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Comparison of soil properties between upland and paddy fields based on the soil fertility index (SOFIX)

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ABSTRACT

The soil fertility of agricultural fields is highly influenced by land use systems such as cultivated crops. In this study, the soil fertilities of upland and paddy fields were compared using the soil fertility index (SOFIX). The SOFIX database of 795 agricultural fields showed that the average bacterial biomass was higher in paddy fields than in upland soils despite the low level of organic matter in paddy field soils. The difference in soil properties between upland and paddy fields might be influenced by water management, cropping system, and fertilizers. Based on the bacterial biomass and total carbon (TC), the agricultural fields were divided into four groups and each group corresponded to a particular type of agricultural management. One group with high bacterial biomass and high TC seemed to be related to the appropriate use of organic fertilizers without agrochemicals. The values of SOFIX parameters of this group were suitable to maintain the optimum level of microbial abundance and activities. The optimal conditions for the upland and paddy field soils were determined based on the SOFIX database.

KEYWORDS: bacterial biomass, organic matter, paddy field, SOFIX, upland field

1. INTRODUCTION

As plants take up nutrients from the soil, physical, chemical and biological properties of the soil are important factors for the growth and survival of plants. In natural environments, nutrients are supplied to living organisms continuously through the decomposition of organic materials by the activities of microorganisms. In agricultural fields, the natural equilibrium of organic material in soil is disturbed by agricultural management practices.

Conventional agricultural systems mainly use chemical fertilizers and agrochemicals to enhance productivity [1-3]. As chemical fertilizers that contain no organic matter directly affect the plant growth [4, 5], the long-term use of chemical fertilizers leads to reduced abundance and activities of soil microorganisms [6]. The uses of agrochemicals in processes such as soil fumigation can adversely influence soil microorganisms [7]. As a result, the amount of organic matter in soil is reduced and the biological properties deteriorate.

With increasing concern about conventional agricultural systems in terms of environmental impacts [5, 8], food security [9-11] and economics [12], there is increasing interest in organic agriculture. As organic agricultural systems are usually complex [13], crop yields are usually lower when compared to conventional agricultural systems [2, 3] and incorrect organic treatments can reduce biodiversity [14, 15]. Therefore, a new agricultural system based on biomass resources and biodiversity that provides high yield and high quality of agricultural products is needed [16].

Soil management practices also vary according to the types of cultivated crops. The management of paddy fields is quite different from that of upland soils; in particular, water and fertilizer management are different for these two environments.

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The soil fertility index (SOFIX) was developed considering the importance of biological factors in soil fertility [17]. According to the concept of SOFIX, bacterial biomass and their activities are the main factors that determine the soil fertility. In this article, we characterized soil conditions based on the SOFIX parameters for upland and paddy field soils. The soil conditions and management of agricultural fields for enhancing soil fertility were also discussed.

2. MATERIALS AND METHODS

2.1. Sample collection

Soil samples were collected from 795 agricultural fields in Japan from 2014 to 2016. A composite sample from each field was taken up to the depth of 15 cm from at least five randomly selected points. The soil samples included 702 upland fields growing multiple products such as vegetables, flowers and cereal crops and 93 paddy fields. The soils were sieved through a 2-mm sieve and kept at 4 °C until analysis.

2.2. Analysis of soil properties

Fifteen parameters of the soil fertility index (SOFIX) were analyzed for the collected soil samples [17]. Wet soils were used for all the analysis. Bacterial biomass in the soil was estimated by quantifying the environmental DNA (eDNA) extracted by the slow-stirring method [18]. Two indicators of microbial activities (nitrogen (N) circulation and phosphorus (P) circulation activities) were examined according to our previous studies [19, 20], in which N circulation was calculated based on the values of NH_4^+ oxidation and NO_3^- oxidation activities and bacterial biomass. Total carbon (TC) was determined by using a Total Organic Carbon Analyzer (TOC-VCPH; Shimadzu, Kyoto, Japan) and solid sample combustion unit (SSM-5000A; Shimadzu). Amounts of total nitrogen (TN) and total phosphorus (TP) were measured using a UV Visible Spectrophotometer (U-1900 Spectrophotometer; Hitachi, Tokyo, Japan); total potassium (TK) was measured by atomic absorption spectrometer (Hitachi, Japan) after digestion with a Kjeldahl digestion unit (Kjeldahltherm; Gerhardt, Königswinter, Germany). C/N and C/P ratios were calculated by using the TC, TN and TP values. Inorganic forms of N (NO_3^--N and NH_4^+-N) were analyzed after KCl extraction using a UV Visible Spectrophotometer. Soluble phosphorus (SP) and soluble potassium (SK) were analyzed after water extraction using the same methods used for TP and TK.

2.3. Data analysis

To determine the features of the soil, agricultural fields were firstly grouped into two cultivation types: A) upland, a relatively aerated land where vegetables, cereals (except rice) and flowers were cultivated and B) paddy, a place where rice was cultivated with flooded water. Secondly, the soils in each cultivation type were further grouped into different patterns based on the two SOFIX parameters of bacterial biomass and TC. Among the 15 parameters, bacterial biomass is the most important indicator of the biological properties of soil, whereas TC indicates the level of soil organic matter required for the growth of microorganisms.

The measured SOFIX parameters were statistically analyzed. Correlations between the parameters were analyzed for all parameters and for each field type (upland and paddy) with Pearson's correlation values. Statistical analyses were performed using SPSS software and the R package.

3. RESULTS AND DISCUSSION

3.1. Characterization of agricultural fields

To characterize the features of the agricultural fields (upland and paddy), SOFIX analysis was carried out. In all of the 795 agricultural soils, the average bacterial biomass was $7.5 \pm 9.8 \times 10^8$ cells/g-soil, (mean ± SD) ranging from below the detection limit (ND; less than 6.6×10^6 cells/g-soil) to 9.7×10^9 cells/g-soil (Table 1). The bacterial biomass was lower than 1.0×10^8 cells/g-soil in 164 (21%) soils including 115 (14%) samples with no detectable bacteria. The averages of N circulation and P circulation activities were 29.6 ± 27.3 and 34.9 ± 33.5 points, respectively. TC and TN varied greatly among the soils, ranging from 1,900 to 98,000 mg/kg for TC and 160 to 14,000 mg/kg for TN. SP and SK ranged from 0 to 38,000 mg/kg and 0 to 34,000 mg/kg, respectively.

The values of TC and TN highly correlated with each other ($r = 0.68$, $p < 0.01$; Fig. 1A), and TP also

Table 1. The average values of SOFIX parameters in soils of total agricultural fields and each cultivation type (upland and paddy).

Field	Type	Sample No.	Bacterial biomass ($\times 10^8$ cells/g)	TC (mg/kg)	TN (mg/kg)	N circulation activity (point)	NH_4^+ oxidation rate (point)	NO_2^- oxidation rate (point)	P circulation activity (point)
All field		795	7.5 ± 9.8	23,600 ± 14,900	1,370 ± 1,040	29.6 ± 27.3	35.1 ± 28.8	52.2 ± 32.5	34.0 ± 33.5
	Upland	702	6.9 ± 9.0	24,600 ± 15,400	1,420 ± 1,080	30.9 ± 28.4	37.8 ± 28.9	53.7 ± 32.8	32.8 ± 33.2
	Paddy	93	12.1 ± 13.8	15,320 ± 5,220	1,010 ± 450	19.6 ± 13.61	12.3 ± 13.1	41.1 ± 27.1	43.47 ± 33.83

C/N ratio	C/P ratio	TP (mg/kg)	TK (mg/kg)	NO_3^--N (mg/kg)	NH_4^+-N (mg/kg)	Soluble P_2O_5 (mg/kg)	Soluble K_2O (mg/kg)	pH
19 ± 10.4	22 ± 37.4	2,400 ± 2,690	6,230 ± 6,000	25.1 ± 73.7	6.5 ± 28.8	64.0 ± 106.4	157.3 ± 224.1	6.5 ± 3.3
20 ± 10.7	21 ± 37.5	2,610 ± 2,790	6,660 ± 6,240	27.7 ± 78.0	6.1 ± 27.3	70.1 ± 111.6	172.8 ± 233.0	6.4 ± 0.8
17 ± 7.3	25 ± 36.6	860 ± 407	2,920 ± 1,400	5.5 ± 8.8	9.5 ± 38.2	18.6 ± 20.5	40.4 ± 64.1	7.7 ± 9.3

±: SD

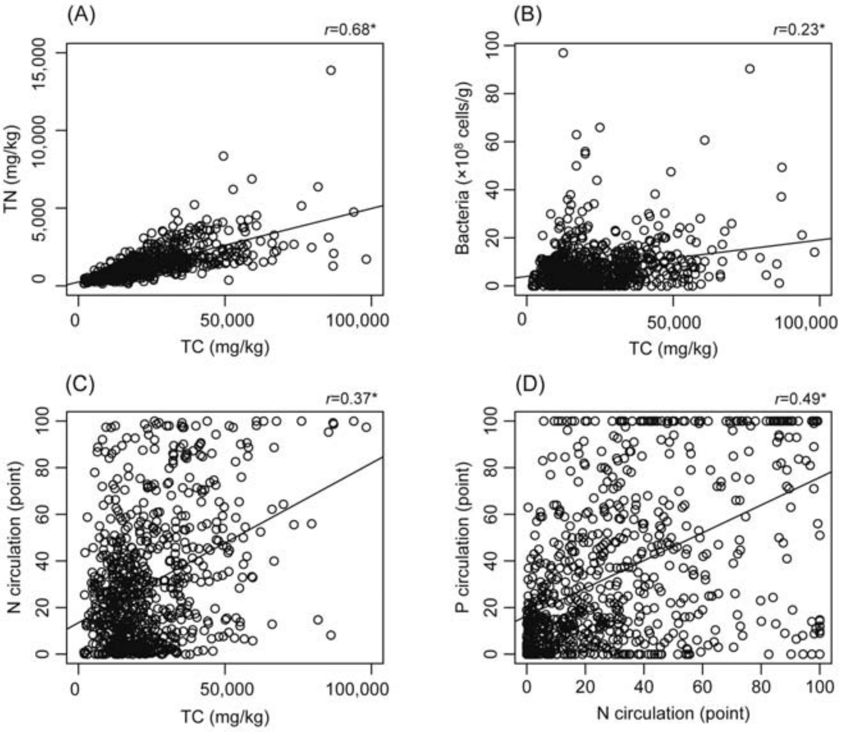

Fig. 1. Correlations between SOFIX parameters of 795 agricultural field samples. (A) TC and TN, (B) TC and bacterial biomass, (C) TC and N circulation activity and (D) N and P circulation activities. *indicates $p < 0.01$.

correlated with TC and TN ($r = 0.39$ and $r = 0.61$, respectively, $p < 0.01$). Bacterial biomass and the N circulation activity weakly correlated with TC ($r = 0.23$ and $r = 0.37$, respectively, $p < 0.01$; Fig. 1B and C). These results suggest that the concentration of nutrients and other factors are important for bacterial activity. The N circulation and P circulation activities correlated with each other ($r = 0.49$, $p < 0.01$; Fig. 1D), suggesting that suitable biomass and nutrient control could lead to maintenance of bacterial biomass and their activities.

The correlations between bacterial biomass and NH_4^+ oxidation, NO_3^- oxidation, and P circulation activities were positive but weak ($r = 0.23$, $r = 0.21$, $r = 0.16$, $p < 0.01$). These results indicated that material circulation activities were primarily influenced by bacterial biomass but other factors also seemed to interfere with the activities of microorganisms in the soil [20, 21].

3.2. Differences between upland and paddy fields

To understand the differences in soil properties between upland and paddy fields, the SOFIX data for both groups were compared. The average value of bacterial biomass was significantly higher in paddy fields than in upland fields (Table 1). Specifically, 16% of samples in upland soils had bacterial biomass below the detection limit (< 6.6×10^6 cells/g-soil), whereas only 5% were below the detection limit in paddy soils (Fig. 2C). In addition, many samples with low levels of bacterial biomass (< 2.0×10^8 cells/g-soil) were observed (33%) in the upland field soils, whereas the bacterial biomass in paddy field soils had a wide range with no polarization. Therefore, the frequency distributions of bacterial biomass were quite different between upland and paddy field soils. This result indicates that the water flooding system in paddy fields provided suitable conditions for environmental microorganisms.

The P circulation activity showed a similar trend to bacterial biomass in upland and paddy field soils, but the N circulation activity was lower in paddy fields than in upland fields (Table 1, Fig. 2D and E). As rice plants efficiently use the NH_4^+ form of N, the amount of NH_4^+-N seemed to be lower in the paddy fields. As a result, the NH_4^+ oxidation rate was lower in paddy fields (12.3 points) than in upland fields (37.8 points).

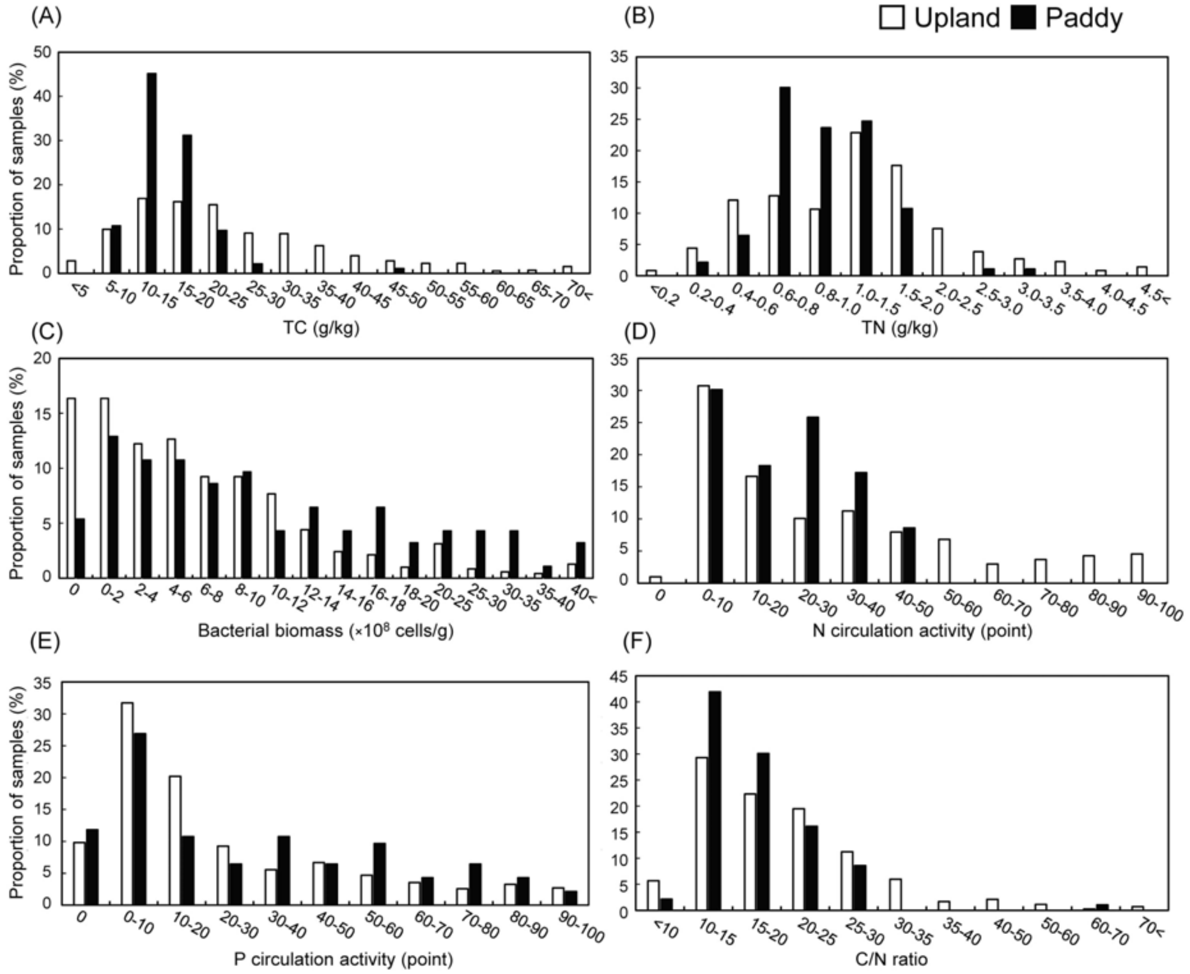

Fig. 2. Frequency distribution of the six SOFIX parameters for upland and paddy fields. (A) TC, (B) TN, (C) bacterial biomass, (D) N circulation activity, (E) P circulation activity and (F) C/N ratio are shown. White bar shows values for upland fields and black for paddy fields.

In paddy fields, both TC and TN were lower than those in upland fields (Table 1). The frequency distributions of TC, TN, and the C/N ratio were similar in the two fields, but the range was narrow in the paddy fields (Fig. 2A-C). In addition, other nutrients such as TP, TK, NO_3^--N, SP, and SK were also lower in the paddy fields than the upland fields, which might be caused by the difference in fertilizer management between the two field types.

3.3. Relationship between bacterial biomass and TC

Among the SOFIX parameters, bacterial biomass and TC are among the most important factors related to soil fertility. Generally, bacterial biomass is enhanced in TC-rich soil, but no correlation was found between these two parameters (Fig. 1B). The features of SOFIX parameters were quite different between upland and paddy fields, and therefore the relationship between bacterial biomass and TC was analyzed separately in upland and paddy fields. In upland soils, a large number of samples had high TC (above 25,000 mg/kg), but the range of TC values in paddy field soils was narrow, ranging from about 10,000 to 30,000 mg/kg (Fig. 3A-B). Low or undetectable (below the detection limit) levels of bacterial biomass were frequently observed in the upland field soils, while bacterial biomass in the paddy field was distributed over a wide range. Therefore, the soil properties based on SOFIX parameters were largely different between upland and paddy fields.

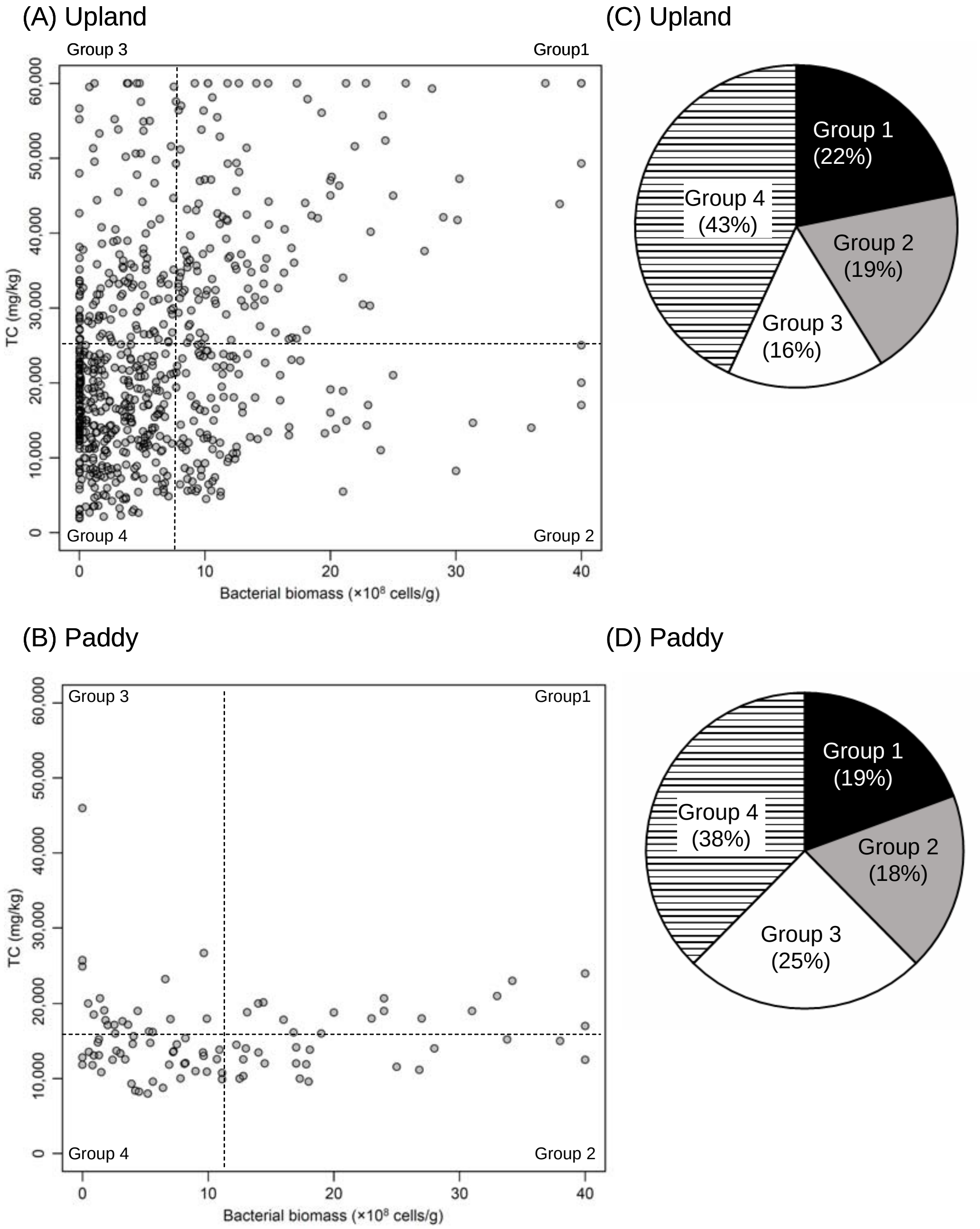

Fig. 3. The relationships and categories between bacterial biomass and total carbon (TC). Distribution of bacterial biomass and TC for each sample are plotted in (A) upland and (B) paddy fields. Dashed lines show the average values of bacterial biomass and TC in each field, categorized into the four groups. The proportion of soil samples in each group for (C) upland and (D) paddy fields. Black shows group 1, gray is group 2, white is group 3 and banding pattern is group 4.

3.4. Features of upland fields

To understand the agricultural environment in upland fields, the upland soils were categorized into four groups based on bacterial biomass and TC (Table 2). The four groups, group 1 (high bacterial biomass and high TC), group 2 (high bacterial biomass and low TC), group 3 (low bacterial biomass and high TC), and group 4 (low bacterial biomass and low TC), were defined by the average values of bacterial biomass and TC (Table 1 and Fig. 3A).

Table 2. Categories of each pattern for upland and paddy fields.

Pattern	Upland		Paddy		
	Bacterial biomass (×10^8 cells/g)	TC (mg/kg)	Bacterial biomass (×10^8 cells/g)	TC (mg/kg)	Soil property
1	≥ 7.0	≥ 25,000	≥ 12.0	≥ 15,000	High bacterial biomass and high TC
2	≥ 7.0	< 25,000	≥ 12.0	< 15,000	High bacterial biomass and low TC
3	< 7.0	≥ 25,000	< 12.0	≥ 15,000	Low bacterial biomass and high TC
4	< 7.0	< 25,000	< 12.0	< 15,000	Low bacterial biomass and low TC

About half of the upland field soils belonged to group 4 (Fig. 3C), suggesting that conventional agricultural management systems in Japan have led to a decrease in both TC and bacterial biomass. Samples with high values of bacterial biomass and TC (group 1) had generally been treated with suitable organic fertilizers, but the sample number was limited (22%). Group 3 had high organic content in the soil environment (high TC) but the bacterial biomass was low, indicating that these upland fields might have used organic fertilizers but had also been treated with agrochemicals. Conventional agricultural management usually causes a reduction in bacterial biomass, but the appropriate use of chemical fertilizers and agrochemicals can lead to maintenance of bacterial biomass in soil (group 2) [22].

The N circulation and P circulation activities in group 2 were lower than those in group 1, but bacterial biomass was almost the same in these groups (Table 3). This result suggests that the nutrient status in the soil affects bacterial activities. Thus, it is considered that the values of SOFIX parameters of group 1 should provide a suitable environment for both microbial growth and the material circulation in the soil.

Many crop species are cultivated in the upland fields and soil fumigation is sometimes necessary to prevent continuous cropping failure. The excessive and extensive use of agrochemicals for long periods seems to reduce the viability of microorganisms in the soil (bacterial biomass below the detection limit in groups 3 and 4). Extremely low levels of bacterial biomass because of the long-term use of pesticides such as dichloropropan-dichloropropene (DD), fosthiazate, and chloropicrine have been reported in our previous study [23].

3.5. Features of paddy fields

The average value of TC in the paddy field soils was lower than that in the upland field soils, but the range was narrow (15,320 ± 5,220 mg/kg; Fig. 3). The paddy soils were also categorized into four groups in the same way as for the upland soils (Fig. 3B).

The proportions of groups 1 and 2 (19% and 18%) of the paddy field soils were almost the same as for the upland field soils (Fig. 3D), but the ranges of bacterial biomass were wider when compared with the upland fields. Values of bacterial biomass in groups 3 and 4 of paddy field soils were relatively higher than those in groups 3 and 4 of the upland field soils (Tables 3 and 4). These results indicate that the environmental conditions of the paddy field, including cultivation under flooded conditions, are suitable for the growth and viability of microorganisms. In fact, nitrogen-fixing bacteria and facultative anaerobic bacteria coexist in the rice field soil and these microorganisms contribute to the nitrogen supply capacity of the soil [24, 25].

In the paddy fields, a single plant species (rice) is cultivated every year and an established agricultural system has been used in most fields of Japan for a long time. Continuous cropping failure is rare in paddy fields even though it is a mono-cropping system. Soil fumigation is not generally needed because of the tolerance of rice plants and the flooded cultivation conditions. About 5% of paddy soils had bacterial biomass below the detection limit, and the bacterial biomass in all groups was relatively high compared with those in the upland fields, suggesting that the accumulation of agrochemicals in paddy fields might be low compared with that in the upland fields [26].

Table 3. The average values of SOFIX parameters in four groups of upland.

Group	Sample No.	Bacterial biomass ($\times 10^8$ cells/g)	TC (mg/kg)	TN (mg/kg)	N circulation activity (point)	NH_4^+ oxidation rate (point)	NO_2^- oxidation rate (point)	P circulation activity (point)
1	158	20.9 ± 11.0	4,1800 ± 14,600	2,280 ± 1,070	59.1 ± 27.6	52.0 ± 33.4	78.8 ± 29.1	47.9 ± 37.2
2	140	16.7 ± 9.6	14,700 ± 5,900	980 ± 450	44.5 ± 24.1	43.9 ± 27.7	55.0 ± 28.5	40.4 ± 35.3
3	114	22.2 ± 1.9	37,200 ± 11,700	2,100 ± 1,540	19.4 ± 19.9	32.7 ± 25.3	50.6 ± 31.9	26.5 ± 30.4
4	312	19.2 ± 1.8	14,900 ± 5,900	890 ± 480	13.3 ± 14.9	27.3 ± 24.3	44.3 ± 31.4	27.0 ± 29.4

C/N ratio	C/P ratio	TP (mg/kg)	TK (mg/kg)	NO_3^--N (mg/kg)	NH_4^+-N (mg/kg)	Soluble P_2O_5 (mg/kg)	Soluble K_2O (mg/kg)
21 ± 9.4	29 ± 51.3	3,640 ± 3,830	9,590 ± 9,120	21.2 ± 24.0	7.3 ± 26.4	113.6 ± 181.9	284.4 ± 323.7
17 ± 7.9	18 ± 39.6	1,970 ± 1,680	5,200 ± 3,370	21.34 ± 41.0	5.8 ± 24.9	84.8 ± 85.5	142.4 ± 171.5
22 ± 14.0	254 ± 37.9	3,850 ± 3,570	7,740 ± 7,870	56.03 ± 132.2	7.2 ± 28.8	73.8 ± 101.8	200.1 ± 200.0
19 ± 10.6	17 ± 24.3	1,790 ± 1,630	5,310 ± 3,450	22.7 ± 77.5	9.9 ± 34.9	38.3 ± 49.1	112.8 ± 179.7

±: SD

Table 4. The average values of SOFIX parameters in four groups of paddy fields.

Group	Sample No.	Bacterial biomass ($\times 10^8$ cells/g)	TC (mg/kg)	TN (mg/kg)	N circulation activity (point)	NH_4^+ oxidation rate (point)	NO_2^- oxidation rate (point)	P circulation activity (point)
1	18	26.4 ± 10.8	18,800 ± 2,500	1,390 ± 330	30.3 ± 9.5	23.6 ± 15.8	35.9 ± 27.3	58.6 ± 29.2
2	17	22.0 ± 12.0	12,200 ± 1,600	860 ± 170	25.5 ± 11.1	18.7 ± 17.6	40.9 ± 24.0	43.6 ± 28.5
3	23	3.6 ± 3.0	20,100 ± 6,500	1,070 ± 680	14.4 ± 13.5	8.8 ± 9.0	46.5 ± 37.0	34.7 ± 36.2
4	35	5.5 ± 3.6	12,000 ± 2,000	840 ± 260	15.0 ± 12.7	9.0 ± 9.9	40.3 ± 20.4	40.4 ± 36.0

C/N ratio	C/P ratio	TP (mg/kg)	TK (mg/kg)	NO_3^--N (mg/kg)	NH_4^+-N (mg/kg)	Soluble P_2O_5 (mg/kg)	Soluble K_2O (mg/kg)
14 ± 3.0	49 ± 53.0	820 ± 500	3,300 ± 1,760	11.8 ± 14.1	2.2 ± 1.8	7.1 ± 10.0	27.1 ± 48.1
15 ± 2.9	24 ± 29.2	800 ± 380	2,430 ± 520	5.7 ± 5.5	0.9 ± 1.2	12.6 ± 10.9	16.0 ± 16.9
23 ± 11.1	26 ± 45.1	750 ± 480	2,760 ± 1,290	3.7 ± 7.6	8.9 ± 10.8	19.2 ± 20.6	42.7 ± 57.7
15 ± 4.7	12 ± 2.8	970 ± 280	3,070 ± 1,520	3.2 ± 5.8	17.83 ± 61.1	27.2 ± 24.5	57.8 ± 83.5

±: SD

3.6. Summary of soil fertility in upland and paddy fields

Features of the soil in the upland and paddy fields were clearly different, especially when comparing the ranges of bacterial biomass and TC. Cropping system, fertilizer management, water management and the soil environment seemed to affect the soil fertility.

The values of organic matter, bacterial biomass, and material circulation activity were relatively higher in group 1 soils of both fields. In the upland fields, the optimal values of soil fertility ranged from 27,000 to 61,000 mg/kg of TC, 1,200 to 3,700 mg/kg of TN, 600 to 6,000 of TP, 2,400 to 26,100 of TK, 11 to 31 of C/N ratio and 7 to 68 of C/P; 80% of group 1 soils fell within these ranges. In the paddy fields, the optimal values of soil fertility ranged from 16,000 to 23,000 mg/kg of TC, 1,000 to 1,900 mg/kg of TN, 200 to 1,600 of TP, 1,000 to 4,800 of TK, 22 to 29 of C/N ratio and 14 to 160 of C/P ratio; 80% of group 1 soils fell within these ranges.

CONCLUSION

Well balanced organic nutrients lead to enhanced microbial activity and material circulation, but persistent agrochemicals and their residues seem to inhibit these activities in this investigation. Hence, it can be concluded that sustainable agricultural management practices to maintain the soil environment are required in Japan.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest.

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