CHEMICAL AND BIOLOGICAL CHANGES RESULTING FROM SOIL SUBMERGENCE

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ABSTRACT

Flooding of a soil for rice production results in significant short and long term physical, chemical and biological changes in soil properties. These changes may have significant impact of the availability of nutrients for plant growth both for aquatic plants growing in the flooded soil and upland plants on the soil when not under flooded conditions. Chief among these nutritional effects are accelerated nitrogen (N) losses, conversion of phosphorus (P) to more available forms during flooding then reversion to less available forms following flooding. The potential also exists for conversion of sulfate to sulfide and formation of toxic amounts of hydrogen sulfide especially in organic soils, and for increased loss of potassium (K) from the soil solution due to its displacement from the cation exchange complex by reduced iron (Fe) and manganese (Mn). Occasional flooding as occurred in the upper Midwest in 1993 would likely result only in short term effects, including N and perhaps K losses plus temporary reversion of P to less plant available forms.

INTRODUCTION

Prolonged flooding results in both short and long term changes in physical, chemical and biological properties of soils. These changes include such areas as reduction in permeability due to deterioration of soil structure and subsequent reduction in pore size, changes in the mineralization-immobilization process that may result in significant N losses, and formation of various oxides of Fe and the reaction of these compounds with P. Such changes may impact on the availability of nutrients to plants growing on these soils. Most of the research in this area has been conducted either with rice paddies or naturally occurring wetlands. Little work has been done on changes that may occur due to natural flooding that occurs only at infrequent time intervals. The objective of this paper is to give a brief overview of changes that are known to occur in soils subjected to recurrent flooding during rice production and from these results speculate on changes that might occur due to seasonal flooding such as occurred in floodplains of the upper Midwest in 1993.

DISCUSSION

PHYSICAL CHANGES

Numerous physical changes occur when a soil is flooded, the most immediate of which is gaseous exchange between soil and air. The presence of a layer of water over the soil surface excludes oxygen from the soil and reduces the diffusion rate by a factor of at least 10,000. Additionally, the added moisture stimulates microbial activity which creates a large oxygen demand and results in the release of large volumes of carbon dioxide. Other gasses that increase in concentration within flooded soils are N_2, H_2, and methane (CH_4). The flooded soil is not uniformly devoid of oxygen; there is a thin layer (1-2 mm) of oxidized soil at the soil:water interface and within the rhizosphere of paddy rice and other wetland plants. These plants have specialized tissue (aerenchyma)which allow oxygen to diffuse from the aerial portions of the plants to the roots. These changes may have significant effects on the availability and losses of such nutrients as N.

Flooding also reduces impedance to root penetration and often results in deterioration of soil structure which, in turn, may reduce the rate of water percolation through the soil especially if the larger soil pores are partially clogged by silt and clay particles.

BIOLOGICAL TRANSFORMATIONS

Within a few hours after flooding the aerobic microorganisms exhaust the available oxygen and either become latent or die. Facultative and obligate anaerobic bacteria take over and new microbial transformations begin to occur. These transformations involve oxidized constituents rather than oxygen as electron acceptors in anaerobic fermentation of organic compounds. The initial decomposition product is often lactic acid which is subsequently changed to acetic, formic and butyric acid. These products along with alcohol, carbon dioxide, methane, and di-hydrogen are formed from carbohydrates whereas ammonia, amines, mercaptans and hydrogen sulfides are formed from proteins. These products may accumulate to toxic concentrations. This is especially true for hydrogen sulfide unless there is sufficient reduced iron to convert the hydrogen sulfide to ferrous sulfide which is highly insoluble. Anaerobic bacteria only assimilate 2- to- 5% of the oxidized carbon into their bodies as compared to 20- to 30% for aerobic microbes thus net mineralization of N will occur at a much lower N concentration of the organic matter. Additionally, the limited number and array of microbes functioning within the flooded soil greatly reduces the rate of organic matter decompositions as compared to upland soils.

PHYSIOCHEMICAL CHANGES

Soil pH, ionic strength and oxidation-reduction potential (redox potential) are the three most important physiochemical changes occurring in flooded soils.

The pH of most soils shifts toward neutrality with time after flooding; reaching an equilibrium between 6.5 and 7.5. In acid soils hydroxides of Fe and Mn are largely responsible for this buffering whereas carbonic acid is probably most important in alkaline soils.

The concentration of ions in soil solution increases following flooding, however, this increase may not persist for the entire season. In acid soils this results largely from the increased solubility of reduced Fe and Mn whereas in alkaline soils calcium (Ca) and magnesium (Mg) ions are largely responsible.

Redox potential (Eh) is the best indicator of the degree of reduction of a soil following flooding. Well oxidized soils have an Eh > +400 mV whereas a highly reduced soil may have an Eh of - 300 mV. The redox potential of the soil is determined by the degree of oxidation or reduction of numerous redox systems in the soil including organic compounds, oxygen, nitrate, Mn, Fe, sulfur, etc. Reduction of the soil occurs in a sequential series of steps with some overlapping between processes. Within a few hours after flooding oxygen is deleted from the soil and the only microbes continuing to function are the facultative and obligate anaerobic bacteria. These bacteria first utilize nitrate (or nitrite if present) as an electron acceptor and reduce it to di-nitrogen gas. Prior to complete reduction of the nitrate the microbes begin to reduce manganese (+4) to manganous (+2). Following reduction of the manganese the microbes begin to reduce ferric (+3) to ferrous (+2) iron. In both cases (Mn and Fe) this conversion is from relatively insoluble to highly soluble forms of the elements. These reduction processes can be carried out by either facultative or obligate anaerobic bacteria. Following reduction of the Fe, obligate anaerobic bacteria reduce sulfate to sulfide thus forming hydrogen sulfide. If the reduction process becomes sufficiently intense carbon dioxide may be reduced to methane. The supply of nitrate in an average soil is normally exhausted within three to five days. The concentration of Mn in soil solution normally begins to increase by about the third day after flooding under warm temperatures. Soluble Fe begins to appear by 10 to 14 days after flooding. Iron and Mn concentrations in soil solution continue to increase for about thirty days then slowly decrease with time as complex ions are formed. Thirty days or more of flooding is normally required before the redox potential reaches the - 150 mV required to reduce sulfate to sulfide. However, these time sequences are governed by such factors as soil pH, temperature and the amount of soluble carbon available to be oxidized. The sequence may not occur deep within the soil profile due to a lack of soluble carbon, a viable microbial population or a sufficiently acid soil pH.

These events have profound effects on the availability of nutrients both to aquatic plants growing in the flooded soils and on upland plants that follow the flooding sequence or sequences.

Inorganic N is very unstable under flooded soil conditions. Any nitrates present within the upper portion of the soil profile at the time of flooding are normally lost by denitrification within three to five days after flooding. As indicated above, these nitrates act as electron acceptors in the oxidation-reduction process. Ammonium N, although much more stable than nitrates under flooded conditions undergoes either immobilization or diffuses to the oxidized boundary of the soil or rhizosphere where it is converted to nitrates and is then lost. Under the warm temperature conditions of a rice paddy ammonium N applied as a fertilizer will normally persist for about three to four weeks. Intermittent flooding with the resulting cycle of oxidized and reduced conditions often results in very large N losses from the soil. Nitrogen is mineralized to nitrate during the oxidized cycle and then is lost by denitrification during the reducing cycle. Additionally, any ammonium present in the flood water may be subject to large losses by ammonia volatilization. Assuming that photosynthesizing algae are present in the water, they will deplete the carbon dioxide concentration of the water in a diurnal cycle of a magnitude that leads to water pH values of > 10.0 by mid-afternoon. This drives the conversion of ammonium to ammonia which is then lost from the flood water.

Leaching of nitrates is not normally a major problem with the average rice paddy because of the typical low permeability of the soil. However, this may be a very important N loss mechanism under floodplain conditions.

The effects of flooding on P are more indirect than for N. Phosphorus does not undergo oxidation-reduction during the normal redox sequence in a flooded soil. However, flooding has a very significant effect of P availability to wetland plants especially in acid soils. In acid soils a considerable portion of the inorganic P exists in association with Fe. These ferric phosphates are sparingly soluble and thus largely unavailable to plants. After flooding the Fe is reduced from the ferric to ferrous form which is much more soluble thus the ferrous phosphate compounds are more soluble and available to plants. Therefore, rice will often not respond to additions of phosphate fertilizers on soils where an upland crop such as wheat will show an excellent response. This does not hold true for calcareous soils where much of the inorganic P is present as Ca phosphates. The Ca does not undergo reduction, therefore, the P is not solubilized by flooding. Flooding of the soil does increase the rate of P diffusion and since practically all of the P taken up by plants is supplied by diffusion this does increase P availability to some extent.

The flooding sequence also has an influence on P availability to other crops in the rotation. During the flooding sequence ferrous oxides are formed and these are converted to amorphous ferric oxides when the soil is drained and becomes oxidized. These amorphous ferric oxides have a very large surface area and are capable of adsorbing very large quantities of inorganic P; rendering it temporarily unavailable to upland plants. In California, where rice if often grown continuously (one crop per year) for ten or more years this process occurs to such an extent that P fertilizer must be banded for the first upland crop following rice. In the mid-south this is often a problem when wheat directly follows rice in the rotation thus P fertilizer is a vital part of a successful wheat production system when it is in rotation with rice.

Although K is not involved in the oxidation-reduction process the concentration of K in soil solution increases following flooding. This is normally the result of the release of manganous and ferrous ions which is turn displace K from the exchange sites on the clay and organic matter of the soil. This may lead to K losses by leaching if the soil is somewhat permeable.

Under highly reducing conditions (redox potential of - 160 mV or lower) sulfate sulfur is reduced to sulfide and normally precipitated as ferrous sulfide in mineral soils. This has led to sulfur deficiency in rice, however, in Arkansas this has only occurred when rice is grown for several successive years on soils with very poor internal and surface drainage. In soils which are inherently low in reducible iron (example: organic soils) the amount of sulfide may be greater than the amount of ferrous iron, leading to elevated levels of hydrogen sulfide which is toxic to plants. This problem is especially prevalent in brackish or saltwater marshes and may lead to deterioration of the marsh.

Iron and Mn are reduced and become much more available to plants under flooded soil conditions. Most aquatic plants tolerate very high levels on Mn in their tissues. Additionally, aquatic plants have the ability to transport oxygen to their root systems, therefore the root surface is oxidizing thus most of the Fe is precipitated on the root surface rather than accumulated in the plant. Aquatic plants do not normally have a problem with toxicity of either Fe or Mn except under very unusual conditions.

Zinc does not undergo oxidation-reduction, however, deficiency is often a problem with rice growing on calcareous soils. The deficiency is aggravated by flooding and water depth. This is generally conceded to be associated with a reduction in the level of alcohol dehydrogenase in the plant when Zn is not present is not present at sufficiency levels. This enzyme is necessary for anaerobic respiration of the roots and formation of the aerenchyma tissue to conduct oxygen from the aerial portions of the plants to the roots.

Based on the typical physical, chemical and biological conversions in soils with a long history of flooding for rice production it would appear that the major changes associated with flooding such as occurred in the Midwest in the summer of 1993 would be as follows. There would be a depletion of nitrate N within the soil profile either from leaching or denitrification or a combination of the two. This might lead to the need to temporarily increase N fertilizer rates for these soils. However, the soil profile should be tested for nitrate concentration before such changes are made. It is very doubtful if any long term effects on N release from these soils will be noted.

Any changes in P availability would be associated with soil pH and the amount of reducible Fe in the soil. On acid soils with high levels of reducible Fe it is possible that sufficient amorphous iron oxides were formed to absorb significant quantities of phosphates, however, as these oxides are gradually converted to crystalline form most of these phosphates will be released. Any major effect would have been noted especially for wheat growing on these soils during the winter of 1993-1994 and should largely have disappeared by this time (October, 1994).

Potassium availability probably would not have been affected by this one time flooding event except on more sandy, highly permeable soils where it may have been displaced from the cation exchange complex and leached downward sufficiently to be below the root zone of plants. Sulfate sulfur may have also been depleted by leaching on these same permeable soils. Routine soil sampling of the profile should indicate if either of these events occurred.

This flooding event probably would have no lasting influence on the availability of any of the micronutrients.

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