ECOLOGICAL SUSTAINABILITY OF THE PADDY SOIL-RICE SYSTEM IN ASIA

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ABSTRACT

The paddy soil-rice system has efficient nutrient replenishing mechanisms. Basic cations and silica are supplied by irrigation water, while biological fixation works as an inexhaustible source of N in the system, and phosphorus availability is enhanced under anaerobic conditions. This, along with almost perfect resistance to soil erosion, gives the paddy rice system high productivity as well as high sustainability.

To cope with an increasing world population, the paddy rice system has to be intensified by developing the infrastructure for irrigation and drainage, and adopting high-input technologies. A tentative conclusion in this paper is that the intensification of paddy rice cultivation is not likely to have as serious an adverse impact on the environment as would be expected from the intensification of upland food production systems.

INTRODUCTION

Agenda 21, released by the UN Conference on the Environment and Development (UNCED), held in Rio de Janeiro in 1992, placed great emphasis on achieving sustainability in agriculture. There is serious concern throughout the world about the sustainability of agriculture, and the impact of agriculture on the global as well as the local environment. Many serious environmental problems are related to agriculture: rapid deforestation and the biodiversity crisis due to expansion of agricultural lands; irreversible land degradation due to soil erosion, desertification and salinization; plus the emission of greenhouse gases from agricultural land, and of materials contributing to acid rains, air and water pollution and human health hazards from chemicals used in agriculture.

In view of the large number of people engaged in agriculture, and the huge land area under agricultural landuse (including forestry and animal husbandry), agriculture obviously has a great impact on the environment. It is necessary for agriculture to minimize its environmental cost, which is why Agenda 21 urged the world community to attain sustainable agriculture.

The purpose of this paper is to evaluate the paddy soil-rice system in Asia from the viewpoint of sustainability. There is no doubt about the importance of this system, which is supporting nearly half the world's population today. Whether it is also environmentally sound is the central issue to be discussed in this paper.

CHARACTERISTICS OF THE PADDY RICE SYSTEM IN ASIA

The origin of paddy rice cultivation is located somewhere in the southeastern part of Asia, and is said to date back at least 7,000 years. Since that time, the distribution of paddy rice cultivation has been greatly expanded, but even today it is basically confined to monsoon Asia, near its place of origin. This is not the case for other major cereals such as wheat and maize, which have expanded their area of distribution throughout the world. Kawaguchi

Keywords: Intensification, monsoon Asia, nutrient replenishment, paddy soil-rice system, soil conservation, sustainability

and Kyuma (1977) consider that this specific distribution pattern of rice is the result of two factors. One is the concentration of rainfall, often more than 1000 mm during the rainy season, and the other is the very large expanse of lowlands in monsoon Asia. The latter is evident from the data in Table 1. This indicates that tropical Asia, with only 1/13 of the world's land area, has more than 1/3 of the potentially arable lowlands. Rice is the crop best suited to such lowlands, where water inundates naturally as rain falls and rivers flood. Thus, a unique combination of climate and landform has helped create the paddy rice system in Asia.

NUTRIENT STATUS OF PADDY SOILS

General Redox Transformations under Waterlogged Conditions

The most characteristic management practice in paddy rice cultivation is waterlogging, or submergence of the land surface. This brings about anaerobic conditions in the soil, due to the very slow diffusion rate of oxygen through water. Biologically, after the oxygen reserve in the soil is exhausted and aerobic microorganisms have all died, facultative anaerobes dominate for some time. As the anaerobioc conditions continue, these microorganisms are gradually replaced by obligate or strict anaerobes.

The biological changes are accompanied by a very characteristic succession of chemical transformations of materials. Following the disappearance of molecular oxygen, nitrate is used as a substrate for denitrifiers. Manganic oxides are solubilized as a result of reduction to manganous ions, likewise orange yellow to reddish colored iron oxides are reduced to soluble ferrous ions, decolorizing the soil. Many fermentation reactions based on various organic substrates proceed along with these mineral transformations, producing carbon dioxide, ammoniacal nitrogen, low molecular weight organic acids, and so forth. As the soil becomes even more reductive, sulfate reducers, which are strict anaerobes, produce sulfides; and methanobacteria, also strict anaerobes, produce methane. Table 2 summarizes the redox transformation reactions that occur after a soil is submerged.

All these biochemical changes occur vigorously for the first month after submergence, when readily decomposable organic matter, the energy source for microorganisms, is abundantly available. Past this stage, there will be a period when the supply of oxygen by diffusion, though extremely slow, exceeds its consumption at the soil/water interface. As all the oxygen is trapped by such reduced substances as ferrous and manganous ions at the interface, a thin oxidized, orange colored layer (normally a few millimeters thick) is differentiated from the underlying bulk of the strongly reduced, bluish-gray plow layer. The great environ-mental difference between the oxidized and the reduced layers exerts a profound influence on nitrogen transformation in the later stages of paddy soil management, as will be explained below.

Supply of Basic Cations through Irrigation Water

At least 1000 to 1500 mm of water is used to irrigate paddy fields during one rice cropping season. Nutrients dissolved in water, particularly basic cations such as calcium, magnesium and potassium, as well as silica, are supplied to rice in the water. If we assume that 1000 mm of water is used for one crop of rice, 1 mg kg^{-1} or 1 ppm of a substance dissolved in water amounts to 10 kg/ha. According to the mean water quality of Japanese rivers, as

Table 1. Area of lowland alluvial soils in Asia

	Land area		Alluvial soil area	
	Total	Potentially arable	Total	Potentially arable
World	13,000	3,152	588	316
Asia*	2,704	620	-	192
Tropical Asia	987	344	168	114

*Excluding USSR

Source: White House 1967

Table 2. Successive chemical transformations in submerged soils

O_2•	Depleted
NO_3•	Denitrified to N_2
Mn (III,IV)	Reduced to Mn^{2+} with higher solubility
Fe (III)	Reduced to Fe^{2+} with higher solubility
Organic compounds	Fermented to produce organic acids, aldehydes, alcohols, etc.
$SO_4^{2\bullet}$	Reduced to $S^{2\bullet}$
CO_2	Reduced to CH_4
pH	Converges to pH 6.5 - 7.5

Table 3. Water quality of Japanese and Thai rivers

(Yield of plot with complete fertilizer = 100)

Crop	No N	No P	No K	No N,P or K
Rice	83	95	96	78
Upland rice	51	84	75	38
Wheat and barley	50	69	78	39

Source: Kobayashi 1958 and 1961

shown in Table 3 irrigation of 1000 mm of water brings to a paddy field 88 kg/ha of Ca, 19 kg/ha of Mg, 12 kg/ha of K, and 190 kg/ha of SiO_2. Usually more than 1000 mm of water is used for irrigation, so the amount of nutrients supplied to rice is larger.

But the question is, to what extent can the supply of nutrients from irrigation water satisfy the needs of rice? The mean yield in Japan is about 6.2 mt/ha of unhusked (paddy) rice. The nutrients contained in this quantity of rice exceed the amount of K and SiO_2 by 3 to 5 times. Of course, soil can supply the greater part of the rest of the rice requirements, but some K and SiO_2 fertilizers should be applied as a supplement. There is, however, no need to apply Ca and Mg, as their supply through irrigation water far exceeds the amount required by the rice.

The situation changes as water quality and rice yield change. In Thailand, for example, the average level of Ca, Mg, and K in river water is roughly twice as high as that found in Japan, whereas the mean yield of rice is about one-third. (Table 3). Thus, if no fertilizers are being applied, the nutrient supply via irrigation water is much more favorable for Thai rice.

However, the two most essential nutrients, N and P, are not supplied in any significant quantity by irrigation water. Normally, less than 10% of the rice requirement for these essential nutrients is supplied through irrigation water, unless the water is severely eutrophied or polluted. Thus, there must be some other mechanism to supply N and P to rice, if a satisfactory yield level is to be maintained without fertilizer applications.

Supply of Nitrogen through Biological Nitrogen Fixation

There are paddy areas where rice has been cultivated for hundreds of years without receiving any fertilizer, but where yields are sustained at 1.5 to 2 mt/ha. It is estimated that about 20 kg of N is required to harvest 1 mt of paddy. Thus, it is difficult to explain how rice yields can be sustained for so long without any application of N.

The greater part of N in paddy soils exists in soil organic matter. This tends to be conserved more in paddy soils than in upland soils, because of the anaerobic conditions. Microbial decomposition of the organic matter gradually releases ammoniacal N (NH_4^+-N). As NH_4^+-N is stable under anaerobic conditions, it is retained as a cation on negatively charged soil mineral and organic particles, until the time when rice roots take it up. Thus, the leaching of NH_4^+-N from paddy fields into the environment is not significant.

There is, however, one condition under which NH_4^+-N becomes unstable. As stated earlier, after a month or so from the start of waterlogging, a thin oxidized layer is differentiated from the reduced plow layer at the soil surface. When NH_4^+-N comes to this oxidized layer, it is readily transformed into nitrate (NO_3^--N), by nitrifying bacteria. As an anion, NO_3^--N is not retained by soil particles, and is readily washed with percolating water into the underlying reduced plow layer. Here, it undergoes denitrification and N is lost to the atmosphere. As a way of minimizing this loss of N, a deep placement technique for ammonium fertilizers has been developed in Japan and is now widely practiced.

Besides soil organic matter, there is another important source of N, i.e. biological N fixation. In paddy soils there are many microbes that are capable of fixing atmospheric N, such as blue-green algae, *Clostridia*, photosynthetic bacteria, and many of the heterotrophic bacteria in the rice rhizosphere. Estimates of the amount of biologically fixed N per crop of rice vary quite widely, but 30 to 40 kg/ha would be a reasonable figure. This amount of N is two or three times higher than the amount of N fixed in ordinary upland soils planted in non-leguminous crops. Interestingly enough, this amount of fixed N can explain the average yields of paddy obtained in unfertilized fields in southeast Asia (1.5 to 2 mt/ha) on the basis of 20 kg of N for 1 mt of paddy.

As explained above, paddy soils are equipped with an excellent N cycling mechanism, with an input through biological N fixation and an output through denitrification, as shown in Fig. 1. This appears to set the basis for sustainability of rice cultivation as an efficient food production system.

Enhancement of Phosphorus Availability

It has been shown that of the three essential macroelements, two of these, K and N, have an assured, if not sufficient, supply mechanism in paddy soils.

Phosphorus has no such supply mechanism. However, it is the 11th most abundant element in the earth's crust, and is present everywhere in the soil in reasonable quantities. Therefore, what matters usually is its availability rather than the absolute quantity present. In acid soils in a humid climate, P is present mainly in the form of iron phosphate (Fe-P) and aluminum phosphate (Al-P). Neither of these is readily soluble. There are, of course, organic forms of P that may be released during the process of organic matter decomposition. However, in contrast to N, the quantity of such organic P compounds is normally very low, compared to the mineral forms of P.

In the process of anaerobiosis in paddy soils, iron phosphate tends to be reduced, with a release of some of the P in available forms. Moreover, reduction of iron oxides releases some of the occluded P into the soil. Thus, there is at least one mechanism to raise the availability of P in paddy soils.

The reduction of paddy soils under submerged conditions is accompanied by an elevation in soil pH. This is the result of H^+ consumption as oxidized materials, such as NO_3^- and Fe_2O_3, are reduced. Usually the pH of acid paddy soils stabilizes at around 6.5. The rise in pH enhances the solubility of iron phosphate and aluminum phosphate, by a factor of 10 times per unit rise in pH. Here is another mechanism to raise the availability of P in paddy soils.

Negative Aspects of Soil Reduction

Rice is known to suffer some physiological disorders under strongly reduced conditions. The best known is a root rot, caused by hydrogen sulfide evolved in soils that are poor in readily reducible iron oxides. These soils are often derived from pale colored, sandy, granitic sediments. They are poor, not only in iron oxides, but also in some other plant nutrients such as Mg, K and SiO_2. It is now known that root rot due to hydrogen sulfide is an acute case of the more general "akiochi" phenomenon observed in these "degraded paddy soils", as characterized above. In Japan, a nationwide project was carried out during the post-war period to ameliorate degraded paddy soils by dressing the soil with Fe-rich, more juvenile materials. With the aid of a government subsidy, the project was successfully completed, so that "akiochi" is no longer seen in Japan.

There are large areas of paddy fields in

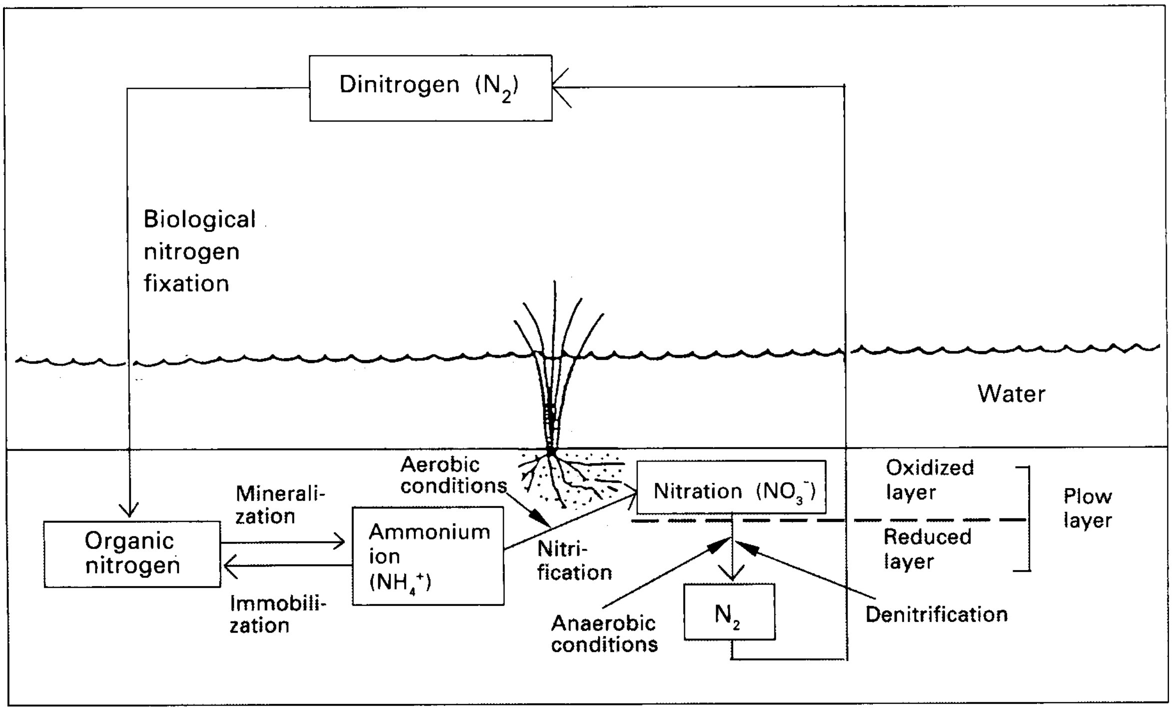

Fig. 1. Schematic diagram of nitrogen cycle in paddy soil ecosystem

southeast Asian countries that are characterized by the very low inherent potentiality of the soil. In fact, some of these deserve the name of "degraded" paddy soils. However, because of the generally low levels of both fertilizer inputs and rice yields, at present they may not be clearly differentiated from "normal" soils.

ADVANTAGES OF PADDY RICE CULTIVATION

Comparison of Paddy Soils and Upland Soils

The above discussion indicates that as far as the nutrient status is concerned, paddy soils have advantages which upland soils lack.

What about the soil physical properties, or tilth? The tilth is not as important in paddy soils as in upland soils. As long as enough water is available to keep the soil submerged, the balance between water retention and aeration, which is vital for upland soils, can be disregarded. Furthermore, a heavy clay soil with a very hard, dry consistency is difficult to till under upland conditions, but is relatively easy to plow and till in flooded lowlands with two buffalo or oxen.

The high level of resistance of paddy soils to erosive forces is even more important, from the viewpoint of sustainability. Upland soils tend to be eroded away unless they are properly protected. This is particularly true in the tropics, where the erosivity of rainfall is very high, and where upland soils usually have poor resistance to erosion. Paddy soils are most resistant to erosion when they are terraced and there are ridges around the field, as measures to retain surface water. In addition, paddy fields in the lowlands receive new sediments deposited from run-off that carries eroded topsoil down from the uplands, thus perpetuating soil fertility and productivity.

Paddy soils have other advantages. In upland farming, crop rotation is a necessity to avoid a decline in yield due to diseases and pests that arise from a monoculture situation (soil sickness). In paddy fields, on the other hand, rice can be grown year after year without any clear sign of yield decline, over a considerable length of time. The alternation from aerobic to anaerobic conditions in a yearly cycle of rice farming is the best measure to remove the causes of soil sickness. No pathogens or soil-borne animals can survive such a drastic change in the redox environment.

The relative ease of weeding in paddy soils compared to upland soils in a humid climate may be counted as another advantage.

Comparison of the Productivity of Paddy Rice and Upland Cereals

Many field experiments have been conducted in Japan to test the effect of fertilizer applications on rice and other cereals. Table 4 gives a summary of the results of these experiments (Kawasaki 1953). In the Table, the yield of the complete fertilizer plot (N, P, K applied) is taken as 100, and the relative yields of the other plots are calculated in percentages. The Table shows a clear difference between paddy rice grown under submerged conditions, and wheat and barley grown under non-submerged conditions. Upland cereals are severely affected by the absence of any of the major elements, while rice is relatively unaffected. Even when P was not applied, the yield decline was only 5% of the complete plot for rice, whereas it was as severe as 31% for wheat and barley. This means that in paddy soils, the mechanisms outlined above maintained the P status at a high enough level, even when no P had been applied.

Similarly in the case of N, the higher biological N fixation rate in paddy soils reduced the effect of eliminating N fertilizer on rice yield. For K, the supply via irrigation water was effective in maintaining the yield of plot with no applied K. The compound effect of the three major elements gave twice as high a relative yield figure for rice, as that for upland cereals. Rice cultivation under submerged conditions is clearly superior to upland cultivation of other cereals, in terms of the efficient use of naturally supplied nutrients and thus yield per unit area.

INTENSIFICATION OF PADDY RICE CULTIVATION AND THE ENVIRONMENT

Rice is the staple food for more than two billion people, most of whom live in developing countries where the population is still rapidly increasing. A study conducted by the International Rice Research Institute (IRRI 1989) reveals that to meet the projected growth in the demand for rice, the world's annual rough rice production must increase from 458 million mt in 1987 to 556 million mt by 2000 and to 758 million tons by 2020. This represents a 65% increase. For the leading rice-growing countries of south and southeast Asia, the same study indicates that the increase needed in rice production by 2020 is even higher, at about double the present level.

By now, the potential for expanding the area planted in rice seems to have become very restricted in south and southeast Asia. Most land resources have already been exploited to their fullest extent, and most of the readily manageable water resources also have been developed to irrigate paddy fields. Therefore, any further increase in the production of rice depends heavily on intensification in existing rice lands.

Impact of Irrigation/Drainage and Chemical Inputs

Intensifying rice cultivation could have various impacts on the environment. If good irrigation and drainage are provided, improved rice cultivars may be introduced, along with better management of fertilizer, weeds and pests. The construction of dams, and of irrigation and drainage canals, would

Table 4. Mean yield indices in fertilizer trials in Japan

(Yield of plot with complete fertilizer = 100)

Crop	No N	No P	No K	No N,P or K
Rice	83	95	96	78
Upland rice	51	84	75	38
Wheat and barley	50	69	78	39

Source: Kawasaki 1953

normally bring more benefits than disadvantages to the regional environment, as long as they are properly planned and implemented. It improves water use efficiency, regulates floods and droughts, and, through these, improves the environmental quality.

Increased use of chemical preparations, such as fertilizers, pesticides and herbicides, could be more hazardous. It is possible that they might pollute irrigation water and soil, and sometimes cause human health problems. This must, however, also be evaluated in comparison with the upland cultivation of other crops.

According to Tabuchi and Takamura (1985), the ratio of leaching loss of fertilizer N to the amount applied to upland soils in Japan normally ranges from 10 to >50% for arable uplands and from zero to 20% for grasslands. The actual rate of leaching loss depends on the type of soil, particularly the soil texture, and on the rainfall or the amount of water percolation. Tabuchi and Takamura concluded that most of the nitrate pollution of inland lakes originates from its leaching from upland soils. In contrast, the leaching loss of P from upland fields and grasslands is very small, particularly in the ando soil or Andisol areas that include about half the total upland fields of Japan.

A summary of their studies of paddy soils is shown in Fig. 2. Measured inputs of N and P (from fertilizer, irrigation, and rainfall) are balanced against outputs (through plant uptake, surface runoff and leaching). In the case of N, supply and loss are more or less balanced, although four out of five cases showed a relatively small net positive outflow which was polluting water. One case showed a net negative outflow, which was purifying the water. Cases of paddy fields with a water-purifying effect are common in Japanese studies.

In the case of P, applied fertilizer was by far the largest input, the greater part of it being retained by the soil. Three cases had a net positive output, and the remaining two cases had a net negative output. But the absolute amount of P in the output, either positive or negative, was very small, and there was relatively little impact on the environment.

There have been local cases of fish-kills due to water pollution with herbicides, and human health-hazards as a result of spraying with pesticides. However, no work has suggested that the paddy rice system is more hazardous than upland crop cultivation. Rather, it has been ascertained that chlorinated hydrocarbons, which are among the most resistant of pesticides and herbicides when used under upland conditions, are decomposed much more readily in paddy soils than in upland soils. By and large, the alternation of upland and submerged conditions in a yearly cycle gives paddy soils more favorable conditions to decompose or detoxify pesticides and herbicides.

Thus, generally speaking, paddy rice cultivation could be less hazardous to the environment if it is intensified, with a high level of chemical inputs, than upland crop cultivation.

Impact of Gas Emissions from Paddy Fields

In relation to the global environment, air pollution from soil emissions is receiving more and more attention. The production of nitrous oxide (N_2O) from N fertilizers and manures is now considered to have an environmental impact. The gas is evolved in both nitrification and denitrification processes. The former is considered more important at present. It affects the destruction of ozone to oxygen, and also acts as a greenhouse gas. However, N_2O emissions from paddy fields are considered to be very low (De Datta and Buresh 1989).

Ammonia volatilization from agricultural land, especially where there is intensive cattle raising, is of particular concern in relation to acid rain in northern Europe (van Breemen and Jordens 1983). The importance of ammonia volatilization as a N loss mechanism from paddy fields has also been established in recent studies (De Datta and Buresh 1989), though its environmental significance is not yet known.

It has been known for a long time that paddy fields emit methane gas, but the implications of this have recently become a point of dispute among researchers. A rapid increase in the methane concentration in the atmosphere has aroused worldwide concern in relation to global warming, since methane is one of the most efficient greenhouse gases. Although data are scarce, some researchers claim that paddy fields are the main cause of the recent increase in methane in the atmosphere. There is no doubt that paddy fields make a significant contribution to the build-up of methane in the atmosphere. According to the scientific assessment of an Inter-governmental Panel on Climatic Change (IPCC) (Watson *et al.* 1990), the yearly methane emissions from paddy fields are estimated to total 110 mt, or about 20% of the world's total methane emission each year. However, Neue *et al.* (1990) gave an estimate of 2.5 - 6.0 mt, based on the data obtained by IRRI. Yagi and Minami (1990) reported a similar figure of 2.2 - 7.3 mt, based on their field measurements under different conditions.

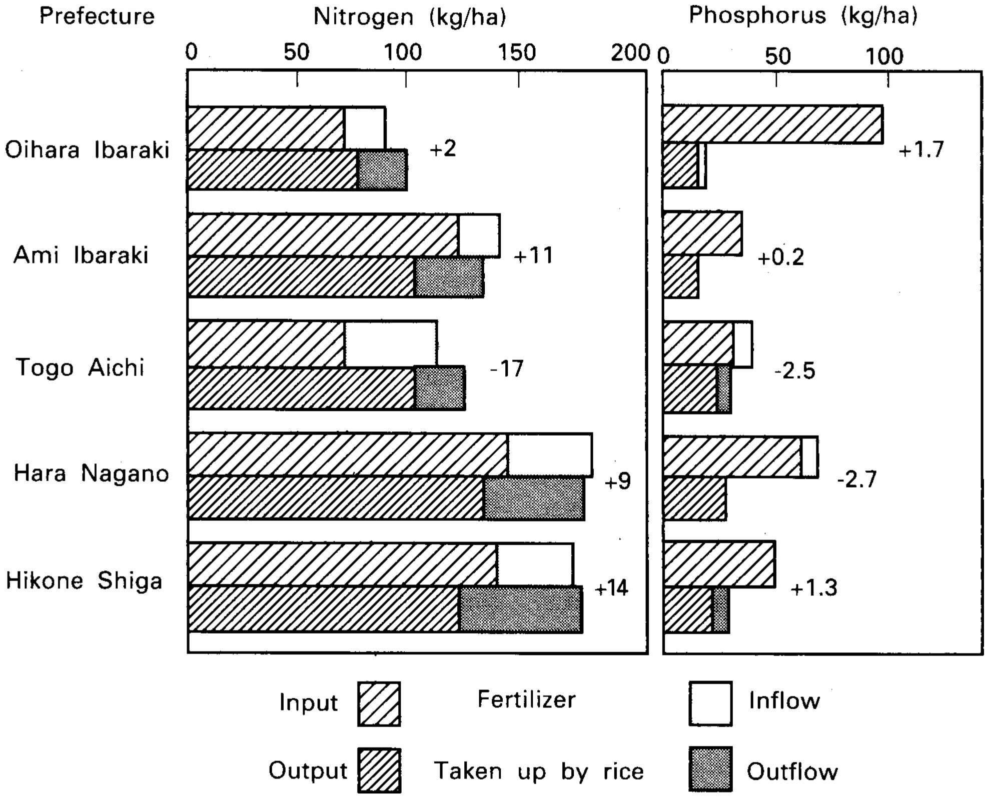

Fig. 2. N and P balance sheets for paddy fields in various parts of Japan. The balance is the difference between inflow and outflow. A minus sign means a purifying effect, and a plus sign a polluting effect, on water.
Source: Tabuchi and Takamura (1985)

Paddy fields have been emitting methane since time immemorial. Therefore, the issue at the present time is the reason for the recent rapid increase in the atmospheric methane concentration of about 1% annually. Certainly, there was a large increase in the area planted in rice during the early postwar period, but if we take the most recent decade, 1980 to 1990, the world-wide annual rate of increase in rice area has been only 0.23% (IRRI 1993). Moreover, the recent increases in paddy area have taken the form either of converting swamps to paddy by drainage, or converting dry land to paddy by irrigation. Swamps are emitting methane even in their original state, and irrigation of upland soils with a low organic matter would not produce much methane. Thus, it is difficult to imagine how paddy fields can have made any great contribution to the recent increase in the methane concentration in the atmosphere. Many studies are now being conducted to obtain more reliable data, so that this issue may be discussed with more confidence.

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DISCUSSION

Participants were interested in the data showing that there is no need to supply calcium amendments to paddy rice, since the amount of calcium in irrigation water is sufficient. Dr. Kyuma was asked whether this would also apply to highly acid soils. He replied that rice cannot be grown in highly acid soils such as acid sulfate soils unless calcium is added, but that most rice fields have enough calcium and magnesium. At one time in Japan, the calcium present in irrigation water had exceeded rice requirements by 3-6 times. Participants also discussed whether it would apply to the highly leached soils of a tropical environment, and Dr. Kyuma suggested that it might not. However, he pointed out that many rivers even in the tropics have higher calcium and magnesium levels than Japanese rivers, although there might be a different situation locally in some small watersheds.

Dr. Mutert pointed out that data on the nutrient levels in Thai and Japanese rivers was comparatively old, and asked whether the present situation might be different. Dr. Kyuma felt that, although the quality of river water may have changed since 1960, this change would probably not be important unless there was extensive pollution. Dr. Park of Korea discussed with Dr. Kyuma the question of whether, in trying to improve soil fertility, it was better to try and raise soil nutrient levels for the short time the crop was growing, or whether the aim should be to achieve a continuous high level of soil fertility. Dr. Park suggested that the latter course might involve a considerable loss of soil nutrients. Dr. Kyuma agreed, and felt that the question of how and when to apply fertilizer is one of the most important factors in making fertilizer recommendations.

Dr. Morris of AVRDC pointed out that Fig. 2 of the paper showed that nitrogen additions and removals are about in balance, but that phosphorus removals exceed the inputs. He asked whether this means that farmers need to keep applying large quantities of phosphorus, and whether this element was building up over time in the soil of countries like Japan. Dr. Kyuma felt that phosphorus is an element which is relatively easy to manage. While Japanese farmers are probably applying more phosphorus than is needed, the surplus is not likely to move out of the soil and pollute the environment.

Dr. William Chiu of FFTC pointed out that scientists in Taiwan are now taking a different view of the importance of paddy fields, which are seen as vital, not only for rice production, but for water conservation. Levels of underground water are now becoming lower in Taiwan and the underground water supply is a major concern. Dr. Kyuma agreed that paddy fields are extremely important as a potential reservoir for rainfall. He pointed out that it has been claimed that the total amount of water in Japanese paddy fields exceeds by many times all the water retained by dams in Japan.

SUMMARY OF FINAL DISCUSSION

INTERNATIONAL SEMINAR ON THE APPROPRIATE USE OF FERTILIZERS

Taiwan ROC, November 6-14 1995.

Final discussion, Saturday November 11 1995
Chairman: Dr. Ahmed Panel: Drs. Freney, Kyuma, Lin, Mutert

Dr. Ahmed reviewed the three objectives of the seminar:

1. Assessing the present situation of fertilizer use in member countries
2. Identifying the impact of fertilizer on productivity and the environment
3. Suggesting appropriate methods of fertilizer utilization and ways of effectively promoting such methods to farmers.

He asked the panel members to deliver a short review on the definition of appropriate fertilizer use; the environmental impact of fertilizer applications; application methods; and nutrient balance and theomax, respectively.

Definition of appropriate fertilizer use: Dr. Lin.

Dr. Lin emphasized that appropriate fertilizer use depends on the properties of the fertilizer itself, as well as the properties of the soil, the plant and the application methods. He suggested that appropriate fertilizer use should meet the following criteria.

- Plant nutrition is appropriate if the realized yield is optimum in both quantity and quality;
- Fertilization is appropriate if it results in a satisfactory supply of plant nutrients to match the nutrient demand of the plant (the fertilization effect).

Dr. Lin outlined how the efficacy of fertilizer is affected by a number of factors: the properties of the fertilizer itself, the properties of the soil (its physical, chemical and biochemical properties); the properties of the plant root system, including mycorrhizae; and the application method followed (rate, placement, and timing). Crop malnutrition can be caused by an undersupply of one or more nutrients, but also by an oversupply or imbalance. Imbalance always results in yields that are poorer in quantity, quality or both (in terms of e.g. nitrate content, amine and amide levels, accumulation of soluble-N, whether produce is succulent or fibrous etc.)

Whether a particular fertilizer regime is appropriate or not depends on the plant species, the expected yield, the characteristics of the fertilizer and of the soil, farm management practices etc. The appropriateness of fertilizer use should take into account not only the agronomic aspects, but also economic and environmental aspects. Appropriate fertilizer use should give farmers a profit, and should not damage the environment.

Environmental aspects of fertilizer use: Dr. Freney

Dr. Freney commented that discussions on the impact of fertilizer use on the environment often pointed out the negative aspects, but there are also positive effects. For example, where shifting cultivation is practiced, the land is being degraded because of insufficient phosphorus. *Imperata cylindrica* (cogon grass) is taking over as the dominant plant species, but is insufficient to hold the soil, and there is rapid loss of soil. Erosion can be overcome by supplying phosphorus. He pointed out that the source of supply must be considered. Phosphate rock is often high in heavy metals such as cadmium, uranium and zinc, while fluorine is another common contaminant.

Dr. Freney discussed nitrogen losses, and the effect of heavy losses on the groundwater which can become contaminated with nitrates. Furthermore, when urea fertilizer is applied, large amounts of ammonia are given off. Although the ammonia can have some harmful effects on health, visibility etc., it stays in the atmosphere for only a few days before being washed out of the atmosphere onto the soil surface. Dr. Freney pointed out that this can cause algae blooms and eutrophication in lakes and rivers, while when it comes down on soils not used for crops it can effect their capacity to take up methane. He also discussed nitrous oxide emissions and their effect on climatic change and the ozone layer. None of these problems would be overcome if organic sources of fertilizer were used in place of chemical fertilizer. In fact, nitrous oxide emissions would probably be even greater. He emphasized that all aspects of fertilizer use need to be considered, especially the environmental consequences.

Methods of fertilizer application: Dr. Kyuma

Dr. Kyuma pointed out that to harvest one mt of paddy rice, some 20 kg of nitrogen are required. Thus, for a harvest of four mt of paddy, at least 80 kg N must be made available to the crop. This represented what could be called the "theoretical minimum" or "theomin".

In practice, it is necessary to apply a higher level of nutrients than the "theomin", because the efficiency of absorption varies widely according to the way fertilizers are applied and soil conditions. Some of the important factors are whether fertilizers are applied as a basal application or split; and if the latter, into how many parts; where the fertilizer is applied, whether on the surface or by deep placement; and the timing of application. Any judgment on whether application methods are efficient can be made only if the traits of the crop variety are known, as well as the characteristics of the soil etc.

When fertilizer recommendations are being made, it is necessary to follow an integrated management approach.

Concepts of the theoretical maximum use of fertilizers and nutrient balances: Dr. Mutert

Dr. Mutert explained that both concepts provide a means of assisting policymakers, researchers, extensionists and farmers to predict the status of the fertilizer nutrient supply from organic and manufactured/chemical fertilizers with regard to under- and over-use.

1. The concept of the "theomax" is using established optimum average application rates of fertilizers to predict the "theoretical maximum" use at any stage of development of an agro-ecosystem. The basic assumption is that optimum average application rates are taking into account all sources of nutrient supply, and that such levels are economically acceptable to farmers as well as ecologically sound.
2. The concept of "nutrient balances" is using actual data of nutrient inputs (farmyard manure, residues, organic and mineral fertilizers, sedimentation, atmosphere etc.) and outputs (removal, losses from soil to water and atmosphere) to determine acute trends of decline or accumulation of plant nutrients in the agroecosystem of countries, regions, cropping sectors, agroecological zones, soilscapes and farms (even for impacts of the international "plant nutritional trade" on the environment).

Dr. Mutert suggested that the concepts of the theomax and the nutrient balance should be applied in order to create awareness – to provide a base for communication and prediction, and a guideline for action.

General Discussion

Environmental pollution from nitrates etc.

Dr. Lim (Malaysia) was interested in the danger of nitrate contamination, since water in some wells on the east coast of Peninsular Malaysia contains nitrate levels that exceeds permissible limits. Although some of this contamination comes from tobacco production, paddy cultivation may also have contributed, since a large amount of nitrogen fertilizer is used. He referred to Dr. Kyuma's suggestion that the paddy system can reduce the nitrogen input into the agro-ecosystem, and pointed out that paddy cultivation for high yields requires large amounts of nitrogenous fertilizer. He asked whether more problems of nitrate contamination may be likely as more fertilizers are applied to maximize yields. He was interested in the effect of dry seeding on nitrate contamination of groundwater, since direct seeding provides a longer period of oxidation. Would this result in a higher formation of nitrates?

Dr. Kyuma felt that the timing of seeding, and of flooding and N application are all related. He suggested that theoretically, denitrification is rather an easy process under reduced conditions. If soil is submerged more than ten days, nitrate will not be released from paddy fields into the groundwater.

Dr. Freney pointed out that the direct seeding of rice has been practiced for a long time in both USA and Australia. Studies on the fate of nitrogen in such as system have been made, and there seems to be no problem of nitrate leaching. He felt that the amount of nitrous oxide produced by the paddy rice system might be a more serious problem. When dry seeding is practiced, the soil is usually flushed with water to germinate the seed and then dried. This is followed by a cycle of drying and flooding over several weeks, during which time the nitrate is lost. By the time the field is permanently flooded, no nitrate is left.

Dr. Melakouti (Iran) suggested that it would be useful to have more information about hazardous limits of nitrogen applied to rice, and about nitrate limits in water. He pointed out that Iran is largely dependent on underground water sources, from which nitrate cannot be removed once it has entered the underground water system.

Using fertilizers to improve soil fertility

Dr. Park (Korea) discussed the improvement of soil fertility in Korea, and explained that when amendments and fertilizers are applied to soil, the utilization rate is low. This causes environmental problems. He asked how long stable soil fertility can be maintained if fertilizers are applied. If fertility is improved, can this be maintained by supplying fertilizer and amendments, or will fertilizer losses increase? He pointed out that thirty years of applying fertilizer and amendments in Korea had not had much impact in terms of improving soil fertility.

Dr. Kyuma discussed how soil fertility can be defined, whether it refers to the level of available nutrients, or the soil's capacity to absorb and release available nutrients. Dr. Park explained that in Korea, estimates of soil fertility are based on production levels. However, even if the target yields are achieved, the utilization rate may be low. He suggested that for this reason, it is very difficult to define optimum levels of fertilizer application.

Soil and plant testing network

Dr. Ahmed asked participants to consider follow-up activities for implementation by appropriate organizations. Dr. Mutert proposed that Asian countries set up a network of soil testing and plant analysis. The idea had been well received by FAO, and he believed that Asian countries had accumulated so much knowledge and experience that they should learn from each other rather than looking too far overseas. He emphasized the importance of knowing the nutrient status of Asian soils, and the need for a reliable soil testing network.

Dr. Morris (AVRDC) pointed out that in Western countries, soil testing is used very effectively, but farms are large while the fields used for single crops are also large. This means that samples from one field represent a large area of land. Farmers are also fairly affluent, and can afford to pay for soil testing. In Asia, on the other hand, farms are small and fields are smaller. Moreover, the cost of testing soils is high relative to the income of typical small-scale farmers. He questioned whether the laboratory analysis systems available to farmers in the West are necessarily appropriate for farmers in tropical Asia. He described AVRDC's search for alternative ways of estimating the fertility status of soils, and asked Dr. Mutert whether he knew of ways of estimating levels of available nutrients that are more appropriate to the structure of agriculture in South and Southeast Asia.

Dr. Mutert suggested that soil analysis could be limited to the most important factors - pH, P, K, organic matter content - while testing for CEC and other nutrients could be regarded as secondary. For the problem of variability, Dr. Mutert suggested starting at a rather general regional level, using representative data from soil samples, and applying these to situations where the same conditions prevailed. He emphasized the need for a high level of reliability in soil testing, and said that he had found a wide range of variation in test results from standard samples done by different laboratories in different countries.

Director Koh (FFTC) referred to recent FFTC training courses which had encountered similar problems, and asked for further details from Dr. Su-San Chang (ROC), who had been involved in helping organize and teach the courses. Dr. Chang described how, before the training course, the Taiwan Agricultural Research Institute (TARI) had prepared two standard soil and leaf samples and sent them to all participants, who were asked to bring the results with them when they came to attend the course. The results had been very variable, including even the determination of potassium levels, for which only 30% of trainees had achieved accurate results. She referred to the cross-checking system set up by Wageningen in the Netherlands, and questioned the need for a new network. She described the use of standard samples at TARI, and how repeated analyses are carried out of these to make sure the analysis is correct.

Dr. Aziz (Malaysia) felt that while setting up a soil analysis network is a good idea, what is more important is how to utilize the results of the analysis. Experience in Malaysia had found that soil analysis alone did not predict yield, and he emphasized the importance of foliar or tissue analysis. He suggested that the integrated use of foliar and soil analysis for diagnosis is desirable for various crops growing on different soils. In this way, analytical results could be used intelligently. Asian countries need to exchange and share their experience regarding the use of analytical data, because not all data is useful and some can be discarded. He described the national network in Malaysia for monitoring laboratory testing, organized by the Malaysian Soil Science Society.

Dr. Chiu (FFTC) felt that the most important problem in appropriate fertilizer use is the nutrient balance. He suggested that in Taiwan, in spite of the strong focus on soil and plant testing, it is still difficult to use the results for fertilizer recommendations, even with constant monitoring and checking. He emphasized the importance of field demonstrations once the recommended rates have been defined, as a way of showing the effectiveness of balanced fertilizer use.

Dr. Lien (ROC) suggested that while the problem of accuracy in analysis is fairly easily solved, there is still great difficulty in applying the results. He questioned the traditional concept of the application of soil testing to get fertilizer recommendations for maximum yield or maximum profit, since in practice this is very difficult. It requires a large number of field tests on correlations between fertilizer use and yield, and this takes a lot of time. In cases when the soil has accumulated nutrients as a result of repeated fertilizer applications, there is almost no response in the field to further applications. He described PK testing in Taiwan, and the detailed work on calibration levels, and pointed out that the results have not really been used in the field. In the past, yield response to P and K applications had been around 7%, but now they are only around 1%. He suggested that the real importance of soil testing is to find what residual levels of NPK are present for the succeeding crops. The target of soil testing should be changed from estimating the theomax to simply estimating the level of residual nutrients in soils, in order to achieve a better nutrient balance.

Other points

Dr. Ahmed asked for comments on the concept of integrated nutrient management. Dr. Morris suggested that although a great deal of research has been done on different aspects related to this, such as soil processes, rapid crop sequence in tropical countries, and the effect of flooded rice cultivation on nutrients for the following crop, there is a great need for all this information to be synthesized. He suggested that preparation of a general review would be very valuable for researchers.

Dr. Lim suggested that fertilizer specialists should become more involved with the process of preparing legislation concerning fertilizers. He pointed out that those preparing legislation have little technical knowledge, while fertilizer manufacturers are very well informed. Scientists are not contributing enough to legislation designed to ensure that fertilizer is of good quality. Dr. Ahmed agreed, but pointed out that it is usually social scientists and political scientists who are high in government circles, rather than agricultural economists.

Mr. Perera (Sri Lanka) commented that fertilizer in Sri Lanka is so expensive in relation to farm incomes that researchers are now recommending that plant residues be incorporated into the soil to save N, K and organic matter. He asked Dr. Kyuma whether this practice could be seen as part of a sustainable paddy rice system. Dr. Kyuma replied that fresh rice straw is also returned to the soil after automatic harvesting in Japan. If the straw is incorporated well before the next crop is planted, not much methane is released. If on the other hand straw is left on the soil surface and the field suddenly submerged, methane production can be a problem.