a. Eluviation of substances from the furrow slice of a paddy soil occurs chiefly during the irrigation season. Under flooded conditions, reduced conditions predominate in the soil of the furrow slice. In the soil of the B horizon, the plow sole and subsoil, it is believed that oxidized conditions exist. Morita's investigations at the experimental farm of Kyoto University show this clearly. 16/ If it is shown definitely that such a situation generally does exist in a flooded paddy soil the nature of eluviation and illuviation of substances in paddy soils can be explained easily. Also, if the soil of the B horizon remains in an oxidized condition after flooding, the organic substances in it will contribute little as a source of nitrogen for rice production.

b. Observations in the field have indicated that the B horizon of a well-drained paddy soil usually remains in an oxidized state under flooded conditions. In order to confirm this observation, the characteristics of the various layers of the profiles of fice soils when air-dried were investigated as shown in Table 18. Sample A was obtained from a paddy field of average productivity at the Agricultural Experiment Station, Konosu, Saitama Prefecture. Organic fertilizer was applied each year to this field. Sample B and C are of alluvial origin (alluvial deposits of the Chikuma River) and were obtained from two neighboring paddy fields at Takagawara, Nagano Prefecture. The field from which sample B was obtained is of very high productivity due to special cultural treatments practised by its owner, while the field from which sample C was obtained is of fairly high productivity. Samples D and E were obtained from two neighboring fields and both originated from lake deposits near Lake Suwa, Nagano Prefecture. The field from which sample D was obtained is of high productivity due to the efforts of the farmer cultivating that soil. The field from which sample E was obtained is of average productivity.

c. In one series the samples were incubated without prior air-drying, and in the other series the samples were incubated after they were air-dried, The depth of the soil was about 9 cm and the depth of the surface water was about 1 cm. The temperature of incubation was 30° C.

d. The results of this investigation, which are given in Table 18, are summarized as follows. After flooding, the soil samples of the B horizon which were not air-dried remained in an oxidized state and ammonium-nitrogen production in them was insignificant. The only exceptions were the soils of the plow sole of both samples from Takagawara, Nagano Prefecture, which became more or less reduced, but the production of ammonium-nitrogen also was insignificant. The soil samples obtained near Lake Suwa showed rather strong reaction to air-drying, but, when flooded without prior air-drying, these samples also remained in an oxidized state.

e. The results of this investigation, which prove that the B horizon of paddy soils is in a state of oxidation under flood on conditions confirm the observations made of paddy fields at many localities.

The reduced conditions in the A horizon and the oxidized conditions in the B horizon may be responsible for the accumulation of iron compounds in the B horizon.

3. Eluviation of ammonium-nitrogen in the profile of flooded paddy soil.

a. In addition to being absorbed by the rice plant, the disappearance of ammonium-nitrogen added to the furrow slice can be attributed to several causes such as (1) lateral flow of surface water containing ammonium-nitrogen to drainage ditches, (2) absorption by autogenetic (naturally living) hydrophytes growing in the surface water, (3) denitrification in the uppermost surface of the furrow slice, and (4) eluviation into the subsoil.

b. The loss of ammonium-nitrogen by lateral flow of the surface water into drainage ditches is not serious if the surface water is not drained within a few days after fertilization. In the case of absorption by antogenetic hydrophytes, there is no actual loss of nitrogen since these organisms will be sooner or later incorporated into the soil by cultivation. 28/ If this is true, the loss of ammonium-nitrogen from the furrow slice can be attributed largely to either denitrification or eluviation or to both. The results of a field experiment (Table 9) show clearly that, when ammonium sulfate is incorporated deep into the furrow slice, rice production is larger than when shallow incorporation was done. This has been proven by many field experiments conducted throughout Japan.

c. It is obvious that more ammonium-nitrogen will be lost through leaching if it is applied deep in the furrow slice than if it is applied in the surface. However, the fact that rice yields are actually lower when shallow nitrogen applications are made than when deep applications are made indicates strongly that denitrification is a more important factor than eluviation in the loss of ammonium-nitrogen in paddy field under flooded conditions. In order to determine the seriousness of the loss of ammonium-nitrogen through leaching into the subsoil, the following experiment was performed in the paddy field at the Agricultural Experiment Station, Konosu, Saitama Prefecture.

d. Several glass tubes, with an average area of 13.2 sq. cm, were inserted into the soil of a flooded paddy field. The top 9 cm of soil from the field was replaced with the soil of the furrow slice from another field that was not fertilized with nitrogenous fertilizer during the year. Care was taken to distinguish the added soil from the plow sole by a thin layer of sand. During the experiment the level of the surface water within the tube was kept the same as the level of the surface water outside the tube. On 22 June, ammonium sulfate was added to each tube, except the check, at the rate of 150 Kg of nitrogen per hectare and was mixed with the soil at one of the following depths: in the surface water; 0-2 cm; 3-5 cm. Analysis was made of ammonium-nitrogen in the soil of one tube (0-9 cm depth) from each treatment seven days, 21 days, and 52 days after beginning of the experiment. The data are given in Table 19, it is obvious that more nitrogen was lost where shallow application was made than where deep application was made in spite of the greater possibilities of more ammonium-nitrogen being lost by eluviation in the latter method. It is believed that most of the ammonium-nitrogen leached out of the furrow slice by the percolating water is absorbed in the plow-sole layer where it is later assimilated by the roots of the rice plant. Therefore, if ammonium sulfate is applied deep in the furrow slice, the portion utilized by the rice crop should be quite large. This had been substantiated by the results of an experiment shown in Table 20.

e. In the experiment summarized in Table 20, 20 grams ammonium sulfate was applied two days before the rice seedlings were transplanted. The rate of application was 0.5 grams of nitrogen per plot (area, 0.5 sq.m). The following depths were used: (1) in the surface water, (2) mixed into the surface soil by hand after addition to the surface water which was 3 cm in depth, (3) mixed into the surface soil by hand after the surface water had been drained, and (4) in the inner layer of the furrow slice (3-6 cm in depth). After the crop was harvested, its nitrogen content was analysed and the percent of the applied nitrogen obserbed by the crop was calculated.

f. The data in Table 20 show that nearly all of the nitrogen applied in the inner layer of the furrow slice (3-6 cm in depth) was taken up by the rice crop. The data also show that where the soil was flooded throughout the year (plot B) more of the nitrogen applied at the surface was absorbed by the rice crop than where similar surface application was made in soil flooded only during the rice season. A previous investigation using the soil from plot B has shown that practically no nitrogen was lost in the oxidized layer of this soil (Table 7). Perhaps, this singular behavior of soil B is responsible for the high returns from the nitrogen applied at the soil surface.

F. Degraded paddy rice soils 22/

1. Characteristics of degraded paddy soils.

a. The paddy soils of Japan mostly are of recent alluvial origin and generally are quite fertile. However, some of these soils are of degraded nature corresponding to the paddy podzols and podzolic soils of China described by Throp 31/ as being formed by the practices employed for rice production. On such degraded soils the roots of the rice plants are damaged, especially during midsummer when growth is vigorous. In addition, the plants usually are attacked by "leaf spot disease" a. During the later stages of the growing season, the growth and appearance of the plants are poor and yields are greatly reduced.

b. Field observations have shown that degraded soils are described by the following characteristics:

(1) The soil of the furrow slice is colored gray and shows little or no evidence of active iron compounds.

(2) The plow-sole layer is usually bleached and resembles the A_2 horizon of a true podzol.

(3) Directly below the plow sole or slightly lower is a layer where ferric oxides accumulate.

(4) In midsummer the reduced layer of the furrow slice emits H_2S gas.

(5) The rice plants growing on a normal paddy soil have healthy root as indicated by a reddish-brown color resulting from a coating of hydrated ferric oxide. The roots of rice plants growing on degraded paddy soils, however, usually are whitish in appearance and are without any visible coating of ferric oxides.

c. The process by which ferric hydroxide is precipitated on the healthy roots of rice plants growing on a normal soil can be explained as follows:

(1) Recently K. Kumada at the author's laboratory Tokyo University has worked on this obscure, but important problem in press. This work has thrown some light on the subject. He has pointed out the existence of a thin seath of water of a width of about one millimeter around the root in the case of the rice seedling grown in a healthy paddy soil under water logged conditions. Across this seath of water, the root hairs, which are formed on the unmature root region where growth of elongation occurs, penetrate their tip into the soil.

As mentioned in a preceding section (A,4), the active forms of iron and sulfur in the reduced layer are Fe and S^{--} ions. In the oxidized layer the active forms are Fe^{+++} and SO_4^{--} ions. The soil of the furrow slice of a normal paddy field usually contains enough active ferrous ions to completely precipitate the sulfide ions as ferrous sulfide, and probably also precipitates soluble organic matter as ferrous compounds or complexes. When the rice roots develop in the reduced layer of a normal paddy soil, the newly elongated parts of the roots of about two centimeters in length from the tip, including the region of the primary meristem locating at the root tip and the region of the root hairs possessing high oxidizing power oxidize the ferrous sulfide to ferrous sulfate, and then to ferric sulfate at the proximity of their peripheries. The ferric ions soon precipitate out as hydrated ferric hydroxide in the soil and form a layer around the roots which protects the young roots against the action of reduced substances in the soil solution. But in the region of the root becoming older, its oxidizing power decreases gradually in intensity, and the front line of the precipitation of hydrated ferric oxide retards nearer toward root surface across the seath of water at the boundary of root and soil. Thus the root becomes stained reddish-brown from a coating of the hydrated ferric oxide as it grows older.

(2) In contrast, the roots of a rice plant growing in a degraded paddy soil lacking sufficient amounts of active iron oxides are not protected by a layer of precipitated ferric hydroxide around their peripheries. Consequently, these roots may be damaged by reduced substances, such as sulfides and organic compounds dissolved in the soil solution.

d. Pertinent information on the chemical composition and behavior of a highly degraded paddy soil, a weakly degraded paddy soil, and a normal paddy soil are given in Table 21 and 22. The data in these tables can be summarized briefly as follows:

(1) The free ferric oxide and active manganese content in the furrow slice of a degraded paddy soil is much less than that of a normal paddy soil.

(2) In a highly degraded paddy soil, the amount of phosphoric acid soluble in hot, concentrated hydrochloric acid is much smaller in the furrow slice (A horizon) than in the zone of accumulation of ferric oxide (B horizon). This relationship is the converse in the case of a weakly degraded paddy soil or a normal paddy soil. From these results it appears that in a highly degraded paddy soil phosphoric acid is leached out from the furrow slice into the subsoil. Hirano has found that some of the P_2O_5 applied as superphosphate in the furrow slice of degraded paddy soils in Hiroshima Prefecture was leached out and deposited in the subsoil.[a]

(a) Private communication by M. Shioiri with S. Hirano at the Agricultural Experiment Station, Saijo, Hiroshima Prefecture.

e. The soils of the reduced layer and the plow sole of a highly degraded paddy soil give off H_2S gas under flooded condition. No H_2S gas is emitted by the soils of the furrow slice of a normal paddy soil under similar conditions. It has been found that if that and B horizons of a degraded paddy soil are mixed there is no emission of H_2S. This indicates that, by mixing the soil of the furrow slice both the subsoil, reclamation of degraded paddy soils is possible.

2. The Mechanism of Degradation:

a. Thorp 31/ has offered an important theory explaining the mechanism of degradation of paddy soils. In laboratory experiments conducted by the writer and his associates, it has been observed that under flooded conditions with unrestricted drainage, Fe compounds, primarily ferrous sulfide, are leached out of the soil of the furrow slice by percolating water into the subsoil. The downward movement of ferrous ions also is aided probably by dissolved organic substances and H_2S. Within the subsoil of paddy fields, the presence of spotty aggregates of MnO_2 often has been observed in the B horizon or in G (gley) horizon or in both horizons. In the B or G horizon, the eluviated ferrous ions are oxidized to form insoluble ferric compounds by the MnO_2, and at the same time, the MnO_2 is reduced to form soluble Mn^{++} compounds. 10/ When the paddy field is drained well, the Mn compounds in the soil solution or in the ground water precipitate as manganous carbonate which is easily oxidized to MnO_2. It has been shown in Table 18 that the Eh value of the B horizon of well drained paddy soil is fairly high even after flooding. Hence, it is possible that active iron in the B