CONF-821118--1

DE83 000994

Conf-8[illegible]18--1

TROPICAL ORGANIC SOILS ECOSYSTEMS IN RELATION TO REGIONAL WATER RESOURCES IN SOUTHEAST ASIA

MASTER

by

Thomas V. Armentano
Holcomb Research Institute
Butler University
Indianapolis, Indiana 46208 USA

Invited paper for: Regional Workshop on Limnology and Water Resources Management in Developing Countires of Asia and the Pacific. 29 November - 5 December 1982. Kuala Lumpur, Malaysia

Organized by The University of Malaya and The International Society for Theoretical and Applied Limnology (SIL).

Work supported in part by the U.S. Department of Energy
under special research contract DE-AC02-81EV10725
Report No. DOE/EV/10725-3

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

TROPICAL ORGANIC SOILS ECOSYSTEMS IN RELATION TO REGIONAL WATER RESOURCES IN SOUTHEAST ASIA

Thomas V. Armentano
Holcomb Research Institute
Butler University
Indianapolis, Indiana 46208 USA

Abstract

Tropical organic soils have functioned as natural sinks for carbon, nitrogen, sulfur and other nutrients for the past 4000 years or more. Topographic evolution in peat swamp forests towards greater oligotrophy has concentrated storage of the limited nutrient stock in surface soils and biota. Tropical peat systems thus share common ecosystem characteristics with northern peat bogs and certain tropical oligotrophic forests. Organic matter accumulation and high cation-exchange-capacity limit nutrient exports from undisturbed organic soils, although nutrient retention declines with increasing eutrophy and wetland productivity. Peat swamps are subject to irreversible degradation if severely altered because disturbance of vegetation, surface peats and detritus can disrupt nutrient cycles and reduce forest recovery capacity. Drainage also greatly increases exports of nitrogen, phosphorus and other nutrients and leads to downstream eutrophication and water quality degradation. Regional planning for clean water supplies must recognize the benefits provided by natural peatlands in balancing water supplies and regulating water chemistry.

Keywords: organic soils, peatlands, nutrient cycling, water quality, swamp drainage, oligotrophy, carbon, nitrogen.

Work supported in part by the U.S. Department of Energy
under special research contract DE-AC02-81EV10725
Report No. DOE/EV/10725-3

Introduction

The interaction of organic soils ecosystems with the inland water resources of Asia and the Pacific can be approached by posing two questions. First, what are the chemical, hydrological and biological influences of undisturbed organic soils pools upon regional water resources, and second, how does human utilization of organic soils change these relationships?

The origin and long-term persistence of most organic soils (histosols) has been determined by their location in lowlands, frequently near the coast or in association with rivers. These topographic relationships also have established physical and chemical linkages with upstream ecosystems and receiving waters. Great variation exists in the more than 20 x 10^6 ha of peatlands in southeast Asia, but they may be divided into relatively fertile eutrophic types and infertile low nutrient, highly acidic oligotrophic types. These categories reflect differences in nutrient cycling and potential for reclamation. Over the past 4000 - 5000 years sequential development of many peat-lands has proceeded from a eutrophic stage which developed in response to rising sea level in lowlands to a oligotrophic stage (Anderson 1964, Notohadiprawira 1979, Morley 1981).

Topographic evolution has brought about changes in soil and vegetation properties that affect the current role of organic soils in the regional water system. Besides a significant decrease in soil mineral storage rates (including mineral nutrients), a decline in total ash, pH, bulk density, rate of peat decomposition, and increased peat depth accompanied topographic evolution (Suhardjo and Widjaja-Adhi 1976). Driessen and Rochimah (1976) describe how topographic evolution caused progressive soil nutrient loss and consequent forest succession to dense, less-productive padang systems consisting of relatively few species having low-nutrient requirements. The common configuration of large peat swamps includes an interior convex peat dome where peat depths may exceed 15 m (Anderson 1964), surrounded by shallow peripheral areas having higher nutrient status. Peripheral and riverine swamps benefit somewhat from surface run-off from the peat dome, but are primarily enriched by contact with ground water, and nutrient inputs from adjacent ecosystems. Central peat areas, in contrast, are usually ombrotrophic, dependent upon small nutrient additions carried in precipitation and dust, rather than fluvial sources or mineral weathering.

Ecosystem Comparisons

Ecosystems can be classified by material cycling relationships which permit comparison of systems of differing physiognomy and location. Oligotrophic ecosystems functioning with limiting nutrients may share common properties although vegetation, climate and soils differ. For example in boreal peatlands topographic evolution towards isolation from groundwater sources and increasing impoverishment has occurred over the last 4000 years (Heinselman 1975) in a way similar to tropical peatlands. Correspondence in the structure of Indonesian peat swamps and raised bogs of the north temperate peat zone were first pointed out by Polak nearly 50 years ago (Anderson 1964). Gradients in nutrient levels and pH are similarly related to slope position and drainage patterns, sufficient to differentiate contrasting vegetation types. Vegetation tends to be more productive on peripheral or mineral rich peats as in Malesian swamp forests. Water movement in deep boreal peats also is principally surficial and the central dome configuration is characteristic in large bogs.

The concentration of most recycled soil nutrients in surface soils and the predominance of shallow-rooted trees are features common to tropical peatlands and certain oligotrophic forests on well-drained soils. In the moist, Amazonian caatinga forest, for example, soils are sandy, Spodosols with thin humus layers. Trees develop a surficial root mat closely associated with the humus (about 40 cm deep) where most nutrients are found (Jordan and Herrera 1981), whereas Driessen (1978) observed a similar nutrient concentration in the top 25cm of tropical peat forest. Caatinga forests are principally dependent upon meteorological nutrient inputs (Jordan 1982), similar to ombrotrophic peatlands. Vegetation biomass and species diversity in caatinga and padang forests, are lower than eutrophic tropical forests on more fertile sites.

Eutrophic forests appear to differ from oligotrophic forests because they grow on fertile soil with nutrients available over greater depths than oligotrophic forests, and by relatively high nutrient leaching rates (Jordan and Herrera 1981). Caatinga forests possess adaptations producing efficient nutrient retention and internal recycling which reduces leaching losses below meteorological inputs. On more fertile forest sites, leaching usually exceeds meteorological inputs.

The acidic nature of peatland and caatinga soils appears to inhibit nitrification thereby reducing leaching of soluble nitrate and also may inhibit ammonia volatilization. The surface distribution of the nutrient storage and roots, and the ombrotrophic condition suggest that tropical peatland nutrients are conservatively cycled as in northern peatlands (Malmer 1975). Further evidence of nutrient retention mechanisms in tropical peat forests is needed however, particularly with respect to plant-soil exchanges. Although differences in histosol and spodosol soils must be recognized in drawing comparisons, the similarity in these oligotrophic ecosystems may provide a basis for increased understanding of the response of peatlands to alteration.

Nutrient Sequestering in Tropical Organic Soils

Peat swamp forests differ conspicuously from other oligotrophic ecosystems (and from most eutrophic systems) by the accumulation of large quantities of detritus and soil organic matter. Available data indicate that carbon accumulation rates in some tropical peatlands far exceed those in eutrophic temperate histosols (Armentano 1981), although accumulation rates are reduced in highly oligotrophic peats. Left undisturbed, peat accumulation, whether in tropical or boreal climates, functions as a long-term repository (sink) for organic matter unless fires burn deep peat sufficiently to reduce previous accumulations. But in humid Malesia, a long-term net sink is characteristic. Chan (1982) estimated that productive dipterocarp forests in Malaysia averaged 22 kg/m^2 of carbon in vegetation and 8 kg/m^2 in soils, whereas in peat forests the values would be 10 kg/m^2 and (to 1m depth) 76 kg/m^2 respectively. Above-ground to below-ground organic matter storage ratios thus differ by 21 times without considering roots.

The production and accumulation of carbon in swamps influences the quality of drainage waters through sorption or chelation of cations by organic compounds. Partly decomposed peat retains many times its weight of water and has a high cation exchange capacity (which may exceed 200 meq/100g) (Driessen 1978). Consequently water draining undisturbed swamps is often very low in mineral content (Viner 1975) and tends to be dominated by H+, Cl$^-$, SO_4^- and dissolved organics rather than Ca+ and HCO_3^- as in minerotrophic wetlands and many upland ecosystems (Malmer 1975, Kirby-Smith and Barber 1979). The peat mass efficiently removes many incoming materials such as nitrogen and phosphorus in association with carbon accumulation as long as inputs do not overload the organic matter increment. The nitrogen and phosphorus are ordinarily unavailable for plant uptake. In the temperate zone the adsorptive capacity of peatlands has been utilized successfully for removal of nutrients from wastewaters (Sloey _et al_. 1978) although part of the stored material may be released during the cold season. The long-term effectiveness of northern peatlands varies with many structural and chemical factors leading to considerable site variation in nutrient removal capacities (Richardson _et al_. 1978). Similar variation probably also applies to tropical peatlands. The year-round biological activity in tropical peatlands, however, may favor a high capacity for reducing the nutrient load of drainage waters. Undeveloped peatlands thus should be evaluated as to their role in contributing to regional water quality.

Nutrient Export from Swamps

Although all ecosystems export organic and inorganic materials to ecosystems by soil percolation and overland flow, losses from lowland floodplain swamps may be particularly high (Brinson 1976, Mulholland 1981). The loss to other ecosystems of mineral and organic materials varies greatly depending on the proximity and hydrological connections of wetlands to rivers and tides. Large export of organic carbon in floodplain swamp streams is related partly to long contact times between overflow water and swamp litter. Rates of nutrient leaching or export are positively correlated with flushing rates, or the hydrodynamic energy gradient while organic accumulation is inversely correlated with flushing rates (Gosselink and Turner 1978). Vegetation production rates also are positively correlated with flushing rates, partially explaining the reduced phytomass in deep central peat deposits. Nutrient losses from large oligotrophic peat-swamp areas not subject to flushing are lower than eutrophic floodwater swamps. Carbon losses from swamps in general are measured as high concentrations of humic and fulvic compounds which are refractory breakdown products of humus.

Tropical Peatland Disturbance

Human utilization of histosols for food production inevitably requires lowering of the water table at least part of the year. Drainage leads to alteration of the ecosystem carbon balance in response to greatly increased microbial activity. The net carbon flux to sediments in undisturbed tropical histosols may be quantitatively significant in the global carbon cycle and functions to partially counter-balance carbon releases from other sources such as fossil-fuel burning and forest reduction (Armentano 1981). However, in some regions of the world the regional net sink in wetland organic soils may be reduced or even lost completely in response to drainage of wetlands (Armentano 1980). In southeast Asia most histosols remain undisturbed although reclamation has been carried out in West Malaysia for decades and is expanding in other areas.

Most deep, ombrotrophic peat formations in southeast Asia may prove unsuitable for productive agriculture, even after new agronomic advancements (Driessen 1978). Nevertheless a significant proportion of swamplands, most of which contain histosols, are regarded as having agricultural potential. Projections of the suitable area vary. Collier (1980) estimated that 10.5 x 10^6 ha of swamp possesses agricultural potential throughout Indonesia (this may include some non-peat soils), while Hanson (1981) concluded that rice production would expand onto, at most, 1 x 10^6 ha of swampland in Sumatra and Kalimantan. The potential for agricultural development of histosols in Malaysia appears greater with commercial cropping already well advanced, although Coulter's (1957) suggestion that most of these lands will eventually be developed for agriculture is debatable, partly because the sustained yield forestry potential of peatlands has become recognized. However, past successes with production of pineapple, oil palm and other crops (Tay 1969), plus agronomic and engineering advancements (Carew 1982, Chew et et. 1981, Ikehashi and Ponnamperuma 1979) indicate that additional areas may be exploited. Furthermore successful techniques developed by native peoples in Indonesia are becoming recognized for their effectiveness in overcoming the limitations of peat soils for subsistence and cash-cropping (Collier 1980).

Drainage Effects

Drainage of marshes and swamps can be expected to alter significantly the chemical character of the exported material transported to downstream ecosystems. Thus ditching associated with rice cultivation has changed local hydrology and salinity regimes in estuarine waters and altered the flocculation of river sediment in Indonesia (Chambers 1980). Furthermore, turbidity of drainage water or lateral streams has been observed to increase 10 to 20 times after alteration in warm-temperate, oligotrophic peatlands (Kirby-Smith and Barber 1979). Phosphorus and nitrogen and chlorophyll a concentrations rose 5 to 10 times higher after ditching. Peak concentrations were associated with the heaviest precipitation, thereby multiplying the total net export of peatland nutrients.

In other organic soil marshes in the temperate zone, drainage for agriculture released over 50 times the amount of nitrogen and 5 to 50 times the phosphorus that was released by conventional upland soils agriculture (Nichols and MacCrimmon 1974, Lee et al. 1975). In general, drainage greatly increases the export of organic compounds and mineralized nitrogen and phosphorus which commonly limit algae and macrophyte growth in receiving waters. The addition of fertilizer to drained sites would be expected to further enhance nitrate and phosphate availability.

Logging also can convert peat swamps into an increased source of minerals in exporting waters. Large reduction in surface soil nutrients can occur (Driessen 1978), leading to significant reduction in total ecosystem nutrient storage. Decreased content of total ash, potassium, ortho-phosphate and silicate in an Indonesian peat swamp after felling, and increased calcium and magnesium were measured (Driessen 1978). Agricultural activity following logging further decreased the inventory of all measured nutrients.

Nitrogen and Sulfur in Organic Soil Ecosystems

Since the C:N ratio in organic soils is around 20 or 30:1, oxidation of organic matter which accompanies disturbance releases large quantities of nitrogen as well as carbon. Drainage increases rates of organic nitrogen mineralization, rates of nitrification and of nitrogen fixation (Notohadiprawiro 1981). Consequently there is an overall increase in plant available nitrogen. In contrast nitrification is usually inhibited in flooded or acidic soils so that NH_4^+ is the principal ion available to plants. Inhibition of nitrification has been suggested as an adaptive mechanism leading to nitrogen conservation since NO_3^- is highly leachable. In contrast denitrification of oxidized nitrogen to gaseous compounds decreases after drainage. Some of the nitrogen which would be converted to gaseous forms by denitrifying bacteria in undisturbed soils is thus converted to highly leachable nitrate (Terry and Tate 1980, Richardson *et al*. 1978).

In drained eutrophic peat soils, organic nitrogen mineralization rates are very high, reaching 1400 kg/ha/yr in the Florida Everglades (27° N Lat.) in association with a subsidence rate of 3 cm/yr (Tate 1976). Nitrate concentrations in the organic soils, which average about 3.5% nitrogen, have been measured at 239 ppm and 127 ppm at 0-15 and 15-30 cm depth, respectively, after drainage (Neller 1944). Some of the nitrogen is released to a nearby lake which serves as a drinking water source. Although the Everglades supplies only 11% of the lake recharge waters, it contributes 35% of the added nitrogen, thus contributing to eutrophication (Terry and Tate 1980). Levin and Leshern (1978) also report high nitrification rates of 0.6 to 1.2 g NO_3-N/m^2/day in a deep-drained reed swamp peat soil in which subsidence occurred at rates reaching 10 cm/yr. The high level of nitrate in these soils far exceeds crop requirements, and therefore is subject to leaching.

In southeast Asia where peats are more acidic, nitrogen content appears to be lower, perhaps no more than 1.5% (Notohadiprawiro 1981). Nevertheless nitrogen storage is still quite high with an estimate of 9.2 x 10^{11} kg, for southeast Asian peatlands as a whole, assuming a mean depth of 2 m (Notohadiprawiro 1981). Low levels of available phosphate in acid peats may limit nitrification rates (Dowding 1981), but if fertilizer phosphate is added, nitrification levels would rise. Thus exported nitrate may supply a limiting nutrient in large quantities leading to nuisance growth of algae and macrophytes.

The presence of oxygen in drained histosols slows but does not fully inhibit denitrification although nitrous oxide (N_2O) replaces gaseous dinitrogen as the principal denitrification product, thus reversing conditions prevailing in flooded soils (Terry et al. 1981). Some of the N_2O escapes in dissolved form in the drainage waters, although most forms a gas. Denitrification is estimated to release 50 to 150 kg/ha/yr of N_2O-N from drained Everglades histosols, a rate over 50 times greater than the average loss from mineral soils (Terry et al. 1981). The net balance of atmospheric N_2O has recently become a topic of global concern in relation to the stratospheric ozone concentration because a net decrease in ozone brought about by N_2O

interaction would greatly increase the penetration of harmful ultra-violet radiation. Drained organic soils may be the most active N_2O source (on an area basis) of all croplands (Terry et al. 1981) similar to their role in CO_2 evolution. Further study is needed on nitrogen transformations in drained and undrained peat soils especially in the tropics.

Like nitrogen and carbon, sulfur is an important component of swamp organic matter susceptible to transformation and export after drainage. Recent studies have established that organic soils, even if undrained, release higher quantities of atmospheric sulfur, than other soils, with emissions taking the form of H_2S, dimethyl sulfide and other organic compounds (Adams et al. 1981a). Much of this material is oxidized in the atmosphere to form SO_2 or $SO_4^=$ which is scavenged by land and water surfaces. In the U.S. coastal and inland marshy soils occupy 7% of the land mass, but contribute 41% to the total atmospheric sulfur flux (Adams 1981a). Substantial release of sulfur in drainage waters also occurs (Viner 1975), and may produce large increases in sulfuric acid content (Stone et al. 1978). Drainage of histosols caused a two-fold increase in sulfur flux, reaching levels of 0.36 $gS/m^2/yr$ in one temperate histosol deposit (Adams et al. 1981b). Furthermore, regional analysis indicates that S emission rates increase exponentially with decreasing latitudes (Adams et al 1981b). Although acid sulfate and marine soils would release more sulfur, tropical peat soils, especially if drained, would also constitute a significant source.

Conclusions

As ecosystems tropical organic soils resemble other oligotrophic ecosystems in that the recycled nutrient stock is principally maintained in the surficial soil layers and vegetation. Jordan and Herrera (1981) have concluded that disturbance of Amazonian caatinga forests can lead to irreversible damage because these nutrient supplies can be easily lost through forest clearing followed by cultivation. Forest regrowth is inhibited by nutrient deficient soils or favors lower quality species adapted to low nutrient levels. Although peat swamps differ in many respects from upland oligotrophic forests, they have in common limited nutrient storage in surface litter and acidic infertile soils. Severe disturbance of peatlands thus may diminish the shallow peat layer where the bulk of nutrients are stored with consequent export of nutrients to drainage waters. Loss of the surface peat and adapted swamp vegetation also may result in colonization by disturbance-adapted species like _Melaleuca_ _leucadendron_ which have lower resource value and may inhibit recolonization by original forest species (Samingan 1979). Thus, disruption of forest soil cycles for forestry or agriculture may degrade sites of limited fertility into highly infertile ones in a retrogressive process similar in effect to, but at a much greater rate than, the natural successional trend in peat swamp development.

Based on research in the temperate zone and to a lesser extent in the tropics, nutrient exports associated with swamp disturbance will affect water quality and fishery values of receiving waters and adjacent ecosystems, stimulate eutrophication and raise the costs of reclaiming the water for drinking or other clean water purposes. Application of fertilizer replaces missing nutrients but may lead to increased export thus aggravating a downstream water quality problem and creating more favorable conditions for soil subsidence. Furthermore, the capacity of swamp ecosystems to sequester inflowing materials from upstream ecosystems will be reduced in proportion to reduction in the active peat mass. Thus in the context of regional development, the ecosystem values of peat swamps must be evaluated in terms of their linkages to surrounding ecosystems and the benefits they provide as intact, fully functioning systems.

References

Adams, D.F., S.O. Farwell, E. Robinson, M.R. Pack and W.L. Bamesberger. 1981a. Biogenic sulfur source strengths. Env. Sci. Tech. 15:1493-1498.

Adams, D.F., S.O. Farwell, M.R. Pack, E. Robinson. 1981b. Biogenic sulfur gas emissions from soils in eastern and southeastern United States. APCA Journal, 31(10):1083-1089.

Anderson, J.A.R. 1964. The structure and development of the peat swamps of Sarawak and Brunei. Journal of Trop. Geog. 18:7-16.

Armentano, T.V. 1981. The potential significance of tropical organic soils for the carbon balance of the terrestrial biosphere. Presented at: International Society for Tropical Ecology Jubilee Symposium, Bhopal, India. Proceedings in press.

Armentano, T.V. 1980. Drainage of organic cycles as a factor in the world carbon cycle. Bio. Sci. 30:825-30.

Brinson, M.M. 1976. Organic matter losses from four watersheds in the humid tropics. Limn. and Ocean. 21(4):572-582.

Carew, B.P. 1982. Tidal swamp development: The Patra Tani Project in South Sumatra, Indonesia. Paper presented at the Agricultural Production on Organic Soils Course, University of Florida Agricultural Research and Education Center, Belle Glade, Florida. 18 pp.

Chambers, M.J. 1980. The environment and geomorphology of deltaic sedimentation: (Some Examples from Indonesia). In J.I. Furtado (ed.), Tropical Ecology and Development. Proceedings of the Vth International Symposium of Tropical Ecology, Kuala Lumpur. pp. 1091-1095.

Chan, Y.H. 1982. Storage and release of organic carbon in peninsular Malaysia. Internat. Jour. of Environ. Stud. 18:211-222.

Chew, W.Y., K.T. Joseph, and K. Rambi. 1981. Influence of liming and soil pH on sorghum (S. bicolor) and groundnut (Arachis hypogaea) in acid tropical Malaysian peat. Exptl. Agric. 17:163-169.

Collier, W.L. 1980. Resource use in the tidal swamps of central Kalimantan: A case study of Banjarese and Javanese rice and coconut producers. J.I. Furtado (ed.), Tropical Ecology and Development. Proceedings of the Vth International Symposium of Tropical Ecology, Kuala Lampur. pp. 1047-1064.

Coulter, J.K. 1957. Development of the peat soils of Malaya. Malayan Horicult. J. 40:188-199.

Dowding, P. 1981. The Effects of artificial drainage on nitrogen cycling processes. Clark, F.E. and T. Rosswall (eds.) Terrestrial Nitrogen Cycles. Ecol. Bull. 33:615-625. Stockholm.

Driessen, P.M. 1978. Peat soils. Soils and Rice, The International Rice Research Institute, Laguna, Phillapines. pp. 763-779.

Driessen, P.M. and L. Rochimah. 1976. The physical properties of lowland peats from Kalimantan. Peat and Podzolic Soils and Their Potential for Agriculture in Indonesia. Soil Research Institute, Bogor. pp. 56-73

FAO/UNESCO. 1979. Soil map of the world-Vol. IX. Southeast Asia. UNESCO-Paris.

Gosselink, J.G. and R.E. Turner. 1978. The role of hydrology in freshwater wetland ecosystems. R.E. Good, D.F. Whigham, and R.L. Simpson (eds.), Freshwater Wetlands, Ecological Processes and Management Potential. Academic Press, New York. pp. 63-72.

Hanson, A.J. 1981. Transmigration and marginal land development. G.E. Hansen (ed.) Agricultural and Rural Development in Indonesia. Westview Press, Boulder, Colorado, USA. pp. 219-235.

Heinselman, M.L. 1975. Boreal peatlands in relation to environment. A.D. Hasler (ed.) Coupling of Land and Water Systems. Springer-Verlag, New York. pp. 93-104.

Ikehashi, H. and F.N. Ponnamperuma. 1978. Varietal tolerance of rice for adverse soils. IN: Soils and Rice. The International Rice Research Institute, Laguna, Philippines.

Jordan, C.F. 1982. The nutrient balance of an Amazonian rain forest. Ecology 63:647-54.

Jordan, C.F. and R. Herrera. 1981. Tropical rain forests: Are nutrients really critical? Amer. Nat. 117:167-180.

Kirby-Smith, W.W. and R.T. Barber. 1979. The water quality ramifications in estuaries of converting forest to intensive agriculture. Water Resources Research Institute of the University of North Carolina, WRRI Report No. 148, 70 pp.

Lee, G.F., E. Bentley and R. Amundson. 1975. Effects of marshes on water quality. A.D. Hasler (ed.) Coupling of Land and Water Systems. Springer-Verlag, New York. pp. 105-128.

Levin, J. and Y. Leshern. 1978. Using forage crops to reduce nitrate accumulation in Hula peat soils. Plant and Soil 50:419-426.

Malmer, N. 1975. Development of bog mires. IN: A.D. Hasler (ed.) Coupling of Land and Water Systems. Springer-Verlag, New York. pp. 85-92.

Morley, R.J. 1981. Development and vegetation dynamics of a lowland ombrogenous peat swamp in Kalimantan Tengah, Indonesia. Jour. of Biogeog. 8:383-404.

Mulholland, P.J. 1980. Deposition of riverborne organic carbon in floodplain wetlands and deltas. Flux of Organic Carbon by Rivers to the Oceans. Carbon Dioxide Effects Research and Assessment Program, U.S. Department of Energy, Washington, D.C.

Mulholland, P.J. 1981. Organic carbon flow in a swamp-stream ecosystem. Ecol. Mono. 5:307-322.

Neller, J.R. 1944. Influence of cropping, rainfall, and water table on nitrates in Everglades peat. Soil Sci. 57:275-280.

Nicholls, K.H. and H.R. MacCrimmon. 1974. Nutrients in subsurface and runoff waters of the Holland Marsh, Ontario. J. Environ. Quality 3:31-35.

Notohadiprawiro, T. 1981. Peat deposition, an idle stage in the natural cycling of nitrogen, and its possible activation for agriculture. IN: R. Wetselaar, J.R. Simpson, and T. Rosswall (eds.) Nitrogen Cycling in Southeast Asian Wet Monsoonal Ecosystems. Australian Acad. of Sci., Pub., Canberra, Australia. pp. 139-147.

Richardson, C.J., D.L. Tilton, J.A. Kadlec, J.P.M. Chaimie, and W.A. Wents. 1978. Nutrient dynamics of northern wetland ecosystems. IN: R.E. Good, D.F. Whigham, R.L. Simpson (eds.), Freshwater Wetlands, Ecological Processes and Management Potential. Academic Press, New York. pp. 217-241.

Samingan, M.T. 1980. Notes on the vegetation of the tidal area of South Sumatra, Indonesia, with special reference to Karang Agung. J.I. Furtado (ed.) Tropical Ecology and Development, Proceedings of the Vth International Symposium of Tropical Ecology, Kuala Lumpur. pp. 1107-1112.

Sloey, W.E., F.L. Spangler and C.W. Fetter. 1978. Management of freshwater wetlands for nutrient assimilation. In R.E. Good, D.F. Whigham, and R.L. Simpson (eds.), Freshwater Wetlands, Ecological Processes and Management Potential. Academic Press, New York. pp. 321-340.

Stone, J.H., L.M. Bahr, and J.W. Day. 1978. Effects of canals of freshwater marshes in coastal Louisiana and implications for management. In R.E. Good, D.F. Whigham, and R.L. Simpson (eds.), Freshwater Wetlands, Ecological Processes and Management Potential. Academic Press, New York. pp. 299-320.

Suhardjo, H. and I.P.G. Widjaja-Adhi. 1976. Chemical characteristics of the upper 30 cm of peat soils from Riau. Peat and Podzolic Soils and their Potential for Agriculture in Indonesia. Soil Research Institute, Bogor. pp. 74-92.

Tate, R.L., III. 1976. Nitrification in Everglades histosols: a potential role in soil subsidence. Publication no. 121 of the Internat. Assoc. of Hydrol. Sci. Proc. of the Anaheim Symposium. pp 657-663.

Tay, T.H. 1969. The distribution, characteristics, use and potential of peat in West Malaysia. Journ. Trop. Geog. 29:57-63.

Terry, R.E. and R.L. Tate, III. 1980. Denitrification as a pathway for nitrate removal from organic soils. Soil Sci. 129:162-166.

Terry, R.E., R.L. Tate, III, and J.M. Duxbury. 1981. Nitrous oxide emissions from drained, cultivated organic soils of south Florida. APCA Journal, 31:1173-1176.

Viner, A.B. 1975. The supply of minerals to tropical rivers and lakes (Uganda). IN: A.D. Hasler (ed.), Coupling of Land and Water Systems. Ecological Studies 10. Springer-Verlag, New York, pp. 227-262.