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Characteristics of Soil in Environment Friendly Rice-wheat Cropping System in Southern Korea

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Abstract: A field experiment was conducted to compare soil microbial populations, microbial-N status and soil physical and chemical characteristics in a no-till, unfertilized, direct-sown, wheat-rice, relay-cropping system (NTWR) and also in a conventional transplanted rice single cropping system (CTR). The wheat-rice system was imposed for 2, 4 and 7 years to identify the time course responses in the soil and crop. Recycling of crop residues in the wheat-rice cropping system generally increased the soil organic matter (OM) contents but reduced the level of available P_2O_5 compared with the conventional system. Generally the soil was fertile with a high initial organic matter contents. Organic matter was increased by 30% during the 7 years of wheat-rice cropping. Other soil physical features, bulk density and permeability to air and water indicated that soil structure could be improved in response to wheat-rice cropping. Seasonal variability of soil microorganisms suggested that 7-year cropping could improve soil physicochemical characteristics but mineral contents in relation to cation exchange capacity (CEC) would decrease after 4-years cropping. Soil tillage may adversely affect soil microbial dynamics. In conclusion, a no-till, unfertilized, direct-sown, wheat-rice cropping system, is likely to sustain grain yield by improving soil bio-physicochemical factors and is one of the most ecologically stable, economically sound and socially supportive wheat-rice production systems.

Key words: Cation exchange capacity, CTR, NTWR, N immobilization, microbial-N, soil chemical factors, soil physical factors, soil microorganisms

Introduction

There are many problems with conventional rice cropping systems in Korea and Japan. For instance, the heavy application of chemical fertilizers to increase rice and wheat grain yields results in the contamination of surface and ground water. In particular, phosphorous fertilizers have been blamed for the invasion of surface waters by algae. In addition, repeated use of pesticides and herbicides significantly reduces biotic populations (both insects and microorganisms) in paddy ecosystems (Lee, 1998). A major hindrance to the adoption of sustainable, low-input rice cultivation systems is the eventual low yields (Cho and Choe, 1999). The main constraint for direct-sown rice in paddy fields is poor seedling establishment primarily due to a low tolerance to O_2 stress. Another constraint is the presence of toxic products of anaerobic decomposition in flooded paddy soils. Wheat straw has been reported to contain inhibitory substances that may exist at higher concentrations in no-till systems (Norstadt and McCalla, 1968). In addition, low soil temperatures following the senescence of crops that leave large amounts of surface-placed residue, lead to slower rates of early-season growth and development of rice (Swan *et al.*, 1987). This situation may be further aggravated if residues from the previous crop or incorporated green manure do not get enough time to be fully decomposed.

In order to overcome these problems in sustainable rice cropping systems in Korea, Cho *et al.* (2001a) introduced a labor saving, ecologically friendly and sound no-till, non-fertilized, wheat-rice cropping system (NTWR). It uses a combine harvester to only harvest the pre-season crop and to sow rice seed using a sowing devise mounted on the rear of the combine harvester. This new cropping system does away with the need for the chemical control of insect pests and weeds without a significant effect on final grain yield relative to conventional cropping systems. In addition, this farming practice enhances the biological control of insect pests by safeguarding their natural enemies.

Crop residues on the soil surface reduce evaporation, thereby conserving soil water (Moody *et al.*, 1961; Smith and Lillard, 1976). Cereal and legume crop residues can be an important source of N for rice (Ockerby *et al.*, 1999a; Cho *et al.*, 2001b). In the past, however, farmers have been reluctant to re-cycle cereal residues for maintaining soil fertility. When added to the soil, cereal residues or organic matter with high C/N ratios (> 80) generally get decomposed slowly and they immobilize native soil-N resulting in N deficiency in the following crop during the early phase of growth (Ockerby *et al.*, 1999b). Low input rain-fed rice cultivation has been viewed as sustainable for centuries and even millennia (Reichardt *et al.*, 1998). This implies that the nutrient supplying capacity of soils under rice cultivation can apparently be maintained over an unlimited period of time. In these systems, nutrients were replenished only through input of recycled organic matter and temporary primary production of higher plants and algae. Given a periodicity of organic matter inputs and of nutrient cycling under oxic and anoxic conditions, population dynamics of key microbial catalysts of nutrient turnover are likely to change during a cropping cycle and beyond. Main determinants of the endogenous dynamics of the microbiota in the soil/floodwater systems are most likely: input of energy (to meet much higher demands by photoautotrophic and chemoautotrophic processes than in non-flooded agroecosystems), water regime and redox conditions. Soil microbiota govern the nutrient supplying capacity in rice ecosystems. Therefore, an insight into the dynamics of both the entire microbiota or biocatalytically relevant parts of them promises to provide clues for gearing up the crop management to optimum nutrient use efficiencies. However, our knowledge on seasonal shifts of microbial populations in drought or submergence-prone rain-fed rice cropping systems during a cropping cycle is fragmentary at best (Reichardt *et al.*, 2001).

Soil aggregates are important for maintaining soil porosity and providing stability against erosion (Oades, 1984; Degens, 1997; Barthes *et al.*, 1999). The stability of aggregates depends mainly on clay and organic matter, involving mechanisms such as chemical bonding by labile organic compounds and physical binding of particles by fungal hyphae and roots (Miller and Jastrow, 1990; Degens, 1997; Angers, 1998). Therefore, besides factors that physically disrupt soil aggregates, management factors that lead to loss of soil organic matter are likely to result in soil structural deterioration and vice versa. Cultivation is one such management factor that affects soil aggregation (Lupwayi *et al.*, 2001).

It is known that the quantity and distribution of organic matter can be changed by tillage. This can significantly affect the quantity, quality and distribution of microbial activity, since organic matter is the source of energy and nutrients for most microorganisms. Organic matter is concentrated on the surface of a no-till soil compared with plowed soil in long-term studies (Costamagna *et al.*, 1982; Fleigem and Baeumer, 1974; Lal, 1976). Dawson (1945) reported that there was little effect of crop residue amendment on bacterial or fungal populations. However, Dawson *et al.* (1948) found that with regard to changes in microbial distribution, the sub-tilled soil had greater population in top 2.5 cm as compared with plowed soil; but the plowed soil had slightly higher populations in the 2.5 to 15 cm depth. Leaving mulch on the soil surface resulted in higher populations of fungi compared to the soil buried residue (Norstadt and MacCalla, 1969; Gamble *et al.,* 1952). On the other hand, Zerfus (1979) reported that minimum tillage decreased aerobic soil microflora including actinomycetes, fungi and nitrifying bacteria as compared with conventional tillage. Doran (1980) surveyed several no-tillage versus conventional tillage experiments. Microbial counts were greater at the top 7.5 cm in the no-till soils but were less at a depth of 7.5 to 15 cm as compared to conventional-till soils. In cases where the soil depth was available for root exploration was 15 cm deep, there was a little difference in microbial populations except for facultative anaerobes and denitrifiers, which were greater in the no-till environment. Staley and Fairchild (1978) found no difference in population size between no-till and plowed soils.

The number and kinds of microorganisms that actively decompose rice straw, increased with the increment of moisture level (Griffin, 1963), humidity (Sain and Broadbent, 1977), temperature (Houng and Liu, 1978), available nitrogen in the soil (Yoshida *et al.,* 1973) and the amount of rice straw (Kanazawa and Yoneyama, 1980). The bacterial biomass in paddy soil varied from 300 to 1000 kg dry weight ha^{-1}, which is equivalent to 30-100 kg N ha^{-1} depending upon the amount of straw (0-40 tones ha^{-1}) applied and time of sampling (Nishio *et al.,* 1978).

The diversity of soil biota is important for sustainable agriculture because microorganisms perform diverse ecological services in agricultural systems, including, recycling of plant nutrients, maintenance of soil structure, detoxification of noxious chemicals and the control of plant and animal pests (Swift and Anderson, 1993; Atieri, 1999; Wenderoth and Reber, 1999; Yan *et al.,* 2000). Lupwayi *et al.* (1998, 1999) reported greater soil microbial biomass and functional diversity under ZT than under CT in the Peace River region.

Fungi as primary microbial digesters of crop residues showed a negative correlation with the soil water content and were predominant only under drought or post-harvest fallow conditions (Reichardt *et al.,* 2001).

Rewetting can lead to considerable release of nutrients from the microbial biomass (Kieft *et al.,* 1987).

There are many reports on soil microorganisms, biomass and soil physicochemical characteristics in conventionally cultivated rice for single cropping systems but there are no reports on soil bio-physicochemical characteristics in a no-till, non-fertilized, wheat-rice relay cropping system.

The objectives of this research were to study the viability of a no-till, non-fertilized, direct-sown wheat-rice cropping system for sustained grain yield (Cho *et al.,* 2001a) and the changes that may occur in soil physical and chemical characteristics and soil microbial-N pattern. The wheat-rice system was maintained for 2, 4 and 7 years in order to study all the possible soil and crop responses to the new cropping system.

Materials and Methods

Site characterization: The data were obtained from experiments conducted in 1997 at Hadong-Gun, Gyeongsang nam-Do, Korea. Hadong is located 35° 10= N and 127° 90= E in a temperate zone with hot humid summers, cold dry winters from November to February and heavy rain from June to August. The soil at the experimental site was a mid-drained Dansung loam. The site had a slope of 7-15° and soil bulk density taken in autumn, was 1.23 gcm^{-3} at 0-20 cm depth. During the 1997 rice-cropping season, maximum and minimum daily temperature ranged from 22 to 32°C and 9 to 18°C. Total rainfall during the cropping season was 450 with 65 mm falling between sowing and until the first irrigation of the wheat-rice cropping systems. The rice crops were not water stressed.

Experimental design, treatments and statistical analysis: The experiment was a non-randomized block design with 4 treatments and 3 pseudo-replications. The control was the conventional Korean wet-sown rice system involving transplanted rice seedlings in a cultivated paddy field with fertilizer and herbicide application. The control was compared with three no-till direct-sown wheat-rice cropping system treatments to which fertilizers and chemicals were not applied. The treatments were 2 year wheat-rice, 4 years wheat-rice and 7-years wheat-rice indicating the number of years that the cropping systems had been applied continuously prior to 1998. In 1997, the treatments had been applied for one, three and six years, respectively. The plot size was 8x10 m. The randomization of treatments was entirely impractical due to the application of water and chemicals to different treatments over the seven years period; however, we performed standard analysis of variance using SAS. While interpreting the results we were cognizant of the fact that using samples as replicates decreased the variance and increased the power of the analysis to ascribe differences between treatments. Essentially this meant that smaller differences between treatment means were required to reject the wheat-rice cropping system as inferior to the conventional transplanted paddy. Multiple spline curves were fitted to the data using SigmaPlot.

Rice in the conventional and wheat-rice cropping system: On June 10, the wheat crop was harvested and 120 kg ha^{-1} of rice seed (cv. Dongjin-Byeo) was direct-sown using a combine-mounted sowing device in the no-till, direct-sown, wheat-rice cropping system (NTWR). The rice seeds were broadcast onto the untilled soil surface, in a 30-cm^2 pattern separated by 10 cm borders and covered with wheat straw chopped into mulch by the combine (Kim *et al.,* 1992). In the conventional, transplanted rice, single cropping system, 30-days old rice seedlings were transplanted into a cultivated paddy field with basal application of 4-7-4 g/m^2 N, P, K respectively. The soil in the conventional rice crop was cultivated to a depth of 20 cm and fertilized with N as urea (46% N), P as single super-phosphate (16% P_2O_5) and K as muriate of potash (50% K_2O). The rates were 110 (40 basal B 40 tillering B 30 heading) N, 100 P and 80 K kg ha^{-1} respectively. Herbicides were applied after transplanting and irrigation was by initially flooding the plots with standing water, 5 cm deep until four weeks after transplanting, before the fields were drained naturally by water infiltration. The plots were again flooded at panicle initiation stage for 3 days. A bare fallow was maintained between annual rice crops.

The final plant density in NTWR was 157 m^{-2} in the 2 years, 183 m^{-2} in the 4 years and 159 m^{-2} in the 7 years wheat rice treatments. The pre-crop wheat yielded 2.5 t ha^{-1} grain and 2.8 t ha^{-1} straw in 1997. The N concentration in the wheat straw was 0.78% and this had mostly decomposed (70% of dry weight) by heading in the rice crop. Initial seed germination in NTWR plots was rain-fed as flooding had to be delayed for 3 weeks to protect seedlings from redox activity. The fields were then irrigated as in conventional production. Drainage rows 200 cm apart, 30 cm wide and 20 cm deep were installed.

Wheat management in the wheat-rice cropping system: Each year at the end of October, in a one-pass operation the rice crop was harvested and 200 kg ha^{-1} of wheat (cv. Gaerumil) seed was direct-sown using a combine-mounted sowing device. The seed wheat was broadcast onto the untilled soil surface and covered lightly with rice straw chopped into mulch by the combine.

Observations and measurements

Soil chemical characteristics of experimental paddy fields: Soil samples were air dried, ground and sieved by 2-mm size mesh.

The C/N ratio was determined by the dry combustion method using a Sumigraph CHN analyzer (Sumigraph NC-90A) (Nelson and Sommers, 1982). The soil pH (H_2O), pH (KCl) was measured using a glass electrode pH meter (soil: water = 1: 5) and exchangeable cations were extracted with 1.0 N NH4OAC (IITA, 1979). An inductively coupled plasma atomic emission spectrometer (Shimadzu ICP 2000) was used to measure K, Ca, Mg, Na and Fe content. Soil reduction potential was measured using a portable ORP meter (RM-12) in the surface soil solution. Soil organic matter was calculated by multiplying organic C by 1.724 (Nelson and Sommers, 1982). Soil exchangeable N was detected in a chemically deoxidised soil solution (10 mL) with 3 g Deburdar's alloy and analyzed on a Kjeltec distilling unit.

Air permeability and water penetration of experimental paddy soil: Air permeability and water penetration of test soil was measured on farm by KM-type penetration test-A and test-W for air (AF 170) and water penetration (AF 173), respectively. Air permeability was measured in one-minute intervals for 5 min from penetration of cylinder air into 5, 10, 15 and 20 cm soil depths. Water penetration into soil was determined as penetration depth of water poured into an open-ended cylinder and maintained for 1 day at a soil depth of 20 cm.

Soil bulk density, porosity and water related factors: The soil surface was bared with a knife and a 100 cc cylinder was placed against the soil and hammered gently up to 3 mm below the soil. The cylinders were excavated and soil was trimmed flush to both ends of the cylinder. Soil samples were collected from depths of 0-5, 5-10, 10-15 and 15-20 cm. The samples in cylinders were placed in polythene bags and weighed before and after oven drying for 24 h at 105°C.

Macro- and micro-porosity were measured as follows:
Soil samples were collected and weighed as described above.
Mass of moist soil+ container (a); Mass of dry soil+ container (b); Mass of water (a-b); Mass of container (c); and Mass of oven-dry soil (b-c) and the specific volume was calculated from 1g/ bulk density,
Field capacity = water content/specific volume,
Macro porosity = total porosity - field capacity

Typical water content values were determined by the following methods
Permanent wilting point and field capacity: Typical total porosities of the light-, medium- and heavy-textured soils were taken to be 0.4, 0.5 and 0.6 cm^{-3} respectively. The ranges of residual porosity and residual + storage porosity were then used to calculate gravimetric water contents.
Saturation percentage : g H_2O cm^3 soil/ g soil cm^3 (bulk density) = g/g or percent.

Soil hardness: Soil hardness was measured using a Corn penetrometer at 0-5, 5-10, 10-15 and 15-20 cm soil depths. It was measured at the same places where the core was sampled to investigate the bulk density. The measurements were performed on three spots with ten replications in each spot. The data was expressed as mg cm^{-3}.

Soil total N and exchangeable N in paddy soil: Soil total N (%) was analyzed by the Kjeldahl method using Kjeltec-2000 for digestion and Kjeltec-2000 distilling unit for distillation. Duplicate samples were analyzed from each plot. For the analysis of soil exchangeable N, the soil solution was extracted at an atmospheric pressure of 1.2 bars by water suction through a ceramic cap, installed 5-10 cm soil deep. Soil exchangeable N was analyzed on a Kjeltec Distilling Unit after chemically deoxidizing the soil solution (10 mL) with 3 g of Deburdar's alloy.

Analysis of soil microbial population: Fresh soils of representative samples were passed through a 2 mm mesh sieve and mixed thoroughly. One gram portions of soil samples were weighed and poured into dilution tubes (18x150 mm^{-2} test tubes) containing 10 ml of distilled water. The test tubes were capped and placed on a shaker for 10 min. This first dilution represents a 10^{-1} time. It was sampled 1 to 9 ml dilution blanks. Subsequent dilution plating of 1 ml of this dilution allowed enumeration of up to $1x10^{-5}$ colony-forming units (cfu) per g soil. Diluted samples were spread on the agar surface using a sterile glass spreader for each plate.
Samples spread evenly over the plates were incubated at 25°C for 2 to 4 d in the dark. After incubation, plates were removed from the incubator and 1 to 100 colonies were counted from each plate. Plates with spreading or swarming growth were excluded for the final count. The colonies were counted manually.
Number of cfu g^{-1} soil = [(Mean plate count)(Dilution factor)/ (Dry weight soil, initial dilution)]
where : Dry weight soil = (Weight moist soil, initial dilution x (1 - % Moisture, soil sample).

Culture media used:
For total bacteria
Nutrient broth agar (NA; Agar 20 g, Nutrient broth 8g/1l sterile water, Cyclohexamide 100 mg kg^{-1})
For total fungi
Potato dextrose agar (PDA ; Agar 15 g, potato dextrose broth 24 g/l sterile water, Streptomycin 100 mg kg^{-1} 10 ml)
For total actinomycetes
Trypticase soy broth (TSA: Agar 20 g, trypticase Soy broth 30 g/l sterile water)
For fluorescent pseudomonas
King's B (KB; Dipeptone NO_3 10 g, Glycerol 10 ml, $MgSO_4.7H_2O$ 1.5 g, Agar 15 g, K_2HPO_4 1.5 gl^{-1} sterile water).
For rhizobium yeast-extract mannitol agar (YEMA)
10 g mannitol, 0.5 g K_2HPO_4, 0.2 g $MgSO_4.7H_2O$, 0.2 g NaCl, 0.5 g yeast extract, 15 g agar, 1 L water.
Rhizobium numbers were greater in all treatments between 5-10 and 10-20 cm soil depths before water submergence but the population was steeply decreased afterwards and re-increased in September in 0-5 and 10-20 cm soil depths (Fig. 2).

Results

Soil chemical properties: Soil characteristics in the conventional tillage treatment in 1997 were similar to those measured at the start of the experiment (Table 1). Recycling of crop residues in the wheat-rice cropping system generally increased the soil OM content but reduced the level of available P_2O_5 compared with conventional production. The change in OM content was apparent after 4 years of wheat-rice cropping and continued to increase when the system was maintained for 7 years. The soil pH was higher after 7 years of wheat-rice cropping, but levels of available P and K were lower after 4 and 7 years of wheat-rice cropping.

Soil bulk density (BD)
Soil BD was lower in the surface soil layer (0-5 cm) than in lower depths (Table 2). Soil below the cultivation zone had a BD of approximately 1.5 g cm^{-3} in all treatments. Soils in all wheat-rice treatments had similar BD, however, disturbed soil in the conventional production system had a lower BD.

Soil permeability to water and air: Soil permeability to air generally declined with an increase in soil depth (Fig. 1). Permeability to air was lowest in conventional production and increased under the wheat-rice system reaching a maximum after 4 years. Permeability to water was also lower in the conventional and 2-year wheat-rice treatments (2.0 and 2.2 cm day^{-1}, respectively) and higher in the 4 and 7 year wheat-rice systems (2.7 and 2.5 cm day^{-1}, respectively with a standard error of approximately 0.3 cm day^{-1}) (Fig. 1).

Soil physical factors; solids, moisture, field capacity and water saturation percent: Soil water related factors viz., moisture, field capacity and water saturation percent, improved with the progress in cropping years (Fig. 2) changed gradually in CTR between a depth of 0-5 and 15-20 cm. However, there was no

Table 1: Changes in the chemical properties of the conventional-rice soil in response to the imposition of a no-till, unfertilised, direct-sown wheat-rice cropping system for 2, 4 and 7 years.

	pH	EC	Av.P_2O_5	Ca	K	Mg	OM
Cropping system	(1:5 extract)		(mg/kg)	(cmol+ /kg)			(%)
Conventional rice	5.7	0.18	68	3.6	1.41	0.76	1.7" 0.13
2-year wheat-rice	5.0	0.14	86	3.5	0.50	0.59	1.9" 0.21
4-year wheat-rice	5.2	0.23	47	5.6	0.51	1.23	2.0" 0.22
7-year wheat-rice	5.5	0.16	44	4.4	0.33	0.91	2.3" 0.23

Table 2: Soil bulk density, total soil N (%) and (kg haG^{1}) before (BC) and after (AC) the conventional rice and the wheat-rice cropping phases in 1997 and the amount of mineralized N during the cropping phase as affected by cropping system treatment and soil depth (cm).

Cropping systems	Soil depth (Cm)	Bulk density (gcm^{-3})	Total soil N (%) BC	AC	Total soil N (Kg ha^{-1}) BC	AC	Mineralized N (kg haG^{1})
Conventional rice	0-5	1.14	0.14	0.11	804	641	162
	5-10	1.24	0.13	0.10	785	594	191
	10-15	1.42	0.12	0.10	859	710	149
	15-20	1.45	0.12	0.11	846	780	66
Mean		1.31	0.13	0.10	823	681	142
2-year	0-5	1.29	0.11	0.09	701	547	154
wheat-rice	5-10	1.53	0.07	0.05	494	413	81
	10-15	1.50	0.07	0.06	503	428	75
	15-20	1.49	0.07	0.06	488	421	67
Mean		1.45	0.08	0.06	546	452	94
4-year	0-5	1.30	0.15	0.12	945	774	170
white-rice	5-10	1.43	0.12	0.10	838	695	144
	10-15	1.48	0.11	0.09	799	651	148
	15-20	1.52	0.10	0.08	732	623	109
Mean		1.43	0.12	0.10	829	686	143
7-year	0-5	1.35	0.11	0.09	770	624	146
Wheat-rice	5-10	1.45	0.07	0.07	593	517	76
	10-15	1.46	0.08	0.07	599	526	73
	15-20	1.52	0.08	0.07	639	536	103
Mean		1.44	0.09	0.08	621	551	71
Duncan's multiple range test ($P < 0.05$)							
Cropping system			0.021	0.02	21.8	21.5	22.5
Cropping system x soil depth			0.038	0.03	43.8	54.2	32.9

significant difference in soil solids content relative to soil depth in NTWR, though it was the lowest of all the other soil layers at a depth of 0-5 cm.

Total soil N: Decreases in the total soil N during the wheat-rice cropping phases in 1997 were large, ranging from 66-191 kg ha^{-1} (Table 2). Presumably total soil N was mineralized to inorganic forms available to the crop. Thus, the amount of mineralized N was lower for the 2 and 7 years wheat-rice systems than for the conventional rice and 4 year wheat-rice system, possibly due to the lower levels of total soil N before the cropping phase. Generally soil BD was lower in 0-5 cm soil layer than deeper in the profile and this compensated for higher N concentrations. Soil BD was also lower in the cultivated layer of the conventional tillage system.

Soil exchangeable N: Immediately after flooding of the rice crop, exchangeable soil -N was greater for 4 and 7 years rice wheat systems, but lower in the 2 year wheat-rice system compared with conventional tillage (Table 2). Twenty days after flooding, exchangeable N had increased in all treatments, but the increases were greater for the wheat-rice systems. In all but the 2 year wheat-rice system, which had a higher level of exchangeable N at 40 d after flooding, exchangeable-N had stabilized at low levels 40 to 50 d after flooding.

Microbial population: Soil bacteria populations decreased rapidly after flooding, showing that flooding causes a decrease in aerobic soil microbial populations (Fig. 2). The degradation of organic matter by aerobic bacteria was strongly inhibited at reduced oxygen levels after flooding (Fig. 2). Aerobic bacterial populations were higher prior to flooding than to counts taken after flooding. Fungal populations were also greater in NTWR than CONV paddy field (Fig. 2).

Populations of actinomycetes showed a response similar to that observed in fungi in response to irrigation or drainage. After drainage, actinomycete populations increased within the surface soil, with the biggest increases occurring in sub-soil of conventionally tilled plots (Fig. 2).

Populations of pseudomonas were greater in flooded conditions (July 4) and shortly after water drainage (Sept. 1). The population of Pseudomonas did not decrease parallel to increases in soil depth (Fig. 2). Extraordinarily high Rhizobium populations in no-till, unfertilized, direct-sown paddy, also contributed to the stabilization of rice grain yields through increased N_2 fixation (Fig. 2).

Both before and after rice cropping, microorganisms almost disappeared in surface soil layer (5-10 cm), indicating a depletion of soil N by the foraging of rice roots observed to be uniformly distributed in surface soils.

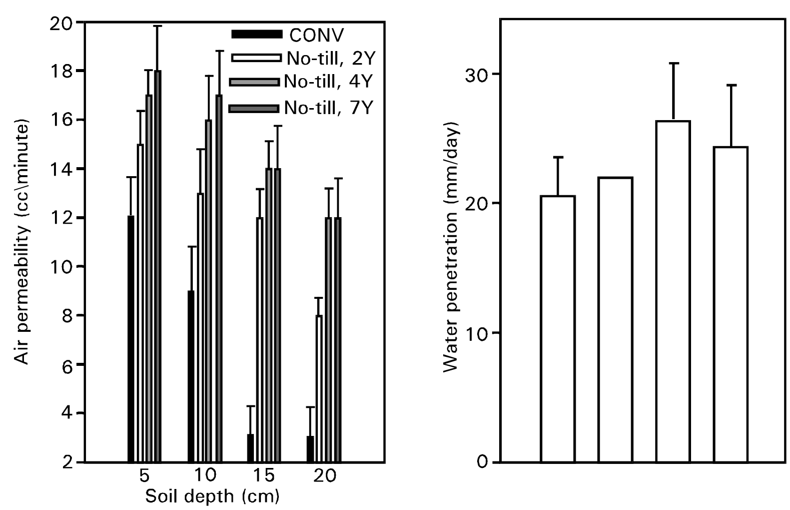

Fig. 1: Air permeation and water peneteration of the soil. Vertical bars represent standard error of mean

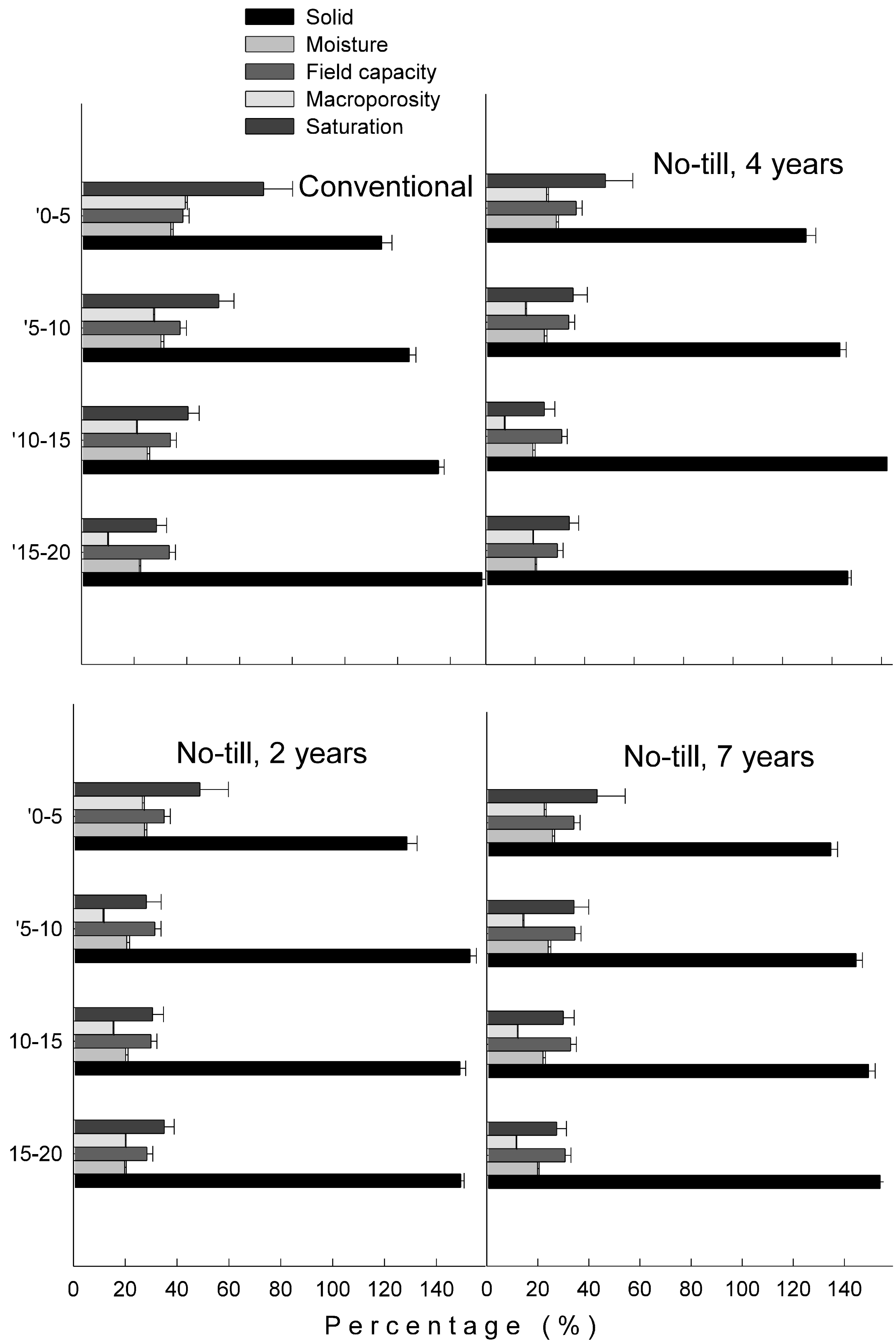

Fig. 2: Soil physical factors, solid, moisture, field capacity, microporosity, and water saturation, as affected by no tillage years and soil depth. Vertical bar indicates standard errors of means.

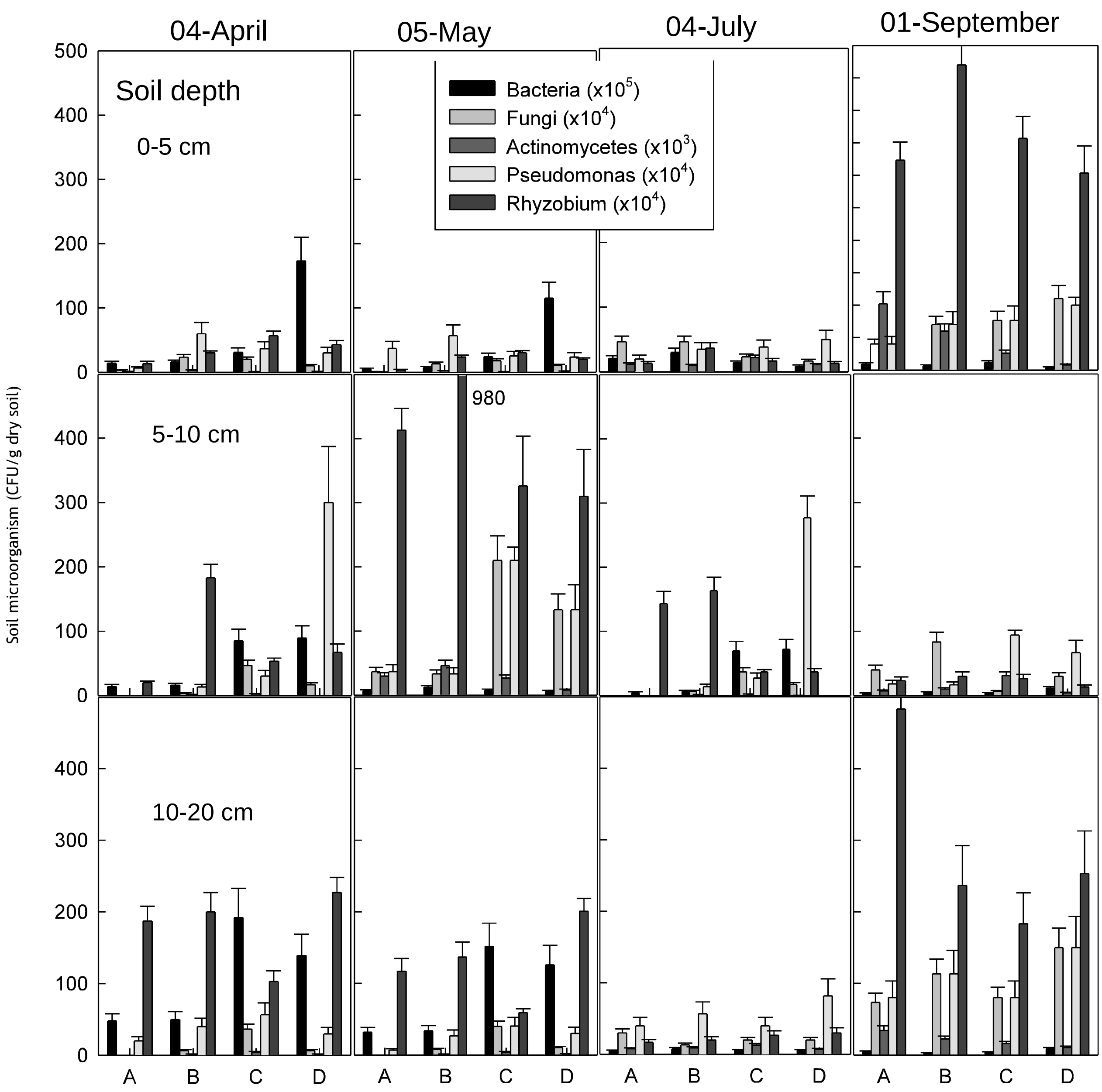

Fig. 3: Soil microorganisms as affected by no-tillage years, soil depth and sampling date (date-month) under rice-wheat relaying cropping system. A: Conventional rice cultivation system, B: No-tillage, 1 year, C: No-tillage, 4 years, D: No-tillage, 7 years. soil depth.Vertical bar indicates standard errors of means.

Bacterial populations were higher in non-tilled than in conventionally tilled and 2 year non-tilled paddy soils after 4 and 7 year cultivation. From theses results, it becomes clear that the supply of nitrogen by organic matter and microbial function was boosted by the artificially repeated adjustments of drainage and flooding.

Discussion

There were non significant differences in soil characteristics between pre-and post-rice cropping in the conventional system (CTR) implying insignificant annual variation. Contrary to the conventional system, recycled crop residues in the wheat-rice cropping system (NTWR) generally increased the soil OM content but reduced the level of available P_2O_5 due to the annual accumulation of organic matter and the absence of soil disturbance (Carter, 1992; Beare *et al.,* 1994). Unlike in legume cultivation (Cho *et al.*, 2001b), soil pH in the wheat and rice straw recycling system remained constant or increased only slightly with continued cropping. This is probably due to the transfer of silica from the straw to the soil. In addition, the lack of fertilization and tillage did not increase the availability of soil nutrients (P, K, Fe) relative to other fertilized conventional systems (Minami and Maeda, 1971; Pal *et al.*, 1975; Kagwa, 1977). However nutrient uptake by the wheat and rice plants reduced available P and K with consecutive cropping due to the non-recycled grain.

Soil bulk density (BD) in the NTWR plots was particularly low in the surface soil layer (0-5cm) as compared with the lower depths and to the conventional cropping system, the reason being an increase in soil bio-diversity and soil macro-and micro-pores due the accumulated organic matter. The disturbed soil in conventional cropping had a lower BD near the soil surface but it steeply increased with an increase in soil depth due to soil accumulation of more soil particles in the region beyond the plow layer. In this experiment, a difference in BD between CTR and NTWR was observed to occur with repeated cropping contrary to seven and ten years results presented by Costamagna *et al.* (1982) and Shear and Moschlet (1969).

Soil air permeability was lowest in the conventional system and increased under the wheat-rice relay cropping, reaching a maximum after 4 years. There was a general decline in soil air permeability with an increase in soil depth in wheat-rice system and it was negatively correlated with soil solid content (Fig. 1). Soil permeability to water was also lower in the conventional and 2 years wheat-rice treatments and higher in the wheat-rice system after 4 and 7 years, which also explains the increase in macro-porosity with number of cropping years.

Contrary to results from other conventional systems (Broadbent, 1970; Dei, 1970; Kai and Kawaguchi, 1977; Kanazawa and Yoneyama, 1980; Kai *et al.,* 1981), the steep increase in soil exchangeable-N in the 4 and 7 years wheat-rice systems may have been due to the lack of organic matter immobilization by soil microorganisms. The microbial breakdown of organic matter with a high C/N ratio leads to depletion of soil N, however, in this cropping system, the anaerobic conditions resulting from the flooding introduced three weeks after rice seeding could have drastically reduced aerobic microbial populations. After 40 d of flooding, there was a significant decrease in soil exchangeable N due to the accelerated uptake by rice plants approaching maximum tillers. In all but the 2 years wheat-rice system, exchangeable-N stabilized at the lower levels at 40 to 50 d after flooding; the 2 years wheat-rice system had a higher level of exchangeable N at 40 d after flooding probably due to plant density and initial N levels. This is because the 2 years wheat-rice system did not yield sufficient straw to adequately cover the surface broadcast rice seed thus leading to a decrease in seedling establishment. In addition the bare patches of the paddy field not covered by the straw could have contributed to increased denitrification or volatilization of soil N.

Similar to the soil microorganism populations, microbial biomass-N was generally lower in conventional production with similar levels at all soil depths and only rising in 0-5 cm layer at sowing. These results resemble those presented by Murphy *et al.* (1998), for 5-10 cm layer after anthesis in upland rice. Generally and with the exception of CTR, soil microbial N was higher in NTWR ranging from 30 to 230 mg kg^{-1} more than as reported by Kushwaha et al. (2001) for experiments done in India. This was followed by conventionally produced dry-land rice with residue-removed straw mulching at 23.9 mg/kg and minimum tillage with residue retained at 49.7 mg kg^{-1}. Soil microbial N was particularly high in the 4 years NTWR in all the layers (0-20 cm). The possible explanation for the variation in results from India and Korea would be the accelerated degradation of residues in India with relatively higher temperatures and a difference in cropping cycles that could have resulted in the production of more crop residues in India and concommitantly a greater improvement in soil bio-physicochemical conditions relative to Korea.

Presumably, total soil N was mineralized to inorganic forms available to the crop. Thus, the amount of mineralized N was lower for 2 and 7 years wheat-rice systems than for conventional tillage and the 4-year wheat-rice system, possibly due to the lower levels of total soil N before the cropping phase. Generally soil BD was lower in 0-5 cm soil layer than deeper in the profile and this was compensated for by higher N concentration. Soil BD was also lower in the cultivated layer of the conventional rice system.

Because of the instability of nitrate (Reddy *et al.,* 1976; Roy, 1981) relative to ammonium (Patric and Mahapatra, 1968; Yoshida, 1981), ammoniacal-N content in the paddy field was much higher than nitrate-N.

Similar to results reported by Lupwayi *et al.* (1998, 1999, 2001) the diversity of soil bacteria was greater under ZT than under CT. It is suggested that when the weather is not stable, paddy fields mulched with crop residues should be maintained at moisture conditions ideal for seed germination after sowing and flooded immediately after seedling establishment. In this way, large soil microbial populations are established and the growth of rice seedlings could be retarded by N immobilization. However, irrigation could be delayed so that the release of soil nitrogen can feed the microbes and rice seedlings. At any time, natural rainfall is considered as the most effective way to increase seedling establishment and growth of rice.

Soil bacteria populations were more near the soil surface and greater in NTWR than in CTR as already reported by Gaur and Mukherjee (1980). In no-till cultivation, bacterial populations were initially high but steeply decreased after flooding, implying that flooding resulted in the decrease in aerobic soil microbial populations. Aerobic bacteria were strongly inhibited by reduced oxygen content during the degradation of organic matter after water supply. Also, fungi populations were higher in non-flooded relative to flooded paddy fields (Fig. 3) similar to results obtained by Reichardt *et al.* (2001).

Generally, biological soil properties can be used to distinguish between a no-till and conventional cropping system. The objective of this study was to examine how rice production might be sustained in a no-till cropping system. The main factors considered to be important in this system are soil microbial activity and populations, the pool of available N, N cycling and related biological properties, such as total N and total aerobic bacteria. Actinomycete, fungal and psudomonas activity was greater in no-till than in conventional tillage at a soil depth of 0 to 10 cm. These properties varied with soil depth, but were similar in both no-till and conventional tillage at a depth of 10 cm and below as in minimum-tillage paddy (Zerfus, 1979). Microbial N, mineralizable N and the net N mineralization rate tended to be higher in no till than in conventional tillage at a depth of 0 to 10 cm. The available N pool, a proportion of the total N pool, was larger in non-tilled paddy soil than in conventionally tilled paddy soil. This indicates that there was an enlarging pool of active soil N due to increased microbial activity in no-till paddy soil. Even after irrigation, microbial populations did not decrease in the no-till soil. In September, microbial populations increased extraordinarily in 0-5 and 10-20 cm soil layers.

There was a trend for higher gross N transformation rates in no-tillage than in the conventionally tilled system. In unfertilized soil, the ratio of gross N immobilization to mineralization was higher in non- tilled than in conventionally tilled soil. Seasonal variability was an important factor influencing the magnitude of the N pool and N transformation rates. These results showed that 7 years cropping could improve the soil physicochemical characteristics but mineral content in relation to cation exchange capacity (CEC) would decrease after 4 years cropping. However, even with a little decrease in CEC levels, a significant decrease in grain yield after 7 year cropping is highly unlikely.

Soil tillage may adversely affect soil microbial dynamics through, amongst other factors, deterioration in soil structure. In no-till, non-fertilized, direct-sown, wheat-rice relay cropping, a decrease in the levels of certain minerals was found to occur between 4 and 7 years cropping, necessitating the application of these minerals in order to maintain a sustainable production system. Accumulated soil organic matter and zero-tillage maintained and sometimes improved soil bio-physicochemical characteristics and grain yield was sustained relative to CTR, even in the absence of chemical fertilization. In conclusion, a no-till direct-sown wheat-rice cropping system is one of the most ecologically stable, economically sound and socially attractive wheat-rice production systems. It is a typical sustainable agricultural system in which nutrient recycling is required and natural enemies are inhibited in the mulch layer and chemicals for disease and pest control can be avoided.

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