Journal of Agriculture and Ecology Research International
8(4): 1-17, 2016; Article no.JAERI.20733
ISSN: 2394-1073

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Nitrate Movement, Transformation, and Accumulation Following Diverse Nitrogenous Fertilizer Regimes in Arable Soils

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Authors' contributions

This was a collaboration work of all authors. The main author BCL designed, performed, analyzed, interpreted, and prepared the first draft of the manuscript. Author MM provided technical support and financial assistance to carry out the research. Author MT provided technical support and revised the manuscript. Authors MF and MI supervised the research. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JAERI/2016/20733
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Complete Peer review History: http://sciencedomain.org/review-history/15217

Original Research Article

Received 6th August 2015
Accepted 21st June 2016
Published 30th June 2016

ABSTRACT

Arable farming with intensive agricultural practices causes severe damage to groundwater quality. Hence study on mechanisms of diverse nitrogenous fertilizer regimes were focused relate to nitrate movement, transformation, and accumulation in arable soils.

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Knowledge of effects of N-leakage from soils of different chemical and physical compositions fertilized by various organic and inorganic N-fertilizers is of upmost importance. Few studies have compared the fate of N in relation to the properties of soils and nitrifying denitrifying potential, when it is applied in the form of municipal solid waste (MSW), commercial organic fertilizer (COF), or commercial inorganic fertilizer (CIF). Tsukuba Kuroboku, Kagawa loamy clay, and Sizuoka sandy soil types were selected as representatives of Andisol, Andosol, and Sandy soils because most of the soils in Japan are based on volcanic ash.

It is concluded that the N transformation and nitrate leaching strongly influenced by the soil's chemical characteristics and secondarily by the physical characteristics in agricultural lands. Denitrification was increased markedly by readily available C. NO_3-N transport was influenced by fertilizer type and soil properties. Nitrogen transformation rates were higher in the Tsukuba Kuroboku soil than in the Sizuoka sandy soil and Kagawa loamy clay soil, however the nitrogen transport rate was lower. The differences were more pronounced between the Kagawa and Tsukuba soils. NO_3-N movement in Andisol columns treated with MSW and COF showed similar patterns however NO_3-N movement in sandy soil columns was more rapid than in the other soil types. Soils treated with COF showed slightly higher crop yield (10%) than soils treated with MSW compost fertilizer.

Keywords: N-transformation; fertilizer regime; nitrification; denitrification; Kuroboku; Andosol.

1. INTRODUCTION

Intensive arable farming worldwide causes several problems, especially in the groundwater. Nitrogen which is a nutrient for plants, microorganisms and can cause water pollution in certain conditions originating from agriculture, and animal and human waste disposal [1]. Although there are numerous reports regarding elevated nitrate levels in the groundwater and its negative effect on human health especially for infants, no mechanism on intensive use of nitrogen fertilizers. Some researchers have suggested arable farming as a solution to reduce the input of inorganic fertilizers into the agro-ecosystem [2, 3].

One suggested change in farming practices is the replacement of inorganic fertilizers with slow-release organic manure. Integrated farming has stimulated nitrification [3], presumably by increased mineralization of ammonium, which is not immediately consumed by the crops or immobilized by the heterotrophic microflora in the soil. Organic wastes, especially animal manure, have long been used as a source of nutrients for crops. Animal manure, sewage sludge, and other organic wastes are often applied to agricultural lands because this provides a convenient method of waste reuse [4,5,6]. In addition, their use can be financially advantageous to the farmer because less inorganic fertilizer may be required by subsequent crops.

Compost made out of Municipal solid waste (MSW) is becoming increasingly recognized as a viable and economical method for waste management [7,8]. Agricultural use is identified as an important market for compost products [9]. MSW is organic manure that has become popular as a soil conditioner that can significantly improve soil properties and increase agricultural production [10]. Denitrification is the process by which the N cycle can be closed in soils where anoxic conditions are prevalent when the redox potential is low. It has been showed that denitrification effectively occurs in the presence of sufficient organic matter to provide an energy source for microorganisms and reduces nitrate levels in soil [11]. The optimum and economic fertilizer application rates are clearly relevant to soil properties and N transformation in soil.

Accurate prediction of N transformation is a prerequisite together with a proper calculation of the N need for plant growth for optimizing N use without leaching into the groundwater in many cropping systems [12,13]. To minimize environmental hazards, current guidelines suggest slow release of organic N application rates lower than the expected N uptake of the crop. Therefore, it is of utmost importance to understand N turnover in different types of fertilizers, such as MSW compost and commercial 100% organic fertilizers (COF), in agricultural soils. Our previous study indicated that organic fertilizers helped to prevent rapid leaching of nitrate compared with inorganic fertilizers. Hence, the objective of this study was to increase knowledge and understanding of the behavior of MSW compost fertilizer and readily available commercial fertilizers, such as COF and commercial 100% inorganic fertilizer (CIF), in several types of Japanese agricultural soils.

Recent research regarding nitrogen transformations in soils and groundwater has focused on denitrification as a remedial process for contamination by nitrogen [14]. Study of N-leakage from soils with different chemical and physical compositions altered by various organic and inorganic N-fertilizers is of upmost importance. Although there have been numerous studies [5,15,16,17,18,19,20,21] that examined the effect of organic and inorganic fertilizer application on subsequent nitrogen transformation and transport in arable soils, no comparative study on the fate of N when applied as MSW, COF, or CIF in relation to the properties of soils has been conducted. For proper fertilizer management, the application of N over several soil layers and leached into groundwater was studied and discussed in relation to values of the N-transformation processes, such as nitrification and denitrification. Furthermore, the nitrifying and denitrifying potential and denitrifying population were measured and compared among soil types.

2. MATERIALS AND METHODS

2.1 History of Soils

Three soils were selected from three agricultural fields, which represented the basic agricultural soil types in Japan. Table 1 describes the chemical and physical characteristics of said soils. Top soil (i.e., 0–20 cm depth) was collected in November 1998 from the three different agricultural fields in the Ibaraki, Kagawa, and Sizuoka prefectures.

The soil types were referred in this study as Andisol, Andosol, and Sandy soil, which represented the Ibaraki, Kagawa, and Sizuoka Prefectures in Japan, respectively. In Japanese *an* meaning dark and *do* soil, a synonym of '*kuroboku'* are soils basically found in glass-rich volcanic ejecta formed in parent material of *volcanic tephra* according to WRB soil classification and Soil Taxonomy. Generally the arable soils of Tsukuba kurobokudo and Kagawa andosol categorized under 'Andosol' by WRB. Tsukuba Kurobokudo and Kagawa andosols have been used for agricultural crops for more than 5 years. All the soils were sieved to remove gravel and debris >2 mm before use in this study.

2.2 Fertilizer Regimes

Two types of organic fertilizer and an inorganic fertilizer were selected for this study. MSW compost was supplied by the Nesco factory (Fukuoka, Japan), which produced MSW fertilizer at a large scale for agricultural use. COF and CIF were purchased from a commercial fertilizer source. These two types were selected, because they are similar to fertilizers that are used in general farming. Some general properties of fertilizers are shown in Table 2.

2.3 Experimental Setup: Soil and Column Installation

Moist soil was packed into 12 polyvinyl chloride (PVC) columns (70 cm high x 20 cm diameter) to a depth of 65 cm. The bottom of each column was filled with 5 cm of gravel to prevent the soil leaching from the columns. As shown in Table 1, fertilizer was applied to the soil at a rate of 30 kg N ha^{-1}. Columns A received MSW compost

Table 1. Chemical and physical properties of soils

Parameter	Soil type		
	Tsukuba soil (Kuroboku soil, Andisol)	Kagawa soil (Clay soil, Andosol)	Sizuoka soil (Sandy soil)
Organic C (g/Kg)	4.27	3.89	0.059
Organic N (g/Kg)	0.42	0.424	0.0036
C/N ratio	10.17	9.17	16.09
pH (water)	6.40	5.18	7.50
Clay (%)	50.2	62.4	0
Silt (%)	33.8	13.3	8.2
Sand (%)	16	24.3	91.8

Table 2. Characteristics of nitrogenous fertilizers and application rates

Fertilizer type	T-N (%)	T-P (%)	T-K (%)	Application rate (30 kgN/ha, g/column)
Municipal Solid Waste compost (MSW)	2.17	3.96	0.39	43.33
Commercial Organic fertilizers (COF)	4	4	4	23.55
Commercial Organic fertilizers (CIF)	6	40	6	15.70

fertilizer, column B received COF, column C received CIF, and column D received no nitrogen fertilizers and served as a control. The Looped Hollow Fiber (LHF) technique [22] was applied to extract the soil solution nondestructively from the root zone. The LHF-sampler was composed of a thin, flexible, polyvinyl alcohol hollow fiber with an external diameter of 900 µm, a silicon tube, and a disposable syringe, and was used to collect soil solutions via suction.

Six samplers were installed in each column at 10-cm intervals and 8 tensiometers were installed at depths of 30 and 50 cm from the top in some columns to monitor the matric potentials of soil and water contents. A schematic diagram of the installation of LHF-sampler and tensiometers is shown in Fig. 1.

2.4 Monitoring Soil-Water Movement by Tensiometers

Tensiometers were used to obtain measurements of soil-water Matric potential between 0 and -1,000 cm. Tensiometers worked in the soil water potential range with the highest unsaturated hydraulic conductivities and, thus, the largest potential for rapid water movement. Multiple tensiometers were used in a profile to calculate hydraulic gradients to determine the direction of water movement and to estimate water flux using unsaturated hydraulic conductivity [22]. Eight tensiometers that were used to monitor water movement through soil columns were attached to a data logger, and soil-water Matric potentials were recorded at 30-min intervals throughout the study. Data logger channel numbers 1 and 2 were used for the sand columns, channel numbers 3, 4, 5, and 6 for Tsukuba soils, and channel numbers 7 and 8 for the Kagawa soil column. The odd channel numbers 1, 3, 5, and 7 were installed 15 mm from the surface of the column and 2, 4, 6, and 8 were installed 55 cm below the surface. Since the matric potential was equivalent to water content of the soils the potential values represented water movement during plant growth.

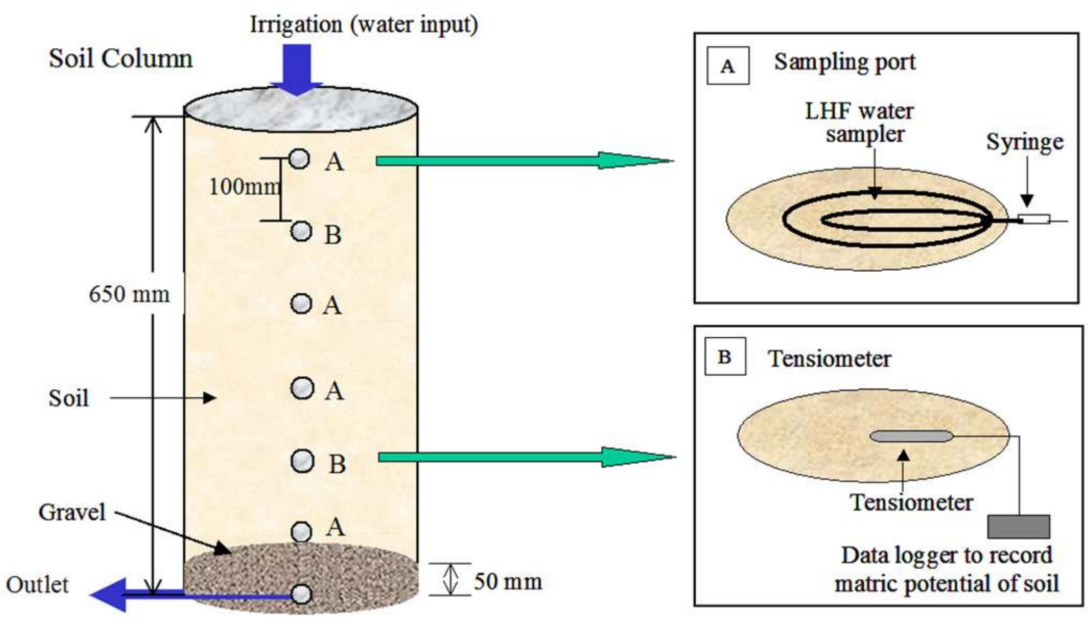

Fig. 1. Schematic diagram of set up of LHF-samplers and tensiometers

2.5 Fertilizer, Plant, and Water Management

Water was applied to columns until it came out from the lower most outlets. Each fertilizer was applied at the rate of 300 kg N ha^{-1}. Italian rye grass (*Lolium multiflorum*) seeds were spread on the top of the soil and covered with a thin layer of soil. After 10 days, 10 plants per column were retained and the others were removed. Water was applied to columns at a rate of 200 mm per day. The experiment was carried out in a greenhouse (controlled temperature of 25℃) at the Osaka University, Department of Environmental Engineering for approximately 170 days.

2.6 Soil Water Sampling and Analysis

Soil water was collected at 10-cm intervals along the columns once a week. Ten or 15 ml of soil solution was collected at each interval by a LHF-sampler [22], which was sufficient for the chemical analysis of this experiment. Water analysis was conducted for NH_4-N, NO_3-N, and NO_2-N by using ion chromatography (Dionex 2010i, column ion pac As4A-Sc, guard column ion pac Ag4A-SC, carrier solution 17 mM $NaHCO_3$, 18 mM Na_2CO_3: flow rate 1.0 ml min^{-1}).

2.7 Analysis of Plant Material

Fifty days past the initial seeding, aerial parts of the plants were harvested by cutting 2 cm above the ground and were then weighed. After washing and drying at 60°C for 72 h, water content was measured and plant tissue was pulverized using a vibratory disk (tungsten carbide) mill type. T-N of plant tissues was analyzed using a modified Kjeldahl method and was measured using a T-N analyzer.

2.8 Soil Sampling and Analysis

Soil samples were collected after the harvesting the Italian rye grass. The column moist-soil samples representing every 10-cm interval up to 70-cm depth were collected, ground sufficiently to pass through a 2-mm sieve, packed in sealable polyethylene bags, and then stored at 4°C until analysis. Parts of each sample were allowed to dry at ambient temperature, crushed, and analyzed for total N and C using a Sumigraph NC-95A NC- Analyzer. Moisture content of each sample was measured, and pH and electrical conductivity (EC) were determined for the water (1:5 soil:water) using pH and EC meters. The amounts of extractable inorganic nitrogen NO_3-N and NH_4-N in the soil samples were determined with a 10% (w/w) KCl solution and the analysis was performed with a Technicon 800 (Bran+LUEBBE) analyzer. In addition, a series of laboratory experiments were carried out to examine the nitrification and denitrification capacities of soils, as well as the subsequent effects on the microbial population, which promotes nitrification and denitrification.

2.9 Determination of Nitrification and Denitrification Capacities

The nitrification capacity of each soil type was compared among different fertilizer treatments, which received organic or inorganic N, by measuring NO_2-N and NO_3-N accumulated during the incubation period [23]. Twenty g of fresh soil, 0.15 g of $CaCO_3$, and 50 ml of nutrient culture medium were placed in a 250 ml flask. To prepare the one-liter of nutrient culture medium, 330 g of $(NH_4)_2SO_4$, 140 mg of K_2HPO_4, and 27 mg of KH_2PO_4 were used. The pH of the culture medium was adjusted to 7.5. Samples were shaken at 150 rpm and 25°C. One mm from each sample was taken after 1 h and 8 h incubations and analyzed for NO_2-N and NO_3-N using ion chromatography. Preliminary experiments demonstrated the linear production of NO_2-N and NO_3-N during 7 h of incubation. Nitrification capacity of the soil at different depths was calculated using the same method. Three replicates were conducted per soil sample and the results were averaged.

The denitrification potential of each soil sample was measured by an acetylene inhibition method [24]. Twenty g of fresh soil were placed in 50 ml of the following nutrient mediums (g/l): KNO_3, 1.01; K_2HPO_4, 0.14; KH_2PO_4, 0.027; Glucose.H_2O, 1.98; chloramphenicol, 0.1 in 100 ml glass bottles. The flasks were flushed with Ar gas. After an additional 10% of C_2H_2 gas to inhibit nitrous oxide reduction, the flasks were placed in a horizontal position in a rotary shaker (180 revolution per minute at 25°C). The gas fraction of the samples was taken through the septum using an air-tight micro-syringe and analyzed for N_2O gas using gas chromatography (Shimadzu 14B: detector ECD; temperature, column 80, ECD 340: column material: Porapack Q 80-100 mesh 3 m [precut] and Porapak 80-100 mesh 1 m [main column]). Denitrification activity was calculated from the slope of the linear progression curve of nitrous oxide concentrations during 8 h of incubation.

2.10 Determination of Denitrifiers

The denitrifying bacterial population was estimated by the most probable number (MPN) method by using the nutrient medium (8 g of nutrient broth and 1 g of KNO_3 per liter) [24]. Samples were prepared by mixing fresh soil (equivalent to 10 g of dry weight) with 90 ml phosphate buffered saline (PBS). For MPN, test samples were diluted using the same buffer PBS. One ml of each sample was added to the previously prepared nutrient medium of 9 ml in a test tube, including a Durham tube. Three replicates were prepared for each diluted sample. Test tubes were incubated at 28°C and the estimation was made when gas bubble production in the inverted Durham tubes lasted for 14 days.

3. RESULTS

Chemical and physical properties of the soils are shown in the Table 1. Tsukuba Kuraboku, Kagawa loamy, and Sizuoka sandy soils are referred to hereafter as Tsukuba, Kagawa, and Sizuoka soils, respectively. Sizuoka soils showed the smallest C and N values. The percentage of clay was higher in Kagawa soil than the other soils. Table 2 shows the characteristics of nitrogenous fertilizers.

3.1 Nitrate Transport

The NO_3-N concentration of soil water during the study period is shown in Figure 2. Before seeding the Italian rye grass, all soil columns were irrigated with water to saturate the soils. Hence, at the beginning of the study, Kagawa and Tsukuba soils showed considerable NO_3-N concentrations. Three soils showed similar patterns of NO_3-N depletion during the study period. At 77 days, the NO_3-N concentration of Tsukuba soils and Sizuoka soils was zero, whereas that of the Kagawa soils did not differ much.

The highest NO_3-N concentrations were observed after 37 days. It was evidenced by the accumulation of NO_3-N at the bottom of the columns towards the end of the experiment. MSW compost treatment and COF treated soil columns showed a similar trend of depletion of NO_3-N in every soil type.

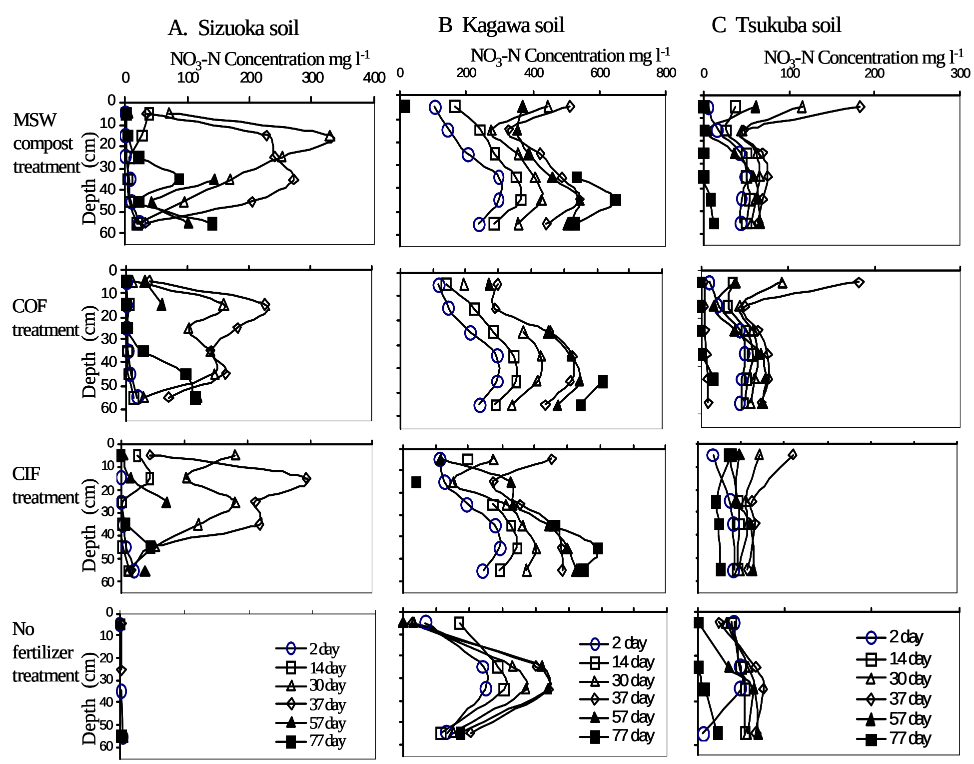

Fig. 2. Nitrate leaching through soil columns which were treated with the different fertilizers

After the fertilizer application, the production of nitrate increased gradually. NO_3-N concentration in Kagawa soils showed high values even after 2 days. This was probably because of the accumulated NO_3-N in the Kagawa soils and watering to adjust the moisture content prior to use in this study. Matric potential during the experimental period is shown in Fig 3. The negative matric potential implies dryness of the soil. Kagawa soils were drier than the other two soils after approximately 45 days. However, plants had grown well in this period (Fig. 4) in the Kagawa and Tsukuba soils. Sizuoka soil water conditions had remained unchanged when compared to the Kagawa and Tsukuba soils.

In Tsukuba soils, inorganic fertilizer augmented columns showed the highest yield, whereas the organic fertilizer augmented soils showed almost similar yields. Plant N uptake of Italian rye grass in fertilizer treated Sizuoka soils showed similar T-N values (9.5 g m^{-2}), whereas there was no plant growth in unfertilized soils (Fig. 4; Sizuoka soils, column D). However, the moisture content of plants in every soil showed similar values of about 89%. Italian rye grass in the Tsukuba and Kagawa pots grew faster and the length of the leaves were longer than 1 m (data not shown).

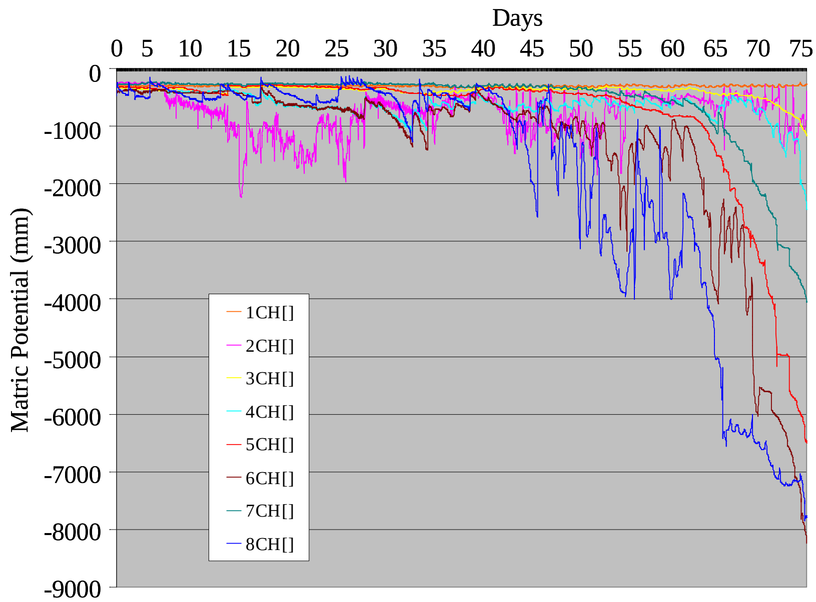

Fig. 3. Matric Potential of Soils. CH 1 and 2: Sizuoka soilds, CH 3, 4, 5, and 6: Tsukuba soils, and CH 7 and 8: Kagawa soils. Odd CH Numbers for 15 cm Depth from the Surface; Even CH Numbers for 55 cm Depth from the Surface; CH = Channel

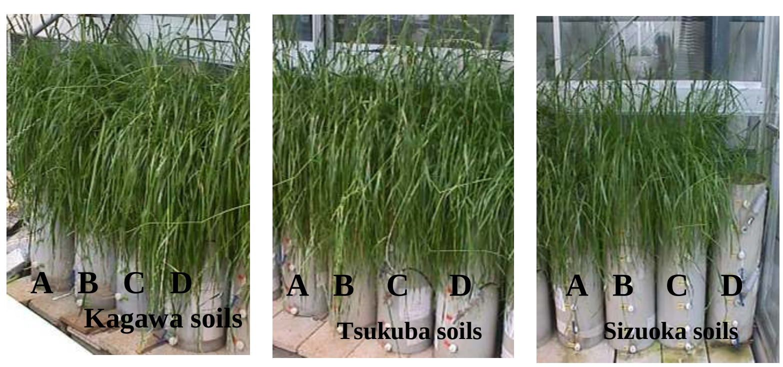

Fig. 4. Plant Growth after 45 Days. Column A: MSW Compost Augmented Soil, Column B: COF Augmented Soil, Column C: CIF Augmented Soil, and Column D: No Fertilizer (Controls)

3.2 Nitrogen Accumulation in Soils

All soil columns, except the unfertilized ones, were treated with 0.9 g N. After harvesting the Italian rye grass, all soils were analyzed for remaining N compounds. Fig. 5 shows variation of T-N accumulation at different depths in each soil with diverse fertilizer regimes. Tsukuba soils showed the highest T-N accumulation of about 0.4 mg kg^{-1}. In contrast, the significant increase in total N in the upper soil layers reflected the N gained after the fertilizer treatments. Below that layer the total N decreased or remained constant throughout the soil columns. MSW compost treated soils showed the highest T-N accumulation among all the soil columns, whereas T-N remaining unchanged in the control soil columns.

Contents of NH_4-N remained less than 1 µg g^{-1} of dry soil at the upper layer of Sizuoka and Tsukuba soils, whereas that of Kagawa soils was around 4µg g^{-1} of dry soil. However, the upper layer of CIF treated Kagawa soils accumulated 16µg g^{-1} of NH_4-N (Fig. 6). Treatment differences in NH_4-N along the columns were not significantly different. However, all the columns showed a similar pattern of NH_4-N distribution along the soil profiles, which in turn indicated the considerable accumulation of N in the bottom layer of the soil columns. This accumulation was far smaller than that of the top layers.

Table 3. N uptake by Italian rye grass in different soils with different fertilizer application

Soil type	Fertilizer treatment	Total plant biomass (g)		Moisture content (%)	T-N (%)	T-N uptake by plant (g/m^2)
		Fresh	Dry			
Tsukuba Kuroboku Soil	MSW compost	214.4	25.18	88.3	2.80	22.5
	COF	237.0	27.30	88.5	2.61	22.7
	CIF	270.6	29.76	89.0	2.70	25.6
	No fertilizer	152.1	20.45	86.6	2.61	17.3
Kagawa Loamy Soil	MSW compost	274.5	27.56	90.0	3.78	33.2
	COF	203.9	16.35	92.0	4.04	21.0
	CIF	295.0	24.06	91.9	4.42	33.9
	No fertilizer	310.8	27.96	91.0	3.94	35.1
Sizuoka Sandy Soil	MSW compost	82.50	7.28	91.2	4.03	9.40
	COF	119.7	10.32	91.4	2.94	9.70
	CIF	125.5	12.87	89.7	2.36	9.30
	No fertilizer	7.1	0.83	88.3	1.39	0.40

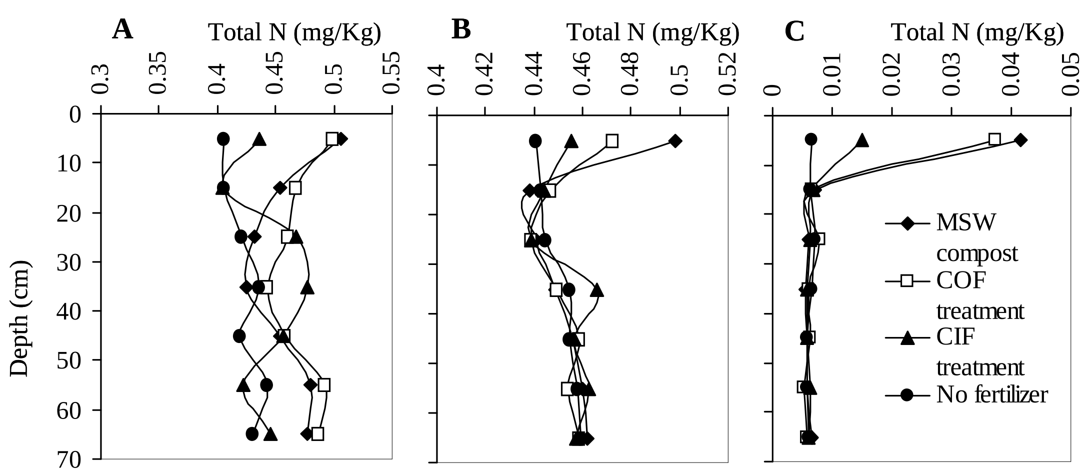

Fig. 5. Variation of T-N accumulation at different depths in each soil with diverse fertilizer regimes. A: Kagawa soil, B: Tsukuba soil, and C: Sizuoka soil
(Note: mg/Kg = mg N kg^{-1} dry soil)

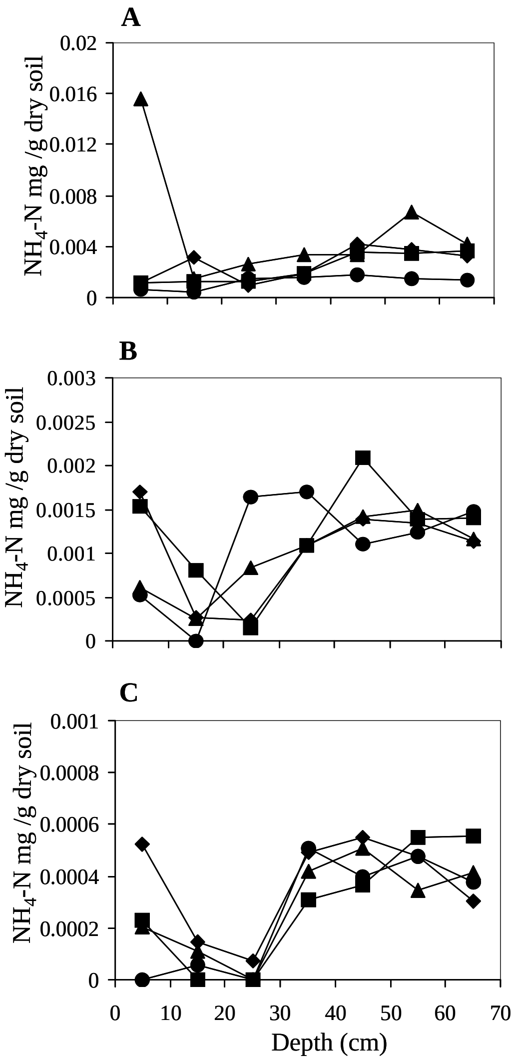

Fig. 6. NH_4-N mg/g (dry soil) along Soil Columns after the Harvest of Italian Rye Grass (A: Kagawa soil, B: Tsukuba soil, and C: Sizuoka soil)

Accumulation of NO_3-N in the treated columns was greater than those untreated with N (Fig. 7). In Sizuoka soils, MSW treated columns showed approximately only 5 µg g^{-1} NO_3-N accumulation, whereas others showed almost zero accumulation. However, for Tsukuba soils, CIF treated soils showed the highest accumulation is <10 µg g^{-1} of dry soil in the top-soil layer. There were no significant differences among other soils; however, the accumulation was approximately 2 µg g^{-1} NO_3-N. In Tsukuba, MSW compost and COF treated soils showed a similar pattern of NO_3-N accumulation. For Kagawa soils, the treated soil columns exceeded those of the control soil column along the profile. In contrast with the other two soil types, fertilizer treated Kagawa soil top layers showed a smaller quantity of NO_3-N than bottom layers. The values were approximately 20 µg g^{-1} for top layers, whereas bottom layers contained >150 µg g^{-1} of NO_3-N. The control soil columns for Kagawa soils NO_3-N remained unchanged along the soil profiles. Accumulation of NO_3-N was almost zero for all soils except Kagawa soils. Kagawa soils exhibited < 0.2 µg g^{-1} of NO_3-N for all four columns.

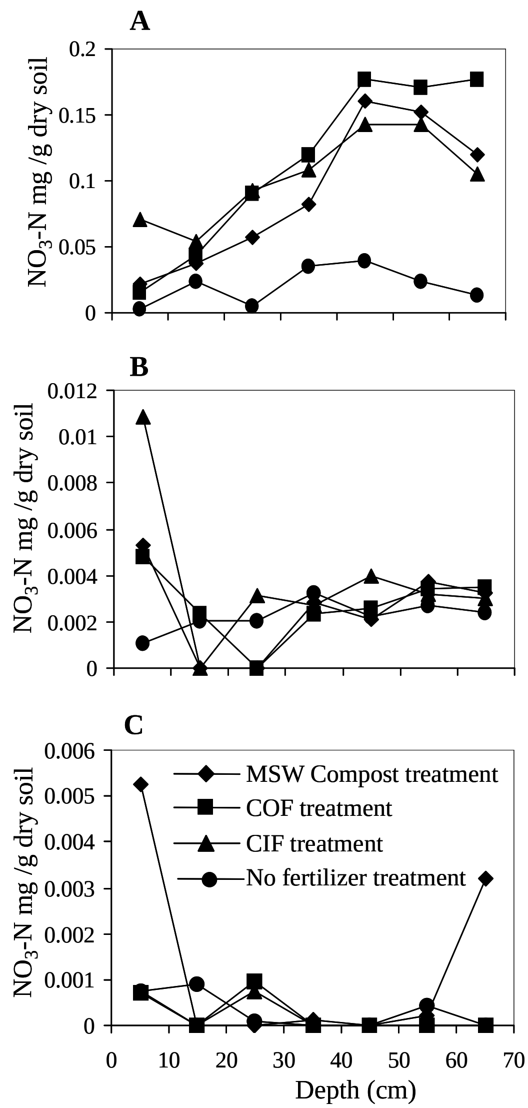

Fig. 7. NO_3-N mg/g (dry soil) along Soil Column after the Harvest of Italian Rye Grass (A: Kagawa soil, B: Tsukuba soil, and C: Sizuoka soil)

3.3 N Transformation Potentials

Nitrification and denitrification potentials of Kagawa, Tsukuba, and Sizuoka soils are shown in Figs. 8 and 9, respectively. Several characteristic patterns emerged when microbial populations of fertilizer treated soils were compared with those of untreated soil columns.

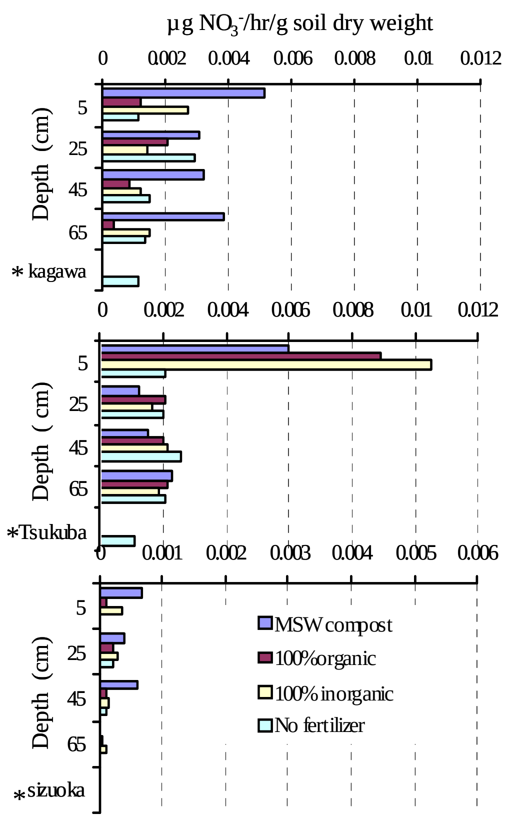

Fig. 8. Nitrification Potentials of Three Soils after the Harvest of Italian Rye Grass
*(*indicate nitrification potential in soils prior to the fertilizer application)*

Sizuoka soils exhibited lower values than the other two types of soil. However, in contrast, Kagawa and Tsukuba soils showed very similar nitrification potential. Kagawa soils showed a higher denitrification and nitrification potential than the other two soil types. Tsukuba soils treated with CIF showed higher denitrification potential than the other three treatments. However, Tsukuba soils treated with COF exhibited a lower nitrification potential.

MSW compost and COF fertilizer augmented soils had higher values than the CIF augmented soils. However, in CIF augmented soils, denitrification potential was higher than unfertilized soils. Denitrification potential increased along the soil columns for all soil types. Tsukuba soils had 10 times higher than Sizuoka soils, whereas the denitrification potential of Kagawa soils was more than 20 times higher. Denitrification potential remained unchanged in untreated Sizuoka soils.

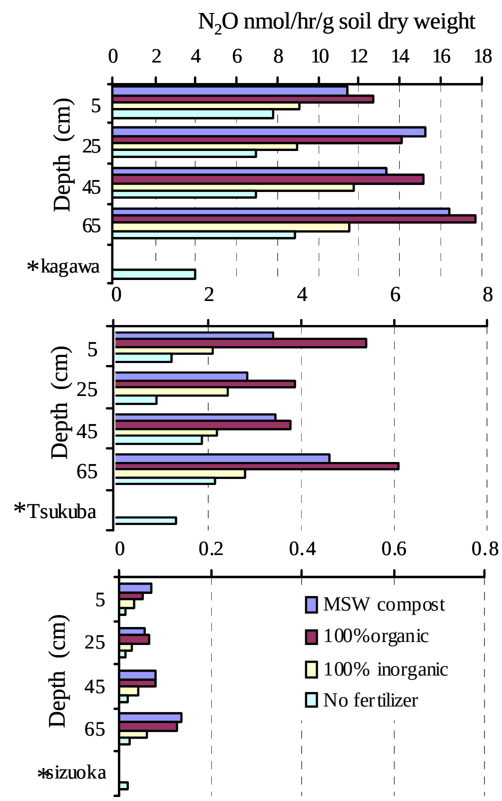

Fig. 9. Denitrification Potentials of Three Soils after the Harvest of Italian Rye Grass
*(*indicate denitrification potential in soils prior to the fertilizer application)*

3.4 Effect on Microbial Population

Kagawa soils had a larger denitrifier population. MSW treated soils had greater populations than the other treatments (Fig. 10).

3.5 pH and EC Values of Soils

Soil pH and EC values are shown in Figs. 11 and 12. The pH of Kagawa soils was far more acidic than the other two soils. Sizuoka soil pH was approximately 7, whereas Tsukuba soil pH was approximately 6, slightly acidic. CIF-treated soils exhibited a considerably higher EC than untreated soils (EC <50 mS), whereas MSW compost and COF treated soils showed a similar pattern for all three types of soils.

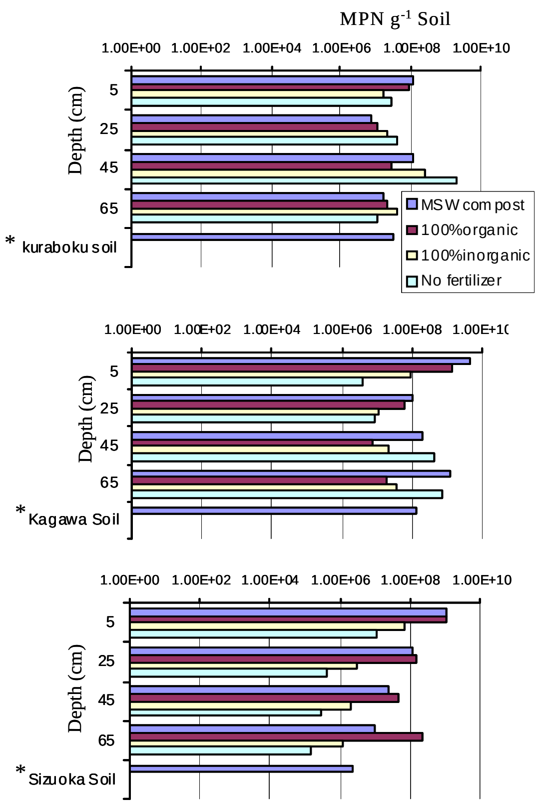

Fig. 10. Denitrifier Distribution through Soil Columns treated with Different Fertilizer Types

*(*denitrification bacterial population prior to the fertilizer application)*

3.6 Crop Yield

The effect of MSW compost and COF application on plant growth was determined by measuring the average yield of Italian rye grass. The soils treated with COF showed slightly higher yield (10%) than soils treated with MSW compost fertilizer. Addition of fertilizer increased the yield of the Italian rye grass in Tsukuba and Sizuoka soils, but not in Kagawa soils. In Kagawa soils the control provided better yield than the COF treatment. Sizuoka soils produced a high yield with the fertilizer application, especially with the application of organic fertilizers. Similar results were observed by other researchers in several soils [9]. These authors showed that organic compost fertilizer acted as a soil conditioner with a higher yield than inorganic fertilizers. It was found that the MSW organic fertilizers significantly increased yield of the Italian rye grass in Captian silt loam soil [25]. Some researchers found that the application of organic fertilizers such as MSW compost promoted higher yields of a wide variety of crops [26]. Hence, from the results shown in this study it can be concluded that organic fertilizers could be a good alternative for inorganic fertilizers to prevent further contamination of groundwater by nitrates.

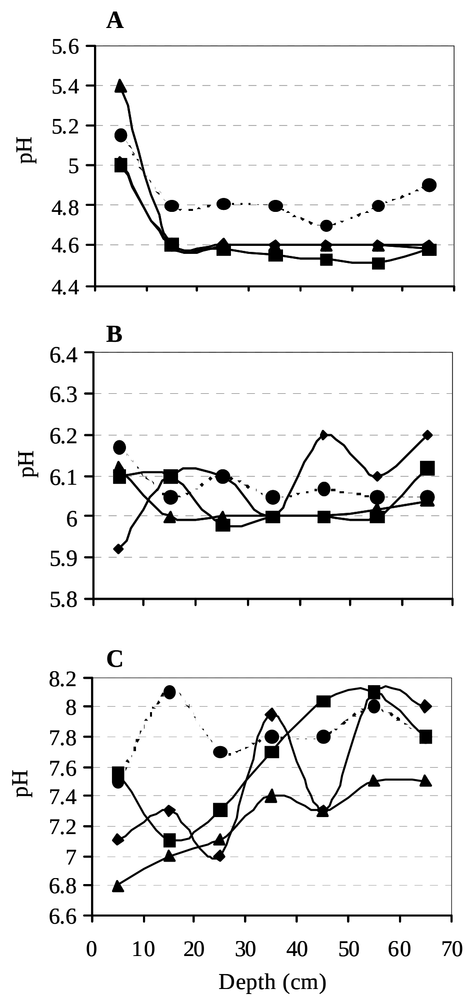

Fig. 11. pH along Soil Columns after the Harvest of Italian Rye Grass

(A: Kagawa soil, B: Tsukuba soil, C: Sizuoka soil)

4. DISCUSSION

4.1 Nitrogen Transformation in Soils

The soils used in this study showed different nitrogen transformation potentials (Figs. 8 and 9).

The transformation potentials were improved by augmentation with organic fertilizers (MSW compost and COF). The production of nitrate by the process of nitrification is highly dependent on the N-transformation processes in the soil [3]. Hence, changes in the type of N compound applied to enrich agricultural soils may affect the production of nitrate. The production of nitrate depends on the N-transformation activity in the soil, as well as C availability [27, 28]. A study carried out using simulated and observed data of two Quebec soils indicated that soil C increased by 20 to 25% when adding organic fertilizers [27]. It was also reported that organic materials improved soil biomass content in Andosol [28] alluvial soils [5] and Chernozemic clay loam soil [29].

The nitrification activities in Sizuoka soils were less than the other two soils. According to the matric potentials (Fig. 3), Sizuoka soils showed the highest matric potential (>-1,000 mm); that is, the most saturated conditions. This condition does not promote nitrification. On the other hand, Kagawa and Tsukuba soils, which were drier making it easier for air to diffuse into the soil, resulting in higher N transformation rates. When considering the nitrification and denitrification potentials in all three soils, there were some differences among the different fertilizer treatments, as well as the soils. Reasons for differences in this study may be caused by the organic fertilizer type and soil texture, which can significantly affect the N transformation rates [5].

The microbial population and organic carbon content appeared to play a major role in determining the nitrification and denitrification potentials of each soil. Sizuoka soil had the lowest nitrification and denitrification potentials when compared with other soil types (Fig. 8). According to some researches [5] Sizuoka soils were poor in C; however, the MSW and COF application improved its N transformation ability. It was also documented that organic fertilizer, such as cattle manure, increased the microbial population and nitrogen cycle microorganisms in soil [29, 30]. Furthermore, physical properties such as texture of the soils, improved the denitrification activity in soil [31] while municipal compost fortified with sewage sludge improved the soil physical properties [32]. In particular, soil structure and aggregate stability had a large influence on denitrification activity. Accordingly, MSW compost and organic fertilizer applied to soils could show higher transformation activity.

4.2 Nitrate Transport through Soils

The nitrogen transport rate was lower in Tsukuba soils than in Sizuoka sandy soil (Fig. 13). The differences were more pronounced in the Kagawa soil than the Tsukuba soil. The main reason was the physical properties of soils, such as hydraulic conductivity, which controlled the water and solute movement through the soils.

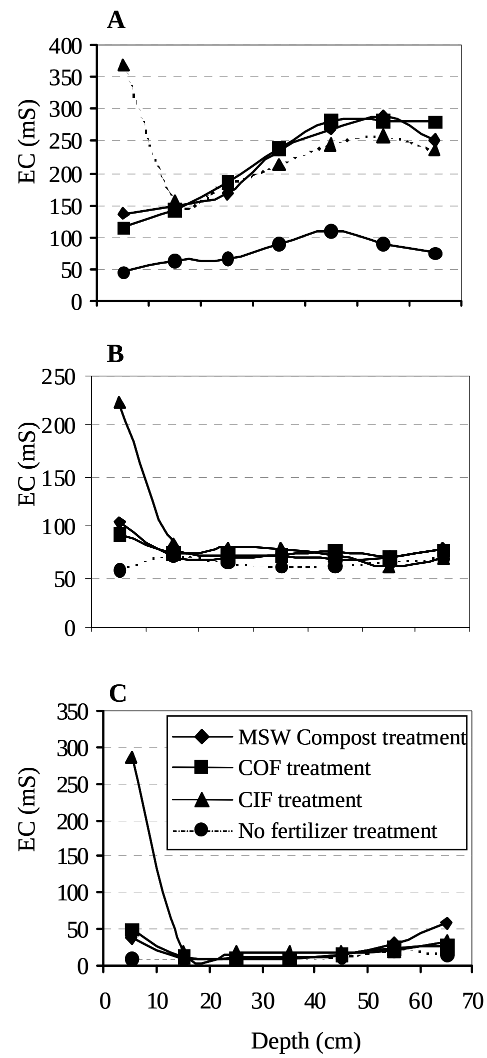

Fig. 12. Electrical conductivity along soil columns after the harvest of Italian rye grass
(A: Kagawa soil, B: Tsukuba soil, C: Sizuoka soil)

Leaching of NO_3-N through soil columns was faster in Sizuoka soil than in the Tsukuba and the Kagawa soils (Fig. 2). Kagawa soils contained a higher percentage of clay than the Tsukuba soils.

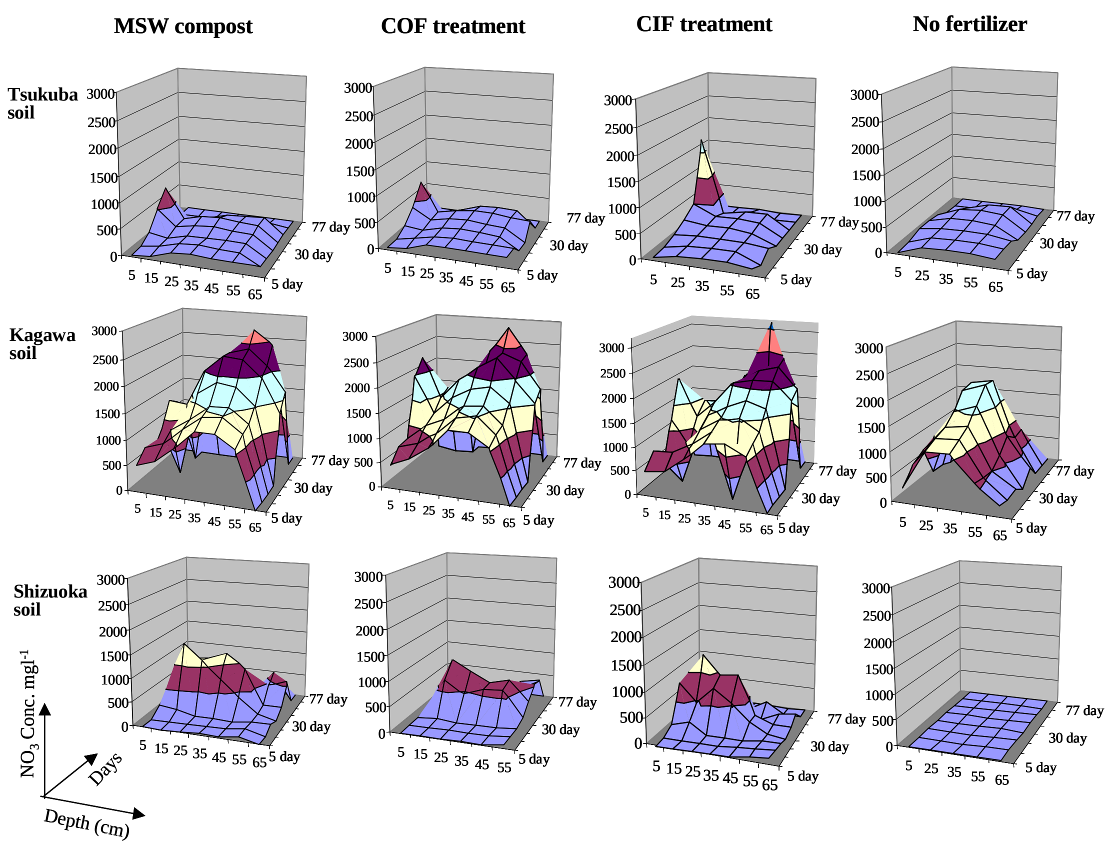

Fig. 13. NO_3-N movement pattern along the soil columns during the study period

However, when the Italian rye grasses had matured the nitrate concentration at the top layers decreased rapidly (Fig. 14). Nitrate transport, as well as nitrogen uptake by plants may be the reasons for its tendency to decrease. Before the harvest of Italian rye grass, the top-soil layers of the Kagawa soil columns had almost zero NO_3-N concentration, whereas the bottom soil layers had a higher NO_3-N concentration. The root depth of the Italian rye grass was around 40 cm in all Kagawa soils columns. Hence, it appeared that the NO_3-N was absorbed by the grass roots to the root depths.

The nitrate transportation rates through Sizuoka sand columns were higher than those of the Tsukuba and Kagawa soil columns. Except for the Sizuoka soil, considerably higher NO_3-N concentrations were obtained in comparison to pre-fertilization. Hence, when the column was irrigated, the NO_3-N remaining in the soils seemed move downwards with the movement of water. When compared with the control soil column, the pattern of the NO_3-N depletion curves at 2 days were similar to each other in all 4 columns.

MSW compost and COF augmented soils exhibited the same pattern of depletion of NO_3-N (Figs. 13 and 14). Hence, it can be shown that the organic fertilizers behaved in almost similar patterns in the same soil, although the origin (municipal solid waste or the animal manure) was different.

The addition of fertilizer significantly affected the NO_3-N in soil water or groundwater and the plants did not uptake, even though the application rate was at the recommended values for Italian rye grass. There are several reports, which showed similar results [5, 33, 18, 34]. Experiments conducted using several types of compost proved that compost fertilization significantly affected NO_3-N leaching [5].

When compared with the MSW compost and COF treatment, MSW treatment exhibited a higher release of NO_3-N than the COF treatment,

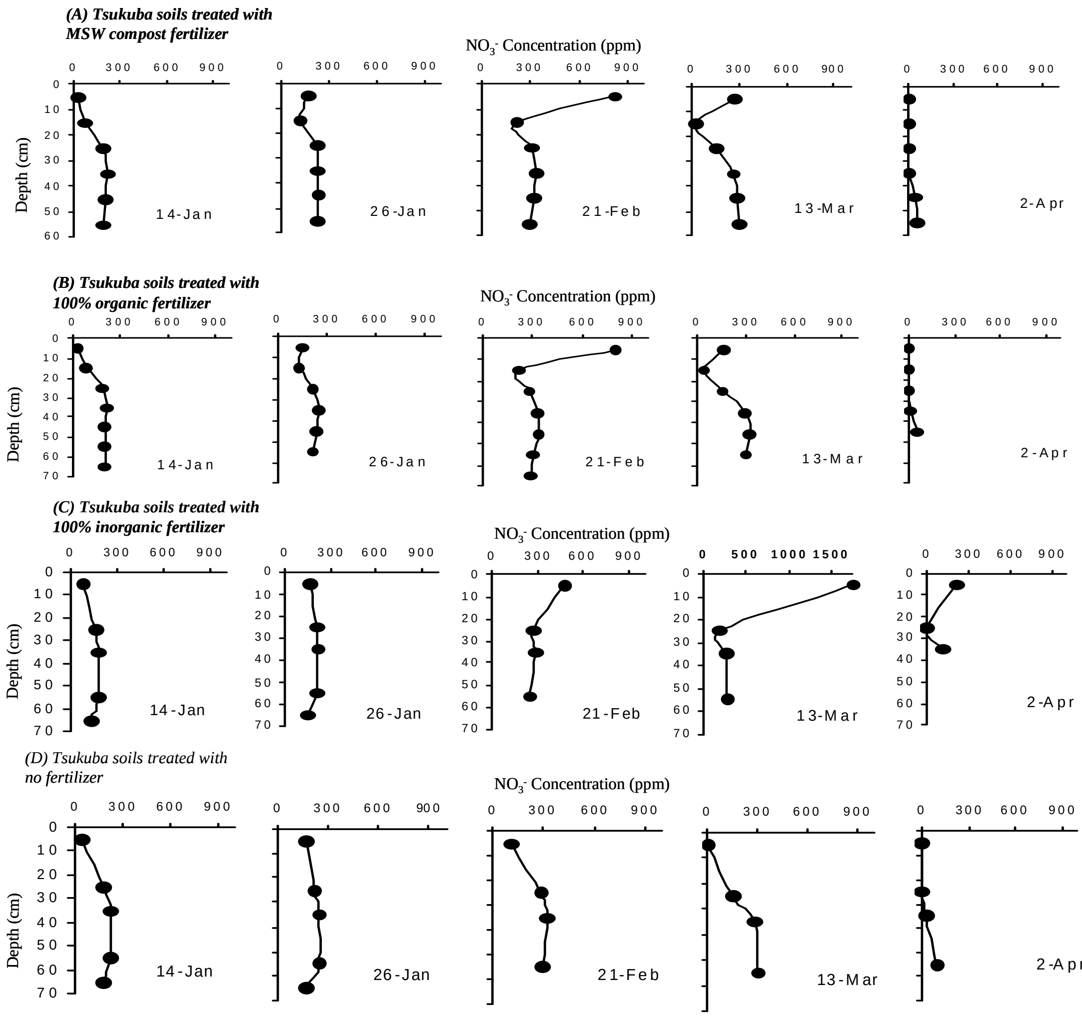

Fig. 14. Nitrate depletion curves for Tsukuba columns treated with different fertilizers and matured Italian rye grass

(Note: ppm = mg/L)

although the application rate was the same. A similar difference in NO_3-N concentration in soils by augmented different type of composts [5]. Accordingly, the biochemical properties of the organic fertilizers are important factors affecting NO_3-N leaching.

Matric potential of soils represented the soil water conditions in soil columns (Fig. 3). Matric potentials of Kagawa soils and Tsukuba soils were reduced after 40 days. Around 40 days, the Italian rye grass had grown fully and started to uptake water in large amounts—thus affecting the soil's water condition. A similar situation occurred in the Tsukuba soils and hence both soil sampling pots did not work properly after 45 days.

4.3. Nitrogen Accumulation in Soils

Soils treated with COF showed a larger amount of NO_3-N accumulation, especially in upper soil layers. A similar but insignificant accumulation of NO_2-N was also demonstrated. Accumulated amount of T-N was 0.5 mg kg^{-1} in Tsukuba soil, whereas it was 0.042 T-N mg kg^{-1} in Sizuoka soils that were treated with MSW compost fertilizer. Soils treated with COF had 0.47 T-N mg $kg^{-1}$and 0.037 T-N mg kg^{-1} in Tsukuba and Sizuoka soil columns, respectively. The accumulation in MSW compost treatment pots was higher than the other two treatments (i.e., COF and CIF applications). The second highest accumulation was provided by COF application.

Considering this fact, it appears that the organic fertilizer treatment may reduce mineralization of nitrogenous fertilizers and, hence, the N may remain in the soils in the NH_4 form (Fig. 6), which is unsusceptible to leaching.

Tsukuba Andisols (Kuroboku) treated with CIF had a higher nitrification potential than the other three treatments, whereas the soils treated with COF exhibited lower values. Nitrogen transformation rates were higher in the Andisols than in sandy and loamy clay soil. The differences were more pronounced between Kagawa loamy clay soil and the Tsukuba Andisol. Sizuoka sandy soil had the lowest nitrification and denitrification potentials when compared with the other soil types. Accordingly, it can be concluded that characteristics of soils and fertilizers influenced the NO_3-N movement and accumulation.

4. CONCLUSION

According to the results, it can be concluded that the N transformation as well as by nitrate leaching in agricultural lands are strongly influenced by the soil's chemical characteristics and secondarily the physical characteristics. In addition, these findings will be used in the future to construct a simulation model. Denitrification was increased markedly by readily available C. NO_3-N transport was considerably influenced by fertilizer type and soil properties. Nitrogen transformation rates were higher in the Tsukuba andisoils than Sizuoka sandy soil and Kagawa loamy clay soil, but the nitrogen transport rate was lower. The differences were more pronounced between the Kagawa soil and Tsukuba soil. However, the application of water and the physical properties of soils appeared to be one of the main factors that controlled nitrate leaching. NO_3-N movement in Andisol columns treated with MSW and COF had similar patterns. NO_3-N movement in sandy soil columns was faster than in the other soil types. Soils treated with COF showed a slightly higher crop yield (10%) than soils treated with MSW compost fertilizer.

ACKNOWLEDGEMENTS

Corresponding author is grateful to the Monbugakusho and Osaka Prefectural Government for scholarly sustenance and Professor Yazuo Ozaki for his numerous support for the success of this research.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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