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BEHAVIOR OF MINOR ELEMENTS IN PADDY SOILS

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BEHAVIOR OF MINOR ELEMENTS IN PADDY SOILS[1]

ABSTRACT

Nutritional disorders of rice associated with minor elements have assumed increasing importance as modern rice technology has spread. Correction of those disorders depends on an understanding of the behavior of the minor elements in paddy soils.

When a soil is converted to a paddy soil by puddling and flooding, it undergoes chemical reduction, a process that profoundly influences the behavior of minor elements. The concentrations of water-soluble iron, manganese, and molybdenum increase, concentrations of copper and zinc decrease, and the concentration of boron does not change appreciably.

The increase in concentration of iron and manganese is due to the reduction of Fe(III) and Mn(IV) to Fe(II) and Mn(II), whereas that of molybdenum appears to be due to desorption from Fe(III) oxides. The concentrations of copper and zinc decrease in spite of desorption by Fe(III) and Mn(IV) oxides, apparently because of the formation of insoluble complexes or sulfides. The concentrations of boron does not increase despite desorption.

The increase in solubility of iron benefits the rice plant by preventing iron deficiency and manganese toxicity, but in strongly acid soils the concentration of iron may reach levels toxic to rice. Although the concentration of manganese is higher in wetland soils than in dryland soils, manganese toxicity is rare in paddy soils because iron depresses manganese uptake. Manganese deficiency is possible on bleached sandy soils and on alkaline soils low in organic matter, even though these soils are submerged. Because of the decrease in the solubility of copper and zinc, deficiencies of those elements are more common in wetland soils than in dryland soils. Calcareous, sodic, and organic soils are likely to be deficient in copper and zinc. Boron toxicity may occur in saline and sodic soils.

Minor element deficiencies are likely to increase with the spread of modern rice varieties, the use of concentrated fertilizers, and double cropping of rice.

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BEHAVIOR OF MINOR ELEMENTS IN PADDY SOILS

Nutritional disorders of rice associated with minor elements have assumed increasing importance as modern rice technology has spread. Those disorders include

1. zinc deficiency on calcareous, sodic, and organic soils;
2. iron toxicity on acid sulfate soils and on strongly acid ultisols and oxisols;
3. iron deficiency on calcareous and sodic soils, and (often regardless of pH) on aerobic soils;
4. manganese toxicity on strongly acid aerobic soils;
5. boron toxicity on saline and sodic soils and on soils irrigated with water with a high boron content;
6. copper deficiency on organic soils.

Deficiencies or excesses of minor elements are main obstacles to the delivery of full potential by modern rice varieties on about 50 million ha of existing rice lands. Minor element deficiences or excesses are also the reason why millions of hectares of tropical and subtropical land, climatically and physiographically suited to rice production, lie uncultivated. An understanding of the chemistry of micronutrients in paddy soils is essential for the best management of both the existing and the potential rice soils.

PADDY SOILS

Paddy soils are managed in a special way -- flooded, and plowed and harrowed wet. Those operations puddle the soil and make it anaerobic. The soils remain flooded while the crop is on the land and are drained about 2 weeks before harvest. Between two crops of rice the soil usually becomes aerobic.

Within a few hours of flooding a soil, aerobic organisms use up the trapped and dissolved oxygen and render the soil virtually free of molecular oxygen. At that point facultative anaerobes and strict anaerobes take over, reducing the soil in the sequence predicted by thermodynamics: Mn(IV) and Fe(III) oxide hydrates are reduced to the more soluble Mn(II) and Fe(II), SO_4^{2-} to H_2S, and CO_2 to CH_4. Soil reduction increases the pH of acid soils, while the CO_2 that accumulates lowers the pH of calcareous and sodic soils. The redox, hydroxide, carbonate, and sulfide equilibria thus generated, along with environmental factors, control the concentrations of manganese, iron, and zinc in the soil solution and pH-dependent surface reactions apparently determine the concentrations of copper, boron, and molybdenum.

On drying of the soil, oxygen reenters the soil and oxidizes the reduced substances, reversing the chemical and electrochemical changes that flooding caused.

IRON

In aerobic soils the concentration of water-soluble iron is governed largely by the solubility of Fe(III) oxide hydrates. The solubility of these oxides is so low that in natural aerobic media the concentration of water-soluble iron, theoretically, cannot exceed 0.001 ppm. The higher concentrations (0.1 ppm) observed in aerobic soils are due to organic complexes and to colloidal Fe(III) oxide hydrates stabilized by organic matter (Krauskopf, 1972).

When a soil is submerged the picture changes drastically. Fe(III) compounds are directly and indirectly reduced to Fe(II) by microorganisms and large amounts of iron are brought into solution. During soil submergence the concentration of water-soluble iron increases to a peak value and then declines, or reaches a plateau. Those changes vary with the pH and organic matter content of the soil (Fig. 1), the content and reactivity of Fe(III) oxides (Fig. 2), temperature (Fig. 3), and the salt content of the soil (Fig. 4). Average concentrations of water-soluble iron are highest in acid sulfate soils with a high content of reactive Fe(III) oxides and are lowest in alkaline soils low in organic matter. Low temperature (Cho and Ponnamperuma, 1971) or the presence of nitrate (Ponnamperuma and Castro, 1964) retards the release of water-soluble iron but does not prevent the later buildup of high concentrations.

The increase in concentration of water-soluble iron following flooding, the peak concentrations and the fairly stable concentrations reached after several weeks of submergence can be described for most soils by the equilibrium

$$Fe(OH)_3 + 3\ H^+ + e = Fe^{2+} + 3\ H_2O \qquad (1)$$

with

$$Eh = 1.06 - 0.059 \log Fe^{2+} - 0.177\ pH \qquad (2)$$

or

$$pE = 17.87 + pFe^{2+} - 3\ pH \qquad (3)$$

where Fe^{2+} denotes the activity of water-soluble Fe(II) (Ponnamperuma et al., 1966)

Conformity of the iron concentrations to those equations suggests that the bulk of the water-soluble iron is present as ionic Fe^{2+}.

Exceptions are organic soils, acid sulfate soils, acid soils low in active iron, and soils with apparently highly crystalline Fe(III) oxides. For such soils the concentrations of water-soluble iron are lower than those predicted by equation (2). After the peak, the concentration of water-soluble iron appears to be governed (with the exceptions given earlier) by the equilibrium

$$Fe_3(OH)_8 + 8\ H^+ + e = 3\ Fe^{2+} + 8\ H_2O \qquad (4)$$

with

$$Eh = 1.374 - 0.0885 \log Fe^{2+} - 0.236\ pH \qquad (5)$$

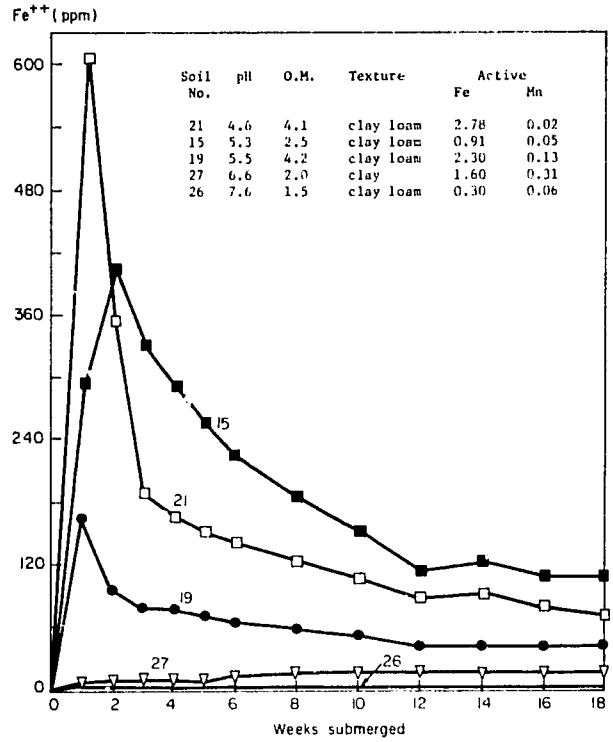

Fig. 1. Kinetics of Fe^{++} in the solutions of five flooded soils.

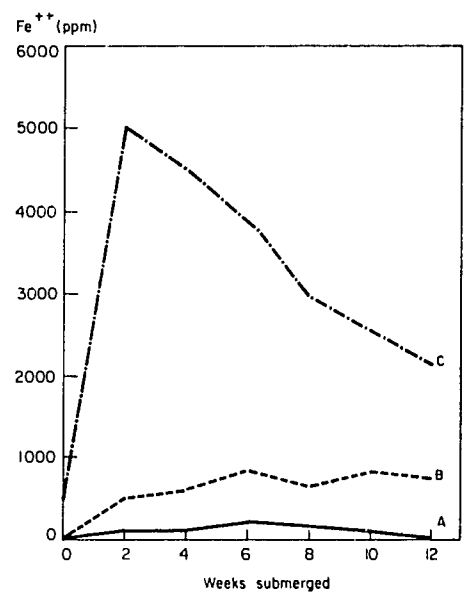

Fig. 2. Kinetics of water-soluble Fe^{++} in three acid sulfate soils.

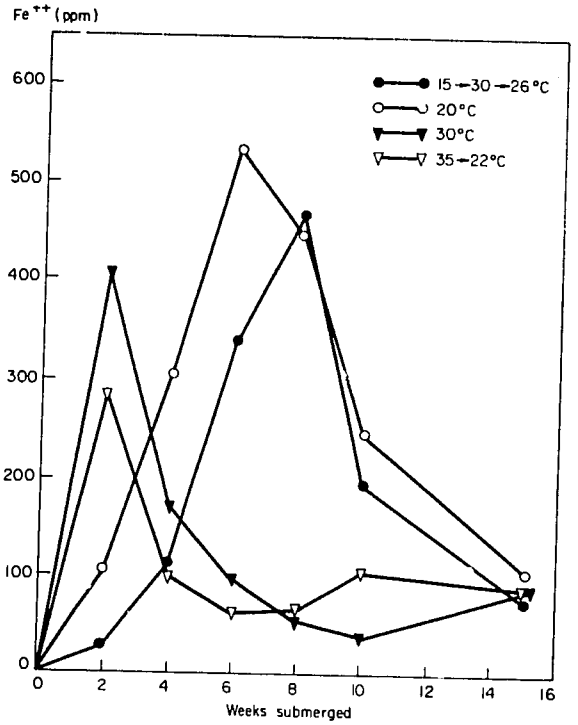

Fig. 3. Influence of temperature regime on the kinetics of water-soluble Fe^{++} in the Korean silt loam.

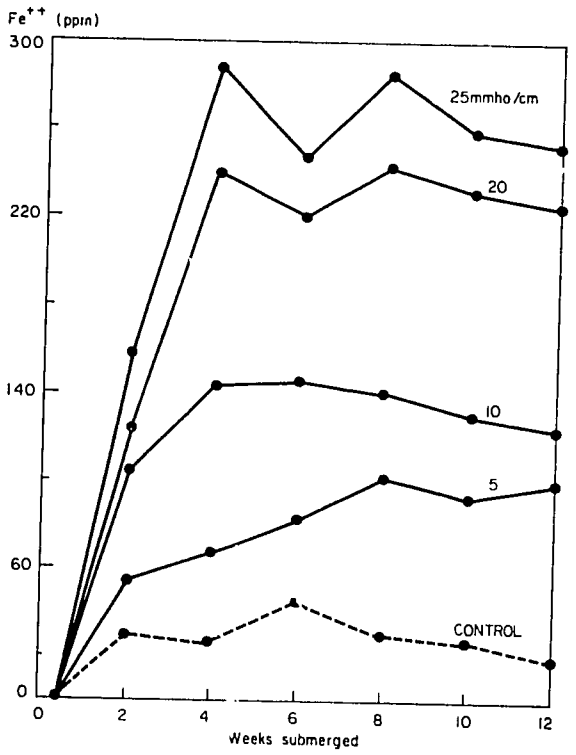

Fig. 4. Kinetics of water-soluble Fe^{++} in a submerged salinized soil.

$$pE = 23.27 + 3/2\ pFe^{2+} - 4\ pH \qquad (6)$$

This suggests that the fairly stable concentrations of iron established some weeks after submergence are regulated by the solubility of $Fe_3O_4 \cdot nH_2O$.

In ultisols, the concentration of water-soluble Fe^{2+} after the peak conforms closely to the equation

$$pH + 1/2 \log Fe^{2+} = 5.4 \qquad (7)$$

For other soils, the values of the constant may be as low as 4.1 (Ponnamperuma, 1972).

Eight of 10 submerged soils, with aerobic pH values ranging from 3.4 to 7.9, whose Fe^{2+} and S^{2-} activities were determined from the H_2S peak onwards, gave values ranging from 17.9 to 18.6 (with a mean of 18.33) for pK_{FeS}, compared with the theoretical value of 18.43 (IRRI, 1972). This suggests that the solubility of FeS controlled the concentration of iron in these eight soils.

Water-soluble Fe^{2+} markedly influences the chemical and electrochemical changes in paddy soils, paddy profile development, and the nutrition of the rice plant.

The kinetics of water-soluble Fe^{2+} is paralleled by the changes in specific conductivity and the kinetics of ($Ca^{2+} + Mg^{2+} + NH_4^+ + Na^+ + K^+$), suggesting ion exchange reactions between Fe^{2+} and these cations (Ponnamperuma, 1972). Water-soluble Fe^{2+} moves down and is precipitated below the plow sole giving an Fe(III) oxide horizon over a Mn(IV) oxide horizon in old paddy soils (Koenigs, 1950; Kawaguchi and Kyuma, 1969). Water-soluble Fe^{2+} may react with other ions leading to the precipitation of $Fe_3O_4 \cdot nH_2O$ (hydrated magnetite), $FeS \cdot nH_2O$ (hydrotroilite), FeS (machinawite), FeS_2 (pyrite and marcasite), $Fe_3(PO_4)_2$ (vivianite), and $FeCO_3$ (siderite).

When the soils dry, oxygen enters the soil and oxidizes these substances to Fe(III) oxide hydrates. In acid sulfate soils, Fe(III) may also be present as $KFe_3(OH)_6(SO_4)_2$ (jarosite), $NaFe_3(OH)_6(SO_4)_2$ (natrojarosite), and $Fe_2(SO_4)_3 \cdot 9H_2O$ (coquinolite).

Apart from increasing the concentration of iron in the soil solution, reduction of Fe(III) oxides may release Cu^{2+}, Zn^{2+}, MoO_4^{2-}, and $B(OH_4)^-$, which are held by iron oxides (Norrish, 1975; Quirk and Posner, 1975; Tiller, 1958; Jenne, 1968; Beckwith et al., 1975; Ellis and Knezek, 1972). The release of those adsorbed micronutrients may be attributed to surface reactions brought about by reduction or to the pH increase accompanying reduction.

Although iron deficiency of upland rice is corrected by flooding, Equation (3) shows that iron deficiency may occur even in flooded soils (IRRI, 1972) if pH and pE are high (e.g. in alkaline soils low in organic matter), whereas iron toxicity is possible on reduced low-pH soils. Several workers report that iron deficiency of rice in submerged calcareous or sodic soils has been corrected by adding organic matter, iron salts or sulfuric acid (Tanaka and Yoshida, 1970; Kanwar and Randhawa, 1974). Iron toxicity on strongly acid soils has been corrected by liming (Ponnamperuma, 1958; Nhung and Ponnamperuma, 1966; Park et al., 1971) and by the addition of wollastonite (Park and Kim, 1970).

MANGANESE

The behavior of manganese in paddy soils is similar to iron in many respects. On flooding Mn(IV) and Mn(III) oxide hydrates are reduced to the much more soluble Mn(II) compounds. Consequently, the concentration of water-soluble manganese increases, reaches a peak, and then declines. The rate of increase in concentration, as well as the peak and the final stable concentrations are determined mainly by the manganese and organic matter content of the soil (Fig. 5). The release of water-soluble Mn^{2+} precedes that of Fe^{2+} because Mn(IV) and Mn(III) oxides are reduced more readily than Fe(III) oxides.

Paddy soils may contain 50 to 3000 ppm reduced manganese in the solid phase and 1 to 100 ppm Mn^{2+} in the solution phase. The concentration of water-soluble Mn^{2+} is low in high-pH soils that are low in organic matter and active manganese, and is high in acid soils high in manganese and organic matter. But attempts to describe the concentration of water-soluble Mn^{2+} quantitatively in terms of the following equations were unsuccessful.

$$MnO_2 + 4\ H^+ + 2\ e = Mn^{2+} + 2\ H_2O \qquad (8)$$

with

$$Eh = 1.23 - 0.0295 \log Mn - 0.118\ pH \qquad (9)$$

$$pE = 20.83 + 1/2\ pMn^{2+} - 2\ pH \qquad (10)$$

The failure is attributed to the presence of coprecipitates and mixed oxides that contain varying amounts of manganese and iron instead of the compounds with the ideal composition, MnO_2 (Ponnamperuma et al., 1969). But the concentration of Mn^{2+} after the peak of water-soluble Mn^{2+} conforms closely to the equation

$$pH + 1/2 \log Mn^{2+} + 1/2 \log P_{CO_2} = 4.41 \qquad (11)$$

This suggests that the fairly stable concentration of Mn^{2+} in paddy soils is regulated by the solubility of $MnCO_3$ (rhodocrosite).

Water-soluble Mn^{2+} moves down the profile and is precipitated in a zone below the Fe(II) oxide layer (Koenigs, 1950; Mitsui, 1960; Kawaguchi and Kyuma, 1969). In paddy soils the downward movement of Mn^{2+} can lead to impoverishment of the top soil in manganese. Because of the impoverishment of such soils in iron and manganese by eluviation, they are called degraded paddy soils (Mitsui, 1960). Degraded paddy soils are low in all nutrients, especially iron and manganese, and they give rise to a nutritional disorder of rice known as *akiochi* (Mitsui, 1960).

Although positive responses of rice to the application of manganese are reported (Mitsui, 1960; Kanwar and Randhawa, 1974; Kaur and Padmanabhan, 1974), manganese deficiency of rice has not been recognized in the field (Tanaka and Yoshida, 1970). But it cannot be ruled out on sandy soils, sodic soils and calcareous soils low in organic matter. Manganese toxicity in rice may occur on aerobic acid soils (IRRI, Undated; Ponnamperuma, 1974).

Apart from its role as a minor element in the nutrition of rice plant, manganese plays an important role in mineral equilibria in paddy soils.

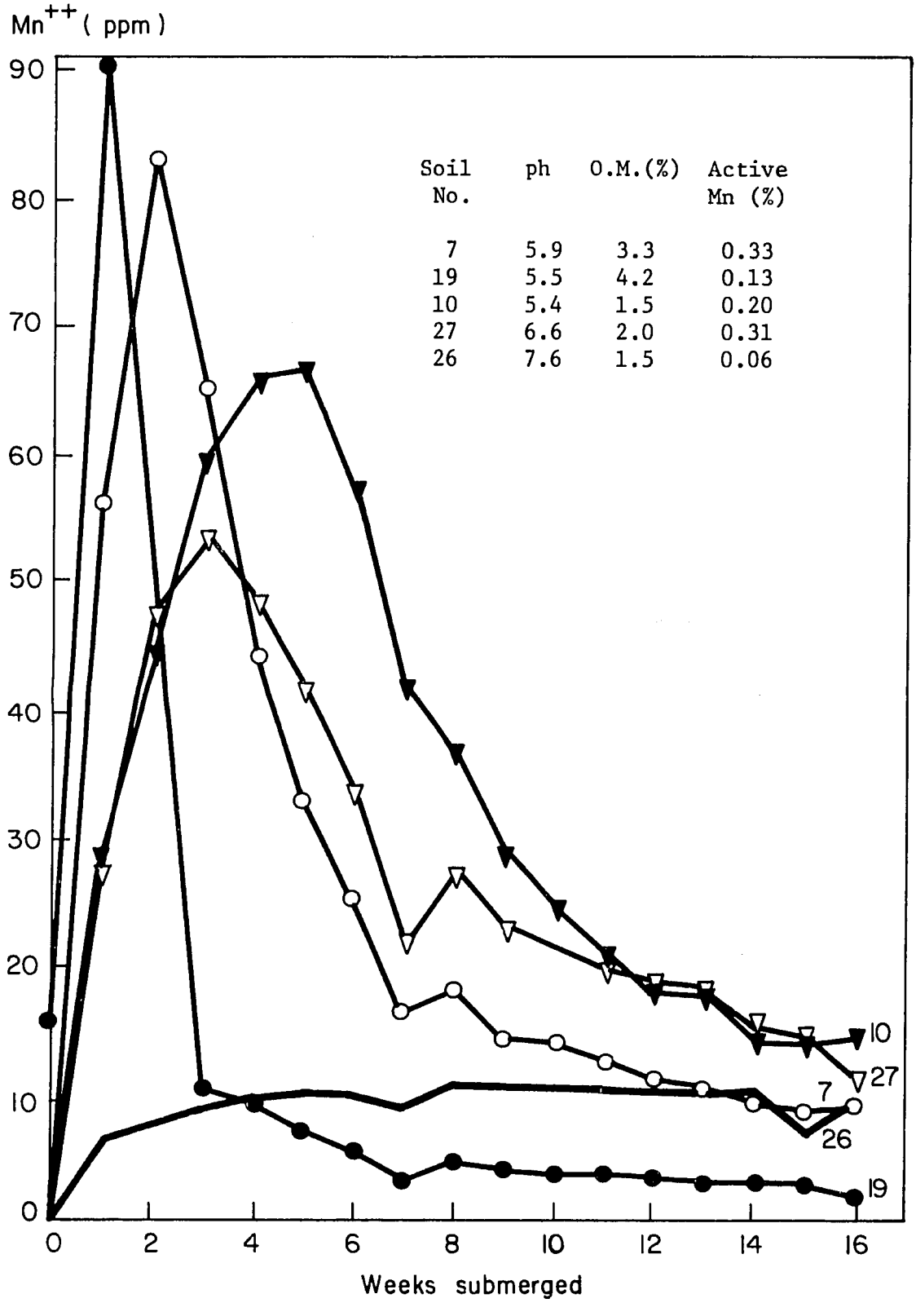

Fig. 5. Kinetics of water-soluble Mn^{++}

Mn(IV) oxides retard the reduction of soils (Nhung and Ponnamperuma, 1966) and manganous carbonate that forms in paddy soils removes carbon dioxide and lowers its partial pressure. The reduction of Mn(IV) oxides releases copper and zinc adsorbed on them (Jenne, 1968).

ZINC

Zinc deficiency of wetland rice has received more attention than any other minor element problem in recent years. Since its recognition as a field problem of rice by Nene (1966), zinc deficiency has been reported in Pakistan, India, the Philippines, Japan, the United States, Colombia, Chad, and Nigeria. First diagnosed on an alkali soil, now zinc deficiency in rice is known to occur on calcareous soils, marsh soils, organic soils, and also on sandy soils low in total zinc.

When a soil is submerged the concentration of most nutrient elements increases. Zinc is an exception. The concentration of water-soluble zinc decreases and reaches values as low as 0.03 ppm despite desorption from Fe(III) and Mn(IV) oxide hydrates. This is reflected in zinc uptake by the plant (IRRI, 1970; Beckwith et al., 1975). In acid soils the decrease in zinc concentration may be due partly to the increase in pH following soil reduction, because the solubility of zinc in water decreases 100 times when the pH increases by one unit (Trierweiler and Lindsay, 1969). But the concentration of zinc decreases in calcareous and sodic soils in spite of the decrease in pH brought about by the accumulation of CO_2. Solubility criteria suggest that ZnS may be present in submerged soils after the peak of H_2S (IRRI, 1972). Zinc deficiency in paddy soils can be prevented by draining and drying the soil before planting (IRRI, 1970). Apparently, ZnS is oxidized by bacteria to $ZnSO_4$ (Engler and Patrick, 1975). In soils containing free $CaCO_3$ or $MgCO_3$, zinc may be strongly adsorbed on them (Yoshida and Tanaka, 1969; Katyal and Ponnamperuma, 1975). In soils rich in silica, zinc forms insoluble zinc-silica complexes (Tiller, 1958). Because the concentration of water-soluble silica increases on flooding, that of zinc should decrease. Other insoluble zinc compounds that may be present in submerged soils are $ZnNH_4PO_4$ and $ZnSiO_3$ (IRRI, 1970).

Zinc deficiency is corrected by applying zinc compounds to the soil or plant (Yoshida et al., 1973; Kanwar and Randhawa, 1974; Mikkelsen and Brandon, 1975) or by dipping the seedlings before transplanting in a two percent suspension of zinc oxide in water (Katyal and Ponnamperuma, 1975).

COPPER

In reduced environments copper may be present as Cu_2O, Cu, CuS, or Cu_2S, and adsorbed on soil minerals (Krauskopf, 1972). It is also probably present as insoluble complexes with organic matter. But the concentration of copper in the solutions of flooded soils is several orders higher than those permitted by the solubility of CuS or Cu_2S (Ayotade, 1972). The concentration of water-soluble copper in a soil decreases on flooding (Table 1) despite desoprtion from Fe(III) and Mn(IV) oxide hydrates. This may be due partly to pH increase, for the solubility of copper decreases 100-fold for each unit pH increase (Norwell and Lindsay, 1969).

Table 1. Kinetics of water-soluble boron, copper, and zinc in four submerged soils.

	Weeks submerged			
	1	2	4	6
	(parts per million)			
	Luisiana clay (pH: 4.8; O.M.: 2.8%)			
Boron	0.55	0.49	0.46	0.30
Copper	0.11	0.11	0.04	0.02
Zinc	0.30	0.09	0.08	0.03
	Maahas clay (pH: 6.6; O.M.: 2.8%)			
Boron	1.80	1.01	1.15	1.18
Copper	0.06	0.05	0.03	0.02
Zinc	0.18	0.08	0.06	0.03
	Keelung silt loam (pH: 7.7; O.M.: 6.9%)			
Boron	0.48	0.55	0.68	0.52
Copper	0.05	0.05	0.04	0.03
Zinc	0.14	0.08	0.04	0.03
	Castañas clay (pH: 3.5; O.M.: 3.3%)			
Boron	n.d.*	0.30	0.51	0.71
Copper	0.08	0.06	0.06	0.04
Zinc	1.38	0.17	0.15	0.08

*Not determined.

Positive responses to the application of copper sulfate have been reported on high-pH soils (Kanwar and Randhawa, 1974) and on organic soils (Green, 1957). Copper toxicity in mining areas was alleviated by liming (Jeong and Kim, 1971).

BORON

Boron is present in soils largely as the hydrated borate ion $B(OH)_4^-$ (Ellis and Knezek, 1972). It is strongly adsorbed by soil minerals, chiefly sesquioxides. When acid soils undergo reduction the adsorbed boron should be released into the soil solution because of the reduction of Fe(III) to Fe(II) and to the increase in pH. But the kinetics of water-soluble boron in flooded soils indicates that the concentration is not affected sensibly by flooding (Table 1).

Boron toxicity in rice was first reported in pot culture with a soil from Silo, Taiwan (Ponnamperuma and Yuan, 1966). Mehta and Paliwal (1971) suggest that excess boron in irrigation water harmed rice plants and Murakami and Sawada (1971) report boron toxicity caused by industrial waste water. Boron toxicity was recently observed at IRRI on a hydrothermal soil.

Cho (1971) reported that borax at 10 kg/ha on a soil on which *akiochi* occurred improved the growth of rice and hastened maturity.

MOLYBDENUM

Soil reduction brought about by flooding increases the concentration of water-soluble molybdenum. This may be due to desorption of molybdenum from Fe(III) oxide hydrates following increase in pH and reduction of Fe(III) oxide hydrates to Fe(II) oxide hydrates with different isoelectric points. A positive response by rice to molybdenum was recently observed at IRRI on an organic soil.

PRACTICAL IMPLICATIONS

The occurrence of deficiencies or toxicities of minor elements in rice is likely to increase in the future because of,

- increased removal of nutrients by the modern rice varieties,
- increased use of concentrated nitrogen, phosphorus and potassium fertilizers,
- replacement of ammonium sulfate by urea,
- production of two or more crops of rice per year,
- gradual displacement of the traditional varieties that are adapted to minor-nutrient deficiencies and toxicities.

LITERATURE CITED

Ayotade, K. K. 1972. Studies on hydrogen sulfide measurement levels and equilibria in solutions of submerged soils. (A terminal report submitted to the International Rice Research Institute, Los Baños, Philippines).

Beckwith, R. S., K. G. Tiller, and E. Suwadji. 1975. The effects of flooding on the availability of trace elements to rice in soils of differing organic matter status. *In* D. J. D. Nicholas and A. R. Egan, ed. Trace Elements in Soil-Plant-Animal Systems. Academic Press, New York.

Cho, D. S. 1971. Effect of slaked lime and borax application upon the yield components of paddy rice /in Korean/. J. Korean Soc. Crop Sci. 10(10):61-71.

Cho, D. Y., and F. N. Ponnamperuma. 1971. Influence of soil temperature on the chemical kinetics of flooded soils and the growth of rice. Soil Sci. 112(3):184-194.

Ellis, B. G., and B. D. Knezek. 1972. Adsorption reactions of micronutrients in soils. *In* Micronutrients in agriculture. Soil Sci. Soc. Am., Madison, Wisconsin.

Engler, R. M., and W. H. Patrick. 1975. Stability of sulfides of manganese, iron, zinc, copper and mercury in flooded and nonflooded soil. Soil Sci. 119:217-221.

Green, V. E. Jr. 1957. The culture of rice on organic soils. A world survey. Agron. J. 49:486-472.

International Rice Research Institute. Undated. Annual report for 1963. Los Baños, Philippines. 335 p.

International Rice Research Institute. 1970. Annual report for 1969. Los Baños, Philippines. 266 p.

International Rice Research Institute. 1972. Annual report for 1971. Los Baños, Philippines. 238 p.

Jenne, E. A. 1968. Controls on Mn, Fe, Co, Ni, Cu and Zn concentrations in soils and water: the significant role of hydrous Mn and Fe oxides. 1968. *In* Trace Inorganics in Water. Adv. in Chemistry 73. Am. Chemical Soc., Washington, D. C.

Jeong, Y. H., and M. K. Kim. 1971. Study on the improvement of copper polluted soil. J. Korean Soc. Soil Sci. Fert. 4(1):49-54.

Kanwar, J. S., and N. S. Randhawa. 1974. Micronutrient research in soils and plants in India. ICAR Tech. Bull. (Agric.) 50. 185 p.

Katyal, J. C., and F. N. Ponnamperuma. 1975. Zinc deficiency: a widespread nutritional disorder of rice in Agusan del Norte. Philipp. Agric. J. 58 (3 and 4):79-89.

Kaur, P., and S. Y. Padmanabhan. 1974. Control of Helminthosporium disease of rice with soil amendments. Curr. Sci. 43:78-79.

Kawaguchi, K., and K. Kyuma. 1969. Lowland rice soils in Thailand. Center for Southeast Asian Studies, Kyoto University, Japan.

Koenigs, F. F. R. 1950. A "sawah" profile near Bogor (Java). Trans. 4th Int. Congr. Soil Sci. 1:297-300.

Krauskopf, K. B. 1972. Geochemistry of micronutrients. *In* Micronutrients in agriculture. Soil Sci. Soc. Am., Madison, Wisconsin.

Mehta, K. K., and K. V. Paliwal. 1971. Leaching of salts and boron from some salt-affected soils of Rajasthan. Oryza 8 (2 suppl.):303-308.

Mikkelsen, D. S. Brandon. 1975. Zinc deficiency in California rice. Calif. Agric. 29(9):8-10.

Mitsui, S. 1960. Inorganic nutrition, fertilization and soil amelioration for lowland rice. Yokendo, Tokyo.

Murakami, H., and S. Sawada. 1971. Excess boron injury of rice plant by industrial wastewater /in Japanese/. Chugoku Agric. Res. 42:9-10.

Nene, Y. L. 1966. Symptoms, cause, and control of Khaira disease of paddy. *In* Proceedings of the Symposium on Diseases of Rice, Maize, Sorghum and Millets. New Indian Phytopathol. Soc.: 97-101.

Nhung, M. T., and F. N. Ponnamperuma. 1966. Effects of calcium carbonate, manganese dioxide, ferric hydroxide, and prolonged flooding on chemical and electrochemical changes and growth of rice in a flooded acid sulfate soil. Soil Sci. 102(1):29-41.

Norrish, K. 1975. The geochemistry of trace elements. *In* D. J. D. Nicholas and A. R. Egan, ed. Trace Elements in Soil-Plant-Animal Systems. Academic Press, New York.

Norwell, W. A., and W. L. Lindsay. 1969. Reactions of EDTA complexes of Fe, Zn, Mn, and Cu with soils. Soil Sci. Soc. Am. Proc. 33:86-91.

Park, Y. D., and Y. S. Kim. 1970. The effect of wollastonite and manganese dioxide on rice grown on flooded acid sulfate soil. J. Korean Soc. Soil Sci. Fert. 3(1):23-28.

Park, N. J., Y. S. Park, and Y. S. Kim. 1971. Effect of lime on growth of rice and changes in pH, Eh, Fe^{2+} and Al in an acid sulfate soil. J. Korean Soc. Soil Sci. Fert. 4(2):167-175.

Ponnamperuma, F. N. 1958. Lime as a remedy for physiological disease of rice associated with excess iron. IRC Newsl. 7(1):10-13.

Ponnamperuma, F. N. 1972. The chemistry of submerged soils. Adv. Agron. 24:29-96.

Ponnamperuma, F. N. 1974. Micronutrient limitations in tropical acid soils. *In* Proceedings of the Seminar in Soil Management and the Development Process in Tropical America, February 1974. Cali, Colombia.

Ponnamperuma, F. N., and R. U. Castro. 1964. Redox systems in submerged soils. Trans. Int. Congr. Soil Sci. 8th Congress, Bucharest 3:379-385.

Ponnamperuma, F. N., T. A. Loy, and E. M. Tianco. 1969. Redox equilibria in flooded soils. II. The manganese oxide systems. Soil Sci 108:48-57.

Ponnamperuma, F. N., E. M. Tianco, and T. Loy. 1966. Redox equilibria in flooded soils. I. The iron hydroxide systems. Soil Sci. 106:374-382.

Ponnamperuma, F. N., and W. L. Yuan. 1966. Toxicity of boron to rice. Nature 211:780-781.

Quirk, J. P., and A. M. Posner. 1975. Trace element adsorption on mineral surfaces. *In* D. J. D. Nicholas and A. R. Egan, ed. Trace Elements in Soil-Plant-Animal Systems. Academic Press, New York.

Tanaka, A., and S. Yoshida. 1970. Nutritional disorders of the rice plant in Asia. Int. Rice Res. Inst. Tech. Bull. 10.

Tiller, K. G. 1958. The geochemistry of basaltic materials and associated soils of Southern and South Australia. J. Soil Sci. 9(2):225-241.

Trierweiler, J. F., and W. L. Lindsay. 1969. EDTA-ammonium carbonate soil test for zinc. Proc. Soil Sci. Soc. Am. 33:49-53.

Yoshida, S., J. S. Ahn, and D. A. Forno. 1973. Occurrence, diagnosis, and correction of zinc deficiency of lowland rice. Soil Sci. Plant Nutr. 15:75-80.

Yoshida, S., and A. Tanaka. 1969. Zinc deficiency of the rice plant in calcarerous soils. Soil Sci. Plant Nutr. 15(2):75-80.

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