Direct Determination of the Differentiation Process of the Oxidized and Reduced Soil Layers in Paddy Fields

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Introduction

Among the losses of fertilizer nitrogen from the soil-plant system in paddy fields, the process of nitrification and subsequent denitrification is the most important factor, especially in ill-drained paddy soils. It is important to clarify this process precisely to increase the efficiency of fertilizer nitrogen for rice plants.

The development of a thin oxidized surface layer overlying a thicker reduced soil layer is necessary for this nitrification and subsequent denitrification in paddy fields. Ammonium nitrogen applied in paddy soils is oxidized to nitrate or nitrite nitrogen in the oxidized surface layer by nitrifying organisms, and these oxidized products diffuse into the reduced underlying layer where they are turned into N_2 or N_2O by denitrifying organisms. However, there is little investigation about the differentiation process of the oxidized and reduced soil layers actually occurring in paddy fields.

In 1930's, Shioiri[9] postulated that in the first period of submergence the whole soil layer became reductive and in the following period an oxidized surface layer differentiated by the predominance of the supply of oxygen over the consumption. This postulation was deduced from the results obtained by flooding air dried paddy soils. It may be valid when well dried soils are flooded. In the practical rice cultivation, however, the soil moisture content before irrigation is different every year and among soils, and most soils are not dried enough before flooding. Differentiation process of the oxidized and reduced soil layer in wet soils is expected to differ from that in air dry soils.

The objectives of the work reported in the present paper were (1) to investigate the differentiation process of the oxidized and reduced layers in ill drained paddy soils in Hokuriku district, the central part of Japan Sea coast, where it is cloudy and rainy in autumn and snowy in winter, and (2) to investigate the effect of the water management during cropping period on the differentiation process.

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Differentiation process of the oxidized and reduced soil layers in ill drained paddy fields

The redox potential was measured periodically with flat shaped platinum electrodes fixed just below the soil-water interface and at 5 cm below this interface from the beginning of flooding to the harvest time in the ill drained paddy fields (clayey gley soil) in the Hokuriku National Agricultural Experiment Station. The soil was submerged for 100 days, and then the submerged water was drained off.

The redox potential just below the soil-

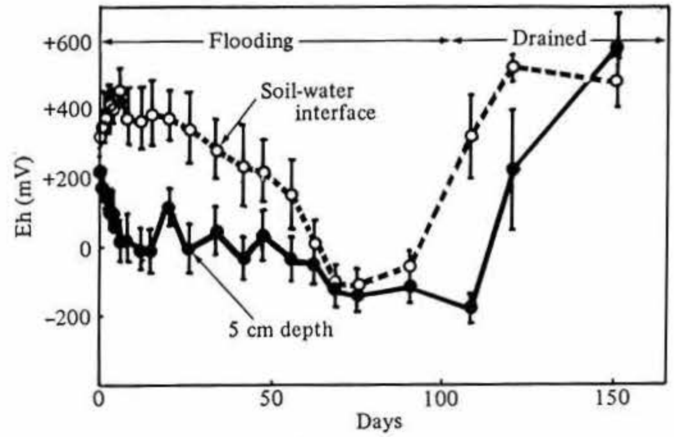

Fig. 1. Redox potential at soil-water interface and 5 cm depth at different days after submergence in ill-drained paddy fields

water interface remained above +200 mV for 50 days after irrigation and began to decline gradually to below 0 mV after 100-day submergence, while the redox potential at 5 cm depth dropped rapidly to 0 mV after irrigation. After the drainage, redox potentials at both positions increased rapidly to more than +400 mV (Fig. 1).

The oxidized layer is defined by different investigators as a layer in which the redox potential is above +350 mV at Eh_5,[8] +300 mV at Eh_6[1] and +200 mV at Eh_7.[7] Yamane and Sato,[11] however, pointed out that it was meaningless to adjust Eh value by pH. In the present paper, +200 mV was adopted as the critical potential to distinguish between oxidized and reduced state without adjusting Eh value by pH.

Fig. 1 indicates that the surface layer remained oxidative for 50 days after irrigation, thereafter the whole soil layer became reductive. After the drainage, however, the whole soil layer rapidly became oxidative.

Two other reports agree with our findings. Mikkelsen and Finfrock[6] measured both redox potentials at 2 mm below and at 5 cm below the soil-water interface for 14 days after submergence in a California paddy soil and found that the redox potential at 2 mm below the interface remained above +350 mV during 14 days of submergence, whereas the redox potential at 5 cm below the interface began to decline gradually. Weeraratna[10] also found that the redox potential at 2 mm below the interface remained above +200 mV for 30 days after submergence, whereas the redox potential at 5 cm below the interface began to decline gradually to 0 mV after 20-day submergence in a Philippine paddy field.

From these two reports and our findings, we assume that the surface layer which remained oxidative just after submergence becomes reductive gradually by prolonged submergence. However, our assumption does not agree with the famous Shioiri's postulation. As described above, this Shioiri's postulation was deduced from the results obtained by flooding air dried soils. Because air dried soils have generally much easily decomposable organic matter, whole layers of these soils are rapidly reduced on flooding, and then a few months after, an oxidized soil layer differentiates by the predominance of the supply of oxygen over the consumption. However, in wet soils the decomposition of organic matter and reduction of the soils may proceed more slowly, and their oxidized layer remains for a long period. Hasebe and Iimura,[2] and Hasebe et al.[4] pointed out that the soil moisture content before flooding greatly influenced the differentiation of the oxidized and reduced soil layers in paddy soils under laboratory conditions. After all, our assumption about this differentiation process is valid when wet soils are flooded, and the famous Shioiri's postulation may be applicable only when well dried soils are flooded.

The period that the surface layer remained oxidative after submergence is important for nitrification and denitrification in paddy fields, because nitrification occurs in the oxidized surface layer and most of nitrate nitrogen formed by nitrifying organisms is destined to be denitrified by denitrifying organisms. If this surface "oxidized" layer disappears and the whole soil layer becomes reductive rapidly, loss of basal fertilizer nitrogen by nitrification and denitrification process will be small, and vice versa. Therefore, the efficiency of basal fertilizer nitrogen for rice plants depends largely on this surface "oxidized" period after flooding.

Effect of water management during cropping period on the differentiation of the oxidized and reduced soil layers

Water management practices such as water percolation and intermittent flooding are necessary for productive rice cultivation. It is important to clarify the influence of water management on the development of the oxidized and reduced soil layers for getting higher rice yields. The following comprises the results of experiments on this aspect.

1) Effect of water percolation on the differentiation process of the oxidized and reduced soil layers

The experiments were carried out under lysimeter conditions by using a loamy sand paddy soil which was collected from the Toyama Prefectural Agricultural Experiment Station. The soil was not dried and the experiments were done under original moist conditions. Redox potentials both at the layer just below the soil-water interface and at that 5 cm deep were measured by the same method as mentioned above. Three plots on

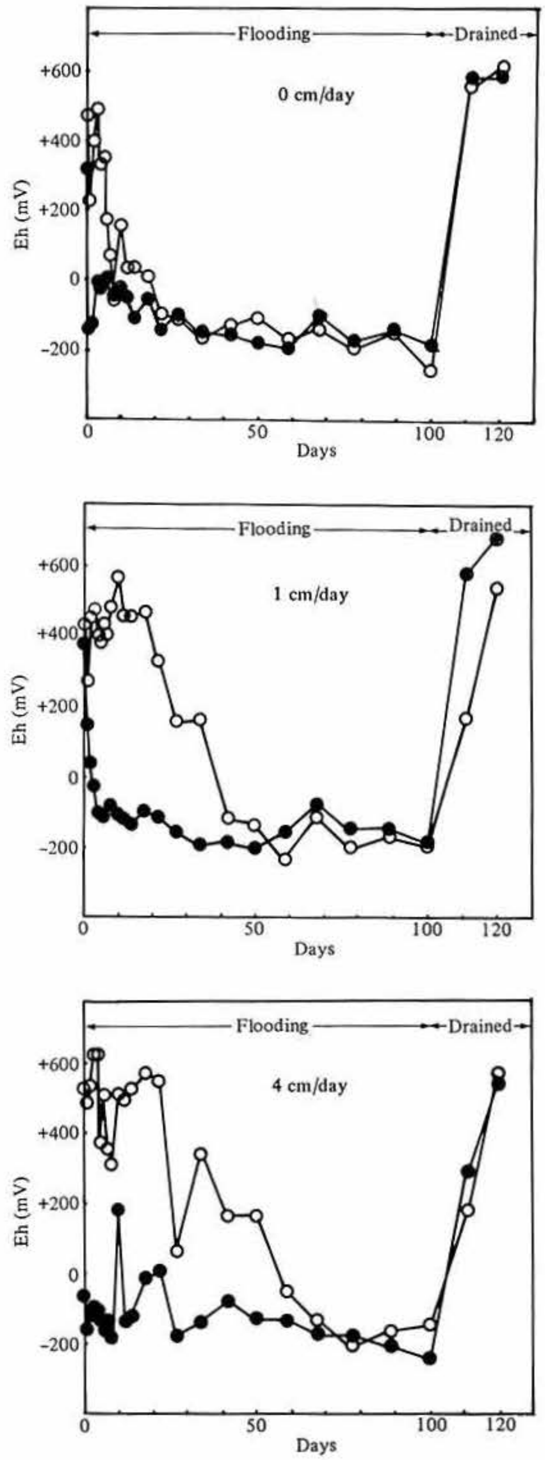

Fig. 2. Effect of water percolation on the redox potential at soil-water interface (○) and 5 cm depth (●) at different days after submergence

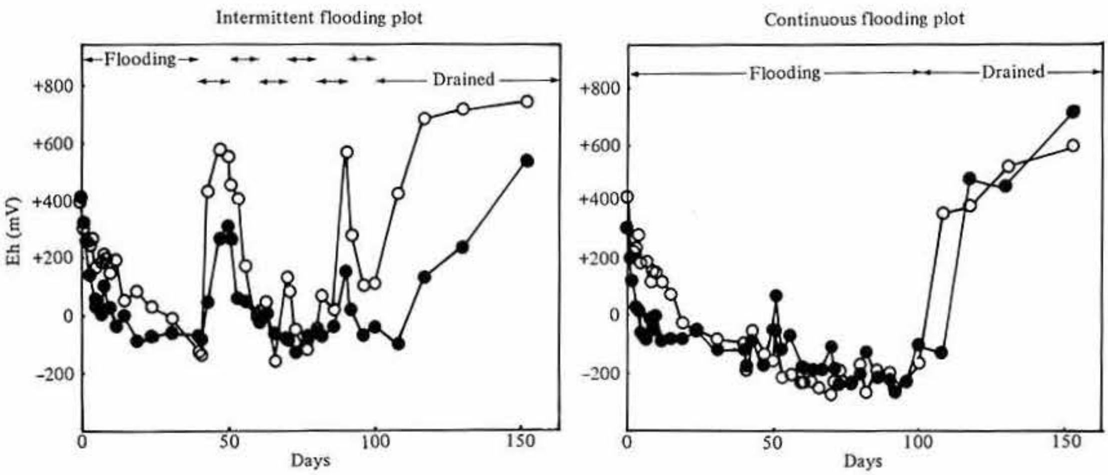

Fig. 3. Effect of intermittent flooding on the redox potential at soil-water interface (○) and 5 cm depth (●) at different days after submergence

the water percolation speeds (0 cm/day, 1 cm/day and 4 cm/day) were prepared. Water percolation speeds were adjusted every day to keep the set speeds, and the soils were kept submerged for 100 days, and then the submerged water was drained off.

In the 0 cm/day percolation plot (non-percolated plot), the redox potential just below the interface remained above +200 mV for 5 days after submergence, then gradually declined and reached to less than −100 mV after 20-day submergence. In the 1 cm/day percolation plot, the redox potential just below the interface remained above +200 mV for 22 days, then gradually declined, and reached less than −100 mV after 40-day submergence. In the 4 cm/day percolation plot, the redox potential just below the interface remained above +200 mV for 34 days, gradually declined, and reached less than −200 mV after 80-day submergence (Fig. 2).

Fig. 2 indicates that the surface layer remained oxidative for longer period by increasing the percolation speed presumably due to the oxygen supply by the percolating water. However, prolonged submergence, say, for 100 days made the whole soil layer reductive. This means that the oxygen supply by the percolated water is not enough to maintain the surface layer in oxidative state for 100-day submergence because its supply is overcome by the high oxygen demand of soil microbes under high soil temperature in summer.

Water percolation elongates the "oxidized" period in the surface, and this condition is favorable to nitrification and subsequent denitrification process. Consequently the loss of basal fertilizer nitrogen by this process may be a more serious problem in well-drained paddy fields than in ill-drained.

2) Effect of intermittent flooding on the differentiation process of the oxidized and reduced soil layers

Effect of intermittent flooding on the differentiation process of the oxidized and reduced soil layers was examined under field conditions. One plot (intermittent flooding plot) was first submerged for 40 days, then 10-day drainage alternated with 10-day submergence was repeated three times, and finally the flooded water was drained. Another plot (continuous flooding plot) was submerged for 100 days, and then the flooded water was drained off.

In the intermittent flooding plot, the redox potential just below the interface remained above +200 mV for 4 days after submergence, dropped gradually and reached less than −100 mV after 40-day submergence. During the intermittent flooding period, the redox potential of this position increased rapidly to above +400 mV by 1st and 3rd drainage and dropped rapidly by subsequent submergence, whereas the redox potential at 5 cm in depth also increased rapidly to above +100 mV by 1st and 3rd drainage and dropped rapidly by subsequent submergence. In the continuous flooding plot, on the contrary, the redox potential just below the interface remained above +200 mV after 4-day submergence, dropped gradually and reached less than 0 mV after 100-day submergence, and the redox potential at 5 cm in depth which remained above +200 mV only 1 day after submergence, dropped rapidly and reached less than 0 mV after 5-day submergence. Redox potentials at both positions, just below the interface and at 5 cm in depth, increased rapidly after drainage (Fig. 3).

Fig. 3 indicates that in the intermittent flooding plot the surface layer which remained reductive after 40-day submergence became oxidative by 10-day drainage and then became reductive again by 10-day subsequent submergence.

Intermittent flooding was often practiced from the beginning of reproductive stage of rice growth, to make the surface soil oxidative by the direct penetration of atmospheric O_2 into the surface soil. Such condition seems to accelerate the nitrification and subsequent denitrification of top-dressed fertilizar nitrogen. The efficiency of top-dressed fertilizer nitrogen, however, is usually higher than that of basal application presumably due to the rapid absorption by well developed root network in this growth stage.[12]

Conclusion

Loss of fertilizer nitrogen by nitrification and denitrification process occurs in most paddy fields. It is necessary to clarify this process precisely for productive rice cultivation. The process of nitrification and denitrification in submerged soils occurs as a result of the development of a thin oxidized soil layer overlying a thicker reduced soil layer. Our investigation reported here clarified that the surface layer which is oxidative just after submergence becomes reductive gradually, and that the whole soil layer becomes reductive by prolonged submergence. This result agrees with the fact that the loss of basal fertilizer nitrogen by denitrification occurs mainly one month after its application.[5]

The differentiation process of the oxidized and reduced soil layers in paddy fields is affected by water management such as water percolation and intermittent flooding, as discussed above. This process may also be affected by other factors such as soil temperature, incorporation of organic material and so on. How these factors influence the differentiation process is a future problem. Moreover, nitrification does not occur, unless nitrifying bacteria are present. Therefore, further studies are needed to elucidate the ecology and physiology of nitrifying bacteria in paddy fields.

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