rice area totals some 1.3×10^6 km^2, of which almost 90% is cultivated in Asia. Africa and South America contribute minor fractions, 3.5% and 4.7%, respectively. The distribution of paddies is shown in Figures 3 and 4a.

The time between planting or seeding and harvest varies between 90 days in some southern parts of China or Taiwan, to 270 days in Bangladesh in the case of deep-water cultivation. Typically a cultivation cycle lasts for 4 to 5 months in most countries and is restricted to the rainy season, when water supply is usually guaranteed, i.e. wet season irrigation, and rain fed cultivation is the dominant practice. Dry-season irrigation in countries with a monsoon climate is restricted to areas with sufficient water supply and may not be possible each year. Year-round cultivation is only found in some Asian countries in the humid tropics with no pronounced wet and dry season such as Indonesia, the Philippines, or Taiwan. The monthly cultivated rice paddy areas in the 10° latitude belts can be depicted from Figure 4b.

5. Net Primary Productivity of Wetlands

Numerous studies on net primary productivity (NPP) have considered wetlands and constitute a fairly broad data base. However, while NPP of boreal and arctic peatlands and temperate marshes are well documented, studies of tropical swamps and marshes are rather few. We used compilations of NPP data (Bradbury and Grace, 1983; Cannell, 1982; Aselmann, 1985) together with other scattered information, mainly on tropical wetlands (Junk, 1983; Thompson and Hamilton, 1983; Walter, 1973) to derive productivity ranges for each wetland category within four general climate zones, i.e. the tropics-subtropics, the temperate, the boreal and the arctic regions as shown in Table IIIa. The NPP values for floodplains were deduced from those for swamps and marshes, since

Rice Paddies

East	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	62.5	67.5	72.5	77.5	82.5	87.5	92.5	97.5	102.5	107.5	112.5	117.5	122.5	127.5	132.5	137.5	142.5	147.5	152.5	157.5	162.5	167.5	172.5	177.5	
88.75																																					3300
86.25																																					10100
83.75																																					16800
81.25												—																									23500
78.75			—	—																	—																30100
76.25													—	—							—	—	—														36700
73.75												—						—	—	—	—	—							—								43200
71.25														—	—		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—						49600
68.75				—	—	—	—	—					—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	56000
66.25				—	—	—	—		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	62200
63.75			—	—		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	68300
61.25		—	—		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—			—	—		74300
58.75		—	—				—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—					—				80100
56.25					—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—				—	—				85800
53.75			—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—				—					91300
51.25		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—			—					96700
48.75	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—								101900
46.25	—	0.8	0.9	—	0.1	—	0.7	0.9	0.7	—		—	1.0	1.0	—	—	—	—	—	—	—	—	—	—	0.3	0.8	—	—	—								106800
43.75	—	—	—	—	—	0.2			—	0.4	—	0.6	—	—	—	—	—	0.7	—	—	—	—	—	—	0.6	1.2	—		—								111600
41.25	—				0.1	0.4	—		—	—		—	0.2	0.4	—	—	1.8	—	—	—	—	4.2	—	—	0.9	—											116100
38.75					—	—	—	—	—	—		—	—	—	—	1.0	—	—	—	—	1.6	1.0	—	—	0.3	6.8		0.8	1.1								120500
36.25	—	—						0.3	—	0.6	0.3	—	—	—	0.8	0.7	0.3	—	—	—	—	—	—	—		9.9		6.4									124600
33.75	—	—						—	0.3	—	—	—	0.3	—	2.8	—	—	—	—	—	—	0.9	0.9	10.2	1.1		3.1	6.2									128500
31.25	—	—	—		—	3.2		—	—	0.9	—	—	—	0.7	7.6	9.8	—	—	—	—	5.5	8.3	12.6	30.7	11.3												132100
28.75	—	—	—	—	—	—	—	—	—	—	0.7	—	—	1.9	—	7.0	6.7	—	—	—	7.1	12.4	17.2	20.7	5.8												135500
26.25	—	—	—	—	—	—	—	—	—	—		—	—	3.6	—	2.0	43.1	19.9	14.3	—	—	2.0	10.0	19.8													138600
23.75	—	—	—	—	—	—	—		—	—	—	—		1.8	3.6	1.2	9.3	43.2	17.6	5.7	1.2	7.5	25.9	12.7	2.9												141400
21.25	—	—	—	—	—	—	—		—	—	—	—			1.6	1.6	18.7	26.4	1.4	9.0	—	19.1	7.2														144000
18.75	—	—	—	—	—	—	—	—	—	—	—				1.7	3.2	7.5			13.5	2.3	6.0	2.4														146300
16.25	—	—	—	—	—	—	—	—		—	—				1.4	4.3	8.3			8.8	19.2	8.2			8.9												148300
13.75	—	—	0.1	—	—	—	—	—		—						10.2					31.7	—			—	2.2											150100
11.25	—	—	—	—	—	—	—	—	—							11.4					2.0	13.0			4.4	2.2											151500
8.75	2.0	—	—	—	—	—	—	—	—	—						3.6	2.0				6.5	5.2				2.2											152700
6.25	0.1	2.0	—	—	—	—	—	—	—	—							2.2				8.0			—	2.1												153600
3.75		0.1	—	—	0.8	—	—	—	—	—										—	1.4			—													154200
1.25			—	—	0.8	—	0.1	—	—											4.7	0.5		0.4	—													154500
-1.25			—	0.5	—	—	0.6	0.1													4.7		—		—			—									154500
-3.75			—	—	—	—	—	—													4.7		1.2		2.4			—	—								154200
-6.25				—	—	—	—	0.6														20.7	20.7						—	—							153600
-8.75				—	—	—	—	0.6																—					—	—							152700
-11.25				—	—	—	—	—	0.1																				—								151500
-13.75				—	—	—	0.2	—		1.3																	—		—								150100
-16.25			—	—	—	—	—	0.2	0.1	1.3																—	—	—	—							0.1	148300
-18.75			—	—	—	—	—	0.1	0.7	1.4															—	—	—	—	—								146300
-21.25				—	—	—	—		0.7	1.4														—	—	—	—	—	—	—							144000
-23.75				—	—	—	0.2			1.4														—	—	—	—	—	—	—							141400
-26.25				—	—	—	—																	—	—	—	—	—	—	—	—						138600
-28.75				—	—	—	—																	—	—	—	—	—	—	—	—						135500
-31.25					—	—																		—	—	—	—	—	—	—	—						132100
-33.75					—																			—	—				—	0.7							128500
-36.25																													—	—							124600
-38.75																																				—	120500
-41.25																														—					—		116100
-43.75																																			—		111600
-46.25																																		—			106800
-48.75																																					101900

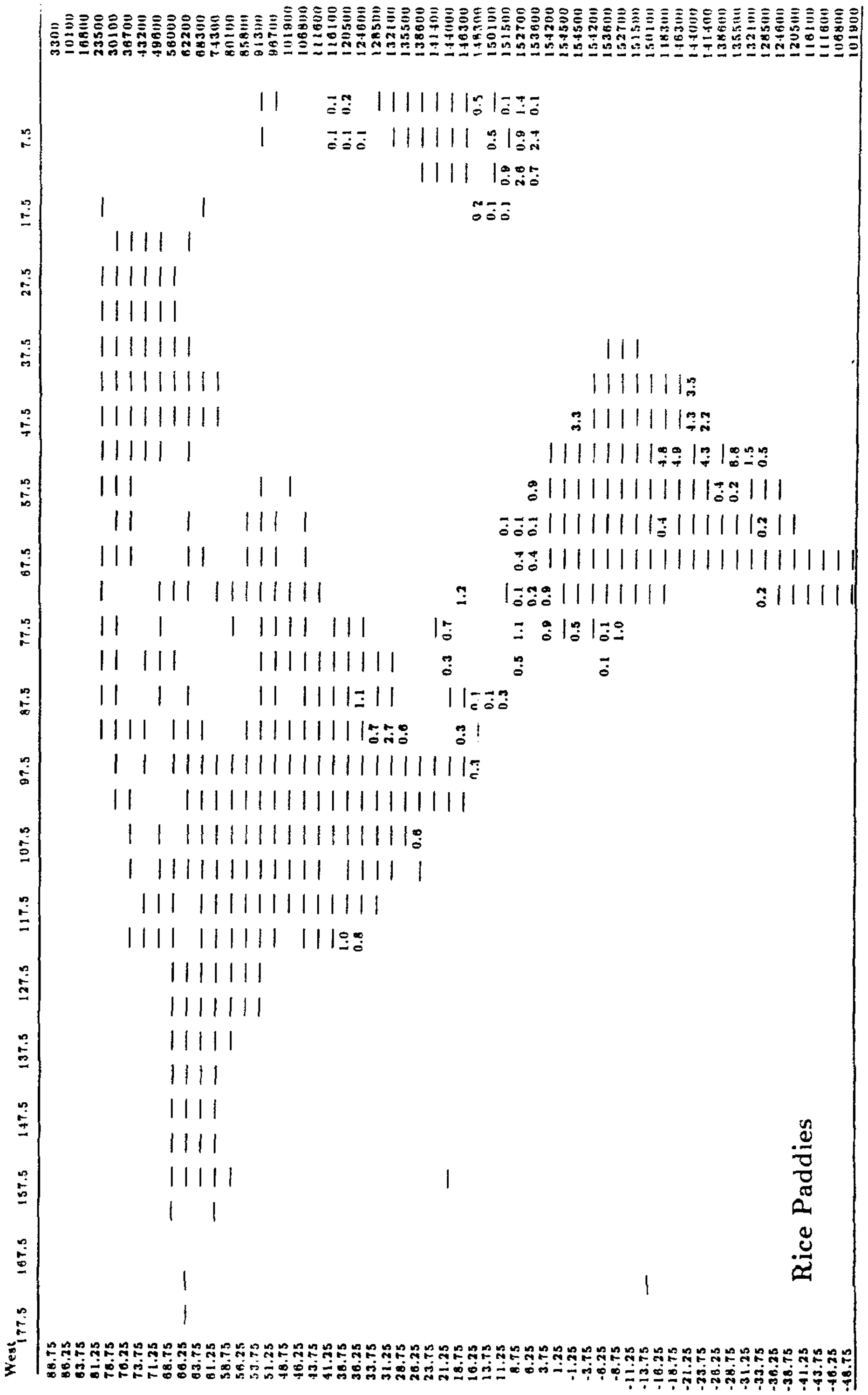

Fig. 3. Distribution of rice paddies (see Figure 2 for explanation).

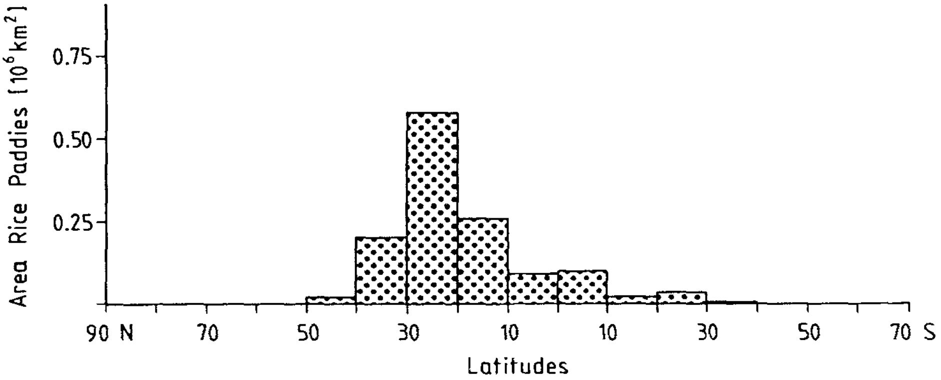

Fig. 4a. Distribution of rice paddies along 10° latitudinal belts.

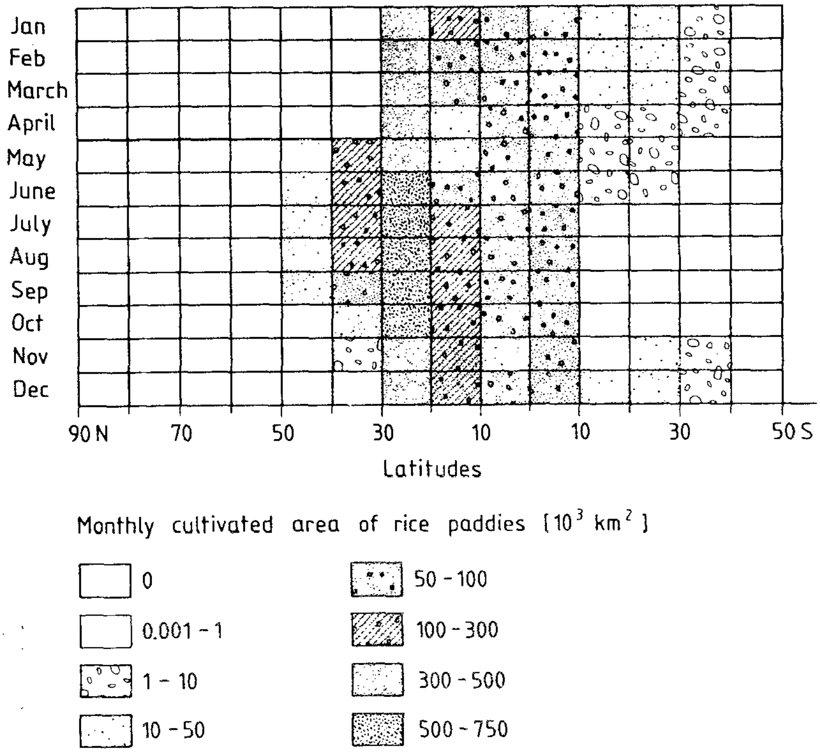

Fig. 4b. The monthly cultivated rice paddy area for 10° latitude belts in correspondence to Figure 4a.

hardly any data were found for this category. Tropical-subtropical swamps and marshes show the highest production, on average 10 times higher than high latitude bogs or fens. We multiplied the NPP ranges in Table IIIa with the areas from Table I and derived a global yearly productivity of wetlands of $4\text{–}9 \times 10^{15}$ g of dry matter. This range is in general agreement with earlier estimates by Ajtay *et al.* (1979), Lieth (1975), and Whittaker and Likens (1975). However, as these authors derive their numbers on the basis of much smaller estimated wetland areas, higher mean NPP values with no latitudinal distinction and coarser classification, disagreement exists. For example, Ajtay *et al.* assume rather high mean NPP values of 1000 $g/m^2/a$ for bogs and 4000 $g/m^2/a$ for swamps and marshes, while their estimates of the areas are 1.5×10^6 and 2×10^6 km^2, respectively. Whittaker and Likens (1975) and also Lieth (1975) consider only one category of swamps and marshes with an estimated coverage of 2×10^6 km^2. Their mean NPP estimates of 3000 and 2000 $g/m^2/a$ are, however, closer to ours as given in Table IIIa. Consequently, their global NPP estimates of 4×10^{15} g/a (Lieth, 1975), 6×10^{15} g/a (Whittaker and Likens, 1975) and 8.75×10^{15} g/a (Ajtay *et al.*, 1979) agree only somewhat fortuitously with the range calculated in here. The NPP of $4\text{–}9 \times 10^{15}$ g/a from natural wetlands would contribute some 3–9% of the entire continental NPP of $1\text{–}1.3 \times 10^{17}$ g/a (Lieth, 1975; Whittaker and Likens, 1975; Ajtay *et al.*, 1979; Esser *et al.*, 1982; Fung *et al.*, 1983).

The NPP data in Table IIIa refer to a yearly basis or to the length of a growing season. Dividing the mean productivity by the length of the frost free or inundation period in each grid for each wetland category, we derive approximate monthly production data that are summarized in the last two columns in Table IIIa. According to this procedure, major plant production takes place between May and October which reflects the dominance of Northern Hemisphere wetlands. Tropical bogs, swamps, and marshes produce about equal amounts in the periods November to April and May to October. Only tropical floodplains with their major area in South America produce most of their NPP between November and April. On global average, wetlands are more productive in terms of plant matter than nonwetland vegetation. The overall mean NPP of wetlands calculated from Table IIIa is about 1000 $g/m^2/a$, whereas the global mean of all vegetation types is less; ranging between 770 and 900 $g/m^2/a$ depending on the estimate considered.

Net primary productivity of agricultural crops, in our case rice paddies, may be deduced from yield statistics with the aid of conversion factors (Aselmann and Lieth, 1983). Worldwide rice production in 1985 was equal to 470 Tg (FAO, 1986) which, on the basis of 2.86 as the mean ratio of total rice plant production to grain yield, converts worldwide to a total dry matter production of 1.4×10^{15} g/a. Table IIIb shows the calculated NPP of rice paddies for 10° latitude belts for two seasons in analogy to natural wetlands. Major plant production takes place in the Northern Hemisphere at latitudes 20–40° in

Table IIIa. Net primary productivity (NPP) and methane emissions from natural wetlands

Type	Climate region[a]	Area [10^{12} m^2]	NPP-Range in dm[b] [$g/m^2/a$]	NPP in dm[b] [Tg/a]	CH_4-Emission[c] [Tg/a]	Seasonal NPP[b]		Seasonal CH_4-emission[c]	
						S1[d] [Tg][b]	S2[e] [Tg][b]	S1[d] [Tg][c]	S2[e] [Tg][c]
Bogs	polar	0.21	100–300	20–60		–	40	–	1
	boreal	1.04	300–700	310–760		27	508	1	14
	temp.	0.42	400–800	170–340		33	222	1	6
	trop.	0.20	600–1200	120–240		90	90	2	2
	total:	1.87		620–1400	7–59	150	860	4	23
Fens	polar	0.54	100–300	50–160		–	105	–	3
	boreal	0.62	400–700	250–430		20	320	1	9
	temp.	0.32	400–1200	130–380		20	235	1	6
	trop.	–	–	–		–	–	–	–
	total:	1.48		430–970	5–41	40	660	2	18
Swamps	polar	–	–	–		–	–	–	–
	boreal	0.01	500–1000	0–10		1	4	–	–
	temp.	0.10	700–1500	70–150		40	70	1	2
	trop.	1.02	1500–3000	1530–3060		1102	1193	30	32
	total:	1.13		1600–3220	19–135	1143	1267	31	34

Marshes	polar	–	–	–		–	–	–	–
	boreal	–	–	–		–	–	–	–
	temp.	0.17	800–2000	140–340		79	161	2	4
	trop.	0.10	1500–4000	150–400		135	140	4	4
	total:	0.27		290–740	4–31	214	304	6	8
Flood-plains	polar	–	–	–		–	–	–	–
	boreal	–	–	–		–	–	–	–
	temp.	0.08	800–1800	60–140		95	5	3	–
	trop.	0.74	1500–2500	1110–1850		962	518	26	14
	total:	0.82		1170–1990	14–84	1057	523	29	14
Lakes		0.12	400–800	50–100	1–5	37	38	1	1
	Total	5.69		4160–8420	50–360	2641	3649	73	98

[a] polar: latitudes 65–90°; boreal: 55–65°; temperate: 30–55; tropical: 0–30°

[b] dm = dry matter

[c] with 45% C in dry matter and assuming that 2–7% of the NPP (C_{CH_4}/C_{NPP}) is released as CH_4

[d] S1 = November–April

[e] S2 = May–October

Table IIIb. Net primary productivity and methane emissions from rice paddies

Lat.	NPP[a] [Tg] Nov.–Apr.	NPP[a] [Tg] May–Oct.	CH_4-Emission[b] [Tg] Nov.–Apr.	CH_4-Emission[b] [Tg] May–Oct.
40–50N	–	29	–	1
30–40N	3	297	–	8
20–30N	183	409	5	11
10–20N	77	137	2	4
0–10N	31	37	1	1
0–10S	51	54	1	1
10–20S	11	3	–	–
20–30S	23	3	1	–
30–40S	3	–	–	–
Total	382	969	10	26

[a] Deduced from FAO (1986) by multiplying rice yields with a factor of 2.86.
[b] Assuming that 4.5% of the NPP (C_{CH_4}/C_{NPP}) is released as CH_4.

summer, but significant production takes further place between November and April at latitudes 10–30° N. Mean NPP of rice fields is about 1050 $g/m^2/a$ which is about equal to the mean calculated for natural wetlands.

Net primary productivity has been related in some studies to methane production. Measured ratios of methane emissions to NPP (on a carbon to carbon basis) are, however, few and results widely scatter. Investigations made in a temperate bog (Clymo and Reddaway, 1971) and in a subarctic peatland (Svensson, 1983) yielded ratios of 1–4.5% and 1–11%, respectively. Mean ratios for the two sample sites are about 3%. DeLaune *et al.* (1983) measured CH_4 emission rates in the Barataria Bay area (southern U.S.A.) in different marsh types and calculated a range of 3–10% for brackish marsh depending on the NPP estimate applied. On the basis of an estimated production period of 150 days and an estimated NPP of northern peatlands of 307 g $C/m^2/a$, Crill *et al.* (1988b) conclude that 7.5% of the NPP is released as methane in their Minnesota sample sites. Sebacher *et al.* (1986) give a mean methane production rate of 12 $g/m^2/a$ for different peatlands in Alaska. This production rate yields a ratio of 5.5% when related to the NPP values in Table IIIa for bogs and fens. In view of these few data we conclude that, on average, methane fluxes from wetlands may equal 2 to 7% of net primary productivity. Thus, the NPP values in Table IIIa convert to 140 Tg CH_4 per year with an uncertainty of 2.5 up or down from natural wetlands. As we will see, the upper values in range are too large to be in agreement with the overall atmospheric CH_4 budget.

Similarly, measured methane production in rice paddies suggest CH_4 emission to NPP ratios of 3–7%. This range is calculated from emission rates by Cicerone *et al.* (1983) and Holzapfel-Pschorn and Seiler (1986) when related to the mean plant production of rice in the U.S. and Italy, where these measurements were made. The ensuing methane production from rice paddies, derived from the NPP values in Table IIIb, accounts for 36 (25–60) Tg annually.

Considering the low relative CH_4 yield of only a few percent from wetland ecosystems, it is clear that much of their organic matter is either oxidized in aerobic sections of the wetlands or that methane produced in anaerobic sections is oxidized to carbon dioxide before it can escape to the atmosphere. This is supported by the analysis of peat bog growth by Clymo (1984), that comes to the conclusion that on broad average only 10% of the NPP in mires is decomposed anaerobically. Most of the organic matter is lost through decay in the surface layer of mires, the so-called acrotelm, in which an oscillating water table and free conductivity of water lead to aerobic conditions, favourable for both plant growth and decomposition.

6. Estimates of Methane Emissions From Natural Wetlands and Rice Fields

In Table IV, we have assigned measured methane emission rates to our wetland categories. The data shown are either cited unaltered or calculated as geometric means in those studies in which individual data were given. The total number of individual measurements comprising the data in Table IV is considerable, covering wetland sites from the Tropics to the Arctic. However, the wide scatter of the measured CH_4 fluxes shows, unfortunately, that a clear picture of what governs flux rates in different wetland types has not yet emerged. Several parameters have been identified as primary factors which control methane emissions, such as temperature (Speece and Kern, 1970; Mallard and Frea, 1972; Zeikus and Winfrey, 1976; Svensson, 1983; Williams and Crawford, 1984; Crill *et al.*, 1988b), moisture or depth of water level (Svensson, 1984; Sebacher *et al.*, 1986), nutrient status (Harriss and Sebacher, 1981), mass of organic matter (Clymo, 1984), type and stocking density of vegetation (Swain, 1973), or transport mechanisms and exchange processes (Crill *et al.*, 1988a). In situ, many factors combine and lead, even within the same habitat, to a 'striking individuality' of emission rates (Clymo and Reddaway, 1971), which in most cases range over several orders of magnitude. For this reason, we prefer the geometric mean, assuming a log-normal distribution of emission rates, rather than the arithmetic mean to calculate the flux rates in Table IV. Despite the wide scatter, the mean emission rates, nevertheless, suggest some clear differences between the categories. The range of calculated geometric mean emission rates is 15 mg CH_4/m^2/day to 310 mg CH_4/m^2/day; in increasing order from bogs, fens, swamps, marshes, and rice paddies. The flux for rice paddies is calculated from data obtained during two studies in Italy and California that covered the entire growing season. Emissions were found to follow bimodal patterns. As the emissions may range over several orders of magnitude during the growing season (Cicerone *et al.*, 1983; Holzapfel-Pschorn and Seiler, 1986) sporadic measure-

Table IV. Measured methane emissions from wetlands (mg $CH_4/m^2/day$)

Bogs	Fens	Swamps	Marshes	Flood-plains	Lakes	Rice paddies	Month	Location	Authors
			157 (68–246)*				autumn/winter	Delaware, U.S.A.	Swain (1973)
	122 (61–183)*						winter/spring	Minnesota, U.S.A.	
4.0[a] (0.7–23)	59[b] (18–195)		175[c] (106–289)				August	Alaska	Sebacher *et al.* (1986)
4.7[d] (1.1–21)	95[e] (26–350)						June–Sept.	Stordalen, Sweden	Svensson and Rosswall (1984)
		37[f] (12–112)	44[g] (20–97)				mostly Jan./Febr.	Florida, U.S.A.	Crill *et al.* (1988b), Bartlett *et al.* (1985a)
106[h] (53–211)	126[i] (22–727)		572[j] (493–664)				May–Aug.	Minnesota, U.S.A.	Crill *et al.* (1988b), Harriss *et al.* (1985)
		4 (1.9–9)					Sept.–May	Virginia, U.S.A.	Harriss *et al.* (1982)
		23.3 (7–73)					summer	S. Carolina, Georgia, Florida, U.S.A.	Harriss and Sebacher (1981)
			304 (168–550)				June–Sept.	Michigan, U.S.A.	Baker-Blocker *et al.* (1977)
23.2[k] (<1–62)							yearly mean	Moore House, England	Clymo and Reddaway (1971)
					49 (24–74)*		summer mean	Manitoba, Canada	Rudd and Hamilton (1978)
			587 (223–951)		49 (24–74)*		yearly mean	Barataria basin, Louisiana	DeLaune *et al.* (1983)
					18.4 (1.9–180)	180[l] (75–300)+	Aug.–Nov.	S. California, U.S.A.	Cicerone and Shetter (1981)
						32[m] (13–68)+	Aug.–Nov.	S. California, U.S.A.	Cicerone and Shetter (1981)
						250[n] (125–375)*	entire grow. seas.	Davis, California, U.S.A.	Cicerone *et al.* (1983)
						96[o] (79–113)	entire grow. seas.	Andalusia, Spain	Seiler *et al.* (1984)
						384[p] (257–511)	entire grow. seas.	Vercelli, Italy	Holzapfel-Pschorn and Seiler (1986)
		192[q] (162–219)	230[r] (158–302)		27 (22–32)		July/Aug.	Central Amazon, Brazil	Bartlett *et al.* (1988)
		108[q] (54–162)*	590[s] (295–885)*		120 (60–180)*		July/Aug.	Amazon, Brazil	Devol *et al.* (1988)
	39[t] (26–52)[u]						year round measurements	Smith Lake, Alaska	Whalen and Reeburgh (1988) Reeburgh, priv. comm. (1989)
15 (1–50)	80 (28–216)	84[v] (57–112)	253 (137–399)	(100)[w] (50–200)	43 (17–89)	310[x] (179–438)			

Values are either cited as given by the authors or calculated as the geometric mean, when individual data were given. Bold faced numbers denote the emission rate followed by the range, in parentheses, derived from the standard deviation, unless otherwise stated. The geometric mean emission rate for each wetland category is shown in the last row. Ranges in the last row were likewise calculated using the values from the standard deviations.

[*] Coefficient of variance of 50% assumed.

[+] Their minimum and maximum value.

[a] Their sites no. 298, 318, 159.

[b] Their sites no. 361, 371, 401, 408, 416, 346.

[c] Their sites no. mp50, mp1372.

[d] Ombrotrophic sites.

[e] Minerotrophic sites.

[f] Wetland forests (fluxes greater than zero only).

[g] Wet prairies and sawgrass marsh (fluxes greater than zero only).

[h] Bog sites WS-1, 2, 4 (from Harriss *et al.* (1985), and Marcell Exp. Forest sites S-1, 2, 4, Bena Bog, Red Lake bogs (from Crill *et al.*, 1988b).

[i] Shoreline fen, Zerkel fen and fen site WS-3 at Marcell Exp. Forest (from Harriss *et al.*, 1985), Marcell Exp. Forest site S-3, Junction Fen and Red Lake fen sites (from Crill *et al.*, 1988b).

[j] Wild rice river sedge meadow and wild rice bed (from Harriss *et al.*, 1985).

[k] Yearly production is 6.27 g CH_4 m^{-2}. Mean production assumes a production period of 270 days.

[l] Fertilized plot.

[m] Unfertilized plot.

[n] Mean of fertilized and unfertilized plot.

[o] Moderately fertilized plot. Soil was probably influenced by sea water through diffusion from the nearby coast.

[p] Mean of fertilized and unfertilized plot, for which no significant differences were found.

[q] Flooded forests.

[r] Floating grass mats.

[s] Water surfaces covered by aquatic macrophytes.

[t] Mean flux of four sample sites from 1987 and 1988 data, weighted with the estimated areal coverage, based on a 5–6 month production period with monthly mean temperature above 0 °C at peat surface.

[u] Range derived from the standard deviations in the reference weighted with the estimated coverage of the sample sites.

[v] Data from the U.S.A. are averaged and counted as one data point [29(21–40) mg/m^2/day] in the overall mean rejecting the value from Virginia which is rather low due to drought influence.

[w] Estimated from swamps, marshes and lakes.

[x] Only 'whole season' data from California and Italy taken.

ments may be misleading. We thus confine ourselves to whole-season data when calculating the mean emission from paddies. We further disregard the mean CH_4 flux measurements by Seiler *et al.* (1984) as the particular Spanish rice field studied was influenced by intrusion of brackish water.

The relatively small emission rates found for ombrotrophic bogs, except for one site in Minnesota, may be due to the predominantly aerobic acrotelm in peat bogs. Marshes resemble rice paddies in respect to their physiognomy, which is reflected in high emission rates for both ecosystems. Yet, considering the large variability of fluxes, the data base is still rather small and conclusions about emission characteristics of various wetland categories can only be tentative. The high emission rates of marshes and paddies need to be confirmed by further measurements especially from Africa (e.g. papyrus stands) and from other tropical regions. Data are also needed about forested ombrotrophic raised bogs in South East Asia.

It has been noted that CH_4 emissions are positively correlated with temperature under controlled laboratory simulations (Koyama, 1963; Svensson, 1984). Methane fluxes from natural wetlands, however, show only occasional correlation of this kind (Crill *et al.*, 1988b). As the most favourable example, Figure 5 displays the emission rates versus temperature for fens. A positive correlation, as observed in controlled laboratory experiments, is apparently masked by other environmental factors. As a consequence, we have ignored the existence of any temperature effect on methane emissions and applied the mean CH_4 flux rates from Table IV to all latitudes to compute the global methane emission from natural wetlands. Methane emissions (E_w) are computed on 2.5° lat. by 5° long. grid elements by using the formula:

$$A_w \times e_w \times P_w = E_w,$$

where A_w stands for the area of the wetland category in a grid, e_w stands for the mean emission rate in mg CH_4/m^2/day and P_w denotes the length of the emission period in days. P_w is determined either by monthly mean temperatures above 0° C (Oort, 1983), or by inundation. Table V and Figures 6 and 7 summarize the computations, which yield an average emission of 80 Tg/a within a range of 40–160 Tg/a. Figure 6 displays the monthly distribution of methane emissions for natural wetlands for the Northern and Southern Hemispheres, corresponding to the results in Table V. As expected, the Northern Hemisphere dominates the global emission from May to October. From November to April the wetlands in the Southern Hemisphere emit the major fraction, albeit at lower levels. Highest emissions of about 9 Tg per month are released between July and September decreasing to a minimum of 4 Tg in December. The latitudinal distribution of fluxes from natural wetlands shown in Figure 7 shows two maxima of 22 Tg between 0–10° S and 23 Tg for latitudes 50–70° N.

Our estimated CH_4 emissions from natural wetlands and their geographical distribution are quite different from those shown by Matthews and Fung (1987).

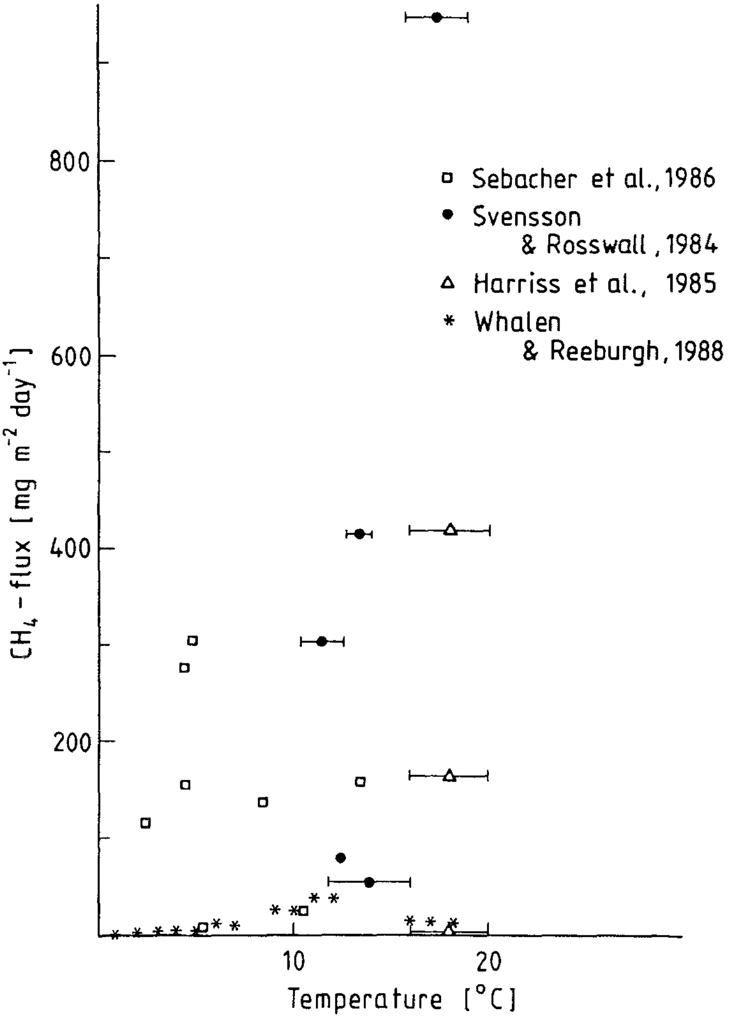

Fig. 5. Methane fluxes versus temperature as measured in various fen sites.

These authors calculate for tropical wetlands between 10° N and 10° S a CH_4 flux of less than 10 Tg per 10° latitude belt which stems primarily from the smaller estimated swamp and floodplain areas in their study. Our higher emissions calculated for the tropics in the Southern Hemisphere are in agreement with an estimated emission of 22 Tg/a for Amazonia by Bartlett *et al.* (1988), who used an area of 0.5×10^6 km^2 of wetlands within the Amazon basin in their extrapolation. Highest emissions of some 65 Tg in the Matthews and Fung study are calculated for latitudes 50–70° N predominantly from forested and non-forested bogs. This is three times as much as our estimate for the same region.

Table V. Global wetland methane emissions extrapolated from measured emission rates in field experiments

Wetland categories	Emission-rate [mg CH_4/m^2/day]	Area [10^{12} m^2]	Mean prod. [period[a] [days]	Emission [Tg/a]
Bogs	15 (1–50)	1.87	178	5 (0.4–18)
Fens	80 (28–216)	1.48	169	20 (7–52)
Swamps	84 (57–112)	1.13	274	26 (18–35)
Marshes	253 (137–399)	0.27	249	17 (12–30)
Floodplains	100 (50–200)	0.82	122	10 (5–19)
Lakes	43 (17–89)	0.12	365	2 (1–4)
Natural wetlands		5.69		80 (40–160)
Rice fields				
1: With a mean emission rate	310 (179–438)	1.31	130	53 (30–75)
2: With temperature dependent emission rates	300–1000	1.31	130	92 (60–140)[b]
Grand total		7.00		100–300

[a] Mean CH_4 productive period comprised of both permanent and seasonal wetland areas in the respective wetland categories. The CH_4 productive period is determined either by monthly mean temperatures above 0 °C or inundation. Swamps with unknown seasonality have been treated as permanent.

[b] Assuming the same uncertainty as obtained in temperate rice field studies.

We may compare these northern peatland emission estimates, which are derived from extrapolated flux rates, with an estimate based on decay rates. Peat formation takes place in the anaerobic layer (catotelm) that underlies the aerobic surface section (acrotelm) of a peatbog (Clymo, 1984). It is the imbalance or balance of the matter transfer from the acrotelm to the catotelm and the integrated decay over the depth of the latter that determines whether a peatland is accumulating peat or in steady state. Differences between the two processes are commonly rather small so that peatlands, in particular bogs, take thousands of years to approach steady state. According to Clymo (1984, and personal communication), a widely applicable decay rate coefficient in peat bogs (proportional to the amount of organic matter) is $2–5 \times 10^{-4}$. Anaerobic decay leads to the ultimate formation of CO_2 and CH_4 (Wolin and Miller, 1987) in varying proportions, typically some 10–50% in peatlands (Clymo and Reddaway, 1971;

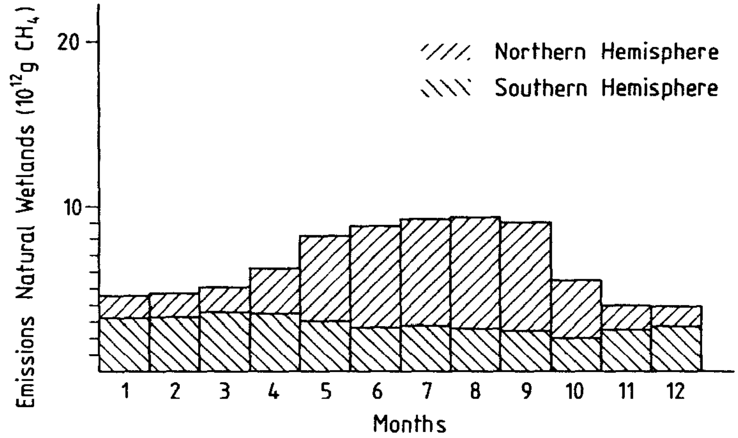

Fig. 6. Monthly distribution of methane emissions from natural wetlands using the mean CH_4 flux rates from Table V.

Svensson, 1983). Considering an area of 3.15×10^6 km^2 of temperate, boreal, and arctic fens and bogs (c.f. Table IIIa) and an average peat mass of 70 kg C/m^2 (Moore and Bellamy, 1974) we calculate with the above information a range of 6–74 Tg CH_4/a. This wide range includes both the estimated methane emissions from northern peatlands by this study (25 Tg) and by Matthews and Fung (65 Tg), however, the latter is at the upper end of this range.

Estimates for rice paddies that are based on a mean CH_4 emission rate of 310 mg/m^2/day would yield a total annual flux of 53 Tg/a with a range of 30–75 Tg/a (see Table V). Yet, as the mean rate of 310 mg CH_4/m^2/day was deduced from rice paddies in temperate regions, it may not apply to the warmer tropics

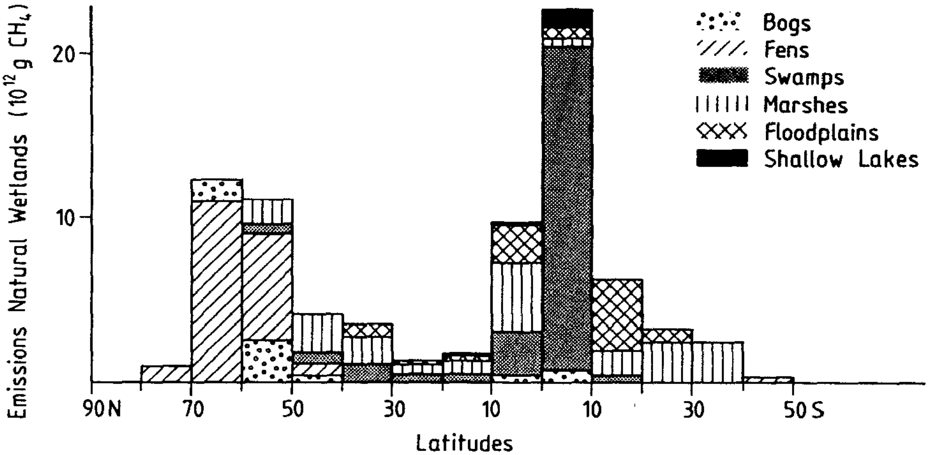

Fig. 7. Latitudinal distribution of methane emissions from natural wetlands based on the same flux rates as used in deriving Figure 6.

and subtropics, where most rice cultivation takes place. Holzapfel-Pschorn and Seiler (1986) found exponentially increasing methane evasion rates from paddies for increasing soil temperatures in the range of 17–25° C. Their function is restricted to temperatures of less than 28 °C and in their global extrapolation they set a limit of 1000 mg CH_4/m^2/day at 30 °C soil temperature, which virtually implies a linear relationship between emission rates and temperature. If we follow this approach and assume a linear function yielding a CH_4 flux of 300 mg CH_4/m^2/day at and below 20 °C and 1000 mg CH_4/m^2/day at 30 °C while adopting mean monthly temperatures (Oort, 1983) to represent mean monthly soil temperatures, a global yearly methane emission of 90 Tg is derived. The range may be 60–140 Tg/a if we assume the same uncertainty as obtained in temperate rice field studies.

The monthly methane emissions for the latter calculation are shown in Figure 8. Fluxes from rice paddies are highest from July to September, mostly due to emissions in the Northern Hemisphere, especially through wet season rice cultivation in South and South East Asia. Maximum emission is calculated for August with about 17 Tg while minimum emissions of 3–4 Tg are predicted for January through April. The contribution from the Southern Hemisphere is, as in the case of natural wetlands, only dominant during the Northern Hemispheric winter months.

The combined emissions from natural wetlands and paddies indicate a maximum in the CH_4 source in the subtropics between 20–30° N, where rice cultivation, according to our calculation, leads to the emission of more than 38 Tg per year (Figure 9). Rice paddies may also dominate the total emission in latitudes north and south of this region. This is further illustrated by the large peak at latitudes 20–40° N in Figure 10, in which monthly emissions from paddies and

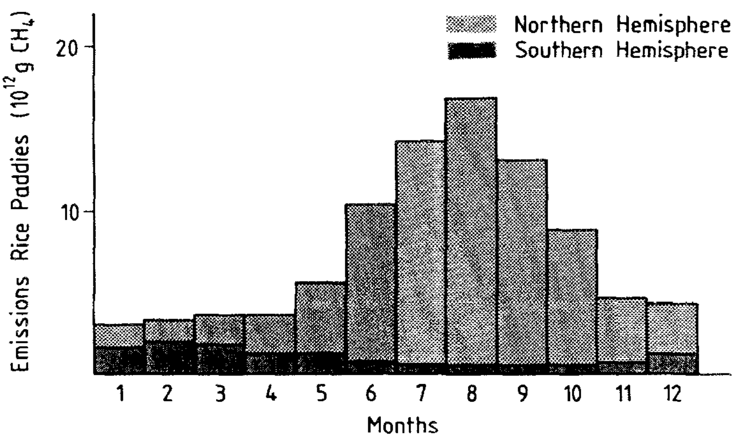

Fig. 8. Monthly distribution of methane emissions from rice paddies computed from temperature dependent CH_4 fluxes in the range from 300 to 1000 mg m^{-2} day^{-1} for temperatures from 20° to 30 °C.

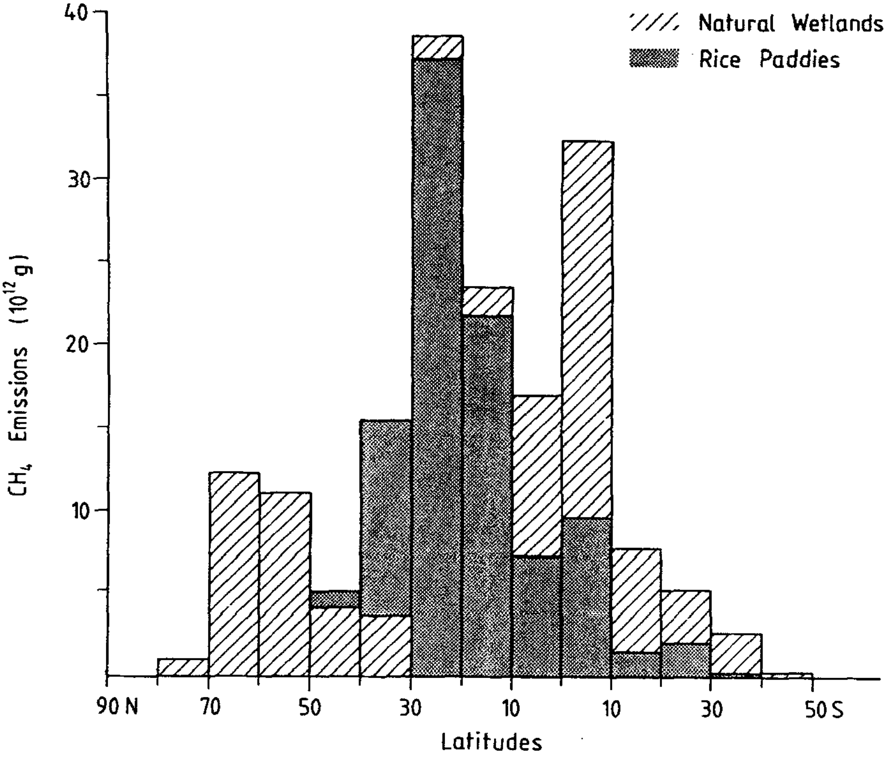

Fig. 9. Latitudinal distribution of the combined CH_4 emissions from natural wetlands and rice paddies.

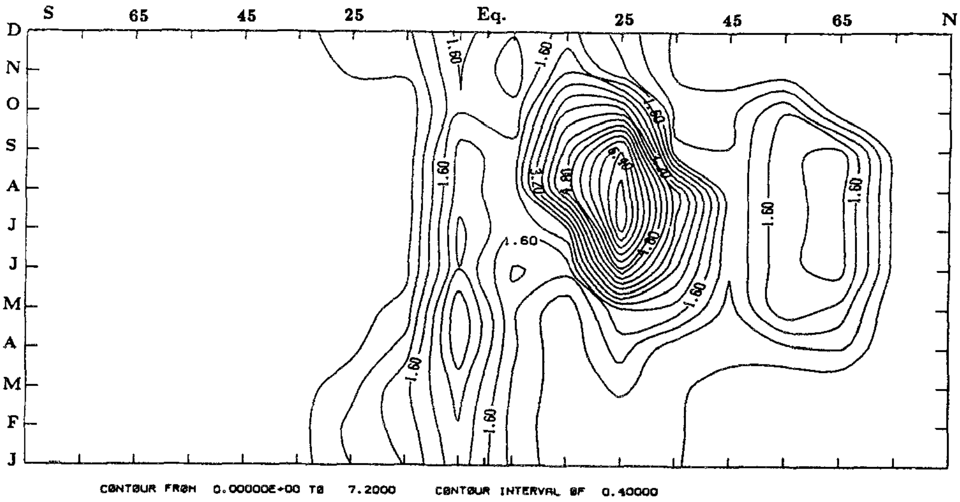

Fig. 10. Combined monthly methane emissions from natural wetlands and rice fields (in Tg) along 10° latitudinal belts.

Table VI. Estimates of global sources and sinks of methane

	Tg/a	Reference
Sinks:		
Reaction with OH	470–510	Crutzen and Valentin (unpublished)
Uptake by aerobic soils	10–30	Seiler *et al.*, 1984; Keller *et al.*, 1983, Harriss *et al.*, 1982; WMO, 1985
Annual growth (~1%/a):	40–50	Blake and Rowland, 1988; Khalil and Rasmussen, 1987; Blake and Rowland, 1986
Required total source	520–590	
Sources:		
Enteric fermentation	80–110	Crutzen *et al.*, 1986
Biomass burning	30–100	Crutzen *et al.*, 1985; Crutzen, 1986
Landfills	30–70	Bingemer and Crutzen, 1987
Fossil sources (fossil fuel exploration, natural gas distribution)	120	Wahlen *et al.*, 1989
Total	260–400	
Possible source from wetlands (paddies and natural)	120–330	by difference

natural wetlands are plotted versus latitudes. Two smaller peaks are further shown in April and May south of the Equator and in latitudes north of 60° N in June and September. In summary, our estimates for annual CH_4 emissions from natural wetlands and rice fields range from 40–160 and 60–140 Tg from these ecosystems, respectively. The total of 100–300 Tg/a overlaps largely with the range of wetland sources of 120–330 Tg/a which is required to balance the global methane budget as shown in Table VI. The analyses of this and the previous chapters indicate that the yield of CH_4 from rice paddies relative to NPP may be significantly larger than the yield from natural wetlands.

7. Conclusions and Discussion

We have shown that published information, together with our own estimates for regions lacking data, yields a global area of 5.7×10^6 km^2 of natural wetlands with the majority in boreal and tropical regions. This is in general agreement with the findings of Matthews and Fung (1987), whose global figure of 5.3×10^6 km^2 was drawn from quite a different approach and data sets. This indicates that previous estimates of methane emissions from wetlands were based on underestimated areas. In disagreement with the study by Matthews and Fung (1987) and based on data given by Junk (1989), we conclude that tropical wetlands are more abundant and that the methane flux from these ecosystems is more important than assumed before. Since for the area of natural wetlands we can only give tentative figures for some regions, our inventory must still be improved. Of particular importance is the question to what extent tundra regions have to be regarded as methane producing environments. If large circumpolar areas regarded as nonwetlands are found to produce significant amounts of methane, present data sets on wetlands need revision. Apart from this problem, the present data set constitutes a suitable ground for future methane release studies, as it combines wetland types, distribution, and seasonality, information required to understand the spatial and temporal distribution and atmospheric chemistry of methane.

Estimates of the global methane emission from wetlands to the atmosphere are still uncertain. The assumption, that 2–7% of the NPP of wetlands is released as methane, leads to a large range of 75–420 Tg per year. The upper value, in conjunction with other known sources (see Table VI), is far too large to be balanced within the global methane budget. Accordingly, a mean global fraction of CH_4 emission to NPP should be well below 5%. This shows that most decay of organic matter in wetlands occurs either aerobically or that most CH_4 produced is oxidized before reaching the atmosphere. Consequently, it is of prime importance to understand these processes. Direct extrapolation from flux rates are likewise shown to be very tentative. The limited set of data that is available at present, does not provide us with a concept that could explain and predict the large variations in methane fluxes as are found in different wetlands. Nevertheless, the mean flux rates in Table IV suggest that our grouping of wetlands into broad categories, i.e. bogs, fens, swamps, marshes, floodplains, and shallow lakes may have some ecological significance in respect to methane emissions. Further measurements of CH_4 fluxes are necessary, but we strongly recommend that future measurement programs do not simply gather more, undoubtedly equally scattered data, but rather, try to base these on ecophysiological principles or models, which explain the processes that are responsible for the observed fluxes. Considering the overall atmospheric methane budget, we could only derive a possible range of 100–300 Tg per year from the flux observations. The average annual emission of 170–200 Tg CH_4 from wetlands might come in roughly equal proportions from natural systems and rice paddies.

Wetlands are not a constant methane source as they undergo continuous modification due to anthropogenic action as well as climatic changes. Conversion of wetlands takes place with accelerating intensity, e.g. in Africa (Howard-Williams and Thompson, 1985) and South America (Junk, 1989), through hydrological constructions and drainage for land reclamation purposes. World rice production is still growing and no doubt will continue to grow with the potential of higher methane emissions. But the development of rice strains that can grow with lesser water requirements may compensate for such an increase (Prof. J. Bardach, personal communication). Further, if predicted changes in climate due to greenhouse gases happen, the distribution of wetlands will alter, triggered by changing patterns in precipitation and river discharges. Maybe, and potentially most important, the expected rise in temperatures, especially at high latitudes in regions of permafrost, may lead to increased decay rates and strongly enhance release of CH_4 to the atmosphere, which in turn may cause important feedbacks on global atmospheric chemistry and climate (Crutzen, 1986). The understanding of the atmospheric methane budget is indeed a major challenge for future research efforts.

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