

Analysis of Chemical and Biological Soil Properties in Organically and Conventionally Fertilized Apple Orchards

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Abstract

We compared chemical and biological properties of soils in organically and conventionally fertilized apple orchards in Nagano Prefecture (one of the major apple producing regions in Japan). Five apple orchards with different fertilizer management systems were used for this study. The total carbon and total nitrogen contents were higher in the organically fertilized orchard, while the total phosphorus and total potassium were at similar levels in both organically and conventionally fertilized orchards. The bacterial biomass did not differ between the two orchards, but the N circulation activity was clearly higher in the organically fertilized orchard from April to December. Total carbon from 50,000 to 60,000 mg/kg, total nitrogen at about 3000 to 4000 mg/kg, and a C/N ratio of 15 - 20 were suggested to be suitable conditions for a high level of apple production under an organic fertilizer management system.

Keywords

Component, Formatting, Style, Styling, Insert, Organic Fertilizer Management System, Apple, Bacterial Biomass, Nitrogen Circulation Activity

1. Introduction

Apples (*Malus domestica* Borkh.) are one of the old cultivated fruits in Japan and several other countries [1] [2]. Apple cultivation requires a deep and well-drained soil with a pH of 5.5 to 6.5 [3]. Soils rich in organic matter and high in available nitrogen, phosphorus, and potassium are most suitable for apple cultivation. In Japan, ap-

ple is cultivated conventionally, relying on the use of large amounts of chemical fertilizers and pesticides. Only 1.4% of the apple and other temperate organic fruit orchards (about 1100 ha) are under organic production systems [4].

The average productivity of apples in Japan is $21.2 \text{ t}\cdot\text{ha}^{-1}$, which is lower than that in other developed countries, such as $77.9 \text{ t}\cdot\text{ha}^{-1}$ in Austria $47.4 \text{ t}\cdot\text{ha}^{-1}$ in New Zealand, and $31.9 \text{ t}\cdot\text{ha}^{-1}$ in the USA [5]. Poor soil fertility seems to be one of the most important reasons for low apple productivity in Japan [1].

Besides chemical fertilizers, two other fertilizer management systems are also practiced for cultivating apple: the integration of organic and chemical fertilizers and the use of organic fertilizers only [6]-[8]. Previous studies suggest that productivity under organic agricultural systems is 20% to 30% lower than that under conventional chemical fertilizer systems [7] [9]. Stable and high agricultural productivity from organic fertilizer based systems can be achieved by improving the number and activity of soil microorganisms through the control of the total carbon (TC), total nitrogen (TN), and C/N ratio in soil [10]. Apple orchards are relatively rich in TC, TN, total phosphorus (TP), and total potassium (TK), compared with the annual croplands such as uplands and paddy fields (Kai *et al.*, 2015). Therefore, the soil fertility improvement under organic fertilizer management systems should be considered for orchard soils specifically.

We have previously studied the effects of physical and biochemical properties of soil on apple productivity under the chemical fertilizer management system and have found that too much TC, TN, TP, and TK lead to yield reduction [11]. In the current study, we compare soil fertility between organically and chemically fertilized apple orchards to determine the suitable soil conditions needed to enhance microbial numbers and activity in an organic fertilizer management system.

2. Materials and Methods

2.1. Study Sites

In 2014, we selected five high yielding apple orchards in Nagano Prefecture, Japan (Orchards A, B, C, D, and E) differing in fertilizer management system (Figure 1). All of the orchards were 10 to 30 years old. The climate of Nagano Prefecture is humid temperate, where July is the warmest and January is the coolest month.

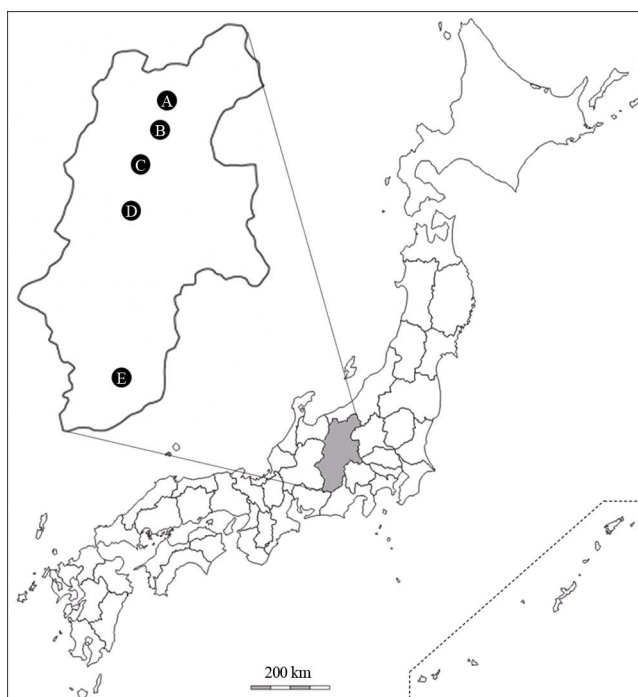


Figure 1. Map of Japan showing locations of the five apple orchards in this study. A, Iizuna Town; B, Nagano City; C, Sakaki Town; D, Ashahi Village; and E, Matsukawa Town.

The main difference between the five selected orchards is fertilizer management. The orchards can be divided into three categories based on the fertilizer management system used over the past 10 years or more: 1) conventional (use of chemical fertilizers only) (Orchards A and D); 2) conventional + organic (Orchards B and E) and; 3) organic only (Orchard C). In Orchards A and D, chemical fertilizers are applied at the rate of 144 kg N, 72 kg P₂O₅, 48 kg K₂O, 4.8 kg MnO, and 2.4 kg B per hectare, annually. Total fertilizer is split into two halves and applied in December (after harvesting) and in March (before flowering). In Orchard C, cattle manure is applied annually at the rate of 35 t/ha. In Orchards B and E, rice straw is applied at the rate of 1.2 t/ha in combination with the chemical fertilizers at the same rate to those in orchards A and D. In all orchards, pesticides are applied according to the recommendations by the Nagano Prefecture Agricultural Policy and Planning Department, Japan [12].

2.2. Chemical Properties of Soils

Composite soils samples (top 15 cm except for the top 2 - 3 cm surface crust) were taken near the bases of five randomly selected trees. The following chemical properties of the composite soil samples were analyzed: TC, TN, ammonium-nitrogen (NH₄⁺-N), nitrate-nitrogen (NO₃⁻-N), TP, water soluble phosphorus (SP), TK, and water soluble potassium (SK). The TC content was analyzed with a TOC analyzer (Model: SSM-5000A, Shimadzu, Kyoto, Japan). NH₄⁺-N and NO₃⁻-N were analyzed by extracting the soil sample with 1 M KCl followed by indophenol blue method and brucine method [13]. To analyze the SP and SK the soil-water suspension (1:20, w/v) was shaken reciprocally at 100 rpm for 1 h and the extracts were analyzed for by the-molybdenum blue method [14] and atomic absorption spectrophotometry, respectively. The TN, TP, and TK contents were analyzed by digesting soils in a Kjeldahl Therm digestion unit (Gerhardt, Königswinter, Germany) with H₂SO₄ and H₂O₂, followed by determinations of NH₄⁺-N, SP and SK in the digest. The pH of the soil-water suspension (1:2.5, w/v) was analyzed using a pH meter (Model: LAQUA F-72, Horiba Scientific, Kyoto Japan).

2.3. Biological Properties of Soils

The following biological properties were analyzed: total bacterial biomass, ammonium oxidation activity, nitrite oxidation activity, N circulation activity, and P circulation activity. Total bacterial biomass was estimated by quantification of environmental DNA (eDNA) using the slow-stirring method following the procedures of Aoshima *et al.* [15]. The N circulation activity was analyzed using the values of ammonium oxidizing activity, nitrite oxidizing activity, and total bacterial number as described by [10] [16]. The P circulation activity was determined by analyzing the rate of release of soluble P from phytic acid (a dominant form of organic P in soil) during a 3-day incubation period [17] T. Kai *et al.*

2.4. Nutrient Contents in Leaves and Fruits

Leaves were sampled during July and fruit was sampled during December. A composite sample was prepared from five randomly chosen trees in each orchard. The TN, TP, and TK in leaves and fruits were analyzed by digesting leaf or fruit tissues in a KjeldahlTherm digestion unit following the same procedures as described above for soil samples.

3. Results

3.1. General Features of Apple Orchards in Nagano Prefecture

Fertilizer management system, average yield, and soil properties (TC, TN, TP, TK, and bacterial biomass) in the five apple orchards A-E are shown in **Table 1**. The average yields in the five orchards ranged from 30 to 50 t/ha. The TC, TN, and TK contents in the orchards ranged between 22,900 and 58,000 mg/kg, 1600 and 3970 mg/kg, and 6130 and 9600 mg/kg, respectively, while a wide range was observed in TP (2430 - 10,870 mg/kg). Most of the apple orchard soils were rich in TC, irrespective of the fertilizer management system, suggesting that the large amount of fallen leaves increased the TC levels in the apple orchard soils. The bacterial biomass in the soil also varied between the orchards (range: 5.7×10^8 to 11.4×10^8 cells/g). Bacterial biomass was enhanced under the organic fertilizer management system and in response to the amounts of TC in the soil.

Table 1. Fertilizer management, yield, soil chemical properties, and bacterial biomass in five differently fertilized apple orchards (Orchards A-C).

Orchard	Location	Fertilizer management ^a	Yield (t/ha)	TC (mg/kg)	TN (mg/kg)	TP (mg/kg)	TK (mg/kg)	Bacterial biomass ($\times 10^8$ cells/g)
A	Iizuna Town	Conv.	30	42,400	3230	2430	7270	8.9
B	Nagano City	Org. + Conv.	50	22,900	1600	4570	9600	5.7
C	Sakaki Town	Org.	45	53,700	3570	5730	6800	11.4
D	Ashahi Village	Conv.	50	48,800	2130	10,870	8770	6.4
E	Matsukawa Town	Org. + Conv.	45	58,000	3970	7830	6130	9.3
Average			44	45,160	2900	6290	7110	8.3

^aConv. = conventional, Org. = organic.

3.2. Comparison of Chemical Properties of Soils between Organically and Conventionally Fertilized Apple Orchards

The organically and conventionally fertilized orchards (Orchards C and D, respectively) were selected to consider the chemical properties of soils sampled from April to December (**Table 2**). The average apple productivity in these two orchards was almost the same (*i.e.*, 45 to 50 t/ha). The TC and TN contents were higher in Orchard C than in Orchard D; however, the TP and TK contents were higher in Orchard D throughout the observation period. Seasonal variations in TP and TK were observed in both orchards, but no significant differences were found. Inorganic N (NH_4^+ -N and NO_3^- -N), SP, and SK contents were slightly higher in Orchard C in April, but no differences were observed in July and December. Higher TP and TK contents but lower SP and SK contents in Orchard D than Orchard C indicate that the rate of fixation of P and K is increased under the chemical fertilizer management system.

3.3. Comparison of Biological Properties of Soils between Organically and Conventionally Fertilized Apple Orchards

Biological properties of soils in organically and conventionally fertilized orchards (Orchards C and D) from April to December are shown in **Table 3**. Bacterial biomass in April and July were at the same level in the two orchards, but the bacterial biomass in Orchard C was about 3 times higher than that of Orchard D in December. The N circulation activities were 63% to 83% higher in Orchard C than Orchard D throughout the observation period from April to December (**Figure 2**). The P circulation activity in Orchard C was higher than that in Orchard D in April, but it became lower than Orchard D in July and December. The soil conditions in an organically fertilized field seem suitable for microbial biomass and microbial material circulation activities.

3.4. Nutrient Contents in Leaves and Fruits

Nutrient contents (TN, TP, and TK) in the leaves (sampled in July) and fruit (sampled in December) in Orchards C and D were analyzed (**Table 4**). Higher levels of TN and TK in both leaves and fruits were observed in orchard C, while the TP in both leaves and fruits were higher in orchard D. In orchard C, the TN contents were 25.9% and 21.2% higher in leaves and fruits, respectively. Similarly, the TK contents were 20.2% and 88.2% higher in the leaves and fruits, respectively. However, the TP contents in leaves and fruits of orchard D were 83.7% and 50.0% higher, respectively. The higher rate of release of nutrients from the decomposition of organic materials by enrichment of bacterial biomass in Orchard C may enhance the levels of TN, TP, and TK in the tree leaves and fruits.

3.5. Suitable Soil Conditions for Organic Apple Production

In this study, five high yielding apple orchards were selected. The average apple yield in Orchard C was 45 t/ha, which was similar to that in orchards A, B, D, and E (**Table 1**). Based on the high levels of bacterial biomass and nutrient circulation activities and a high level of fruit yield, the soil conditions in orchard C can be considered suitable to enhance apple production in organically fertilized soil. Similarly, the average contents of TP

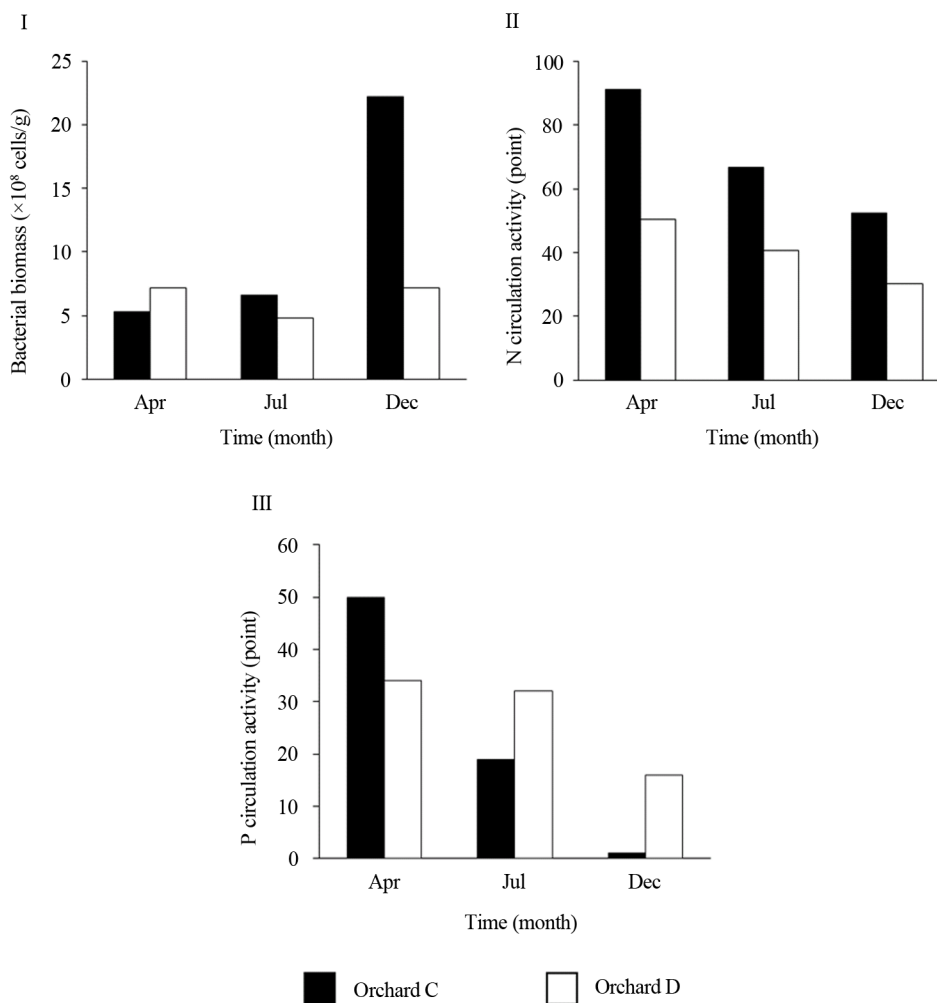


Figure 2. Seasonal changes in bacterial biomass (I), N circulation activity (II), and P circulation activity (III) in two orchards with different fertilizer management systems (Orchard C, organic; and Orchard D, conventional).

Table 2. Chemical properties of soils in two apple orchards (Orchards C and D).

Property	Orchard C			Orchard D		
	Apr	Jul	Dec	Apr	Jul	Dec
Total carbon (TC) (mg/kg)	58,100	35,800	67,200	45,700	42,300	58,300
Total nitrogen (TN) (mg/kg)	3000	1500	6200	2200	1600	2600
C/N ratio	19	24	11	21	26	22
NH ₄ ⁺ -N (mg/kg)	1	1	5	0	0	1
NO ₃ ⁻ -N (mg/kg)	4	6	0	0	0	9
Total phosphorus (TP) (mg/kg)	8600	4300	4300	13,400	7900	11,300
Soluble phosphorus (SP) (mg/kg)	163	30	7	143	52	81
Total potassium (TK) (mg/kg)	7600	6800	6000	7100	4700	14,500
Soluble potassium (SK) (mg/kg)	146	44	38	112	62	156

Table 3. Biological properties of soils in two orchards with different fertilizer management (Orchard C, organic; and Orchard D, conventional).

Property	Orchard C			Orchard D		
	Apr	Jul	Dec	Apr	Jul	Dec
Bacterial biomass ($\times 10^8$ cells/g)	5.3	6.6	22.2	7.2	4.8	7.2
NH ₄ ⁺ oxidation activity (%)	98	50	40	14	23	40
NO ₂ ⁻ oxidation activity (%)	99	52	84	23	100	36
N circulation activity (point)	91	67	52	50	41	30
P mineralization activity (%)	50	19	1	44	32	16

Table 4. Nutrient concentrations in leaves and fruits of apples grown in two orchards with different fertilizer management (Orchard C, organic; and Orchard D, conventional).

Plant part and orchard	TC (mg/kg-fresh weight)	TN (mg/kg-fresh weight)	TP (mg/kg-fresh weight)	TK (mg/kg-fresh weight)
Leaf (orchard C)	223,400	14,100	4300	11,300
Leaf (orchard D)	237,700	11,200	7900	9400
Fruit (orchard C)	61,300	400	200	3200
Fruit (orchard D)	60,800	330	300	1700

and TK in Orchard C can be considered suitable for apple production under the organic fertilizer management system. These optimum values for organic apple production are as follows: TC from 50,000 to 60,000 mg/kg, TN from 3000 to 4000 mg/kg, C/N ratio from 15 to 20, TP from 5000 to 6000 mg/kg, and TK from 6000 to 7000 mg/kg (Figure 3).

4. Discussion

In response to concerns about health and environmental issues, there is increasing pressure to use organic agricultural systems rather than conventional or chemical systems [18] [19]. An excellent organic agricultural system is necessary to meet our demand for healthy, tasty, and nutritious foods; however, the productivity of organic agriculture is often lower than other systems [9] [20]. Control of the suitable conditions of soil for higher number and activity of microorganisms can help to enhance not only the yield but also the quality of the agricultural products.

Growth and activity of soil microorganisms are enhanced in soils rich in organic matter. In this study, a high TC content is observed in apple orchard soils (average: 45,160 mg/kg), and the values are clearly higher than those in annual uplands and paddy fields [10]. Usually, most of the plant biomass is removed under the annual croplands (such as vegetables and cereal crops), which lead to a reduction in TC content. In contrast, only fruits are harvested and other biomass remains in the field for several years in the orchards. Large amounts of fallen leaves annually result in the accumulation of carbon in the apple orchard [11] [21] [22].

In addition to TC, most of the apple orchard soils in this study are rich in TN, TP, and TK. The use of large amounts of fertilizers and decomposition of the fallen leaves are likely to have caused the accumulation of these nutrients in the orchard soils [23]. Haynes and Goh [24] report that each year approximately 30 kg·N·ha⁻¹ is contained in leaves that have fallen from apple trees. The removal of accumulated nutrients may be necessary for the sustainability of orchards.

Average apple productivity in Japan is 21 t/ha (FAO, 2014), and poor soil fertility is one of the reasons for low apple production [25]. In this study, we select five high yielding apple orchards (30 to 50 t/ha), including an organically fertilized orchard (orchard C), to determine the suitable soil conditions for high levels of apple production under the organic agricultural system. Compared with the Japanese national average productivity (21 t/ha), almost double productivity (45 t/ha) is observed in the organically fertilized orchard. In this orchard, there is a high level of bacterial biomass and nitrogen circulation activity. In addition, levels of N, P, and K in leaves and fruits are higher in the organically fertilized orchard than in the conventionally fertilized orchard. Effec-

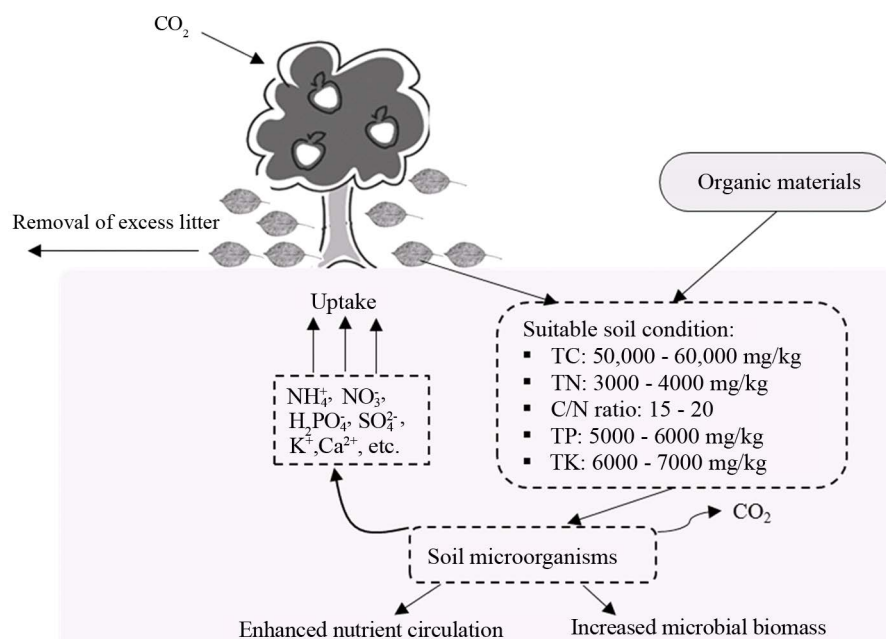


Figure 3. Schematic diagram showing the suitable conditions required for enhancing microbial numbers and nutrient circulation in soil for higher productivity of apples under the organic agricultural system.

tive management of the TC, TN, and C/N ratio in soil (TC of 50,000 - 60,000 mg/kg, TN of about 3000 mg/kg, and C/N ratio of 15 - 20) may enhance the bacterial biomass and activities; therefore, the environmental conditions in the organic orchard seem to be suitable for microbial decomposition of organic materials to increase the availability of mineral nutrients for plants [10]. Higher bacterial biomass and nitrogen circulation activities in the organically fertilized orchard (Orchard C) than in the conventionally fertilized orchard (Orchard D) also suggest that apple productivity can be improved by maintaining suitable conditions for soil microorganisms.

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