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WISCONSIN'S WETLAND SOILS

A REVIEW

By

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ABSTRACT

Literature dealing with wetland soils was reviewed. Included are writings on soil morphology and classification, soil chemistry, interrelationships between soil and various plant communities, and soil properties in relation to land use.

Wetland soils consist of porous materials usually saturated with and overlain by, water. The soils are either mineral, organic or usually both. Mineral materials comprise the land form in which the wetland is located. Organic soils tend to form on top of mineral materials. Organic soils of wetlands are classified as either aquatic or terrestrial. Aquatic deposits are sedimentary, composed mostly of material formerly in solution, suspension or floating in overlying waters. Terrestrial organic soils are composed of the remains of rooted plant species. Organic soil in wetland communities nourishes non-rooted plants by contributing to the fertility of the overlying water. Plants rooted in the soil derive nutrients directly from it.

The plants involved in early succession are the hydrophytic emergents, such as cattail. By invading open water areas they tend to reduce wave turbulence, favoring peat deposition and initiating the soil building process.

The organic soils are either peat or muck depending on the water table fluctuation and location. Mucks are more common in southern Wisconsin and peats are more common in northern Wisconsin.

Wetland properties have not always been considered when determining their use, and this oversight has created problems. Characteristics of the wetland soils which should be considered when they are used for farming are soil composition, erodibility, hydrology, and presence of harmful chemical substances.

Filling of wetlands in order to use them results in their destruction.

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INTRODUCTION

Soil is a significant part of wetland ecosystem, but it has received little direct attention as a functioning entity. This paper attempts to bring together literature bearing on wetland soils from the fields of limnology, agronomy, ecology, soils, and game and fish management, and to present this information in a form useful to conservation managers.

There is a vast body of literature that touches upon this subject, and no attempt was made to read it all. Textbooks, literature reviews, and monographs were the primary sources of information used; these have extensive bibliographies and present general trends rather than the detailed data found in individual papers. It is hoped that this approach will present a clearer overall picture. The result shows numerous gaps in our knowledge of wetland soils. Some will have to be filled before wetlands can be managed on other than an empirical basis.

Wetland soils consist of porous materials usually saturated with, and overlain by, water. Water in pores moves at different rates depending on the ground water gradient and the saturated flow rate in the soil (2). In most wetlands the rate of movement is negligible; but, in some areas, such as along fast-moving streams, it can be rather rapid. The rate of movement is significant in that dissolved oxygen in water is quickly exhausted by soil microorganisms decomposing organic matérials present in surface layers of soils (59). If water moves through the soil quickly, both water and soil tend to remain partially aerated: when it moves slowly they become deoxygenated (51). Sparling (61) found that water flowing at a rate of one centimeter per second was oxygen saturated, while slower-moving water had proportionately less oxygen.

In the absence of oxygen, anaerobic bacteria are the primary decay organisms. They differ from the aerobic forms in their end products and in their lesser efficiency. Aerobic organisms can decay organic materials completely, releasing to the environment carbon dioxide, water, and oxidized forms of nutrients. Anaerobic bacteria derive much less energy from the substrate, and can attack only the more readily decomposed portions of it. Therefore, an accumulation of partly decayed organic matter is characteristic of anaerobic decay, as is the formation of methane, ammonia, hydrogen sulfide, and reduced forms of other nutrients as primary decay products (55).

Wetland soil skeletons are either mineral, organic, or usually both. Mineral materials comprise the land form in which the wetland is located, and tend to predominate in drier wetland sites and in deep water areas low in production of organic life (28). Organic soils tend to form on top of mineral materials in shallow fertile water areas, and in places where the rate of production of organic material exceeds the decay rate. Soils are said to be organic if they contain about 30 percent (by volume) organic materials in depths of 1 foot or more. This is an arbitrary but useful distinction (26).

SOIL MORPHOLOGY

Mineral Soils

Mineral soils found in drier portions of wetlands are described as poorly or very poorly drained by the Soil Conservation Service. These are "wet" members of various soil parent material groups, identified by color patterns in their surface horizons that are associated with iron solubility under anaerobic conditions (60).

Iron is an important element in determining soil color. It occurs in well drained soils as insoluble trivalent ferric iron. Under anaerobic conditions ferric iron is reduced to the ferrous form, which is soluble and tends to move with the soil water. The reduction of iron from the ferric to the ferrous state is dependent upon the presence of anaerobic decay products (17).

In only periodically saturated soil parts, iron often accumulates in rust-colored spots, or mottles. Mottles often can be observed around roots in the soil, suggesting that some of them form when plant roots excrete oxygen in order to absorb nutrients and water from an oxygen-deficient soil environment. There the iron is changed back to the ferric form. The chemistry of manganese is similar to that of iron, and it often accounts for the reddish specks of color in mottles (55). In soils consistently saturated, iron remains in solution and the soil eventually takes on a grey or bluish grey color due to its loss. Such soils are termed gleyed and are usually leached of other nutrients, such as manganese and phosphorus as well (54).

Pans frequently occur in wet mineral soils. Ironpans form under conditions similar to those that induce mottling. They may result from the general amalgamation of individual mottles, or from later oxidation of iron at the top of a gley (38). In both cases ironpans are formed by reduction of iron in anaerobic soil zones and concentration of it in oxidized ones. The formation of claypans and hardpans in these soils is less well understood. They apparently result from the nature of clay formation and mineral weathering that proceeds in oxygen-deficient strata. Silicates are more soluble there than in better-aerated conditions and are the primary components of mineral soils and of pans (55).

Pan formation is not restricted to wetland conditions and may occur on relatively dry sites. In fine textured materials of flat-lying or slightly depressed topography, pans may develop to the point of perching water in their upper layers. Such soils are termed planosols, and they often support wetland vegetation (55).

A wet mineral soil.
The hand points toward mottles.

Cattail growing on sandy alluvial soil. The black zone is an old surface horizon that has been buried under inwashed sand.

An organic soil in the making. Old cattail stems have broken off and drifted ashore. This material will probably support a new cattail community in a short time.

These morphological characteristics form in soils that have been in place for long periods of time. Alluvial soils, on the other hand, are often still being deposited in floodplains. They are usually alternating layers of mineral and/or organic materials, sometimes showing the development of mottling, gleization, or pan development (60).

Organic Soils

Organic soils occupy about 4 million acres (11.4%) of Wisconsin's land surface (21). They vary in depth from one foot, by definition, to many feet. Organic soils are not necessarily restricted to wetland sites, but the conditions necessary to their development are usually found there.

Organic soils can accumulate at an average rate of one foot every 500 years, with a general range of 200 - 800 years per foot (22). However, such averages are of little value. Curtis (20) reports two organic soil areas in Wisconsin within a mile of each other, one 50 feet deep, the other 5 feet deep, both of the same approximate age. The rate of accumulation depends on the balance between vegetative growth and decay, both of which are affected by numerous environmental factors (state of succession, absence of fire, etc.)

Organic soils of wetlands are classified as either aquatic or terrestrial. The deposits of aquatic origin are sedimentary, resulting in a laterally uniform, thin layered structure. They are composed mostly of material formerly in solution, suspension, or floating in overlying waters. Terrestrial organic soils are composed of the remains of rooted plant species, usually growing above the water (21).

Terrestrial organic soils vary in chemical and physical properties with the plant species in their makeup and their degree of decomposition. Terrestrial peats are usually named for the predominant terrestrial species comprising them, as sedge peat, moss peat, woody peat, etc. Mucks are treated as a unity, though they probably also vary considerably (21).

The Soil Conservation Service maps terrestrial organic soils by (1) the state of decomposition of the surface foot of soil (muck or peat), (2) the botanical composition of the peat in general, (3) pH, and (4) the depth of the soil and its underlying material if less than about 4 feet deep. They do not map the aquatic peats (of marshes) except when they are the material underlying terrestrial peats. These are considered bottom material and not soil (60).

The terms peat and muck are used to describe organic soils. Peats are the primary product of anerobic decay, and consist of plant materials whose origin is recognizable. Muck results from the aerobic decay of peat, and is a black substance lacking uniform structure (21).

Aquatic peats have been termed gyttja, diatomaceous earth, dy, marl, and dopplerite (22, 57). Gyttja and diatomaceous earth are both derived from plankton; gyttja from the soft cell walled species, and diatomaceous earth from the siliceous diatoms. Various mixtures of sands, silts, clays, pollen, and deep water precipitates (calcium sulfate, iron sulfides, etc., mostly in nodules) also occur in mixture (21).

Dy is a soft, plastic, yellow deposit of colloidal humus.[1] Welsh (63), and Davis and Lucas (21) state that dy is of non-lake origin. Welsh says that dy is often formed where soft bog waters, rich in humus, encounter harder water. The calcium of hard water forms a salt with the colloidal humic acids of bog water, which tend to settle out of suspension. Davis and Lucas say that dy is usually material derived from sedges and reeds. They also apply the term dy to peats of any origin that have become dy-like due to extended water-logging and anaerobic respiration. Hutchinson (33), on the other hand, states that dy is of lake origin, probably planktonic, and is a deposit of the yellow acids of lake waters. Therefore the term dy is more a descriptive one than a definitive one. Marl and dopplerite are somewhat similar deposits. They are both high in lime but they arise from different sources. Marl results mostly from the loss of carbon dioxide from water, which causes an upset of the disassociation reaction of calcium bicarbonate, and lime $CaCO_3$ is deposited (57). This loss of carbon dioxide is mostly through its absorption by phytoplankton and aquatic plants, but some is lost by diffusion to the atmoshpere. Dopplerite is a calcium humate substance, mostly the remains of the algae *Chara*, which absorbs large amounts of lime (20, 21).

SOIL RELATIONSHIPS IN WETLAND COMMUNITIES

One of the several roles of organic soil in wetland plant communities is in relation to the fertility of the overlying water, and the non-rooted plants that absorb nutrients from it. Another is in relation to the plants rooted in the soil. In the first, the soil is in an equilibrium of sorts with the water and its population. The plankton and benthic flora absorb from the water nutrients which result partially from the decay of former generations of similar plants. In the second the plants are rooted in the soil and derive nutrients directly from it.

General fertility considerations

The effect of water fertility on productivity of plankton communities has been well established in recent studies of lake eutrophication. Most of these studies deal with nutrient pollution of water by the activities of man, resulting in accelerated growth of algae and in rapid accumulation of bottom materials. But variation in fertility of

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[1] Colloidal humus is small particles of organic materials which are easily suspended in water.

unpolluted water is also related to productivity of lakes and wetlands. Moyle (46) found that lakes of high alkalinity, an index of fertility and hardness, were much more productive of fish than were soft water lakes. Jahn and Hunt (34), observed a similar correlation for waterfowl production. The following discussion attempts to review some of the general factors affecting water fertility in lakes and wetlands.

All wetlands and lakes receive water that originally fell as precipitation on other land areas. In moving from the point of impact to the wetland, water dissolves carbon dioxide forming a mild acid which has the capacity of leaching bases from the soil (57). Thus the fertility of wetlands is determined in part by the area, the fertility, and the rate of leaching of the soils in their watersheds. Fertility of soils in Wisconsin is dependent upon the fertility of the geologic material from which the soils are derived, the influences of vegetation on the leaching rate, and the effects of man, particularly the use of commercial fertilizers.

In northern Wisconsin, most of the soils are derived from glacial till composed of acidic igneous rock. These have a low fertility, and usually support forest vegetation. Rainwaters percolating through the surface organic layers of forest soils pick up substances that increase the leaching rate. Over the thousands of years that this has been happening the soils have become rather impoverished in nutrients (5). This leaching process is most extreme under conifers, and somewhat less severe under deciduous forest vegetation (64). Such leaching must have resulted in fertile wetlands when the forests first became established and this may help explain the marl beds found under many of our present-day bogs.

In southern Wisconsin, the common parent material is inherently fertile dolomitic limestone, either as glacial till or bedrock. Because of climatic differences, less water runs off these soils: more of it returns to the air through evapotranspiration at the soil surface. Such climatic differences also increase the incidence of fire, which favors the growth of prairie or oak-savannah communities rather than forest. Prairie vegetation tends to increase soil fertility, while the scattered oaks of savannahs have only mild leaching tendencies. Farming with large amounts of commercial fertilizers, much more common in the south than in the north (20, 64), add to soil fertility.

All sorts of variations in these two basic type areas exist. Poff (52), presents detailed water analysis and a discussion of 5 major geochemical regions in Wisconsin. Soil zones are discussed by Beatty et al (5). And the relationship between Wisconsin soil types and productivity zones as they relate to wetland values for waterfowl are discussed by Mann (39).

Water may reach the wetland by surface or subsurface flow. Jahn and Hunt observed that, within any one region, landlocked wetlands were less fertile than those receiving surface water. They reasoned that streams serve as collecting agents for nutrients, which tend to accumulate in basins.

Nutrients in wetlands are either absorbed by plants, deposited on the bottom, or lost through surface or subsurface flow. Moyle (46) and Cook and Powers (17), found that surface flow of water out of wetlands results in lower fertility. The extent of subsurface flow of water out of wetlands is not known. It probably is slight in areas of fine textured sediments containing aquatic peats. It may be fairly rapid in sands or gravels, but this would depend on the groundwater gradient and the absence of blockage of soil pores by lake sediments (63).

Water loss through evapotranspiration is quite high in wetlands, approaching that of potential evapotranspiration (3). Emergents retard this process somewhat by reducing the effect of wind, as does the surrounding vegetation in the case of small ponds (17). This loss of water results in a concentration of nutrients and probably has much the same effect as fertilization. It may even be more effective, since the concentration of carbon dioxide is also increased.

Nutrients absorbed by plants or deposited on the bottom enter the nutrient cycles of wetlands.

Soil and water fertility in marshes

The soil, or bottom, consists of two general chemical zones. The greater part of it consists of a reduced, anaerobic zone. This is overlain by a thin zone, at the bottom-water interface, which may be oxidized or reduced depending on the oxygen content of the water immediately overlying it. This thin layer is a significant one in many ways (45, 27).

The substances released in anaerobic decay in the reduced zone rise to this surface. If these substances are in an oxidized state, some are partially transformed or absorbed. If they are reduced they enter the water. When the surface goes from an oxidized state to a reduced one, absorbed elements there go into solution. The soils role in relation to individual compounds will be discussed in the following paragraphs.

Nitrogen is one of the more important elements in wetland productivity. It enters wetlands mostly through inwash of surface waters or by fixation from the atmosphere by microorganisms. Groundwaters normally have low concentrations of this nutrient, and the quantities annually added by precipitation directly over the wetlands are apparently minor (33). Blue-green algae, particularly Anabaena cylindrica have been cited by several investigators as important fixers of atmospheric nitrogen (33, 17).

Nitrogen in wetlands is rapidly assimilated and, in the course of time, is reduced to ammonia, the primary form of inorganic nitrogen released in protein decomposition. This compound is strongly adsorbed to the surface of colloids possessing the property of base exchange (43). These colloids may be part of the soil or may be in suspension in water. Much of the ammonia is adsorbed to the surface of colloids of the oxidized surface soil. It is held there until the surface is reduced during periods of water anaerobicity when the ammonia is released. Ammonia adsorbed to water-borne colloids is a source of nitrogen for plankton.

Hutchinson found a large concentration of ammonia at the water surface, as compared to depths only a few centimeters below the surface. He postulated that the ammonia was adsorbed to colloids, and that the colloids were more numerous at the water surface due to attraction by the molecular forces that go to make up surface tension.

Much of the adsorbed ammonia, in water or on the oxidized surface, is converted to nitrate, a process that occurs only to adsorbed ammonia, and only in an alkaline or neutral environment (33). These nitrates may be lost through denitrification by bacteria, which convert them to atmospheric nitrogen. Some of these bacteria use nitrates as an energy source for converting sulfides to sulfates, possibly an important reaction in wetlands as it tends to reduce the nitrogen supply, decrease the sulfide toxicity, and to acidify the water (33).

Ammonia in the soil forms some sort of decay-resistant complex with peat. This appears to be a minor part of the nitrogen in the ecosystem, but probably accounts for a significant part of the nitrogen found in old peat beds (6).

The adsorption of ammonia on colloids of the soil surface tends to neutralize the acidity of the organic colloids, and to make an imbalance of the nutrients needed for emergent rooted vegetation. Ammonia is adsorbed preferentially to colloid surfaces over most of the other common cations[2], and is abundant in eutrophic marshes (43).

Phosphorus chemistry within the reduced soil zone is not known. It is generally soluble as long as iron is in a reduced state, and calcium is not too abundant. Both ferric iron and calcium form insoluble precipitates with phosphorus. At the surface zone some of the phosphorus may be absorbed to ferric hydroxide (or oxide) colloids if the surface is oxidized. If this zone is in a reduced state, phosphorus is free to move into the overlying waters. Once there, it may be precipitated again as calcium phosphate or be absorbed to slowly settling lime particles. Or, during turnover, it may be precipitated as ferric phosphate as the iron becomes oxidized. Much of the phosphorus in water is caught up in this cycle with iron (45).

Low phosphorus supply seems to limit the plankton growth in some Michigan marl lakes, making them unproductive of fish. Phosphorus fertilization of such lakes is apparently inefficient for plankton growth, because the phosphates are either absorbed to particulate lime or precipitated directly as calcium phosphate (32). Growth stimulation is limited to the benthic algaes. Schelske et al. (58) added both phosphorus and iron chelate (artificial colloids) to marl lakes. They found that the two together cause a large plankton growth increase, but that either one alone had less effect. It appeared that low iron supply as well as low phosphorus supply was limiting growth. These investigators and Mortimer suggest that much of the available

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[2] Cations are positively charged ions in solution.

phosphorus in epilimnion water is carried there on organic colloids during periods of overturn. Such colloids are lacking in marl lakes due to flocculation by the large amounts of calcium present. Mortimer postulated that the phosphorus is absorbed to ferric colloids at the oxidized surface, and that these, in turn, were absorbed to organic colloids.

Peek (50), added marsh water to cultures of Anabaena cylindrica. He found that both iron and phosphorus were more soluble than in distilled water solutions, and that both were absorbed by the microorganism in quantities more favorable to growth. These effects seemed to be related to the presence of humic substances in the marsh water.

While nitrogen and phosphorus are popular research report subjects potassium has seemingly been neglected in the literature. Although potassium is known to be required in large quantities by land plants, very little is known about its importance in aquatic plant nutrition. Welch presents analysis of ash of two algae species and of five higher aquatic plants. The algae ash contained zero and 0.58% K_2O, while the higher aquatic plant ash ranged from 2.08% to 5.48% K_2O. So it would appear that potassium is not needed in as great quantities by algae as it is by rooted aquatics.

Potassium apparently is necessary for synthesis of protein from amino acids in plant tissue. Also, some plants are unable to synthesize amino acids when supplied with ammonia rather than nitrate nitrogen when potassium is not present. Under these circumstances ammonia accumulates in the cells and may be toxic (42). Since ammonia is the primary form of nitrogen in wetlands, it may be that potassium is also of some significance to higher plants growing there.

Sulfur chemistry is also important in marshes. Hydrogen sulfide is produced in anaerobic decomposition and may be toxic in fairly dilute concentrations, but most of this reacts with heavy metals, particularly iron, to form very insoluble sulfide precipitates. These are stable in anaerobic environments but may be oxidized to sulfates when aerated (21, 33).

Green and purple photosynthetic sulfur bacteria also oxidize sulfides to sulfates in oxygen-deficient areas, given even a small amount of light. On the other hand, there are bacteria capable of reducing sulfates to sulfides in peaty anaerobic environments. Mortimer (45) found sulfate content increased in hypolimnion waters of lakes as long as the soil surface was oxidized; its reduction brought an increase in sulfides. And with the increase in sulfides there was a decrease in soluble iron, as iron sulfide was formed. This left phosphates in solution which would not be precipitated as ferric phosphate when the water was again aerated. Some investigators propose adding sulfate to increase the amount of soluble phosphate in lake waters subject to stratification (33).

Manganese sulfide also forms in wetlands, but it is less insoluble than the sulfides of the heavy metals (33). This plus the prevalence of manganese in wetlands and its toxicity to plants in fairly dilute concentrations make it a likely suspect in cases of mortality of wetland vegetation.

Peat in the presence of ammonia can absorb large quantities of hydrogen sulfide (22), but the extent of this reaction in natural conditions is unknown.

Methane, or marsh gas, is produced in abundance in anaerobic organic soils. It is a product of methane-producing bacteria which, according to Welch, function only in an alkaline environment. Russell (55) reviewing literature on rice paddy soils, states that some of this gas is transformed to carbon dioxide by other organisms in the oxidized surface layer or in the water immediately above it. Methane gas is often released directly to the atmosphere either as gas bubbles through water or, in dry periods, by direct diffusion. Hartman and Brown (29) found methane in the internal atmosphere of Elodea and Myriophyllum during hours of darkness in summer and under ice in winter; however, it disappeared rapidly during periods of photosynthesis.

The soil surface layer would seemingly always be oxidized in marshes in summer, and reduced in winter; but Cook and Powers found stratified wetlands in New York State during the summer. The extent of stratification in Wisconsin wetlands is unknown.

Disturbance of the soil surface and the consequent turbidities in the overlying waters probably tend toward stratification. Cook and Powers found greatly increased alkalinity values in such water, and Edwards and Rolley (24) found that oxygen consumption was proportional to the amount of agitation of the mud. Turbidities lower the light penetration and interfere with the oxygen production of benthic photosynthetic species. These help to maintain the oxidized state of the surface by absorbing decomposition products and liberating oxygen. Carp and other organisms that disturb the bottom appear to increase the tendency toward chemical stratification (9).

The benthic animal communities of ponds have been described by Welch (63) as being extremely variable. Pond faunas, particularly those of temporary ponds, are largely composed of species which may pass a part of the life cycle out of water. Amphibians are usually abundant. Fish, often present in permanent ponds, are usually absent in temporary ponds. Among the invertebrates, Protozoa, rodifers, insects, crustaceans, and snails are all important, with insects displaying the greatest diversity of species. In anaerobic sediments or in areas where the overlying water contains little oxygen the invertebrate bottom fauna may be abundant, but very low concentrations of dissolved oxygen include some species of oligochaeta, red tendipedid dipteran larvae, psychodid larvae, and the rat-tailed maggot larva, Tubifera tenax. The relationship between benthic communities and the bottom materials are not well documented, but most of these organisms require an oxidized surface; its reduction results in destruction of the communities or a shift to more tolerant forms (13).

into soil. The latter investigators found ferric iron coatings on the roots of healthy aquatics, and felt that the release of oxygen served as a barrier to protect the roots from harmful reduced substances, particularly iron and manganese. It would be interesting to know how much the anaerobic reduced soil zones are changed by invasion of emergents. And also, how much effect emergents have in overcoming anaerobicity and chemical stratification that normally occurs in marshes in winter.

Emergents have a greater capacity for anaerobic respiration than do many other plants (35, 36). Most higher plants can respire anaerobically for short periods but they are apparently less tolerant of the accumulation of end products (alcohols and acids) of the process than are the emergents. There is also much less energy released in the process; not enough for active nutrient and water absorption (42). Drought and nutrient deficiency symptons are characteristic of plants lacking oxygen around their roots. Passive water absorption is also inhibited by high CO_2 concentrations, (56). It appears that periods of aerobic respiration are necessary for hydrophytes but they can respire anaerobically for long periods of time without harm.

The features that allow emergents to pioneer water areas apparently restricts them in competing with better adapted species in shallower water areas. And because they are invading water depths at their threshold of tolerance, they are quite sensitive to higher than normal water depths. The harmful effects of water level fluctuation on emergents is noted repeatedly by Zimmerman (66) in his survey of waterfowl habitats in Wisconsin.

In shallower water areas emergent communities are often invaded by sedges of the Carex genus. These are similar to the emergents in that they are perennials that spread primarily by aerenchymous rhizomes but often they also have growth habits that allow them to take advantage of fluctuating water levels (20).

The tussocks or hummocky ground areas formed in southern Wisconsin by Carex stricta are a good example of this (18). Its rhizomes successfully invade water to depths up to two feet, root, send up rosettes of leaves, and eventually form tussocks 2-3 feet high and several feet in diameter. Carex stricta can send roots down several feet from these tussocks to obtain water if necessary. This species, in effect, changes the soil level to one more favorable to its own growth and less favorable to the pioneer emergents. Other sedges have a similar effect through rapid growth of their rootstocks and rhizomes, according to Curtis, but do so in a less spectacular way. Such "autogenic" processes apparently raise the soil surface up to the water level in a fairly short time (20).

The soils of sedge meadows are usually organic, though they also may be wet mineral soils. The organic soils are either peat or muck depending on the water table fluctuation and location. Mucks develop rather easily in southern Wisconsin when peats are exposed to the air by a drop in the water level. In northern Wisconsin peats in sedge meadows seem to be more common. This may be due to cooler—

Rooted plants and soils

The plants involved in early succession are the hydrophytic emergents, such as cattail. By invading open water areas they tend to reduce wave turbulence, favoring peat deposition and initiating the soil building process. These plants have their roots in the soil and their leaves in the air, with varying depths of water and stems between the two. They are perennials with large root stocks, and invade new areas primarily by rhizomes. This growth habit allows only slow spread, but once rooted they are better established than seedlings and are long-lived. Variation between species in the tolerance of their rhizomes to conditions encountered in extension apparently is one of the main factors involved in differentiation of early emergent communities (7.8).

Dean (23) studied the rooting habits of several emergents. He found that all of them developed a deep, branching root system in aerated soils, but in anaerobic ones they had shallow, stubby root systems, branching only in the surface soil. Cattail, unlike the others, developed a water root as well as a soil root. This root developed at the highest portion of the basal node, and grew upward and outward along the soil surface. Cattail was the only species he studied capable of invading deep water areas, and he felt the two might be related. Such roots would be exposed to both aerated water and to the rich aerated bottom materials.

Aerenchyma tissue[3] appears to be the significant anatomical feature that allows emergents to root where they do. Conway (15), studied the internal atmosphere of emergent roots and found that damage to them was evident when their oxygen content fell below 10-11%. Aerenchyma tissue in normal healthy aquatics maintained oxygen concentrations up to 18%. But when the aerenchymous stems were cut and submerged below water, the oxygen concentration in roots fell to 1-3%.

Aeration of roots appears to be necessary in winter as well as in summer. Laing (37) found winter aeration can be critical to the survival of cattail communities. He stated that green tissue was necessary for gaseous exchange. Marsh, however, found that the rate of movement of gases through dry brown aerenchyma tissue was rapid (40), so green tissue may not be a requisite. The exposure of aerenchyma tissue to the air by breakage or tearing of the brittle, dead leaves by the wind may also be of significance. Curtailment of winter aeration through the under-ice clipping of aerenchymous stems by muskrats was suspected as a cause of vegetation die-off at Horicon Marsh (41).

The need for aeration during the winter is probably partly for aerobic plant respiration and partly for improvement of the soil. Armstrong (1) and Cook and Powers found considerable diffusion of oxygen from roots

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3 Aerenchyma tissue is specialized plant tissue for the exchange of gases between parts of the plant - usually roots and leaves.

Big bluejoint grass sod. It consists of about 6 inches of intertangled live and dead roots and other soil material. Below it lies a gleyed zone with few roots.

temperatures in wetlands there, or to differences in ease of decomposition of the peat. The presence of earthworms in aerated lime enriched southern meadows may also be a factor (48). Within either area, mucks are generally more fertile, as they contain the products of peat decomposition. Mucks are also often a better root environment than are raw peats. Haslem (30) found early hydrosere community species composition was greatly affected by both water table fluctuations and the resulting fertility differences.

Changes in soils resulting from progressive succession have been studied by Pearsall (48), Misra (43), and Gorham (28). These are an increase in the organic matter content of the soil, an increase in acidity, an increase in base exchange capacity, an increase in the carbon-nitrogen ratio of the soil, and a decrease in total bases.

Anaerobic muds tend to be alkaline, fertile, and to have much nitrogen per unit of carbon. Ammonia absorbed on the colloid surfaces accounts for much of the alkalinity and for the low carbon-nitrogen ratio. At the oxidized surface of inundated soils and in exposed peats ammonia is partially converted to nitrates. Nitrate tends to make water more acid (forming dilute nitric acid) and at the same time there is a loss of alkalinity due to the loss of ammonia. Because nitrates are highly soluble and not held by colloid surfaces, there is a widening of the carbon-nitrogen ratio and a loss of total bases in the soil.

Aerobic decay also produces colloidal sized organic particles. These often have a net negative charge as the result of loss of hydrogen ions. They have properties similar to both clay particles and organic acids. In an alkaline environment they adsorb bases to their surfaces, while in an oligotropic[4] environment they act as acid anions[5] (55).

Another source of acidity in areas with a fluctuating water table are the sulfur compounds. Heavy metal sulfides are formed during anaerobic periods, which are oxidized to sulfates when dry. Sulfates tend to form sulfuric acid in solution (33).

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[4] Oligotropic environments are those which show little or no geologic aging.

[5] Anions are negatively charged ions in solution.

There are also significant chemical changes in the soil at various levels of aeration, which probably have effects on species composition and growth at various stages of succession. Patrick (47), Mortimer (45), and Pearsall and Mortimer (49), studied these chemical changes using the oxidation-reduction potential to characterize the degree of aeration in the soils. The potential is zero, or sometimes negative, in anaerobic soils. At these levels, and up to about 0.1 volt, sulfides are formed rather than sulfates (45). Iron is in the ferrous form from zero to 0.35 volt, when it is oxidized to ferric (49). Manganese is less readily oxidized than iron, and exists in a reduced form beyond 0.35 volt. Nitrates accumulate rather than ammonia above about 0.34 volts (47). And organic acid colloids begin to form at 0.3 volt (49). Aerated soils have potentials of 0.38 volt (45), and surface waters in periods of photosynthetic activity have potentials of 0.5 to 0.6 volt (49).

Sphagnum bogs are unique communities, and have received a great deal of attention from botanists, but little is known about their soil relationships.

The soil is loose green moss on the surface of these bogs, becoming quite dense and compact with depth. The lower layers become very nearly impermeable to water. Heinsellman, (31) studying bogs in Minnesota, found this impermeability was the key to the paludification process, (the spread of organic soils out of wetlands into uplands) creating muskeg. The moss created perched-water table wetlands conditions in the uplands, resulting in the gradual death of the mesic communities occupying the site. The process is apparently abetted by climate also, as no such spread of muskeg is apparent in Wisconsin, although it has been observed in Alaska (21).

The water in bogs is usually not moving, and anaerobic conditions prevail below its surface. If the water level is consistently close to the surface, bogs may tend to be alkaline or neutral rather than acidic (48). As in other wetlands acidity tends to increase with aeration. Fluctuating water levels might be expected in bogs in view of their perched water tables. And sulfide precipitates, particularly iron sulfides (bog ore) are often present in bogs in abundance. Presumably sulfide oxidation helps explain the very acid condition of many bogs.

Acidity also increases in bogs due to cation absorption by sphagnum (20). While differences do exist between species of the genus, they are all quite resistant to decay (14, 16). So once a cation is absorbed it is generally lost from the ecosystem. This results in lower bog fertility, since the absorbed cations are also nutrients. It also results in loss of calcium and magnesium, the more prevalent basic cations in Wisconsin's soils and waters. In water these cations neutralize the acidifying tendencies of both dissolved carbon dioxide and of humic colloids. In soils they replace hydrogen on colloid surfaces and raise the pH. Both soil and water are rendered more acid because of the absorption of these divalent cations by sphagnum.

The hydrology of bogs in relation to plant communities was studied by Bay (4), and by Chapman (11). Bay studied two bogs in Minnesota, one with a perched water table, the other connected to the true water table. The perched one has a more fluctuating water level, a more acid pH, less fertile water, and fewer types of plant communities than the non-perched one. Chapman found plant community distributions on bogs were dependent on nutrient concentrations, which in turn were dependent on water movement through the bog.

Toxic substances in bog waters have been postulated by several investigators. Curtis suggests that sphagnum and other bog plants excrete anti-biotic substances from their roots, which are toxic to other plants. Richards and Wadleigh (53) reviewed literature indicating that "reduced forms of certain components prevailing under the anaerobiosis of waterlogged soils are specifically toxic to plants and that these substances are readily oxidized and rendered harmless under aerobic soil conditions." These compounds appear to be the aldehydes and organic acids produced by plants and microorganisms in anaerobic respiration, as well as the other reduced substances previously discussed. Russell (56) reviewed literature showing that some of the aldehydes and organic acids produced by anaerobic respiration have germination-inhibiting properties. He also lists manganese, iron, and hydrogen sulfide as toxic substances.

In combination with the severe microclimate of most bog sites, and their low fertility, sphagnum bogs are a rigorous environment for most land plants.

WETLAND SOIL PROPERTIES IN RELATION TO LAND USE

Soil properties should be considered in determining land use, but they sometimes are not. This oversight often leads to individual and social problems of considerable magnitude. Thus, the pineries were cut and burned to make way for farms, even on sand soils too dry and infertile to support continuous cropping. This created rural poverty, loss of income from sustained forest yields, and deterioration of the soil itself. The problems have only partially been ameliorated by rural resettlement and creation of state, county, and national forests.

Similar oversights have occurred in wetlands. Some cities are located on floodplain soils created by deposition during periods of river overflow; so floods which could easily have been foreseen and avoided bring property destruction and sometimes death to the inhabitants. Solutions to these problems have been the building of flood control structures, and, more recently, floodplain zoning ordinances. The delineation of floodplains for zoning purposes is difficult in some areas even with soil maps (10), but the more obvious alluvial deposits can be easily ascertained.

In other wetlands similar oversights have been made. This section will attempt to review some of the more significant properties of wetland soils in light of land use.

Lowering the water table

Wetland soils are greatly affected by changes in the water level, particularly the organic ones. Organic soils are in equilibrium with the anaerobic, reduced environment and its microorganisms. When this environment is changed to an aerated and oxidized one by lowering the water level and exposing them to air, they are no longer stable. Peats then undergo subsidence caused by shrinkage from drying, compaction, and oxidation. Subsidence occurs most rapidly when the material is first exposed, but continues throughout the period of exposure (62).

Sheboygan County marsh during drawdown. The soil is muck overlying marl.

Water occupies a large part of the total volume in saturated organic soils. When water is removed organic soils tend to contract both vertically and laterally. The amount of contraction depends partially on the colloid content; aquatic peats shrink more than do the terrestrial ones. Shrinkage calculated as a percentage of original volume may vary between 90% for aquatic peats, to 40% for terrestrial ones. Shrinkage also varies with the height above the water table (21, 62). It appears that the height above water affects moisture content through capillary conductivity and retention (2), and that the amount of shrinkage is dependent on the moisture content (21, 44).

A small study of shrinkage of marsh soils was conducted at Sheboygan Marsh during the summer of 1968. These were black, finely divided mucks rather than peats. Shrinkage was 38% of the original volume, a decrease in depth of about 10-11 inches. Exact values for depth cannot be given because measurements were volumetric, and the extensive horizontal cracking that developed in the lakebed indicate that the normal assumption of equality of vertical and volumetric change is not valid. It appeared that the main part of the shrinkage that occurred at the marsh was due to loss of water.

When reflooded, peats will expand somewhat, but do not return to their original moisture content or volumes. This property apparently has to do with the destruction of the original structure, and the formation of air films, and of ferric humate colloids during the dry period. Dried bottom sediments often tend to float when reflooded, as their organic materials are light, porous, and resistant to wetting.

Compaction results also from the removal of water, as the weight of the peat above a point bears on the underlying material fully, rather than being buoyed up by water. However, peats are quite light and compaction from this cause appear relatively slight. Compaction tends to reduce pore size and thus to reduce aeration and increase water holding capacity. Farmers often intentionally compact drained organic soils in order to bring these changes about (21).

Oxidation is the most significant long-run effect of drainage. Oxidation involves the conversion of peat to muck and of muck to its inorganic constituents. All exposed peats will eventually oxidize completely. The rate of oxidation, however, depends on a number of factors, most of which affect the type of microorganisms present and their rate of metabolism.

Nitrogenous compounds usually decompose readily, and these are the first to be decayed when peats are exposed to the air. Thus, newly drained wetlands characteristically have high nitrate nitrogen contents. Some nitrogen remains in soil, perhaps tied up in nitrate-loving plants such as nettle (65) or in microorganisms, while some is leached out and carried away in the drainage water. The supply of nitrogen diminishes with time in wetlands, and the soils remaining after a period of years are usually decay-resistant ones with low nitrogen content. Decay-resistant organic materials often have low ash contents and less than 1.0% nitrogen content (21), which require inputs of nitrogen for decomposition.

The rate of decomposition is also affected by pH, temperature, moisture, and aeration. Cool, wet, acid conditions result in slow rates of decay, usually by fungi, while warm, moist, alkaline conditions are conducive to rapid decay by bacteria (38). This perhaps helps explain the prevalence of peat soils in northern Wisconsin as opposed to the mucks in the southern part of the state. Fungi communities were studied in northern Wisconsin by Christiansen and Whittingham (12). Representative fungi were correlated with the species composition and maturity of the overlying higher plant communities in bogs and conifer swamps. Different fungi communities were found in each.

Oxidation involves the liberation of all of the nutrients in organic soils, and approximates the effects of fertilization. However, iron, phosphorus, and manganese are often locked up as insoluble precipitates in aerated environs, particularly the alkaline ones. Other elements that may be present in small amounts are potassium, copper, boron, zinc, molybdenum, sodium, and sulfur. Some of these elements vary in availability with acidity, and may be overabundant, leading to toxicity, depending on the pH (21).

These changes occur in organic soils whenever they are exposed to air above the water surface. Such exposure may result from the gradual rise of the wetland soil surface in hydrosere succession, by drought, or through natural or artificial changes in drainage. In any case there is a general increase in fertility, a shrinking back toward the water level, and perhaps an increase in acidity.

Fire and burning

Fire is a significant hazard in dry peat materials. Peats burn readily, and are used for fuel in many parts of the world. Fire is rapid oxidation, as opposed to the slower microbial process, but the end results are similar. The main difference is that the nutrients are liberated all at once rather than over a period of years. Fire may result in an excessive concentration of some elements, resulting in toxicity. Also, the ash following fire has a liming effect, and pH increases of 1-2 pH units are common after burning (11).

The principal effect of fire is the destruction of the combustible peat. The depth of material destroyed and the character of the remaining material determine the severity of the effects on both natural and artificial plant communities (20).

Fire has been the cause of failure of some of the larger wetland drainage projects in the upper midwest. Inadequate safeguards against fire were characteristic of some of them, as was poor site selection. Shallow organic soils overlying sand, dense clays, boulders, and marl were drained. When these burned or oxidized there was nothing left to cultivate and the areas were abandoned (19).

These drained, burned, and abandoned sites are often dominated by long-term nettle communities in southern Wisconsin (20), and by off-site aspen, or sedges and rushes, in the central Wisconsin sands (65). Their best use appears to be reflooding and management for marsh habitat. Probably many of the drained lands now in farms will also become submarginal farmland over the years through oxidation, and will become available for this use. Such rehabilitated marshes will probably need fertilization (65).

The effects of peat fire in natural wetlands are not all bad. These are usually followed by an increase in fertility and a reversion to early hydrosere succession species when the water table returns to its normal level. Such fires are viewed as natural occurrences by plant ecologists, and their effects are discussed by Curtis at some length in his community descriptions. It may be that, with adequate water level controls and safeguards, peat fires could be useful in manipulating the vegetation and water depths in marshes managed for fish and wildlife.

Clearing, farming, and building

Drained organic soils are poor building sites. They are difficult to drain adequately, and when they are drained they subside rapidly. Septic tanks are unusable. The soils also have low bearing strengths and, because of their light weight, they are subject to wind and water erosion. However, they have been used for buildings.

Farming is the more usual pursuit on such lands. The following characteristics should be considered.

Microclimate

Most wetlands occur in basins noted for their cold air drainage. The frost danger there is increased by the dark surface of organic soils, which radiate heat rapidly at night, lowering the temperature. These soils also warm up slowly in spring due to their slow heat conductivity and high specific heat (2). Their growing season is thus considerably shorter than in adjacent uplands due to frost and to the effects of low soil temperature on early germination and growth. In northern Minnesota, farmers burn off shallow organic soils in order to grow grain; otherwise, the growing season is too short (21).

Soil characteristics

Deep alkaline, terrestrial peats overlying loams or other medium textured materials are the best soils for most crops, though cranberry and blueberry culture are better on acid peats. Shallow terrestrial peats over aquatic peat, marl, clay, sand or boulders should be avoided, as the surface will soon oxidize and the substrata are not good farmland. Drained aquatic peats shrink and develop cracks that allow water to pass through them too readily. Away from the cracks, they tend to be impermiable to water. The two properties make proper water control difficult. They also tend to be easily eroded by wind or water and they contain toxic substances more often than do terrestrial peats (21).

Marl is more rock than soil material, and is neither permeable nor soft enough for root penetration. Clays are nearly impermeable too, especially if they have been waterlogged for extended periods, as have those in wetlands (21).

Erodibility

Peats are very light, and when exposed they are extremely susceptible to both wind and water erosion. Ditches have been blown shut by a single windstorm, and a "gulley-washer" is damaging even in flat-lying peats. Adequate windbreaks and crop cover must be provided to minimize erosion (21).

Hydrology

Water control is an important part of peat farming. Water must be drained off adequately for crop growth, but kept shallow enough to slow down the soil subsidence rate. Problems have been encountered in wetlands on both counts. The Horicon Marsh area could not be drained adequately for farming after several decades of trying. On the other hand, where water levels are not maintained during the warm part of the growing season, high rates of soil subsidence occur. The dams, dikes, levees, or wells used to maintain the water levels may be as costly as the drains and ditches used to lower them. The hydrology of wetlands should be investigated before drainage proceeds (21).

Harmful chemical substances

Various harmful substances have been found in drained organic soils. These include excessive nitrogen, sulfur compounds, and marl.

Excessive nitrate nitrogen may be liberated in the first few years after draining eutrophic-type marshes. This leads to lush vegetative growth but lowers frost resistance and reduces the starch content of seeds and tubers of plants. Plants containing excessive nitrogen are poor cattle feed, as nitrates are converted to nitrites in their stomachs. This enters the bloodstream and lowers its capacity to carry oxygen, resulting in abortion of unborn calves and sometimes of death of the cow itself.

Sulfur compounds in soils are usually sulfides in the undrained state which are converted to sulfates when drained. Sulfur itself may be toxic, while the sulfates increase acidity and cause other elements to become more soluble which may be toxic. Also the sulfide precipitates are usually those of heavy metals which are also released by sulfide oxidation and these are often types toxic to plants.

Marl near the surface of organic soils can raise the pH so much that most of the important nutrients are rendered insoluble and generally unavailable.

Filling

Filling results in the destruction of wetlands. It is perhaps unavoidable in a high value urban area, though some argument can be made for them even there, as in Madison's arboretum. However, fill should be limited to inorganic materials. Garbage dumps in wetlands, most of which are part of the groundwater, can have some serious repercussions on water quality. Engineering-Science, Inc., a California consulting firm, reviewed much of the literature available on refuse dumps (25). This indicated that the harmful effects on water are (1) high carbon dioxide content, leading to water hardness, (2) large amounts of dissolved organic materials, creating a high BOD, (3) increased content of inorganic salts, particularly nitrogenous ones, iron, and possibly sulfides, and (4) presence of intestinal-type bacteria.

These bacteria are probably present on the refuse when deposited, and they develop in the anaerobic conditions that often arise 2-4 feet below the surface of refuse. Water in wetlands would, of course, increase the tendency toward anaerobicity. In other dump sites, these bacteria are filtered out of the dump effluent after running a relatively short distance through sands, gravels, etc., but in wetlands they are washed directly into the water, creating a health hazard.

The other harmful effects of dumps on water quality tend to increase eutrophication and fish kill, both leading to an inferior environment. Burning of refuse diminishes the amount of carbon dioxide pollution in water somewhat, but it also increases the hydrogen sulfide production within the fill. Sulfides are normally tied up there with iron, as in bottom deposits, but some appear to be soluble. Sulfides as high as 30 ppm have been found in refuse percolates, as have BOD's of 30,000 ppm. Either one would be toxic to fish.

Filled wetlands may also be poor building sites, though they have been and are being used for this purpose. Deep inorganic fill over net mineral soils may be adequate, but garbage over peats would seemingly be subject to great and uneven subsidence, unusable, unhealthy domestic water systems and wet basements. Floodplains should be avoided in all cases.

SUMMARY

Wetland soils consist of porous materials usually saturated with and overlain by water. The soils are either mineral, organic or usually both. Mineral materials comprise the land form in which the wetland is located. Organic soils tend to form on top of mineral materials in shallow fertile water areas and in places where the rate of production of organic material exceeds the decay rate.

Mineral soils found in drier portions of wetlands are those described as poorly or very poorly drained by the Soil Conservation Service. These are "wet" members of various soil parent material groups, identified by color patterns in their surface horizons that are associated with iron solubility under anaerobic conditions. Pans frequently occur in wet mineral soils.

Organic soils are not necessarily restricted to wetland sites but the conditions necessary to their development are more often found there than elsewhere. Organic soils of wetlands are classified as either aquatic or terrestrial. The deposits of aquatic origin are sedimentary, resulting in a laterally uniform, thin layered structure, composed mostly of material formerly in solution, suspension or floating in overlying waters. Terrestrial organic soils are composed of the remains of rooted plant species, usually growing above the water.

Organic soil in wetland communities nourishes non-rooted plants by contributing to the fertility of the overlying water. Plants rooted in the soil derive nutrients directly from it.

Fertility of soils in Wisconsin is dependent upon the fertility of the geologic material from which the soils are derived, the influences of vegetation on the leaching rate, and the effects of man, particularly the use of commercial fertilizers.

In northern Wisconsin, most of the soils are derived from glacial till composed of acidic igneous rock. In southern Wisconsin the common parent material is inherently fertile dolomitic limestone, either as glacial till or bedrock.

Nutrients in wetlands are either absorbed by plants, deposited on the bottom, or lost through surface or subsurface flow. Surface flow of water out of wetlands results in lower fertility.

Water loss through evapotranspiration is quite high in wetlands. Emergents retard this process somewhat as does the surrounding vegetation in the case of small ponds. This loss of water results in a concentration of nutrients and probably has much the same effect as fertilization.
bottom-water interface which may be oxidized or reduced depending on the oxygen content of the water immediately overlying it. Substances released in anaerobic decay in the reduced zone rise to this surface and if in an oxidized state, are partially transformed or absorbed. If they are reduced they enter the water. When the surface goes from an oxidized state to a reduced one, absorbed elements there go into solution. These elements are nitrogen, phosporus, potassium and sulfur.

The plants involved in early succession are the hydrophytic emergents, such as cattail. By invading open water areas they tend to reduce wave turbulence, favoring peat deposition and initiating the soil building process. The features that allow emergents to pioneer water areas apparently restrict them in competing with better adapted species in shallower water areas, where they are often invaded by sedges. The soils of sedge meadows are usually organic, though they also may be wet mineral soils. The organic soils are either peat or muck depending on the water table fluctuation and location. Mucks are more common in southern Wisconsin and peats are more common in northern Wisconsin.

Progressive succession results in an increase in the organic matter content of the soil, an increase in acidity, an increase in base exchange capacity, an increase in the carbon-nitrogen ratio of the soil, and a decrease of total bases.

Wetland properties have not always been considered when determining their use, and this oversight has created problems such as flooding of cities located on floodplain soils created by deposition during periods of river overflow. Other problems include shrinkage compaction or oxidation of marsh soils due to a lowered water table and loss of combustible peat by fire in drained wetland areas. One problem resulting from building on drained organic soils is erosion. Farming is the more usual pursuit on such lands. Characteristics of the wetland soils which should be considered when they are used for farming are soil composition, erodibility, hydrology, and presence of harmful chemical substances. Filling of wetlands in order to use them results in their destruction.

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