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A survey of soil fertility in turfgrass soil of Japanese golf courses by using SOFIX technique

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ABSTRACT
Japan has numerous golf courses, covering up to 0.37% of the country's total land area. These golf courses require intensively managed turf, and the soil environment in turfgrass fields differs significantly from that in agricultural environments. To understand the characteristics of turfgrass fields in Japan, a study was conducted that constructed and analyzed a database of 178 soil samples from golf courses across the country using the soil fertility index (SOFIX) technique. The turfgrass field database was statistically compared with agricultural field databases, including upland, paddy, and orchard fields, using the Mann-Whitney U test. The results indicated that the average bacterial biomass in turfgrass fields was 6.1×10^8 cells per gram of soil, which is comparable to that in orchard and upland fields ($p > 0.01$). The average values for total carbon (TC), total nitrogen (TN), total phosphorus (TP), and total potassium (TK) were 9,960 mg/kg, 540 mg/kg, 390 mg/kg, and 1,560 mg/kg, respectively, with these values distributed within narrow ranges. Although the levels of TC, TN, TP, and TK in turfgrass fields were lower than those in agricultural fields ($p < 0.01$), the bacterial biomass remained relatively high. These findings suggest that turfgrass fields in Japanese golf courses are likely managed with similar practices, characterized by intensive application of chemical fertilizers. The high bacterial biomass is attributed to carbon sources from clipping activities and reduced fumigation practices on golf courses. Further research on the application of organic fertilizers is recommended to promote sustainable land use and improve turfgrass management practices in golf courses across Japan.

Contribution/Originality: Unlike ordinary agricultural fields, turfgrass fields involve intensive soil management practices as a perennial cultivation system. This study presents the characteristics of soil fertility in turfgrass fields of golf courses in comparison with upland, paddy, and orchard fields in Japan.

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1. INTRODUCTION

Approximately 12,000 species of grass have been identified worldwide (Liu et al., 2021; Soreng et al., 2017), but only about 50 are used as turfgrasses (Beard, 1973). Based on seasonal growth, horticultural turfgrasses can be classified as warm- and cool-season grasses. The optimal growth temperatures for cool- and warm-season grasses are 16–24°C and 27–35°C, respectively (DiPaola & Beard, 1992). Turfgrasses are primarily cultivated in golf, soccer, and baseball fields worldwide. In the United States, the total area of turfgrass and crops is 163,812 km^2, which is three times larger than that of any integrated crop (Milesi et al., 2005). According to Weinand, Pelser, Kleinebrahm, and Stolten (2025), there were approximately 38,400 golf courses worldwide, with 80% located in the top ten countries in 2024. The United States has the highest number of golf courses, with over 16,000, followed by the United Kingdom with approximately 3,100, and Japan with around 2,700. On average, Chinese golf courses are the largest, about 0.8 km^2, followed by Japan at approximately 0.5 km^2. Golf courses in Japan occupy a significant area of land use, accounting for 0.37%.

Because living turfgrass fields are ecosystem services, proper management practices of turfgrass are beneficial to the environment and human health (Braun, Mandal, Nwachukwu, & Stanton, 2024; Côté & Grégoire, 2021; Ives et al., 2017; Kondo, Jacoby, & South, 2018). Particularly, soil management is crucial for turfgrass since it is a perennial grassland ecosystem. Carbon and nitrogen contents in turfgrass soil are mainly from grass mowing and accumulate after long-term cultivation (Gautam, Young, Sapkota, Longing, & Weindorf, 2020; Law & Patton, 2017; Phillips et al., 2023). However, soil improvement practices such as ploughing or using solid organic fertilisers cannot be applied in turfgrass fields. Therefore, liquid and granular chemical fertilisers are typically used in turfgrass fields. In this situation, the soil environment of turfgrass fields is different compared to ordinary agricultural fields, such as paddies, uplands, and orchards.

The soil fertility index (SOFIX) was developed to evaluate soil fertility and shows the biological, chemical, and physical parameters of the soil. A database for upland, paddy, and orchard fields in Japan was constructed using SOFIX analytical data (Pholkaw et al., 2020) and displayed the specific tendencies of soil fertility in each field. Owing to the unique management of turfgrass, soil fertility in turfgrass fields might be different from that in agricultural fields. Recent studies separately focused on microbial community, soil organic carbon, or physical properties in turfgrass soil (Beirn et al., 2017; Chou et al., 2024; Lewis, Gaussoin, Shearman, Mamo, & Wortmann, 2010; Singh et al., 2019). However, the database of soil fertility in turfgrass fields in Japan has not been thoroughly analyzed. This study investigated the soil fertility of golf course fields in Japan using SOFIX to construct a database. The features of turfgrass fields were clarified based on the SOFIX database and compared with agricultural field data.

2. MATERIALS AND METHODS

2.1. Collection of Soil Sample

Soil samples were collected from putting greens across 178 golf courses in Japan between 2018 and 2020. Samples were taken from the top 0–5 cm soil layer, an area strongly affected by fertilizer application and mowing. The samples were sieved through a 2 mm mesh and stored at 4 °C until analysis. Subsequently, soil biological and chemical properties were analyzed.

2.2. Analytical Methods

Bacterial biomass was estimated by quantifying environmental DNA (eDNA) using the slow-stirring method (Aoshima et al., 2006). Soil samples (1.0 g) were mixed with 8.0 ml of DNA extraction buffer [100 mmol/l Tris–HCl (pH 8.0), 100 mmol/l sodium EDTA, 100 mmol/l sodium phosphate, 1.5 mol/l NaCl, and 1% hexadecylmethylammonium bromide (CTAB)] and 1.0 ml of autoclaved 20% (w/v) sodium dodecyl sulfate (SDS) solution. The sample solution was mixed in a 50-ml tube with propeller agitation at 1,500 rpm for 20 min at room temperature. Next, 1.5 ml of the sample solution was transferred to a 1.5-ml microtube. After centrifugation at 6,000 × g for 10 min at 20°C, 700 µl of supernatant was transferred into a 1.5-ml microtube into which an equal volume of chloroform–isoamyl alcohol [24:1 (v/v)] was then added before centrifugation at 18,000 × g for 10 min at 20°C. The aqueous phase (500 µl) was recovered into a 1.5-ml microtube by centrifugation at 18,000 × g for 20 min at 20°C and mixed with 300 µl of isopropanol. The pellet was then washed with 1.0 ml of cold 70% ethanol and centrifuged at 18,000 × g for 5 min at 20°C. The pellet of crude nucleic acid was dissolved in 50 µl of TE buffer (Tris/EDTA = 10:1 mmol/l) after drying under reduced pressure (eDNA solution). The extracted eDNA was quantified based on the intensity of the eDNA bands after electrophoresis on an agarose gel using Kodak 1D 3.6 Image Analysis Software (Kodak, CT, USA). The bacterial biomass in the soils was estimated using the equation $Y = 1.70 \times 10^8 X$ ($r^2 = 0.96$), where Y and X represent the bacterial biomass (g^{-1} of soils) and the amount of eDNA (µg/g), respectively.

Nitrogen (N) and phosphorus (P) circulation activities were examined. In brief, a 1-gram soil sample was mixed with a phytic acid solution (pH 7) containing 3.9 mg of phosphorus and incubated for three days at 25°C. A control sample was prepared using distilled water. Water-soluble phosphorus (SP) was extracted from the sample using 20 mL of distilled water and subsequently measured through the molybdenum blue assay. The increase in SP concentration served as an indicator of phosphorus cycling activity. The P circulation activity was calculated using the following formula and expressed on a scale from 0 to 100.

$$\text{P circulation activity (point)} = \frac{(\text{SP in P3} - \text{SP in P0}) - (\text{SP in W3} - \text{SP W0})}{\text{Total added P}} \times 100 \quad (1)$$

The analysis of N circulation activity was performed based on bacterial biomass, ammonium oxidation rate, and nitrite oxidation rate, with these parameters subsequently scaled from 0 to 100, where a bacterial biomass of 6.0×10^8 cells/g corresponded to a value of 100. Soil samples treated with ammonium sulfate or sodium nitrite (60 µg N/g dry soil) were incubated at 25°C for three days. The percentage reduction in the added nitrogen was used to determine the ammonium and nitrite oxidation rates. A radar chart was constructed utilizing the calculated values of bacterial biomass, ammonium oxidation rate, and nitrite oxidation rate. The relative area of the inner triangle within the radar chart represented the N circulation activity, with its area calculated according to the following formula.

$$\text{Area} = \frac{(a\times b)+(b\times c)+(c\times a)}{4} \times \frac{\sqrt{3}}{100} \quad (2)$$

Where a, b, and c denote the bacterial biomass, ammonium oxidation rate, and nitrite oxidation rate, respectively. The N circulation activity was assessed by calculating the relative area of the inner triangle in the following manner.

$$\text{N circulation activity (point)} = \frac{\text{Area of the inner triangle}}{\text{Area of the outer triangle}} \times 100 \quad (3)$$

The total carbon (TC) of the samples was analyzed using a total organic carbon analyzer (SSM-5000A, Shimadzu, Kyoto, Japan). The total nitrogen (TN), total phosphorus (TP), and total potassium (TK) contents were analyzed after Kjeldahl digestion with copper sulfate, concentrated sulfuric acid, and hydrogen peroxide at 420 °C. In particular, TN and TP were determined by the indophenol blue and molybdenum blue methods, respectively, using a UV-visible spectrophotometer (U-1900 Spectrophotometer; Hitachi, Tokyo, Japan). The TK content was determined using an atomic absorption spectrophotometer (AA-7000, Shimadzu, Kyoto, Japan).

Soil pH and EC (1:2.5 soil-water mixture, w/v) were analyzed using a pH meter (LAQUA F-71, Horiba, Kyoto, Japan) and an electrical conductivity (EC) meter (5LE1-408, Kenis, Hyogo, Japan), respectively.

2.3. Data Analysis

Correlations (Pearson analysis) between parameters were determined using SPSS software (version 16.0, Chicago, USA). In all analyses, a probability value less than 0.01 was considered statistically significant ($p < 0.01$). Data on soil fertility in ordinary agricultural fields (orchard, paddy, and upland fields) were cited from our previous study for comparison (Pholkaw et al., 2020). Specifically, the database of soil samples was collected from 442 agricultural fields in Japan between 2014 and 2019. The soil samples included 190 from upland fields, 113 from paddy fields, and 139 from orchard fields. Soil samples in the upland fields, where vegetables, flowers, and cereal crops were cultivated, were collected. Orchard fields included apples, grapes, tea, and other crops. The Mann-Whitney U test, with a significance level of $p < 0.01$, was used to compare the differences in soil parameters (bacterial biomass, TC, TN, TP, and TK) between turfgrass fields and agricultural fields.

3. RESULTS

3.1. Analysis of Soil Components of Turfgrass Field by SOFIX

The chemical and biological properties of 178 soil samples from turfgrass fields were presented in Table 1 and compared to those from the agricultural fields in Table 2. TC values ranged from 4,470 to 23,000 mg/kg, with an average value of 9,960 mg/kg. Approximately 80% of the soil samples had values between 7,230 and 13,420 mg/kg. TN values ranged from 90 to 2,420 mg/kg, with an average of 590 mg/kg. TP values ranged from 120 to 1,090 mg/kg, with an average of 390 mg/kg. TK values ranged from 450 to 4,800 mg/kg, with an average of 1,760 mg/kg. Bacterial biomass values ranged from not detected (N.D., below 6.6×10^6 cells/g soil) to 24.9×10^8 cells/g soil, with an average of 6.1×10^8 cells/g soil. The nitrogen (N) and phosphorus (P) circulation activities varied significantly across different golf courses. The average N and P circulation activities were 16.5 and 5.3 points, respectively. Soil pH, electrical conductivity (EC), and water content showed minimal variation in turfgrass soil.

As a result, the values of TC, TN, TP, TK, and bacterial biomass in turf soil were low and showed narrower distributions compared to those in the agricultural fields. Therefore, soil management practices appear to be similar among golf courses across Japan.

Table 1. Analysis of soil fertility in turfgrass field.

TC (mg/kg)	TN (mg/kg)	TP (mg/kg)	TK (mg/kg)	Bacterial biomass ($\times 10^8$cells/g-soil)	N circulation activity (Point)	P circulation activity (Point)	pH	EC (ds/m)	Water content (%)
9,960 ± 3,270	590 ± 380	390 ± 170	1,760 ± 740	6.1 ± 4.1	16.5 ± 13.0	5.3 ± 9.0	6.4 ± 0.4	0.06 ± 0.08	16.4 ± 5.3

Table 2. Range of soil fertility in turfgrass fields compared to that in agricultural fields.

Field	Bacterial biomass ($\times 10^8$cells/g-soil)	TC (mg/kg)	TN (mg/kg)	TP (mg/kg)	TK (mg/kg)
Turfgrass	N.D. ~ 24.9	4,470 ~ 23,000	91 ~ 2,420	120 ~ 1,090	450 ~ 4,800
Upland	N.D. ~ 49.4	2,110 ~ 118,700	224 ~ 4,430	29 ~ 8,600	430 ~ 33,600
Paddy	N.D. ~ 97.0	7,990 ~ 26,640	380 ~ 2,750	0 ~ 2,800	410 ~ 11,000
Orchard	N.D. ~ 77.0	2,670 ~ 128,100	130 ~ 6,400	140 ~ 5,360	1,210 ~ 18,160

Note: N.D. is not detected bacterial biomass lower than lower than 6.6 $\times 10^6$ cells/g.

3.2. Relationship Between Total Carbon (TC) And Bacterial Biomass in the Turfgrass Field and Ordinary Agricultural Fields

Figure 1 presents the relationship between TC and bacterial biomass of turfgrass soils. TC values were clustered around the average value (9,960 mg/kg), while the total bacterial biomass was distributed over a wide range. A weak correlation (r = 0.43, p = 0.00) was observed between TC and bacterial biomass. Figure 2 presents the comparison between TC and bacterial biomass of turfgrass fields with that of upland, paddy, and orchard fields. TC and bacterial biomass were distributed within a narrow range in the turfgrass field, a tendency resembling that observed in paddy fields. TC values in the turfgrass field were the lowest of the four fields ($p < 0.01$); however, bacterial biomass was almost the same as that in upland and orchard fields ($p > 0.01$).

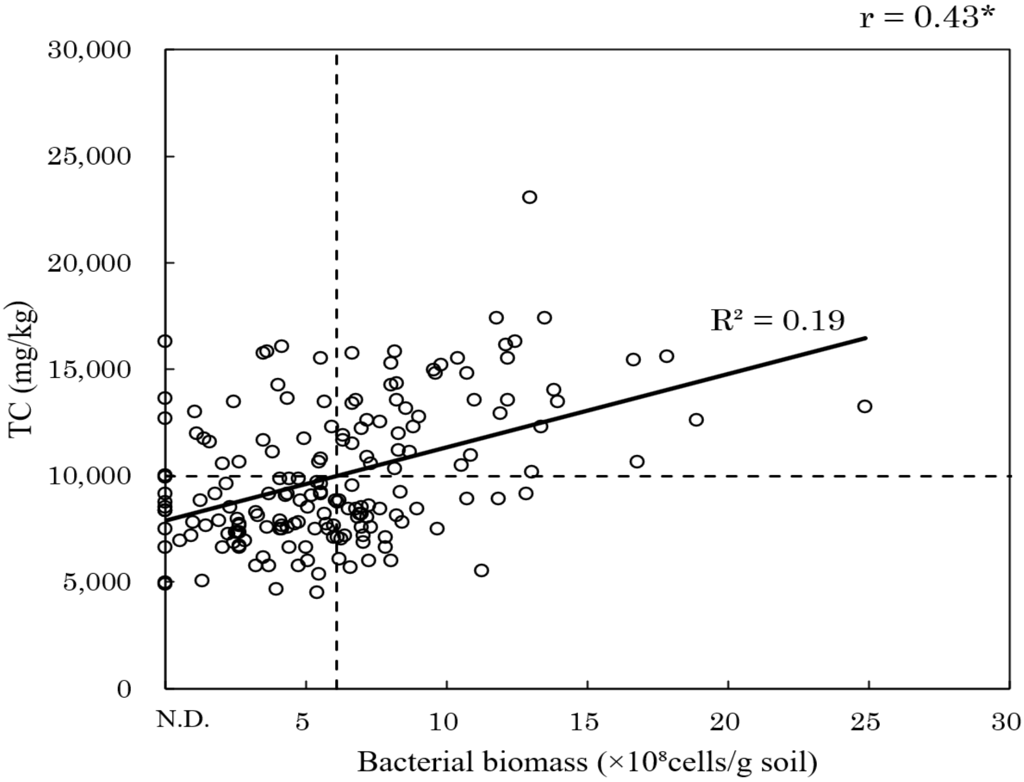

Figure 1. Relationship between TC and bacterial biomass of turfgrass field.

Note: A positive correlation was statistically significant between TC and bacterial biomass. * indicates significant correlation at 0.01 level. N.D. is not-detected bacterial biomass lower than 6.6 × 10^6 cells/g soil. The dashed line shows average values.

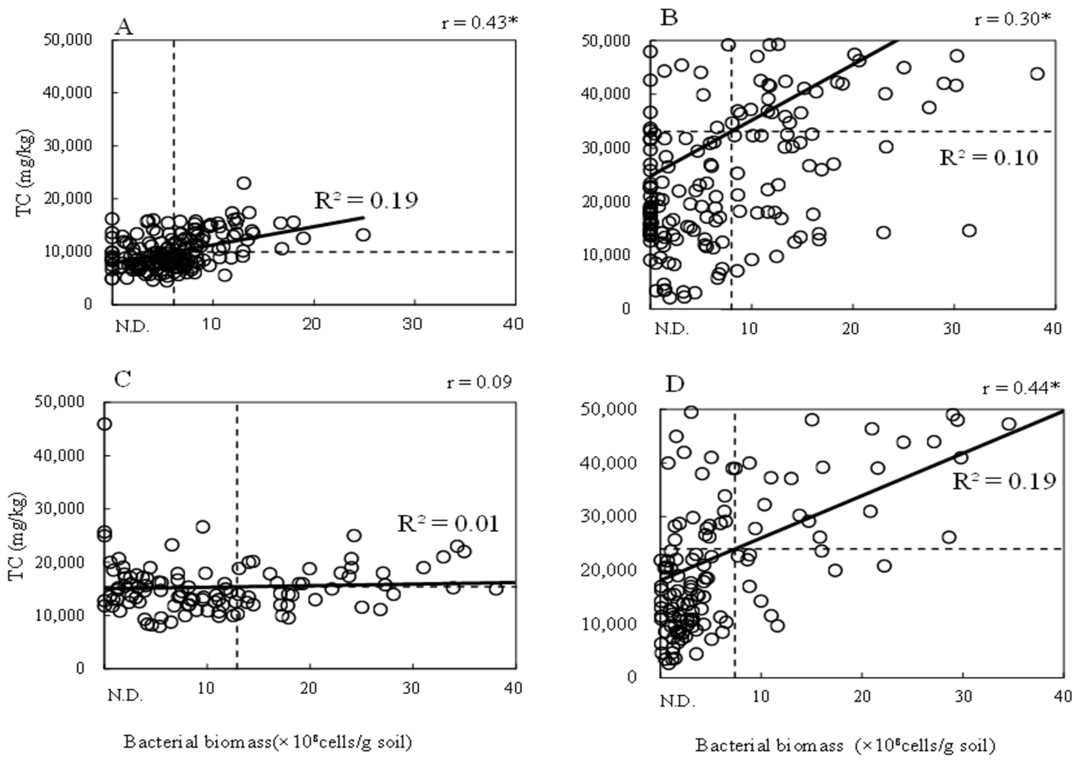

Figure 2. Relationship between TC and bacterial biomass of turfgrass field (A); upland field (B); paddy field (C); orchard field (D).

Note: Correlations were significant between TC and bacterial biomass in all fields, except for the paddy field.* indicates significant correlation at the 0.01 level. N.D. indicates bacterial biomass lower than 6.6×10^6 cells/g soil. The dashed line shows average values.

3.3. Relationship Between Total Carbon (TC) and Total Nitrogen (TN) in the Turfgrass Field, and Comparison with That in the Other Fields

The relationship between TC and TN in the turfgrass soils is shown in Figure 3. TC and TN were distributed within a narrow range and showed a weak correlation (r = 0.31, p < 0.01). The TC and TN databases from turfgrass fields were compared with those from upland, paddy, and orchard fields (Figure 4). The correlations between TC and TN in the upland, paddy, and orchard fields were relatively strong.

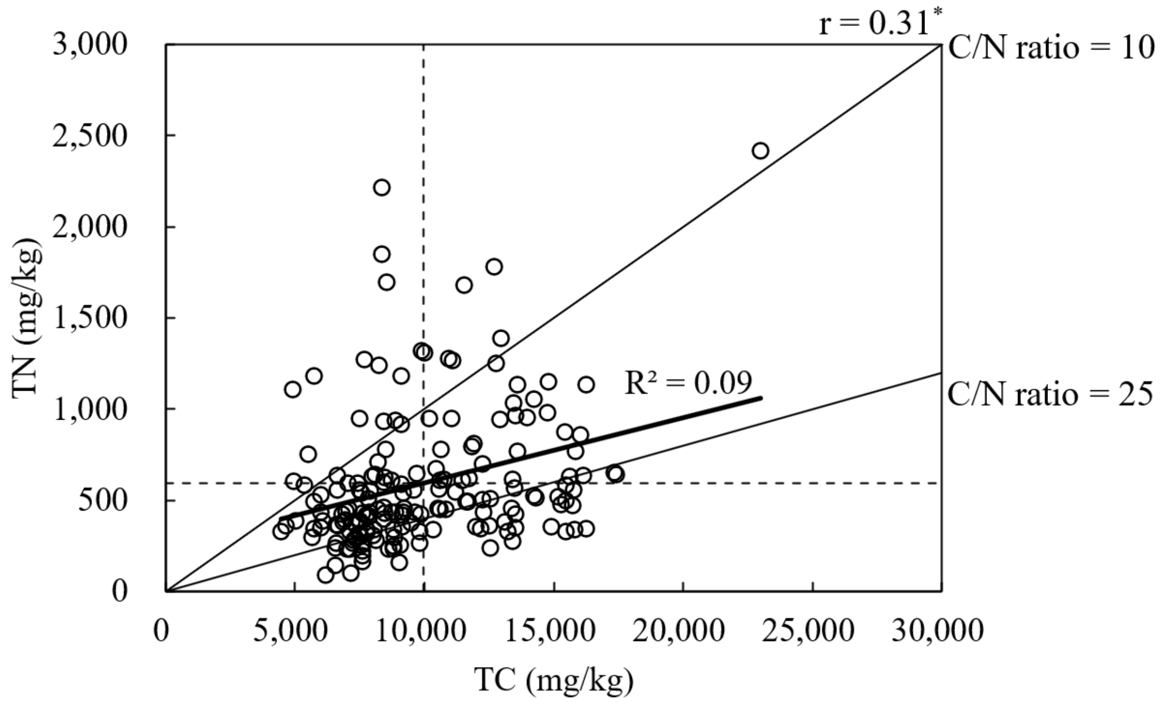

Figure 3. Relationship between TC and TN of turfgrass field.

Note: As a result, TC was significantly correlated with TN. * indicates significant correlation at 0.01 level. The dashed line shows average values.

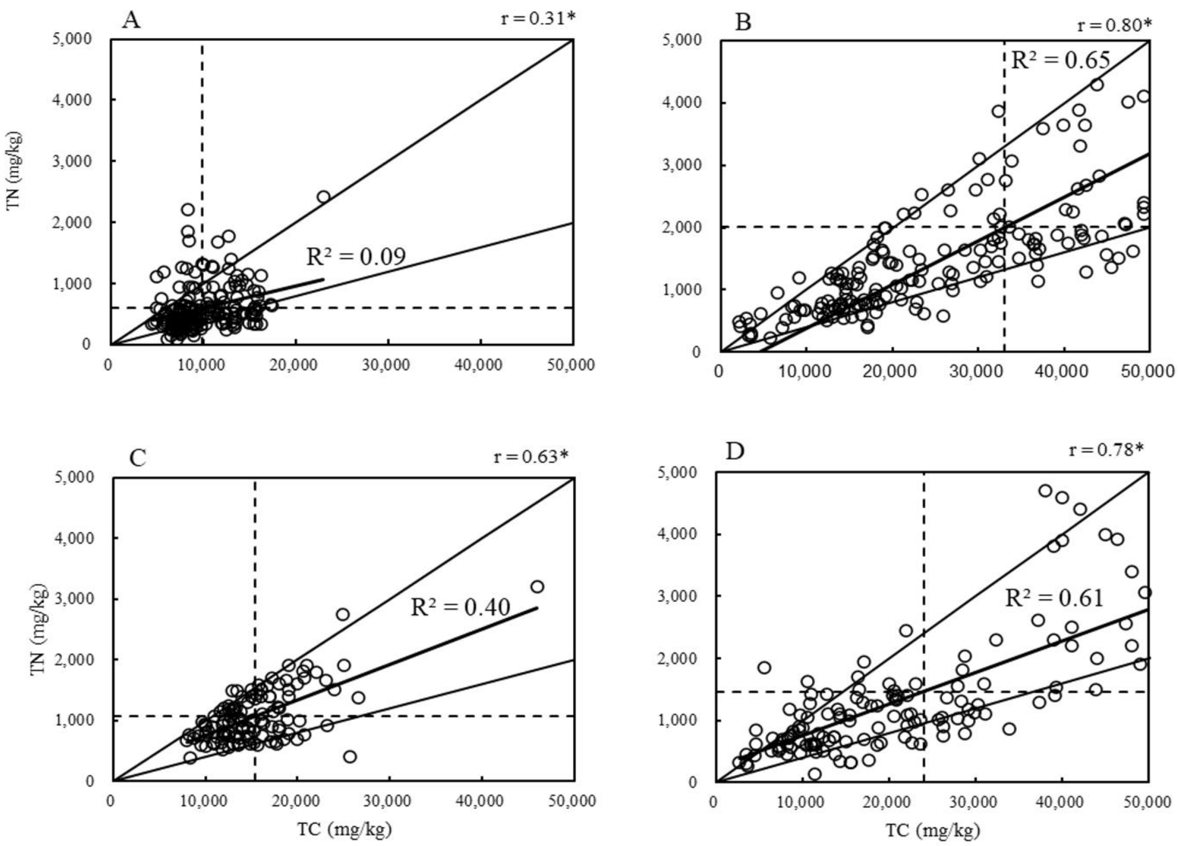

Figure 4. Relationship between TC and TN of turfgrass field (A); upland field (B); paddy field (C); orchard field (D).

Note: There were significant correlations of TC and TN in all fields. * indicates significant correlation at 0.01 level. The dashed line shows average values.

3.4. Relationship Between Total Carbon (TC) and Total Phosphorus (TP) in the Turfgrass Field, and Comparison of Other Fields

Figure 5 presents the relationship between TC and TP in turfgrass soils. TC and TP values were distributed within a narrow range, similar to TC and TN values. TC and TP values showed a weak correlation ($r = 0.31$, $p < 0.01$). The database of TC and TP from turfgrass fields was also compared with those from upland, paddy, and orchard fields (Figure 6). The TC and TP values were both clustered around their average values, similar to those in paddy fields.

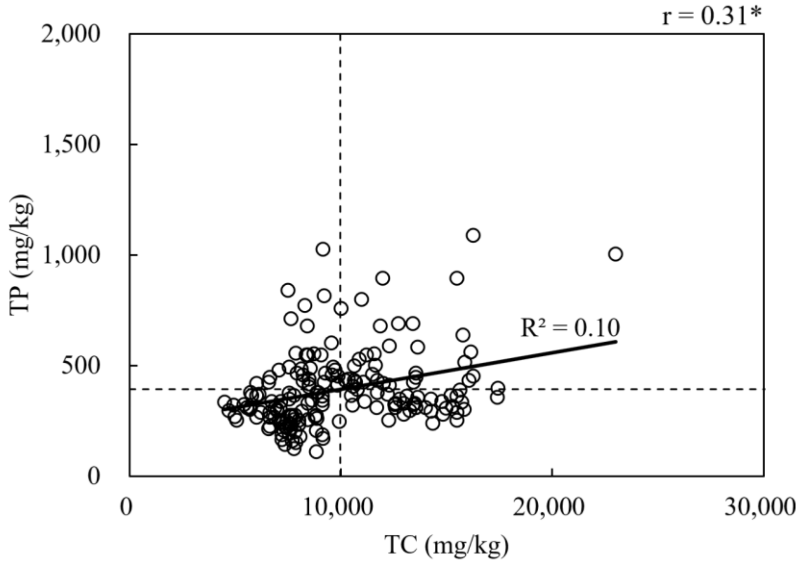

Figure 5. Relationship between TC and TP of turfgrass field.

Note: The data showed a significant correlation between TC and TP contents. * indicates significant correlation at 0.01 level. The dashed line shows average values.

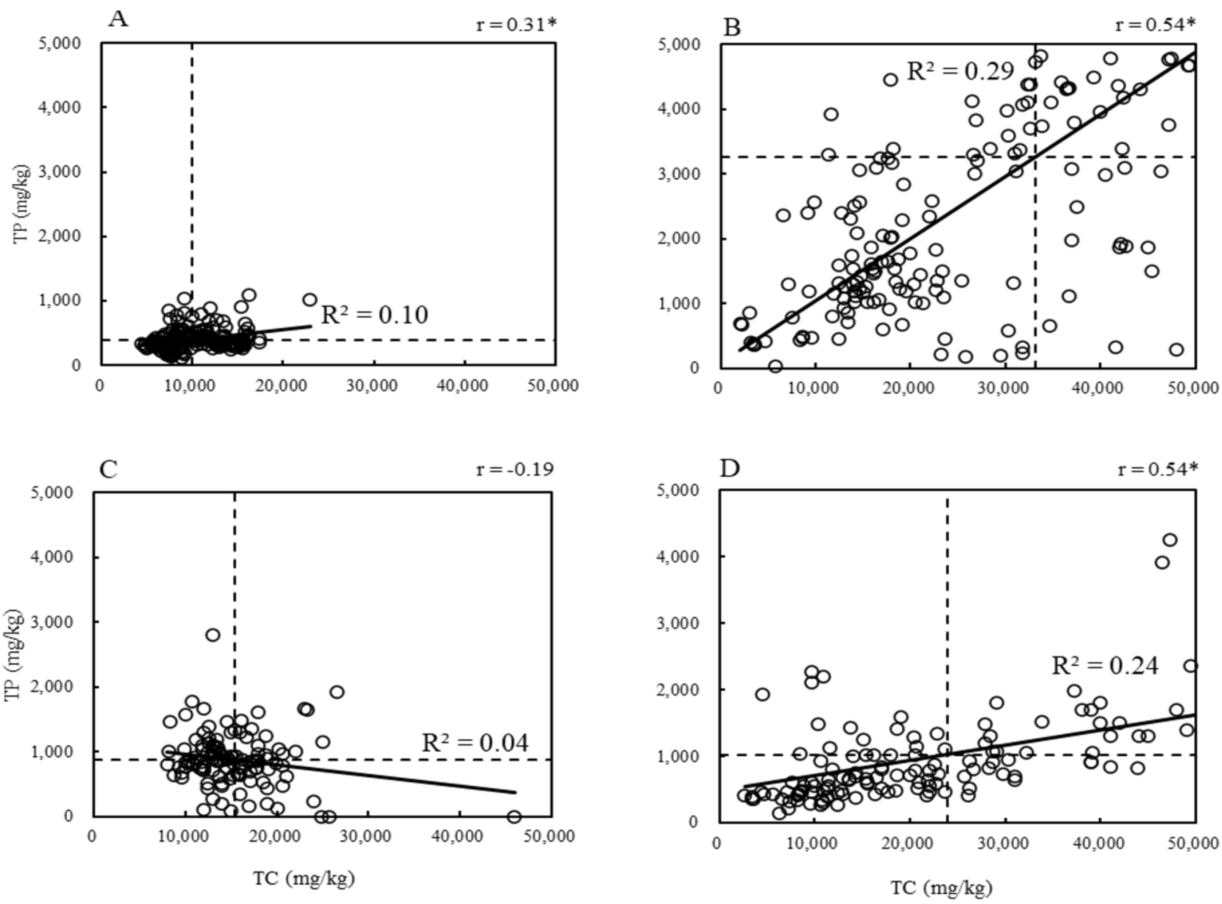

Figure 6. Relationship between TC and TP of turfgrass field (A); upland field (B); paddy field (C); orchard field (D).

Note: A significant positive correlations was observed between TC and TP at all fields, except for paddy field. * indicates significant correlation at 0.01 level. The dashed line shows average values.

3.5. Relationship Between Total Carbon (TC) and Total Potassium (TK) in the Turfgrass Field, and Comparison with That in Other Fields

The relationship between TC and TK in turfgrass soils is shown in Figure 7. The TC and TK values were also distributed in a narrow range. TC and TK values were weakly correlated (r = 0.27, $p < 0.01$). TC and TK values were also clustered around their average value. Figure 8 shows the TC and TK databases in the four fields. The distribution of TC and TK values between turfgrass and paddy fields was similar.

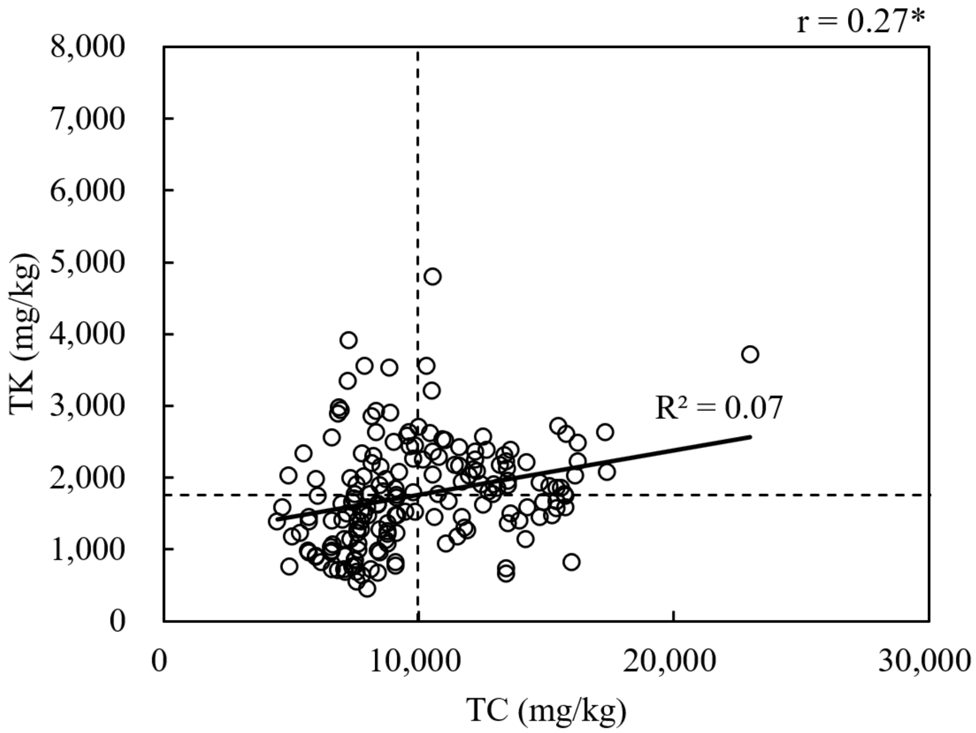

Figure 7. Relationship between TC and TK of turfgrass field.

Note: The Pearson correlation coefficient between TC and TK indicated a weak correlation. * indicates significant correlation at 0.01 level. The dashed line shows average values.

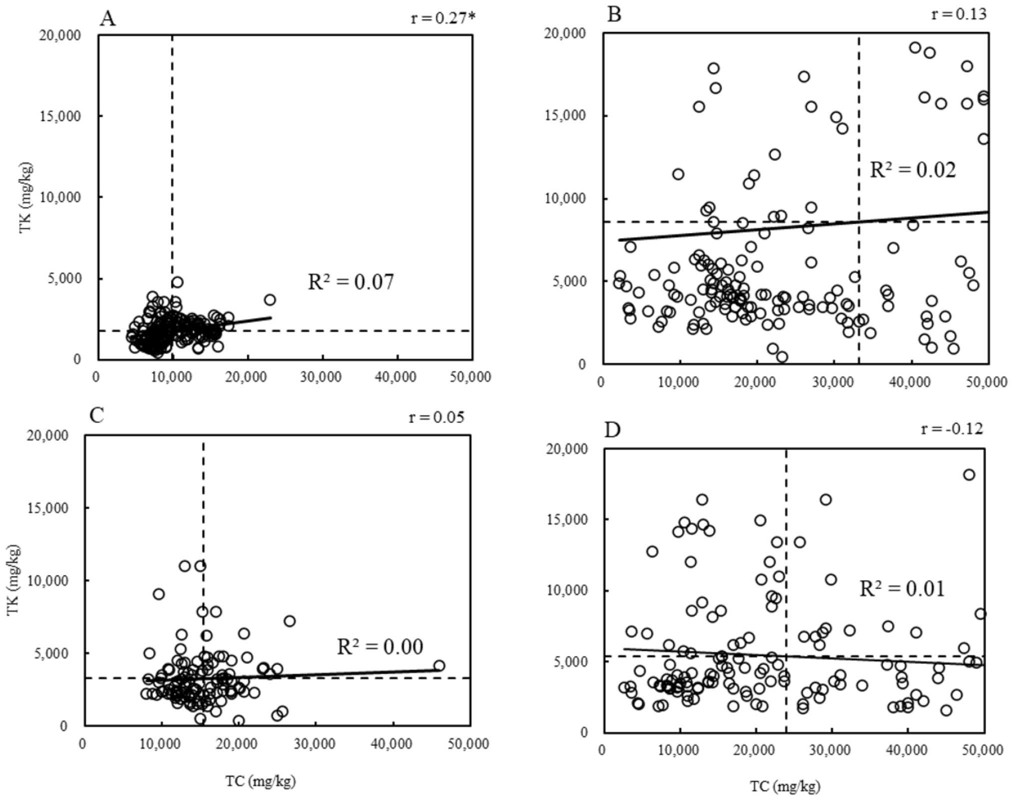

Figure 8. Relationship between TC and TK of turfgrass field (A); Upland field (B); Paddy field (C); Orchard field (D).

Note: In contrast to turfgrass fields, no significant correlation was observed between TC and TK in the agricultural fields. * indicates significant correlation at the 0.01 level. The dashed line shows average values.

3.6. Features of Turfgrass Field

The distributions of bacterial biomass, TC, TN, TP, and TK in turfgrass were within a narrow range compared to those in agricultural fields and resembled those in paddy fields. The results indicate that the unique construction practices of golf courses led to similar soil conditions in turfgrass fields across Japan.

4. DISCUSSION

4.1. Variation of Bacterial Biomass

The variation in bacterial biomass in golf course turfgrass was narrower than in ordinary agricultural fields (Fig. 2). Although the average TC value in turfgrass was lower than in orchard and upland fields, the bacterial biomass values were similar. Generally, soil bacterial biomass depends on the total amount of organic matter in the soil. Soil samples in the putting greens were collected at a 0–5 cm depth, which was affected by clipping activities. In turfgrass fields, mowing frequency provides a constant source of organic matter for bacteria. The easily decomposable organic compounds from clipping grass maintain bacterial biomass in the soil. According to Shi, Muruganandam, and Bowman (2006), with only a small fraction of clipping grass, up to 20–30% of clipping C and N are mineralised within seven days, and rapid decomposition coincides with active microbial growth. Soil microbial biomass at a depth of 0–5 cm remains stable during several chronological developments of turfgrass. Bacterial phyla and fungal classes in turfgrass soils remain consistent over time and across plant compartments (Doherty, Crouch, & Roberts, 2021). In addition, fumigation management is likely not popular in turfgrass fields. In some prefectures in Japan, it is prohibited to use chemicals to control weeds and pests in golf courses built after 1994 (Yasuda & Koike, 2006; Yasuda, Koike, & Terman, 2008) since it presumably protects bacterial biomass in the soil.

4.2. Nutrient Circulation Activities

Nitrogen circulation activities refer to the nitrification processes, wherein ammonium is converted to nitrite and nitrate, while phosphorus circulation activities refer to phytate conversion to soluble inorganic phosphorus by bacterial activities. Nitrogen and phosphorus circulation activities are lower in turfgrass stands than in agricultural fields. Nitrogen circulation activities are strongly affected by the activities of bacterial biomass, whereas phosphorus circulation activity is dependent on the bacterial biomass and mineral content in the soil. Overall, the nitrogen circulation activities (16.5 points) were higher than the phosphorus circulation activities (5.3 points) (Table 1). Turfgrasses require significantly less phosphorus (P) compared to flowering crops; therefore, P is not typically applied to established golf courses. Moreover, while animal manures are commonly utilized in the cultivation of most agricultural crops, their use in turfgrass management is comparatively limited. This limitation arises from several factors: the higher cost of granulating manure fertilizers, the difficulty of applying them in liquid form, and the objectionable odor associated with these fertilizers, which is not suitable for the aesthetic standards of a golf course. In contrast, nitrogen sources in golf course soils come from chemical N-rich fertilizers and clipping grass (Law, Trappe, Jiang, Turco, & Patton, 2017). Nitrogen circulation is controlled by soil nitrifying bacteria. In soil, ammonium is assimilated by heterotrophic microbes and then used for nitrification. However, nitrifiers in turfgrass soils compete with heterotrophs and increase their nitrification activity (Beirn et al., 2017; Shi, Yao, & Bowman, 2006). The integration of chemical and organic fertilizers, along with the development of organic agricultural systems for turfgrass management, will enhance material circulation, particularly P cycling activities.

4.3. The Variation of Soil Chemical Properties

The TC, TN, TP, and TK contents in the turfgrass field were lower than those in the agricultural fields. As organic fertilizers cannot be applied for turfgrass management, TC in turfgrass fields almost solely originates from clippings. Since the correlation between TC and TN in turfgrass fields was weaker than in agricultural fields, chemical fertilizer treatments are widely applied. The variations in TC, TN, TP, and TK were narrower in turfgrass fields than in agricultural fields, suggesting that the management practices of turfgrass fields are similar across Japanese golf courses.

Returning clippings to the field can gradually increase total carbon (TC) and nutrients in the soil because mineralisation is promoted by high bacterial biomass. Returning clippings for 10–50 years reduces nitrogen (N) fertilisation by 25% compared to returning clippings for 1–10 years and increases soil carbon sequestration by 11–59% for 10–50 years after turf establishment (Knot et al., 2017; Law et al., 2017; Qian et al., 2003). Furthermore, the application of organic fertilizers can rapidly enhance soil carbon sequestration and improve the carbon-to-nitrogen (C/N) balance, either prior to turf establishment or during cultivation.

5. CONCLUSIONS

This study aimed to characterize the soil fertility of turfgrass fields in golf courses in comparison with agricultural fields (orchards, paddies, and uplands) in Japan. Bacterial biomass in turfgrass was relatively high and similar to that in orchards and upland fields, while TC, TN, TP, and TK values were lower than those in the agricultural fields and within a narrow range. N- and P-circulation activities were lower in turfgrass fields than in agricultural fields. As a result, putting greens at golf courses, characterized by their intensive chemical fertilizer management practices and perennial growth, create a distinct environment that differs from any conventional agricultural cropping system. To promote material circulation and sustainable land use for golf courses, the application of suitable organic fertilizers can be considered for further research in turfgrass soil.

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Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.
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