RESEARCH

Impacts of 25-year rotation and tillage management on soil quality in a semi-arid tropical climate

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ABSTRACT

Soil deterioration, yield decline and soil microbial activity reduction caused by banana (*Musa × paradisiaca* L.) monoculture is threatening the sustainability of banana production in China. Therefore, it is necessary to study the benefits of rotation on soil quality. This study aimed to assess the effects of rotation and tillage on soil properties in a banana plantation for 25 yr. Treatments consisted of three rotation methods (banana-pineapple, BA; banana-cowpea, BP; banana-rice, BR) and banana monoculture (CK) combined with two tillage intensities (no-tillage, NT; conventional tillage, CT). Soil samples were taken at depth of 0-40 cm in 2019-2020. In comparison with CK, BA and BR increased soil moisture, pH, total organic C and available P, but decreased soil bulk density. Microbial biomass C and N at booting stage were 46.1% and 39.2% higher in BA and BR than those in CK. Urease, dehydrogenase and β-glucosidase obtained a mean of 34.1% increase in BP and 23.8% increase in BR compared with BA. Higher total N, NO_3-N, available K and macroaggregate were showed in NT compared with CT, whereas porosity was 24.8% lower in NT than in CT. CO_2, N_2O and CH_4 emissions were in average around between one third and two fifth lower in no-tillage compared with conventional tillage. In general, rotations combined with no-tillage led to a positive effect on soil quality, as evidenced by increase of soil moisture, total N, microbial biomass C and urease and accompanying increase in banana yield. In order to sustain higher productivity, application of rotation and no-tillage is of considerable importance.

Key words: Gas emission, microbial biomass, monoculture, rotation, tillage.

INTRODUCTION

Rotation, no-tillage and crop residue addition greatly improve soil quality, mainly including soil physicochemical and biological properties (Shiwakoti et al., 2019). These practices finally increase crop yield and reduce greenhouse gas emissions (Zuber et al., 2017). For example, rotation potentially improves soil structure and density, decreases acidification and increases nutrient availability (Deuschle et al., 2019). No-tillage involving surface crop residue application has been adopted as a means to promote organic matter storage (He et al., 2020a), which often results in greater soil bacteria biomass and abundance. Meanwhile, no-tillage separates soil organic C (Xavier et al., 2019) and thus to ameliorate CO_2 emissions.

Soil microbial properties, such as microbial biomass and enzymes have been suggested as potential indicators for soil quality evaluation because they are involved in soil organic matter decomposition, C sequestration and nutrient availability (Legrand et al., 2018). Furthermore, they are easy to measure (easily adopted for routine laboratory testing), response rapidly to slight changes in less tillage and temporary changes originated by crops rotation. Actually, soil physicochemical and microbial parameters are mutually dependent. Many researchers pointed out that changes in microbial attributes with rotation and tillage should provide practical tools to complement physicochemical test (He et al., 2019) and, thus, evaluate the effects of conservation tillage.

With the decrease of per capita arable land area and the increase of cropping intensity, agricultural lands throughout the tropical region are being degraded. Conservation tillage such as integration of no-tillage and residue return into banana-based rotation systems has been proposed as a promising management option to support fruit productivity (Zhong and Zeng, 2020), reduce soil degradation and improve nutrient mineralization in tropical climate. Soil enzymatic activities and microbial biomass as integrative indicators of soil degradation had been assessed in monoculture combined with intensive tillage systems in subtropical climate (Mu et al., 2016), and were shown to be positively affected by conservation tillage practices in short-term studies (Yang et al., 2018). For example, long-term conventional tillage decreased soil enzymes (Bera et al., 2018) and 2 yr tobacco-based rotation increased soil bacterial biomass (Brandan et al., 2017). However, we are uncertain if there will be differences in these soil properties after long-term conservation tillage, especially under tropical fruit plantations. Therefore, the current study measured selected soil quality characters such as soil microbial biomass C and N, enzymatic activities and greenhouse gas emission involved in C and N cycling after 25 yr in banana-pineapple, cowpea and rice rotation compared to a 25 yr banana monoculture under no- and conventional tillage.

MATERIALS AND METHODS

Site descriptions

The experiment was carried out on the Ledong Experimental Station (18°36’39.2” N, 108°47’54.9” E), Chinese Academy of Tropical Agricultural Sciences since 1994. Climate of the region is tropical monsoon. Average annual temperature is 25.8 °C and average annual precipitation is 2065 mm. The test soil is aquic Cambisol (13.6% clay, 23.1% silt and 63.3% sand) according to the USDA texture classification; 7.12 g kg^{-1} total organic C, 0.76 g kg^{-1} total N, 0.59 g kg^{-1} total P, 1.21 g kg^{-1} total K and pH 6.53. Soil moisture, bulk density, porosity, water-stable aggregates (macroaggregate WSA_1, microaggregate WSA_2) were evaluated.

The experiment was a split-plot design with four replicates. Rotation management was the main plot and tillage system was the split-plot factor. Details of the treatments are showed in Table 1. The text field was divided into 32 plots and size of each plot was 80 (10 × 8 m) m^2. Rotation treatments were banana (*Musa ×paradisiaca* L.)-pineapple (*Ananas comosus* [L.] Merr. var. *comosus*) rotation (BA), banana-cowpea (*Vigna unguiculata* [L.] Walp.) rotation (BP), banana-rice (*Orysa sativa* L.) rotation (BR) and banana monoculture (CK). Tillage treatments were no-tillage (NT) and conventional tillage (CT). Each year, cow biochar compost (14.4 t ha^{-1}), with 53.3% water content, 145 g C kg^{-1}, 3.2 g N kg^{-1}, 2.5 g P_2O_5 kg^{-1}, 1.6 g K_2O kg^{-1}, were applied as basal fertilizer. Urea, superphosphate and sulfate were applied as additional fertilizer at 129 kg N ha^{-1}, 68 kg P ha^{-1} and 292 kg K ha^{-1}. CT plots were moldboard ploughed to 40 cm depth every year. NT plots were undisturbed, except when the crop was planted using a NT planter (2BQ-6, Kinze, Williamsburg, Iowa, USA). Residues were incorporated into soil in CT and covered soil surface in NT after harvest.

Soil sampling

Soil samples were taken from 0-40 cm depth at seedling stage (19 September 2019), jointing stage (18 December 2019), booting stage (15 March 2020) and ripening stage (17 May 2020) within the rows of banana for physicochemical properties, microbial biomass and enzymes analysis. Each sample was a composite comprising five random cores (2.5 cm diameter). The fresh samples were sieved through a 2 mm mesh and stored at 4 °C before subsequent analysis. Results were based on oven-dried weight of the soil.

Table 1. Description and site history of different treatments in the study area of a long-term crop rotation experiment.

Treatment	Crops	Planting year
Monoculture (CK)	Banana	June 1995-May 2020
Rotation 1 (BA)	Banana and pineapple	Banana: June 1995-May 2000, June 2005-May 2010, and June 2015-May 2020
		Pineapple: June 2000-May 2005 and June 2010-May 2015
Rotation 2 (BP)	Banana and cowpea	Banana: June 1995-May 2000, June 2005-May 2010, and June 2015-May 2020
		Cowpea: June 2000-May 2005 and June 2010-May 2015
Rotation 3 (BR)	Banana and rice	Banana: June 1995-May 2000, June 2005-May 2010, and June 2015-May 2020
		Rice: June 2000-May 2005 and June 2010-May 2015

In each rotation and monoculture plot, a no-tillage and a conventional tillage treatment were applied.

Soil physical and chemical properties were measured according to Kubar et al. (2018) and Hulugalle et al. (2007), respectively. Soils were weighed wet, oven-dried at 105 °C for 8 h, then weighed again to calculate soil moisture, bulk density and porosity. Soil water-stable aggregates were determined by the wet sieving method. Soil pH was measured in 1:4 soil:water suspension with glass electrode. Total N, NH_4-N and NO_3-N were determined using micro-Kjeldahl method. Total organic C was analyzed by dry combustion, using a total organic C analyzer (TOC 5000 total C analyzer; Shimadzu Corporation, Kyoto, Japan). After nitric-perchloric acid digestion, available P was determined by molybdenum-blue complex method; available K was analyzed by flame atomic absorption spectrometry; exchangeable Ca and exchangeable Mg were determined by atomic absorption spectrophotometry.

Urease, acid phosphatase, and dehydrogenase were determined based on the method of Tabatabai (1994). For urease, 5 g soil were incubated with 10 mL 10% urea solution for 24 h at pH 7.0 at 37 °C; for acid phosphatase, 1 g soil was incubated with the *p*-nitrophenyl phosphate substrate for 1 h at pH 6.5 at 37 °C; for dehydrogenase, 6 g soil were incubated with 5 mL 3% triphenyltetrazolium chloride for 24 h at pH 7.5 at 37 °C. Invertase, β-glucosidase and catalase were estimated according to the method of Notaro et al. (2018). For invertase, 5 g soil were incubated with 15 mL 8% sucrose solution for 24 h at pH 5.5 at 37 °C; for β-glucosidase 1 g soil was incubated; and for catalase, 2 g soil were incubated with 5 mL 0.3% H_2O_2 for 30 min at pH 7.0 at 30 °C. When their interactions were significant, individual comparisons were based on *p*-nitrophenyl-β-D-glucopyranoside substrate for 1 h at pH 6.0 at 37 °C. Enzymes were determined in fresh soil and based on the oven-dried soil weight.

Soil microbial biomass was measured by the chloroform fumigation-extraction method (Vance et al., 1987). Greenhouse gas emissions were measured every 40 d after crops transplanting; CO_2, NO_2 and CH_4 emissions were measured by non-steady state flow-through chambers (da Vitória et al., 2019). The chamber (0.5 m × 0.5 m × 2.0 m) with water groove on the top edge, was randomly installed into each plot to a 20 cm soil depth between two rows of bananas. A rubber stopper with a 3-way stopcock was placed in the wall of each chamber to take gas samples. Samples were analyzed by gas chromatography (HP-6890 gas chromatograph) equipped with a headspace autoanalyzer (HT3) (Agilent Technologies, Barcelona, Spain). Banana yield (t ha^{-1}) was estimated based on bunch weights, mat spacing, and average crop cycle duration (i.e., time between two subsequent harvests from the same mat) as used by Wairegi and van Asten (2010) in the same plots.

Statistical analysis

The genera linear model (GLM) for split-plot design was used to test the overall effect of rotation, tillage and sampling stage on soil microbial qualities and physicochemical properties. Separate one-way ANOVA was used to test the effects of rotation and tillage on soil microbial properties and environmental parameters at each sampling stage. The mean comparisons were based on an independent-samples T test. Linear correlation was used to characterize the relationship between physicochemical-microbiological parameters and greenhouse gas. All statistical analyses were performed by SPSS statistical software (SPSS Inc., Chicago, Illinois, USA). Difference at $P < 0.05$ level was considered significant.

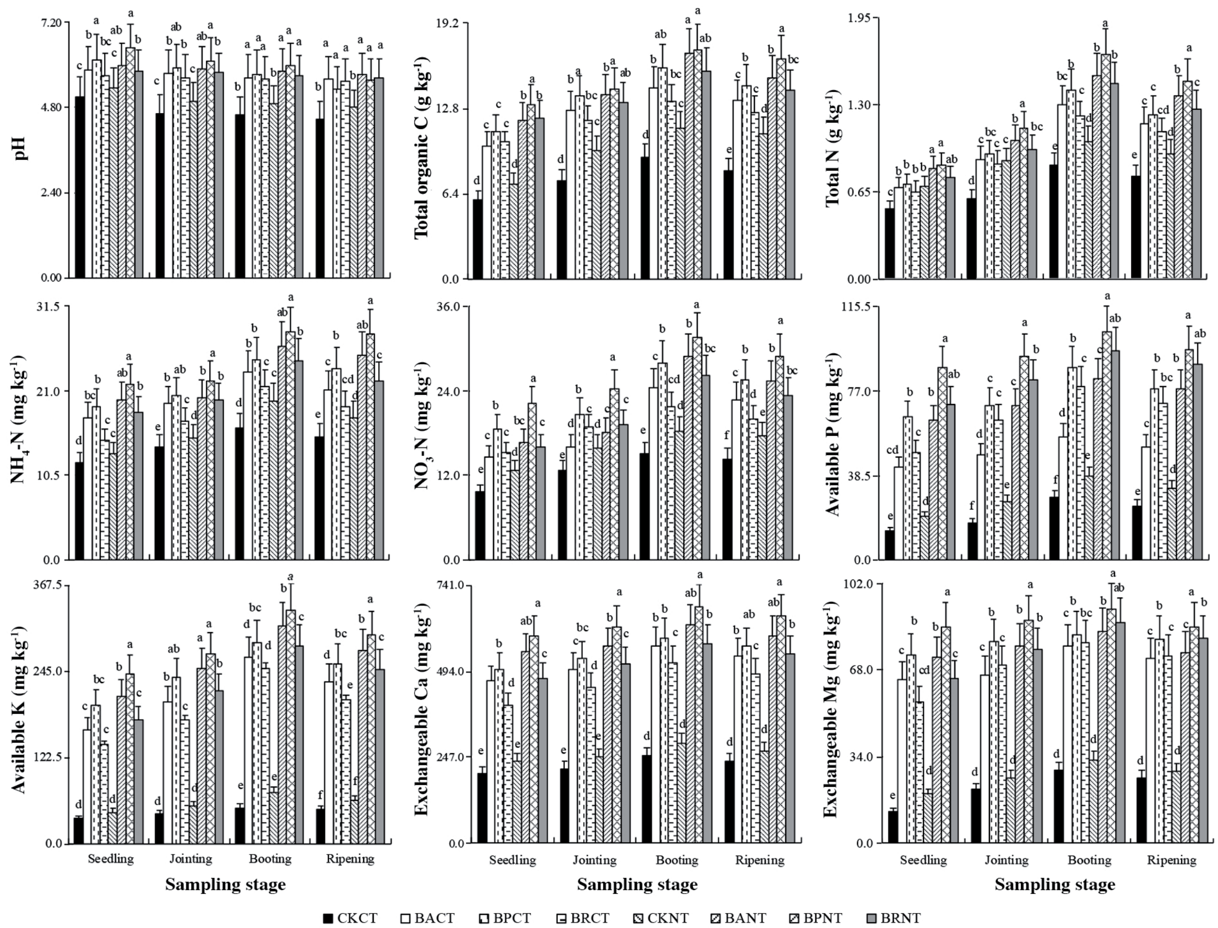
RESULTS

Soil physicochemical property

Compared with monoculture, rotations significantly increased ($P < 0.05$, Figure 1 and Table 2) almost all of the soil physicochemical properties, but decreased ($P < 0.01$) bulk density at the 3rd and 4th stage. For rotation treatments, BA had the lowest total soil organic C and available P; BP had the highest porosity, available K and exchangeable Ca; BR had the highest NH_4-N and exchangeable Mg. Soil moisture, pH, total soil organic C, total N, NO_3-N and exchangeable Mg were on average 39.4% higher in no-tillage compared with conventional tillage.

The amounts of macroaggregates (W_1-W_4) were significantly higher than that of microaggregates (W_5) in all treatments at the 2nd and 3rd stage ($P < 0.01$). The amounts of W_2, W_3 and W_4 followed the range of CK < BA < BP < BR. Higher W_5 were found in NT than in CT ($P < 0.05$, Table 3).

Figure 1. Soil chemical properties in rotation and tillage treatments at four sampling stages in a long-term crop rotation experiment.



Error bars indicate coefficient of variation. Different letters mean significant difference according to Duncan's multiple range test ($P < 0.05$). BA: Banana-pineapple rotation; BP: banana-cowpea rotation; BR: banana-rice rotation; CK: banana monoculture; NT: no-tillage; CT: conventional tillage.

Table 2. Soil physical properties and banana yield in rotation and tillage treatments at four sampling stages in a long-term crop rotation experiment.

		CK		BA		BP		BR	
Indicators	Sampling	CT	NT	CT	NT	CT	NT	CT	NT
Soil moisture, %	1st	17.2(1.6)d	19.2(1.7)d	22.8(2.1)c	24.9(2.2)c	26.8(2.4)b	29.5(2.6)a	28.1(2.5)ab	30.4(2.7)a
	2nd	19.1(1.8)c	21.9(1.9)c	24.3(2.2)b	26.5(2.4)b	30.7(2.7)a	31.6(2.9)a	31.8(2.8)a	33.1(3.1)a
	3rd	23.4(2.2)c	26.8(2.4)b	28.4(2.6)b	30.6(2.8)ab	32.9(3.0)a	33.4(3.1)a	34.6(3.2)a	35.9(3.3)a
	4th	21.7(2.0)d	24.6(2.2)c	27.8(2.5)c	28.8(2.6)bc	31.5(2.8)b	32.2(3.0)ab	33.3(3.1)a	34.7(3.2)a
Bulk density, g cm-3	1st	1.37(0.13)b	1.51(0.14)a	1.28(0.12)c	1.41(0.13)a	1.32(0.13)b	1.46(0.14)a	1.25(0.12)c	1.39(0.13)ab
	2nd	0.94(0.09)b	1.34(0.13)a	0.88(0.08)c	0.93(0.09)b	0.91(0.09)bc	1.06(0.09)b	0.82(0.07)c	0.85(0.07)c
	3rd	1.09(0.11)a	1.17(0.12)a	1.00(0.09)b	1.02(0.10)b	0.88(0.08)c	0.92(0.09)c	0.93(0.08)b	0.90(0.08)c
	4th	1.13(0.12)a	1.25(0.13)a	0.99(0.09)c	1.07(0.11)b	1.03(0.10)b	1.11(0.11)a	0.95(0.09)c	0.98(0.09)c
Porosity, %	1st	44.4(4.2)c	40.2(3.8)d	48.3(4.5)b	46.7(4.4)bc	55.5(5.3)a	51.0(4.8)ab	53.3(4.8)a	47.9(4.5)b
	2nd	54.3(5.3)c	52.6(5.1)c	61.1(5.9)b	62.3(5.8)ab	67.0(6.3)a	65.9(6.2)a	63.7(6.1)a	60.0(6.0)b
	3rd	57.8(5.5)b	56.3(5.2)c	61.8(5.8)a	58.7(5.6)c	63.6(6.1)a	62.5(6.0)a	60.4(6.0)a	59.5(5.9)ab
	4th	51.7(5.1)c	50.5(4.9)c	58.4(5.7)a	53.0(5.1)b	60.4(5.9)a	57.4(5.8)a	56.6(5.7)a	53.8(5.6)b
Yield, t ha-1		18.1(3.2)d	24.2(3.7)d	35.9(4.0)c	40.4(4.2)c	44.9(4.7)b	50.8(5.0)a	41.7(4.5)bc	48.6(4.6)b

Values represented in the table are means across replicates of each plot. Coefficients of variation are in parentheses.
CK: Banana monoculture; BA: banana-pineapple rotation; BP: banana-cowpea rotation; BR: banana-rice rotation; CT: conventional tillage; NT: no-tillage.

Table 3. Size classes of soil water-stable aggregates (WSA) in rotation and tillage treatments at four sampling stages in a long-term crop rotation experiment.

		CK		BA		BP		BR	
WSA (g kg^{-1})	Sampling	CT	NT	CT	NT	CT	NT	CT	NT
> 5 mm (W_1)	1st	78.9(8.5)d	107.4(11.6)d	122.0(13.1)c	150.4(16.2)b	143.9(15.5)bc	156.7(16.7)ab	134.8(14.5)c	160.2(17.2)a
	2nd	90.4(9.7)e	123.5(13.3)d	138.9(14.9)d	170.6(18.3)b	158.1(17.0)c	175.3(18.9)b	165.7(17.8)bc	189.9(20.4)a
	3rd	132.7(14.3)d	151.3(16.4)c	166.7(17.9)c	198.8(21.5)b	189.6(20.4)b	219.6(23.7)ab	210.4(22.6)b	223.5(24.0)a
	4th	119.1(12.8)d	140.2(15.1)c	149.8(16.2)c	182.9(19.7)b	173.4(18.6)b	200.5(21.7)a	184.5(19.8)b	215.6(23.2)a
5-3 mm (W_2)	1st	163.6(17.7)e	186.1(20.0)d	219.5(23.6)c	240.8(25.9)b	230.7(24.8)b	272.9(29.3)a	259.9(27.9)ab	283.4(30.5)a
	2nd	178.4(19.2)d	194.7(20.9)d	231.4(24.8)c	262.7(28.3)b	250.9(27.0)bc	283.7(30.5)a	271.2(29.2)ab	299.8(32.2)a
	3rd	212.7(22.9)e	226.6(24.4)d	270.0(29.0)c	301.9(32.5)b	278.8(30.0)c	317.5(34.1)a	315.7(33.8)a	324.6(34.9)a
	4th	201.8(21.7)d	207.5(22.3)d	254.6(27.4)c	273.2(29.8)c	266.2(28.6)c	300.3(32.4)ab	291.0(31.3)b	307.8(33.1)a
3-1 mm (W_3)	1st	214.5(23.1)d	229.4(24.7)c	236.9(25.5)c	257.2(27.6)c	289.3(31.1)b	314.6(33.8)a	292.5(31.5)b	318.7(34.3)a
	2nd	221.1(23.8)d	248.3(26.6)c	244.5(26.3)c	280.9(30.2)bc	302.6(32.5)b	330.2(35.5)ab	305.4(32.7)b	341.9(36.7)a
	3rd	255.4(27.5)e	276.8(29.9)d	287.8(30.9)c	310.5(33.4)c	327.1(35.3)bc	360.3(38.7)ab	340.1(36.6)b	374.1(40.2)a
	4th	233.2(25.2)d	261.9(28.2)c	269.7(29.0)c	298.7(32.1)bc	316.3(34.2)b	349.5(37.6)a	329.6(35.4)b	353.4(38.0)a
1-0.25 mm (W_4)	1st	320.6(34.6)e	369.5(39.7)d	398.4(42.8)cd	407.3(43.8)c	435.5(46.9)bc	478.6(51.4)b	460.0(49.5)b	500.8(53.8)a
	2nd	335.9(36.3)e	384.2(41.3)d	400.6(43.1)c	422.2(45.4)c	453.2(48.6)b	502.7(54.1)a	477.5(51.2)b	516.7(55.6)a
	3rd	357.7(38.4)e	421.7(45.3)d	440.3(47.3)d	457.8(49.2)cd	484.4(52.1)c	539.4(58.0)ab	514.8(55.4)b	553.5(59.5)a
	4th	344.8(37.1)e	395.6(42.5)d	428.9(46.2)c	436.1(46.9)c	469.7(50.5)bc	523.2(56.5)ab	495.4(53.3)b	540.9(58.4)a
< 0.25 mm (W_5)	1st	362.3(39.0)e	390.1(41.9)d	430.2(46.4)c	451.9(48.6)c	486.8(52.3)ab	520.5(56.0)a	479.3(51.6)b	525.6(56.5)a
	2nd	388.5(41.8)e	410.8(44.2)d	439.5(47.2)c	465.6(50.1)bc	499.9(53.8)b	531.1(57.3)a	490.9(52.8)b	549.2(59.1)a
	3rd	416.5(44.9)d	444.4(47.8)d	472.1(50.7)c	506.7(54.5)bc	536.6(57.7)b	559.8(60.2)a	521.7(56.1)b	578.4(62.2)a
	4th	404.0(43.4)e	426.3(45.8)d	457.7(49.6)c	480.4(51.7)bc	511.5(55.0)b	546.9(58.8)ab	507.2(54.5)b	567.3(59.9)a

Values represented in the table are means across replicates of each plot. Coefficients of variation are in parentheses.
CK: Banana monoculture; BA: banana-pineapple rotation; BP: banana-cowpea rotation; BR: banana-rice rotation; CT: conventional tillage; NT: no-tillage.

Soil biochemical property

Microbial biomass C (MBC), urease (UA), β-glucosidase (GA) and dehydrogenase (DHA) were significantly higher ($P < 0.01$, Table 4) in the treatments NT than in CK-CT. Microbial biomass N (MBN), invertase (IA), DHA and acid phosphatase (APA) were on average 42.1%, 47.9% and 36.7% higher in BA, BP and BR compared with CK, respectively. Average MBN and catalase (CA) were 28.1% and 39.6% higher in NT compared with CT (Figure 2). At the booting stage, MBC, MBN and DHA were much higher than those at other stages.

Greenhouse gas emissions

Peaks of N_2O (NE) and CO_2 (CE) emissions in rotation and tillage were detected at 200 and 240 d followed by 160, 280 and 320 d, while 40 and 80 d had the lowest emissions (Figure 3). Average CE ranged from 11.8 to 31.9 μmol m^{-2} s^{-1}, with the following order: BP < BR < BA < CK; average NE ranged from 14.9 to 38.1 μmol m^{-2} s^{-1}, with the following order: BR < BP < BA < CK; average CH_4 emissions (ME) ranged from 10.5 to 25.7 μmol m^{-2} s^{-1}, with the following order: CK < BA < BP < BR. Average CE, NE and ME were 36.5% lower in NT compared with CT.

Microbial biomass C was positively correlated with total organic C ($P < 0.05$, Table 5) and negatively correlated with bulk density ($P < 0.01$). Urease was positively correlated with NO_3-N ($P < 0.05$). CH_4 emissions were positively correlated with exchangeable Mg and macroaggregate ($P < 0.01$).

Banana yield

Rotation effect was significant on banana yields ($P < 0.05$, Table 2). The average banana yields in BA, BP and BR were, respectively, 41.6%, 58.7% and 49.9% higher than those in CK, and 23.3% increase was observed in no-tillage compared with conventional tillage (Table 2).

Table 4. Two-way ANOVA table of P values showing the significance of the effects of different crop rotation and tillage practices on soil properties in a long-term crop rotation experiment.

Indicators	Rotation (R)	Tillage (T)	Stage (S)	R×T	R×S	T×S	R×T×S
SM	<0.01	< 0.01	ns	< 0.01	0.037	ns	ns
BD	< 0.01	< 0.01	< 0.01	ns	< 0.01	ns	ns
PO	0.044	0.019	< 0.01	0.043	ns	0.048	ns
WSA_1	< 0.01	< 0.01	ns	ns	ns	ns	0.020
WSA_2	< 0.01	0.031	0.049	ns	ns	ns	0.024
pH	< 0.01	< 0.01	ns	0.018	ns	ns	ns
SOC	< 0.01	< 0.01	ns	< 0.01	ns	ns	ns
TN	< 0.01	< 0.01	< 0.01	< 0.01	ns	ns	ns
NH_4-N	< 0.01	0.049	< 0.01	ns	ns	ns	ns
NO_3-N	< 0.01	< 0.01	< 0.01	< 0.01	ns	ns	ns
AP	< 0.01	< 0.01	ns	0.016	ns	ns	ns
AK	0.042	< 0.01	< 0.01	0.033	< 0.01	ns	ns
ECa	< 0.01	0.039	ns	ns	ns	ns	ns
EMg	< 0.01	ns	ns	ns	ns	ns	ns
MBC	< 0.01	< 0.01	< 0.01	ns	ns	ns	ns
MBN	< 0.01	< 0.01	< 0.01	ns	0.047	ns	ns
UA	< 0.01	< 0.01	< 0.01	ns	ns	ns	ns
IA	< 0.01	< 0.01	< 0.01	0.023	ns	ns	ns
DHA	< 0.01	< 0.01	< 0.01	ns	ns	ns	ns
APA	< 0.01	0.022	ns	ns	ns	ns	ns
GA	< 0.01	< 0.01	< 0.01	ns	< 0.01	ns	ns
CA	< 0.01	< 0.01	< 0.01	ns	ns	ns	ns
NE	0.026	0.013	0.027	ns	0.014	ns	ns
CE	0.017	< 0.01	0.031	ns	ns	ns	ns
ME	< 0.01	< 0.01	< 0.01	< 0.01	ns	ns	ns
Yield	< 0.01	< 0.01	< 0.01	0.029	ns	ns	ns

SM: Soil moisture; BD: bulk density; PO: porosity; WSA_1: water-stable macroaggregate; WSA_2: water-stable microaggregate; SOC: soil total organic C; TN: total N; AP: available P; AK: available K; ECa: exchangeable Ca; EMg: exchangeable Mg; MBC: microbial biomass C; MBN: microbial biomass N; UA: urease activity; IA: invertase activity; DHA: dehydrogenase activity; APA: acid phosphatase activity; GA: β-glucosidase activity; CA: catalase activity; NE: N_2O emission; CE: CO_2 emission; ME: CH_4 emission; ns: nonsignificant.

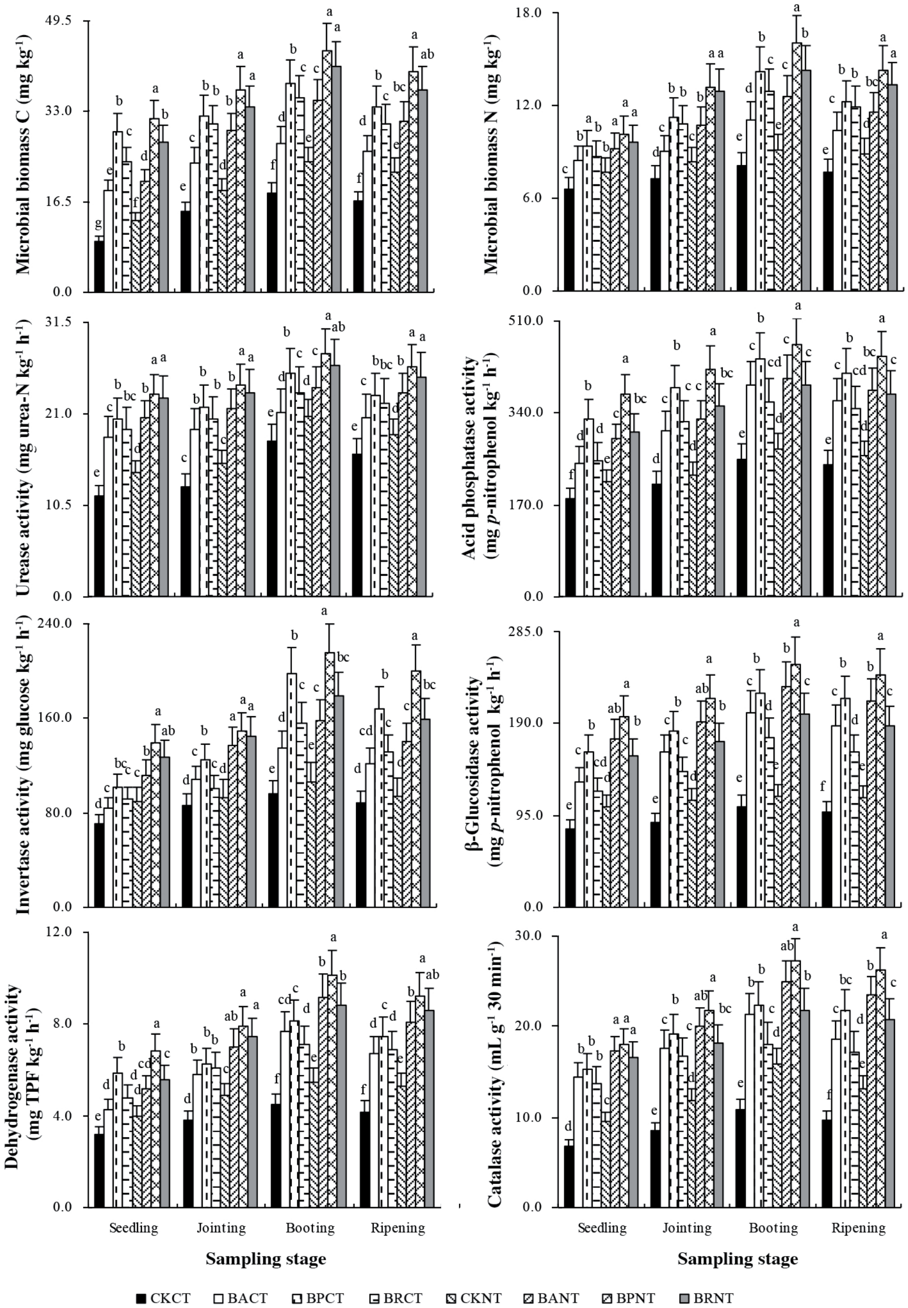
DISCUSSION

Effects of rotation on soil quality

pH increased 0.89 units in the rotations compared with monoculture, which is in agreement with the results of Dasa et al. (2018). These results suggest that root exudates of pineapple, cowpea or rice mitigate soil acidification. Total N and NO_3-N were much higher in BA than in CK, which were consistent with our previous studies (Zhong and Zeng, 2019). The differences were due to larger root quantity in rotations decreasing percolation water with N nutrients than in monoculture (Belmonte et al., 2018). AP and AK were on average 34.6% higher in BA and 43.7% higher in BP than in CK. Other researchers found similar results (Xu et al., 2020). They suggested that soil pH maintaining neutral range in rotations prevents P and K from fixation.

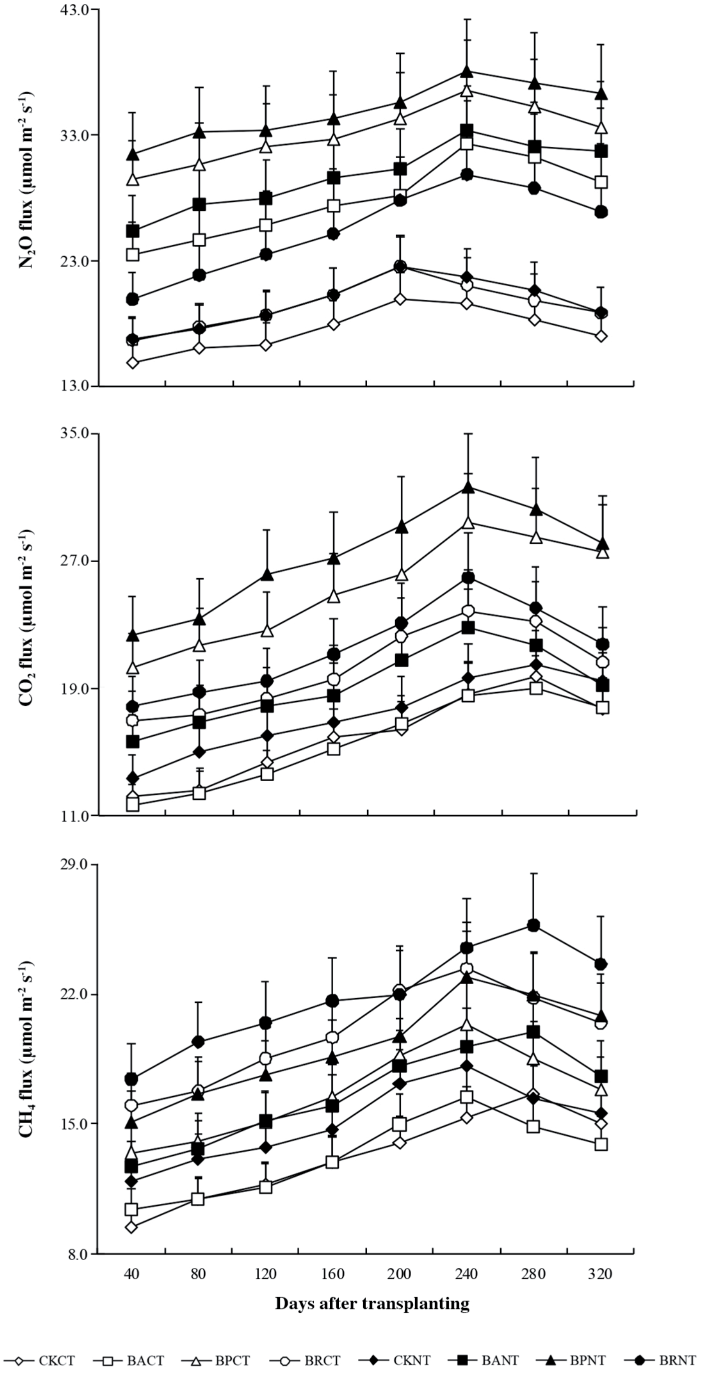
Urease, invertase, dehydrogenase and β-glucosidase obtained a mean of 51.7% increase in BP and 40.2% increase in BR compared with CK. These results were consistent with those of previous studies (Singh et al., 2018) that soil enzymes were stimulated by various crop sequences. The possible reason is that compared with monoculture plots, rotation plots have improved soil structure (Yang et al., 2020), stabilized microclimate (Adegaye et al., 2019) and greater abundance of rhizospheric microbes (mainly including rhizobia, gram-negative bacteria and *Pseudomonas*). Rotations emitted large amounts of CH_4 to atmosphere, especially flooding rice cultivation. Pareja-Sánchez et al. (2019) reported similar findings. In their view, soil moisture and Fe^{2+} in BR were significantly higher than those of less irrigated treatments, thus increasing the abundance of methanogenesis.

Figure 2. Soil microbial properties and enzyme activities in rotation and tillage treatments at four sampling stages in a long-term crop rotation experiment.



Error bars indicate coefficient of variation. Different letters mean significant difference according to Duncan's multiple range test ($P < 0.05$). BA: Banana-pineapple rotation; BP: banana-cowpea rotation; BR: banana-rice rotation; CK: banana monoculture; NT: no-tillage; CT: conventional tillage; TPF: triphenylformazan.

Figure 3. Greenhouse gas emissions in rotation and tillage treatments at eight sampling stages in a long-term crop rotation experiment.



Error bars indicate coefficient of variation. Different letters mean significant difference according to Duncan's multiple range test ($P < 0.05$). BA: Banana-pineapple rotation; BP: banana-cowpea rotation; BR: banana-rice rotation; CK: banana monoculture; NT: no-tillage; CT: conventional tillage.

Table 5. Pearson correlation coefficients between physicochemical-microbiological parameters and greenhouse gas across rotation and tillage treatments

Indicators	MBC	MBN	UA	IA	GA	APA	DA	CA	CE	NE	ME
SM	0.307	0.047	0.614**	-0.277	0.209	0.362	-0.323	0.156	-0.462*	0.142	-0.293
BD	-0.726**	-0.495*	0.223	0.059	0.120	0.178	0.446	0.197	0.334	0.301	0.395
PO	0.174	0.566*	0.682**	0.155	0.367	0.547*	0.434	0.228	0.057	0.076	0.099
WSA_1	0.420	0.349	0.039	0.671**	0.008	-0.106	0.710**	0.045	-0.580*	0.180	0.633**
WSA_2	0.538*	0.136	0.388	-0.395	0.505*	-0.475	0.179	0.553*	-0.528*	0.453	0.065
pH	0.370	0.143	-0.568*	0.007	0.072	-0.606**	0.133	0.653**	0.231	0.036	0.250
SOC	0.588*	0.367	0.249	0.040	0.029	0.168	0.061	-0.196	0.504*	0.143	0.470*
TN	0.137	0.416	0.507*	0.152	0.125	0.511*	0.575*	0.069	0.385	0.439	0.198
NH_4-N	0.030	0.670**	0.319	-0.049	-0.178	0.596*	0.304	0.210	0.108	0.528*	0.467*
NO_3-N	0.296	0.479*	0.532*	0.285	0.303	0.424	0.407	-0.273	0.263	0.602**	0.274
AP	0.544*	0.262	0.480*	0.134	0.311	0.463*	0.329	0.138	-0.165	0.094	0.163
AK	0.508*	0.519*	0.415	0.183	0.355	0.259	0.111	0.085	0.066	0.187	0.052
ECa	0.403	0.488*	0.336	0.354	0.566*	0.284	0.153	0.742**	0.193	0.208	-0.030
EMg	0.364	0.201	0.400	0.416	0.449*	0.376	-0.427	0.328	0.124	-0.146	0.681**

*, **Significant at the 0.05 and 0.01 probability levels, respectively.
MBC: Microbial biomass C; MBN: microbial biomass N; UA: urease activity; IA: invertase activity; DHA: dehydrogenase activity; APA: acid phosphatase activity; GA: β-glucosidase activity; CA: catalase activity; NE: N_2O emission; CE: CO_2 emission; ME: CH_4 emission; SM: soil moisture; BD: bulk density; PO: porosity; WSA_1: water-stable macroaggregate; WSA_2: water-stable microaggregate; SOC: soil organic C; TN: total N; AP: available P; AK: available K; ECa: exchangeable Ca; EMg: exchangeable Mg.

Effects of tillage on soil quality

Soil moisture and water-stable aggregates increased on average 32.5% in NT compared with CT, which were because crop residues returning on soil surface reduced evaporation and less soil disturbance improved soil structure. The results were in agreement with other studies (Zhang et al., 2017). In NT plots, soil consolidation will continue augment until an equilibrium bulk density is reached, range of 1.2-1.5 g cm^{-3} for our soil type (Sayed et al., 2019). Our results were consistent with those of Sauvadet et al. (2018), who found that reduced tillage doubled soil organic C (SOC) compared with CT. They suggested that residues covering on soil surface decreased soil temperature and prevented C mineralization. The content of exchangeable Ca (ECa) in NT was 35.7% higher than that in conventional tillage. Similar results were reported in same soil types (He et al., 2020b). The process was explained as crop residues in NT released large amount of soluble Ca^{2+} to replace H^+ (Moghimian et al., 2019).

Average MBC and MBN increased 40.3% and 32.5% in NT compared with CT. The positive responses of microbial biomass to NT were attributed to the large amount of C and N substrates provided by cowpea and pineapple residues addition (Saikia et al., 2019). N_2O and CO_2 emissions were 32.5% and 22.9% lower in NT than in CT. The results were consistent with the studies of Behnke et al. (2018). Unlike CT, which distributes organic matter in 0-40 cm plow layer, NT leaves organic matter close to soil surface, thus, it prevents the release of greenhouse gases into the atmosphere.

Effects of stage on soil quality

Microbial biomass C, acid phosphatase and dehydrogenase gradually increased and reached peak at booting then decreased afterwards. The fluctuation was consistent with banana growth. Notaro et al. (2018) also observed an increase of rhizosphere products, such as root exudates, mucilage and sloughed cells at booting, which increase the abundance of rhizospheric microbes.

N_2O and CO_2 emissions increased dramatically from March to May, which were the warmest season of 2019-2020. Similar results were reported by Piotrowska-Dlugosz et al. (2019). They attributed the reasons to the continuous increase of soil moisture, temperature and C input from jointing to booting.

CONCLUSIONS

The increased soil microbial biomass and enzyme activities in rotation soils are accompanied by an increase in microbial activity. The decreased greenhouse gas emissions and increased soil organic C and total N could explain the higher C and N sequestration in no-tillage than in conventional tillage. Therefore, rotation and no-tillage practices effectively improved soil quality and increased banana yield in tropical environments. In conclusion, integration of no-tillage into rotation systems provides a sustainable management in banana production.

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