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NITROGEN CYCLING AND REMOVAL EFFICIENCY IN A RICE FIELD

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The major sources and sinks of nitrogen (N) were calculated during the rice growth cycle in a lowland paddy field in Japan in order to better understand contamination of surface and groundwater. Deposited nitrogen totalized 106 kg ha^{-1}, entering the field primarily through fertilizers and irrigation waters. Nitrogen outputs represented 93 kg ha^{-1}, most of it removed when crops were harvested. Excess nitrogen (13 kg ha^{-1}) was assumed to be stored in soils. The distribution of nitrogen concentrations clearly correlated with agricultural land use patterns. The nitrogen cycle was affected by the unique characteristics of submerged soils and involved complex transformations, mostly governed by the activity of microorganisms. Although there were some considerable losses as infiltration and surface runoff, the mass balance calculations showed that the paddy field was a nutrient sink within the region. Nitrogen assimilation capacity was higher than similar systems, and remained invariable during all the recorded period. The results demonstrate the importance of using a mass balance approach to evaluate the effects of agricultural production on water quality, and to assess how to reduce negative impacts through improved management strategies.

INTRODUCTION

Fresh water is a vital resource currently being threatened by human interference. Nowadays, there is worldwide concern about the deterioration of these natural systems by agricultural production, which comprises the bulk of non-point pollution sources. Primary concern is due to nitrate contamination of surface and groundwater, usually associated to oversupply of nitrogen through high fertilizer-manure application rates (Strebel et al., 1989). Mass balance calculations proved to be useful techniques to identify N cycling in agricultural areas but, despite the important number of studies already carried out, there is still considerable lack of reports about certain vulnerable systems such as rice fields, where the water table remains close to the ground during a great part of the year. Furthermore, estimation of the effects of agriculture on water quality remains a problematic issue, as many approaches were based on processes under controlled experiments rather than natural conditions, while some others have just taken into account simple inflow and outflow concentrations instead of measurements of all input and outputs. Although the actual conditions for an exact nitrogen budget are seldom determined with certainty, the present study contributes to filling the information gaps about nutrient dynamics in paddy fields, dealing with all the hydrological parameters involved and covering each one of the N sources and sinks throughout the rice growing season.

High nitrate levels in water can promote severe diseases and health effects, such as certain cancers, spontaneous abortions and birth defects (Spalding and Exner, 1993). They also contribute to eutrophication and biomass increase in water bodies. However, paddy fields can retain and remove large amounts of nutrients from water flowing to them through a variety of mechanisms including adsorption, plant accumulation, denitrification and others. Thus, identifying the role and importance of the various nitrogen sources and sinks by a mass balance approach may lead to optimizing the actual management practices, and to mitigating the negative impacts in agricultural systems.

The data collected by this research can be used for a variety of analyses, but the main objectives for this paper were to quantify the major nitrogen imports and exports in a paddy field system, to make clear the processes and transformations taking place in flooded soils, and to evaluate the field nutrient retention and removal efficiency occurring in this peculiar environment during the crop season.

STUDY SITE

The study was conducted on a paddy field located in a rural environment at Tsukuba City, Ibaraki Prefecture, 60 km north of Tokyo, Japan. The field dimensions are approximately 100 x 50 m occupying the floodplain of the Kokai River, which runs about 500 m south of the plot. The relief is nearly flat and underlain by several meters of alluvial sediments from the Holocene, product of a complex history involving periodic erosional and depositional episodes. They include mainly silt and clay deposits arranged in horizontal layers, with high vertical and lateral variability. Layers tend to be discontinuous and their thickness rarely exceeds 50 cm. High clay content prevents water infiltration down through the soil profile, enabling for rice cultivation under flooded conditions from mid April to early September. Surface water enters from the west via irrigation, and leaves the area through two discharge outlets at the opposite side of the field.

Climatic conditions are mild, with annual precipitation close to 1300 mm, most of it supplied during the rainy season from mid May to late July. At the end of August, the region is covered by typhoons coming from the south, which bring strong winds and storms.

METHODS

The various routes of input and output of nitrogen were considered in order to determine the mass balance during the rice-growing season in the paddy field. Figure 1 illustrates the nitrogen mass balance model used in the study. Nitrogen sources were assumed to be commercial fertilizers, animal manure, rainfall, irrigation and biological fixation while N sinks corresponded to surface draining, infiltration, fertilizer volatilization, denitrification and crop harvest. The excess of inputs over outputs (ΔS) is equivalent to the total amount of nitrogen stored in the system. The nutrient loads entering and leaving the field were closely related to the water dynamics, since import and exports occurred primarily through hydrologic pathways. In view of this, the role of water movement and a detailed understanding of the hydrologic processes taking place, constituted a crucial requirement to evaluate the N cycling and nutrient removal performance in the area. Hydrologic data were collected through an extensive instrument network and the paddy field water balance was computed as a preliminary step. A detailed description of the water budget exceeds the purposes of the present paper, but its interaction and influence on the nutrient processes is taken into full consideration.

Background waters were sampled manually for chemical analysis on a fortnightly basis. The daily nitrogen concentration was obtained by regression between successive samples and, combined with the corresponding flow rate, used to derive a nutrient load from that source. In the case of rainfall inputs, the average concentration of nutrients from five rain events was used, with the total precipitation over the studied period used to derive its loading. Samples were stored in polyethylene bottles and kept at 4 ºC until chemical analysis. Nitrate-N (NO_3^-), nitrite-N (NO_2^-) and other anions were analyzed using a Dionex QIC^{TM} ion chromatograph. Ammonium (NH_4^+) concentration was determined by a DKK Corp IOL-40 Multi Channel Ion Meter, while Total Dissolved Nitrogen (TDN) was determined by the ultraviolet absorption spectrophotometer method in accordance with the Japanese Industrial Standard JIS K 0101, 1991. Organic nitrogen was calculated by the difference between the total and the inorganic components.

Surface flows were sampled at each one of the outlets, while percolating water was obtained through four pressure vacuum samplers at a depth of 30 cm. Nine bores provided data about groundwater characteristics and chemistry. Three casing volumes were removed before sampling. Electrical conductivity, pH and temperature were directly measured in the field.

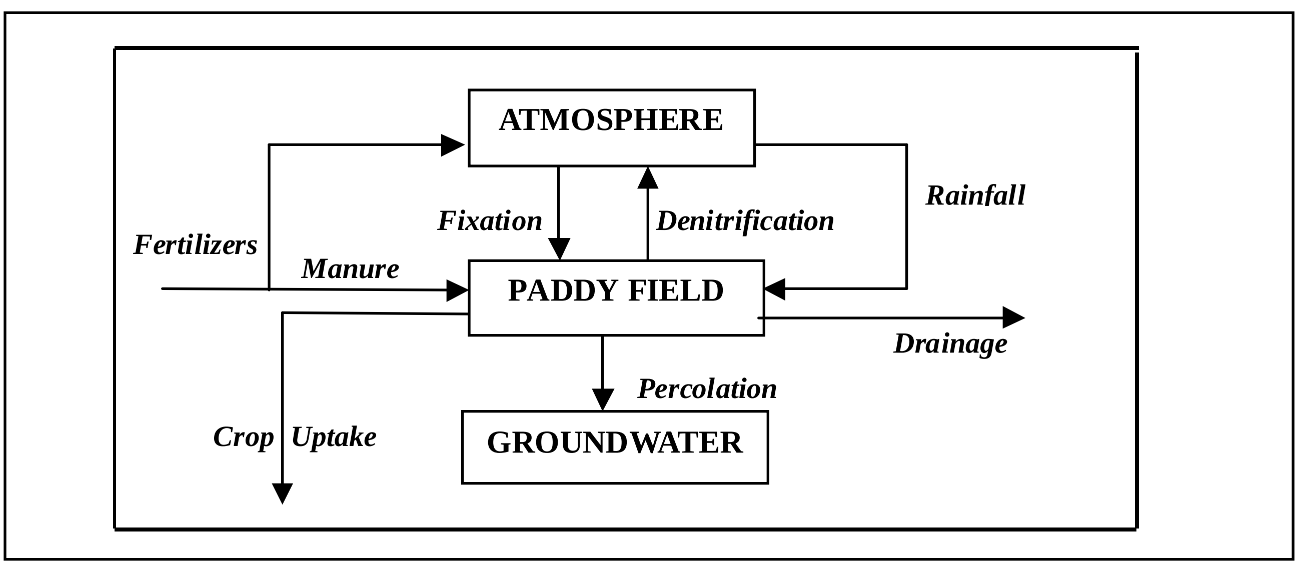

Figure 1. Model for the nitrogen mass balance.

Fertilizer and manure amounts were based on farmer's information, and their N content was established in the laboratory. Volatilization losses were experimentally estimated by reproducing as much as possible the real field conditions.

The amount of nitrogen contained in the harvested portion was calculated according to rice plant density, and individual N content was obtained by Takamura (2001) for the area of study.

Denitrification was considered as 15% of the inorganic nitrogen contributed by fertilizers and manure following the criterion of Meisinger and Randall (1991), who developed a set of estimates based on the assumption that oxygen is the major factor influencing losses.

Flooded rice fields provide ideal conditions for the growth of blue-green algae. In the absence of direct measurements, N_2 fixation rates by cyanobacteria were assumed to represent 12 kg N ha^{-1} over the growth period of one crop season, as reported in a study carried out in 190 rice fields (Ledgar and Giller, 1995, after personal communication with P.A Roger).

RESULTS

The nitrogen mass budget calculated for the rice-growing season in the paddy field is displayed in Figure 2. It was essentially balanced, with slightly larger N imports over exports. Bulk deposition of total nitrogen represented 106 kg ha^{-1}, 44 % of which was attributed to the fertilizers-manure input. Management operations started at mid April when an estimated 2.6 tons of livestock wastes were spread onto the field as soil amendments. Manure comprised a solid of cow dung previously stored in a farmyard, with high NH_4-N and organic nitrogen concentrations distributed in approximately similar proportions. Much of the organic nitrogen probably had the urea form $CO(NH_2)_2$ as the dominant component (Jarvis et al., 1995). Urea might have been hydrolyzed rapidly possibly within one day, resulting in an increase in soil ammonium absorbed later in the soil CEC (Pakrou and Dillon,

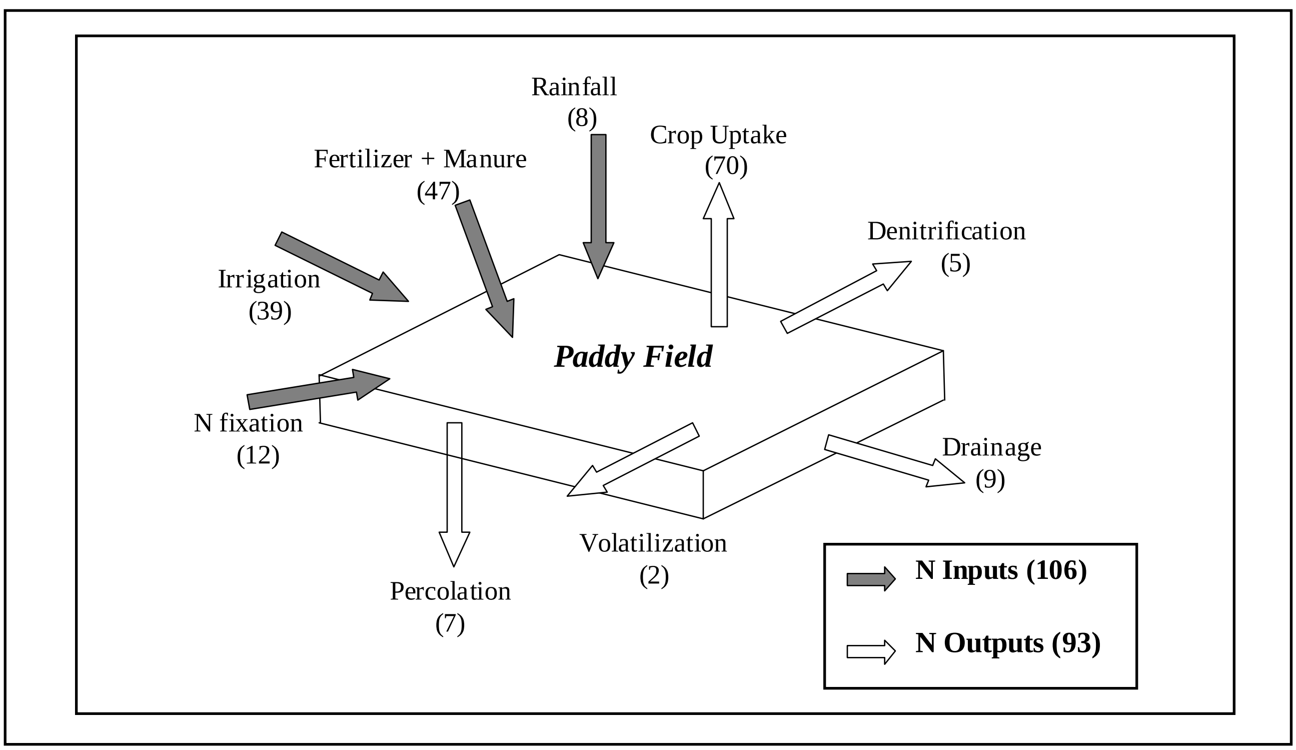

Figure 2. Nitrogen inputs and outputs in the paddy field for the period April–September 2001. Total nitrogen amount in parenthesis. Units in kg N ha^{-1}.

1995). Although the considerable variability in N content of manure makes interpretation of analytical results an ongoing problem, a mean load estimation of 14.7 kg ha^{-1} seems to be an accurate figure.

One week after the manure input, 260 kg of ammonium sulfate granules 8 percent in NH_4^+ were spilled over the field surface with minimal soil incorporation. Ammonium sulfate is a traditional fertilizer source for rice either for dry or wet soil conditions. Acidic soils prevalent in paddy fields tend to inhibit fertilizer volatilization, but nearly 5% of the applied fertilizer was experimentally determined to be lost to the atmosphere, probably as a result of the shallow placement of the granules. This value is consistent with estimated 2 to 10% reported by other authors (Schilke-Gartley and Sims, 1992; Schlesinger and Hartley, 1992; Jordan and Weller, 1996).

Nitrogen entering the field via irrigation totaled nearly 39 kg ha^{-1}, 36% of the inflows into the system. Its main component was nitrate (65%) associated with its high solubility, mobility in waters, and being repelled by clay minerals (Follet, 1995), with subordinated organic forms (28%). Nitrate-N across the period remained below 3 mg L^{-1}, with homogeneous values all over the watershed, indicating that these waters might be influenced at the regional scale by diffuse inputs rather than by an individual field.

Rainfall was a minor constituent accounting for less than 8% of the total N deposition. As an average, the quantity of nitrogen in precipitation for the studied period was estimated to be 0.9 g m^{-2} with a mean concentration of 2.2 mg L^{-1}. The majority of nitrogen deposition came as nitrate and organic forms were mainly supplied during May and June.

Despite their role, most studies ignored or assumed negligible atmospheric fixation as a nitrogen source. However, rice fields are privileged niches for the growth of cyanobacteria and their consequent fixation activities (Roger, 1995). A large biomass of algae was observed in the floodwater of the crop early in summer. Such blooms often contain 50% blue green algae bacteria (Whitton et al., 1989), and generally contain important amounts of nitrogen. Thus, a contribution of 12 kg N ha^{-1}, corresponding to 13% of the total load, was considered a consistent estimation for the cropping period.

Nitrogen leaving the field was calculated as 93 kg N ha^{-1}, with crop harvest representing 75% of the outflows. Uptake is mainly in the form of NH_4^+ and NO_3^-, and would have been continuous through all phases of plant development, with the major requirements during the early portion of the vegetative growth and later at the beginning of the panicle initiation.

Exports through drainage totaled 8.5 kg N ha^{-1}, 64% attributable to the organic component, the rest distributed between nitrate and ammonium. Concentrations reached maximums of 12 mg L^{-1} at the beginning of the season, stabilizing below 2 mg L^{-1} after around one week. Total nitrogen loads leaving the field through draining, plotted against runoff flow volume is seen in Figure 3. Even though N loads are dependent on draining flows, changes in discharge alone did not explain a large proportion of the variability in the concentration data, suggesting that nutrient outputs are affected by other factors as well. The low correlation between N deposition and surface discharge losses is attributed to terrestrial demand (Johnson, 1992; MacDonald et al., 1992). Nitrogen must be apportioned first to crops and microbial processes, with the remainder available for exports.

In spite of the low permeability of soils , 7 kg N ha^{-1} moved to the groundwater through infiltration, mainly during the first days of operations. However, contrary to runoff losses, nitrate comprised more than 70% of the dissolved N.

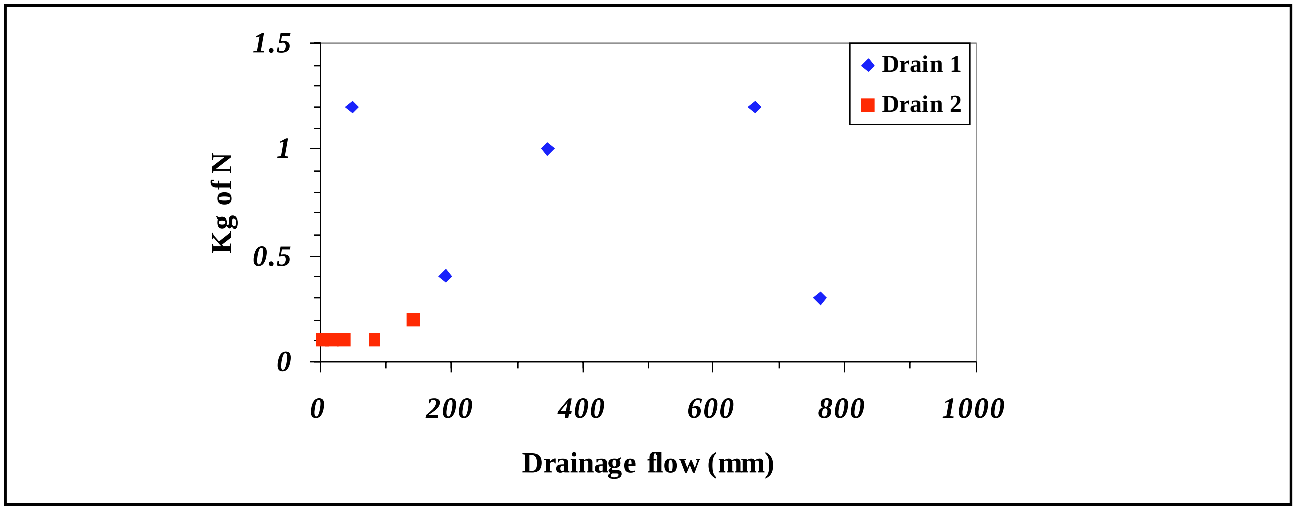

Figure 3. Total nitrogen leaving the field at different drainage rates

Assumed denitrification is in accordance with reports that indicate that even under the best management conditions, N losses of 10-20% are unavoidable. Biological activity is favored in fine-grained soils as in paddies, where colloidal particles concentrate both bacteria and organic materials and hence are micro sites of denitrification. The high amounts of nitrate input into the system would also confirm that significant rates of denitrification could have occurred. Temperature and pH would not have been principal constraints in the area, since growing plants have similar requirements. However, these two parameters may have had some role in limiting the maximum rates of denitrification losses (Aulakh et al., 1992).

DISCUSSION

Nitrogen Dynamics

Maximum nitrogen inflows and water quality deterioration occurred at the beginning of the study in direct connection with the field fertilization. Ammonium appeared in waters immediately after the fertilizer application, and the highest concentrations remained for about one to two weeks. After that period, nitrogen was reduced to the level of a non fertilized plot, in agreement with the situation in other paddy fields (Tabuchi, 1976). The substantial decrease in NH_4-N would have been related to its effective fixation into soil complexes and sorption by the soil cation exchange capacity. A great deal of nitrate entered the field via irrigation. Since its concentrations remained relatively low throughout the study period, it is possible to infer that peaks in N loads through this route were primarily a consequence of the large volume of water discharged. Thus, just for the first ten days of the crop season, irrigation N imports comprised more than 30% of the total input during the study, directly related to the maximum soil water requirement. Waters moved readily from the irrigation sources to the drainage outlets but, unlike inflows, the surface outflows N pool was dominated by organic forms rather than nitrate. Although organic N concentrations in the floodwater and drainage did not show significant variations, its proportion in the runoff showed a sharp increase from negligible amounts in April, to almost 95 % of the total nitrogen at the beginning of summer. Even when running waters may have incorporated some organic-N from suspended particulates and animal manure, it was not enough to totally explain such a drastic raise, suggesting therefore that there was some production in the paddy field itself via those processes of the nitrogen cycle such as immobilization, which involves the assimilation of inorganic N by soil microorganisms, and the transformation into organic compounds. Transformations would have been promoted by middle

June, when nitrogen is heavily emitted from the soils because of higher ground and water temperatures, enabling microorganisms in the submerged soil to become more active (Murakami, 1983).

Interestingly, chemical changes also occurred in percolating waters during summer associated with field draining operations. Ammonium-N increased several fold becoming almost 50 % of the nitrogen content in infiltration. As a matter of fact, this observation is contrary to what was expected, since ammonium-N is stable under reductive conditions, and when air began to enter the soil by the release of floodwater, the anaerobic environment which had predominated until that moment changed to aerobic, enhancing the transformation of NH_4^+ to NO_3^-. A possible explanation can be related to the fact that even when some nitrification was taking place, NH_4^+ would have basically originated in situ by mineralization processes occurring at the same time in the subsurface. This process involve enzymatic hydrolysis of organic forms to NH_4^+ carried out by soil organisms, and is usually coupled by the inverse immobilization, resulting in a flux of organic nitrogen to mineral forms and mineral forms back to organic nitrogen. In addition, as a result of the drastic flushing of the field, ammonium sorbed to the surfaces of clays and finer sediments could have been detached from the parent soils with the subsequent enrichment of water. (Follet, 1995).

Throughout the intermittent irrigation period until the end of the season N fluxes were essentially governed by surface flows, which did not show much variation with respect to the preceding periods. Nitrogen concentrations in drainage waters dropped substantially due to the increase in absorption associated with the re-flooding conditions as reported by Murakami (1983).

Denitrification losses are supposed to have occurred soon after the field fertilization. Soil submergence and waterlogged conditions caused by an almost permanently high water table limited the oxygen availability, forcing the nitrifier bacteria to meet their metabolic requirements by reducing nitrogen oxides. Nitrate would have become highly unstable under these conditions, and large denitrification events might have occurred when the surface was re-flooded, and then continued during flooding in the soil devoid of oxygen (Buresh and DeDatta, 1991). Alternating oxidizing and reducing conditions by drainage and flooding periods should have resulted in greater total N loss from the soil than would have been found under continuously reduced conditions, with high N_2O production during these transitional stages (Wijler and Delwiche, 1954).

The balanced loss is defined as the difference between the incoming (gains) and the outgoing (loss) nitrogen, and the relation is shown in Figure 4. The difference between N imports and exports fluctuated over the range of -1 kg to +1 kg, with most of the points clustered between ± 0.5 kg. In accordance with the relation measured in several paddy fields in Japan for Tabuchi and Ogawa (1995), data are displayed following a straight distribution with a slope of 45 degrees and a tendency of output values to increase directly with an increases in input. An outflow N loading that is lower than inflows means the field was removing large amounts of nutrients from waters flowing through it. In view of this N retention, the studied paddy field can be considered an absorber type, with the desirable function of pollutant removal. From the results of the mass balance, the area showed good performance in the purification function for nitrogen, with an important storage capacity and pollutant sink behavior. The effectiveness of the rice field in improving input water quality can be related to the nutrient removal efficiency, representing the amount of nutrient stored or eliminated from the system without causing environmental degradation, which averaged 78 %, a value which is higher than the observed range of removal efficiency reported for similar environments (Moustafa, 1996). Nutrient removal effectiveness was based on differences between inflow and outflow

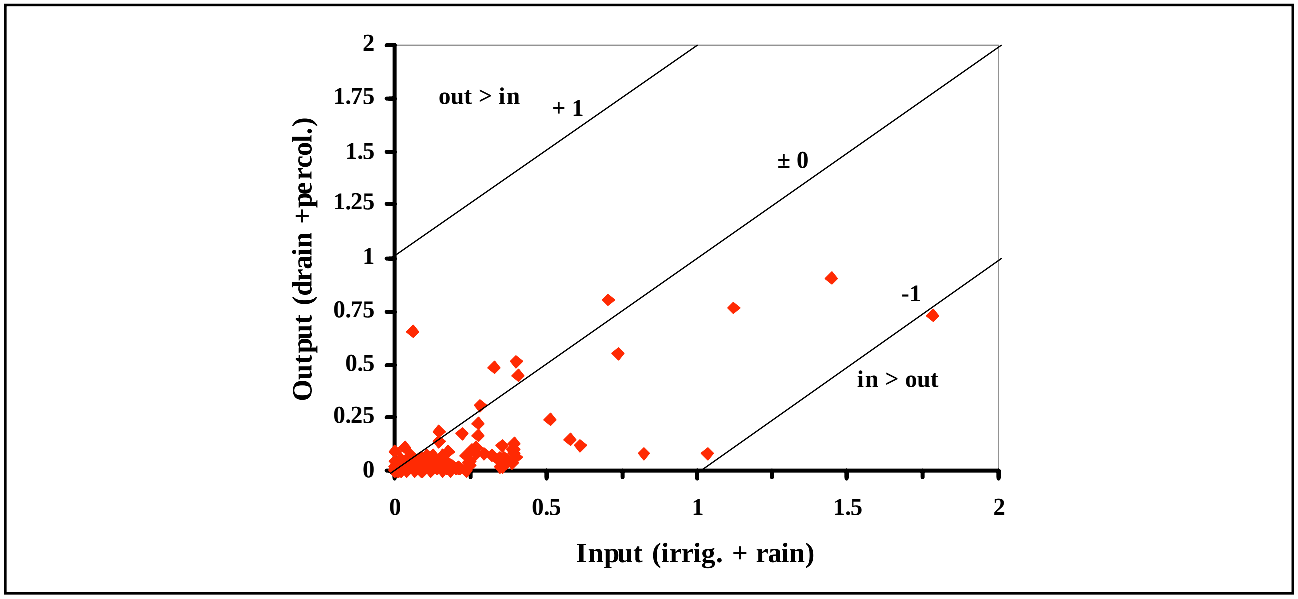

Figure 4. Daily relation between nitrogen inflows and outflows. Unit: kg of nitrogen.

concentrations. However, the study was limited to one crop season, raising the issue that the area removal efficiency may decline after some period of time, losing its ability to retain nitrogen. For this reason, the cumulative mass of N retained and the cumulative mass loading (Figure 5) were correlated to see if there was any removal decrease during the studied period. A positive correlation indicated no decline in N retention. If the paddy field efficiency had declined over the time, the straight line depicted in Figure 5 would have been represented by a power function that leveled off after the area had reached its maximum storage capacity. The storage compartment responsible for causing a constant trend would be the soil, and a great part of this stored nitrogen was finally removed by crop harvest.

The budget also raises the question of what stage the paddy field is in terms of response to chronic levels of nitrogen deposition. Clearly, nitrogen export is much less than import, suggesting that N saturation (stage 2, as defined by Aber et al., 1989) has not been reached yet, but since some export

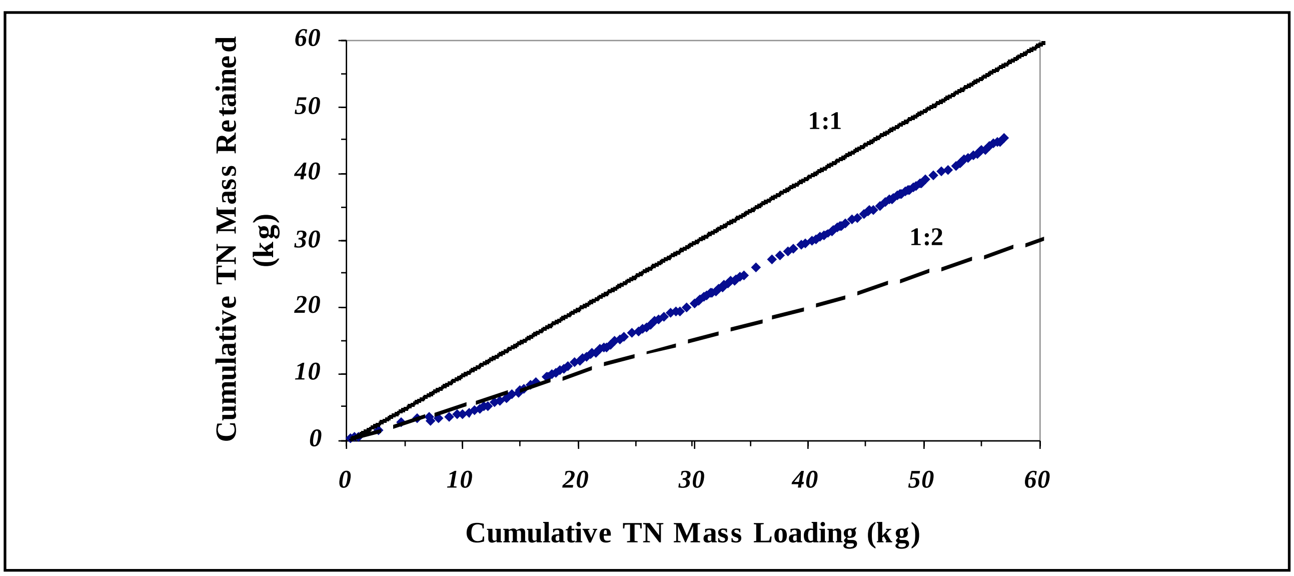

Figure 5. Cumulative N mass retained (kg) versus cumulative mass loading (kg) in the paddy field during the 2001 rice growing season.

is occurring, the area would not be at stage 0 either (Aber et al., 1989). Thus, the paddy field can be related to an intermediate stage, indicating that the initial effects of nitrogen deposition have been reached (stage 1).

Comparison with other Rice Fields

The total nitrogen load estimated for the studied field (106 kg ha^{-1}) is comparable with the results obtained by Takamura et al. (1977) for paddy fields in the neighboring Kasumigaura basin, where inputs range between 87 and 163 kg ha^{-1} under fertilized conditions. Inorganic fertilizers play a dominant role in the nutrient budget of rice fields, generally being the most important load to the systems. The studied area is not an exception and therefore was highly affected by fertilization, although the 47 kg ha^{-1} applied was below the usual amounts. In Japan, fertilizers can represent more than 75 % of the total supplied nitrogen, averaging 101 kg ha^{-1} yr (Japan Environmental Agency, 1993), while in nearby rice growing countries reports indicate amounts as high as 217 kg ha^{-1} (Cho et al., 2000).

Irrigation loads reported for some fields in Ibaraki Prefecture fluctuate between 7 and 15 kg ha^{-1}, with total nitrogen concentrations up to 3.2 mg L^{-1} (Japan Environmental Agency, 1993). In the studied area concentrations also averaged approximately 3 mg L^{-1}, but final inputs were well above the mean, explained by the large amount of water supplied, which were aimed at compensating for some shortage in fertilization and the summer drought.

In most paddy fields, the main nitrogen output is crop harvest. It accounted for 75 % of the losses in the investigated field, highly correlated to the 78 % N outflow from fertilized poorly drained paddy fields in a nearby area (Takamura et al., 1977).

Finally, leaching in the area of the study was basically limited to the initial stages, but it can be of significance in well-drained paddy fields, where important portions of the applied nutrients may move down rapidly to the groundwater. Nitrogen leaching is quite variable according to the individual area, and the losses estimated from the studied plot (7 kg ha^{-1}) can be judged to be acceptable. In Aichi Prefecture, Japan, some measured percolation losses totaled less than 2 kg ha^{-1}, while loads of more than 55 kg ha^{-1} are mentioned for some places in Nagano Prefecture (Japan Environmental Agency, 1993). Cho et al. (2000) estimated the loss ratio of N by infiltration at a paddy field in Korea as 9.4 % of the amount applied, and Ha et al. (2001) found that 11.3 – 13.3 kg ha^{-1} would percolate to the aquifer in another rice field in Vietnam.

CONCLUSIONS

The mass balance approach was shown to be a good indicator of the sustainability of a paddy field area, and provided valuable information to evaluate the nitrogen utilization within the system and the potential effects on the environment. The area receives moderate N imports in comparison with other sites across Japan. It falls in an intermediate range in which leaching and runoff losses are relatively low, although they should not be overlooked in the long term as the soils nutrient storage capacity is assumed to be limited. Nitrogen inflows were higher than outflows, pointing to a pollutant purification performance of the field. Removal rates were positive during all the study period, with values higher than those reported for comparable environments. Results indicated that the nitrogen retention was linearly proportional to the loading amount. The capacity to keep the nutrient assimilation ability will depend on the balance between imports and uptake rates, and can remain sustainable through proper agricultural management practices. Some measures to decrease nitrogen losses would include planting crops with high nitrogen requirements (although this action is not always profitable), deep placement of fertilizer granules, using a reliable irrigation scheme to prevent excessive water supplies, proper soil compaction to prevent leaching losses, and maintaining healthy rice root conditions avoiding toxicities and weed competition, which are yield limiting.

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