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RESEARCH ARTICLE

LARGE-SCALE FARMING BENEFITS SOIL ACIDIFICATION ALLEVIATION THROUGH IMPROVED FIELD MANAGEMENT IN BANANA PLANTATIONS

Donghao XU[1,2], Jiangzhou ZHANG[2,3], Yajuan LI[1,2], Shiyang LI[1], Siyang REN[1,2], Yuan FENG[2], Qichao ZHU (✉)[1,2], Fusuo ZHANG[1,2]

1 College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China.
2 National Academy of Agriculture Green Development, China Agricultural University, Beijing 100193, China.
3 College of Resources and Environment/International Magnesium Institute, Fujian Agriculture and Forestry University, Fuzhou 350002, China.

KEYWORDS

plantations, land transfer, large-scale farming, nutrient management, soil acidification

HIGHLIGHTS

- Large farms had the highest average yield and the least yield variation.
- Greater plant density and optimized nutrient input occurred on large farms.
- Substituting organic N for mineral fertilizers prevented soil acidification.
- Large-scale farming had lower soil acidification but higher risk of P losses.
- Large-scale farming benefits sustainable soil management and banana production.

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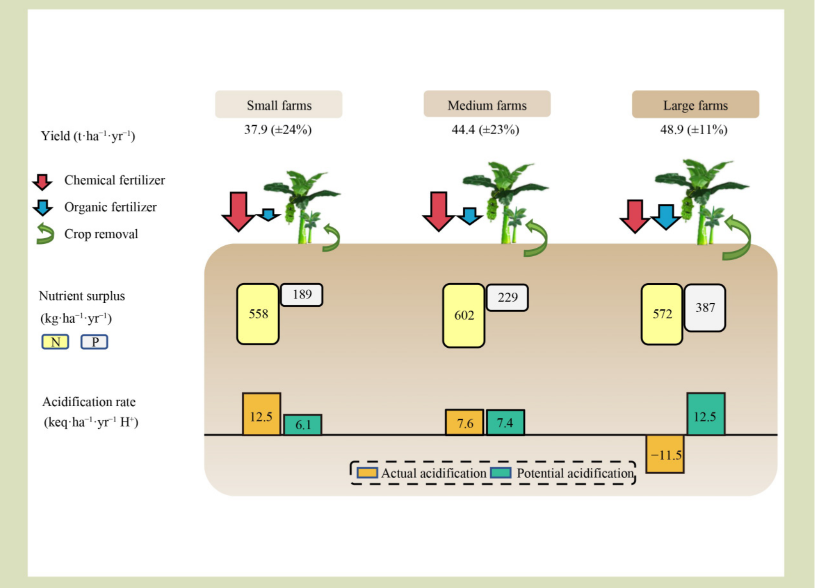
Correspondence: qichaozhu@126.com

GRAPHICAL ABSTRACT



ABSTRACT

Large-scale farming by agricultural land transfers has been increasingly promoted in recent years, but the possible impacts on crop production, especially cash crops, and soil acidification remain unclear. This study obtained data for 110 banana plantations in Long'an County, China, and categorized them into small (< 0.67 ha), medium (0.67−6.7 ha), and large (> 6.7 ha) to determine banana cultivation, nutrient management, and soil acidification rates on farms of the three sizes. Banana yield per unit area significantly increased with increased farm size, and large farms had the highest average yield (48.9 $t \cdot ha^{-1}$) with the least variation. Despite a significant increase in organic fertilizer and base cation inputs, nitrogen (N) surplus did not differ significantly with increasing farm size. With large farms, actual soil acidification rate was significantly lower by 19.1 to 24.0 $keq \cdot ha^{-1} \cdot yr^{-1}$; however, potential soil acidification rate increased with increased overuse of phosphorus. Overall, larger banana plantations used fewer mineral N fertilizers reducing the rate of soil acidification and increasing the H^+ buffering provided by organic fertilizers. It is concluded that larger farms deliver the dual benefits of higher, less variable banana yield and mitigation of soil acidification by substituting organic N for mineral N fertilizers, supporting sustainable soil management and food production.

1 INTRODUCTION

As soil degradation due to unsuitable agricultural practices is threatening food security, environmental quality and human health, modern agriculture faces a great challenge for sustainable soil management[1,2]. Over the past 30 years, intensified agriculture in China has immensely increased food production and enhanced cropland soil acidification due to the overuse of nitrogen (N) fertilizers[3,4]. Zhu et al.[5] estimated that even with no N fertilizer increase after 2020 there might be a 16% loss in cereal production due to soil acidification until 2050, and cash crops (vegetable, fruit and tea) tend to acidify more rapidly because of larger amounts of fertilizer inputs[6]. Soil acidification can impair crop production via aluminum and manganese toxicity, and nutrient deficiency, such as phosphorus, potassium, calcium and magnesium[7–9], as well as increasing bioaccumulation of toxic heavy metals, such as cadmium, in the food chain, threatening food safety[10,11].

Nutrient management strategies require to be optimized to mitigate soil acidification, e.g., increasing base cations (BC) inputs by lime and organic manure application[12] and applying the proper type of N fertilizer at an appropriate rate and time to minimize the N leaching[13]. Many recent studies have shown that expanson of field size can increase agricultural resource use efficiency[14–16], in particular fertilizers. Large-scale farming was estimated to reduce fertilizer application and losses in China by 33% and 50%, respectively, without any reduction in yield and nearly doubling farmer incomes[17,18]. Also, soil acidification rates can reduced through improved nutrient management strategies. Recently, large-scale farming by agricultural land transfers has become increasingly common in China. Until 2050, large-scale farms (i.e., greater than 6.7 ha) accounted for about 20% of total arable land and 80% of national agricultural production[19]. However, the impacts of large-scale farming on soil acidification rates are largely unknown, making it difficult to make recommendations for sustainable soil management.

Banana is one of the major cash crops in China, with a total yield that, in 2021, ranked second in the world (11.7 Mt)[20,21]. Southern China is the major banana production area in China, with the predominant soil types of Ferralsols and Acrisols[22]. A recent meta-analysis showed that soil pH in 78.8% of banana plantations in China was below the optimum value of 5.8[23]. Low pH is often associated with low contents of plant essential nutrients, such as calcium and magnesium, high contents of aluminum and manganese and increased soil fungi[24,25], limiting banana yield and quality with yield decrease, fruit cracking and greater impacts of Fusarium wilt[26,27]. Inappropriate nutrient management, especially overuse of nitrogen, is accelerating cropland acidification in China[3], and is becoming one of the main constrains to banana production[22]. This study aimed to determine the field management and related soil acidification rates in banana plantations of different farm sizes in Long’an County, China based on a systematic farmer investigation. Contributions of fertilizers (mineral and organic) and crop harvest to soil acidification were quantified using mass balance and charge balance methods[28] to propose recommendations for sustainable field management for cash crop production.

2 MATERIALS AND METHODS

2.1 Study site

The study was conducted in Long’an County, Guangxi Zhuang Autonomous Region, located in south-western China (23°0′8″ N, 107°50′15″ E), where cash crops, especially bananas, are essential in crop production[22]. The region has a typical subtropical humid monsoon climate, with mean annual temperature of 21.8 °C and precipitation of 1301 mm[22]. Acid soils such as Acrisols and Anthrosols (average pH ranging from 6.1 to 6.3) occur widely, with low cation exchange capacity ranging from 108 to 117 $mmol \cdot kg^{-1}$ but high manganese and aluminum ion concentrations[29], impairing crop production in the region.

2.2 Data collection

A questionnaire survey was conducted between March and May 2017 in four banana-producing towns in Long'an County; five villages were arbitrary selected from each town, and six farms were arbitrary sampled in each village. The surveyed farms were categorized into three sizes: small farms with a field size less than 0.67 ha, medium farms between 0.67 and 6.7 ha, and large farms over 6.7 ha. The questionnaire collected data on farm size and plant density, banana yield, mineral and organic fertilizers application (type and quantity), crop residue incorporation and tillage. There were 110 valid questionnaires for analysis, including 51 small farms, 23 medium farms, and 36 large farms. Farm size was determined based on literature[30,31] and the local statistical bureau[32,33], which indicated that the average regional farm size per household was 0.67 ha and large-scale specialized and cooperatives often manage over 6.7 ha of land.

2.3 Nutrient input-output budget

2.3.1 Assessment of nutrient inputs

External soil nutrient input (X_{in}) was considered to include atmospheric deposition (X_{atm}), mineral fertilizer (X_{fert}), organic fertilizer (X_{manu}), irrigation (X_{irri}) and biological fixation (X_{fix})[28]:

$$X_{in} = X_{atm} + X_{fert} + X_{manu} + X_{irri} + X_{fix} \quad (1)$$

Where X was the main nutrient in cropland, including N (separately as NH_4^+ and NO_3^-), phosphorus, sulfur, chlorine and BC. It was assumed that all nutrients input were in an ionic state, where P was $H_2PO_4^-$, S was SO_4^{2-}, and BC included potassium, calcium, magnesium and sodium ions. Additional, external acidity (H^+) input was estimated based on the charge balance of all ions inputs based on:

$$H^+_{in} = NO^-_{3in} + SO^{2-}_{4in} + H_2PO^-_{4in} + Cl^-_{in} - NH^+_{4in} - BC^+_{in} \quad (2)$$

Mineral and organic fertilizers

The nutrient input rates from fertilizers were estimated by the type and quantity of mineral and organic fertilizers according to the farm survey results. Mineral N fertilizers were applied mainly as urea and calcium ammonium nitrate; mineral P fertilizers were mainly calcium magnesium phosphate, and mineral K fertilizers were mostly potassium chloride and potassium sulfate. Some surveyed farms also applied multi-nutrient fertilizers, including binary compound fertilizers like diammonium phosphate, potassium nitrate and ammonium nitrate phosphate, and NPK compound fertilizers in which labeled content was N, P_2O_5 and K_2O in equal amounts (mainly NPK 15:15:15 and 17:17:17). Applied organic fertilizers included commercial organic fertilizers and animal manure such as cattle, poultry and swine manure, and other farmyard manures for which the nutrient inputs were estimated by multiplying the application rate by the element contents (Table 1). Note that the NH_4^+ and NO_3^- inputs by fertilizer were based on the total N input and the proportion of NH_4^+ and NO_3^- in those fertilizers. As the H^+ induced by organic N (e.g., N in urea, manure and N biological fixation, see below) is equivalent to NH_4NO_3, organic N in this study was thus treated as equal amounts of NH_4^+ and NO_3^-[12].

Atmospheric deposition, irrigation and N fixation

The average atmospheric deposition of NH_4^+ and NO_3^- in Long'an County was 15.6 and 11.6 $kg \cdot ha^{-1} \cdot yr^{-1}$, respectively[35]. The deposition rates of P, S, K, Ca, Mg, Na and Cl were 0.8, 33.8, 8.6, 37.8, 7.7, 6.1 and 8.5 $kg \cdot ha^{-1} \cdot yr^{-1}$, respectively[36,37]. The nutrient input of irrigation water was estimaged based on the amount of irrigation water and its nutrient content. The irrigation rate in banana plantations in Long'an County was approximately 2000 $m^3 \cdot ha^{-1} \cdot yr^{-1}$[35], and the N, P, S, K, Ca, Mg, Na and Cl contents in the irrigation water were 0.61, 1.1, 1.3, 0.87, 46.0, 11.0, 1.3 and 3.9 $g \cdot m^{-3}$[38]. N in irrigation water

Table 1 Element concentration (%) in the applied animal manure and commercial organic fertilizers

Manure type	N	P	S	K	Ca	Mg
Swine manure[a]	0.55	0.24	0.10	0.29	0.49	0.22
Poultry manure[a]	0.76	0.33	0.15	0.59	1.70	0.24
Cattle manure[a]	0.38	0.09	0.07	0.23	0.43	0.11
Farmyard manure[b]	0.56	0.22	0.11	0.37	0.86	0.19
Commercial organic fertilizers[c]	1.07	1.24	0.11	0.92	1.10	0.30

Note: Na and Cl contents in organic fertilizers were not estimated due to lack of data. [a]Data from National Agricultural Technical Extension and Service Center[34]. [b]Nutrient content of farmyard manure was assumed to equal to the mean of those in swine, poultry and cattle manure. [c]N, P, K, Ca and Mg contents were derived from references[22,35], while other nutrients were assumed to equal to farmyard manure.

was assumed have equal amounts of NH_4^+ and NO_3^-. N biological fixation rate in the banana plantation was estimated at 45 kg·ha^{-1}·yr^{-1} N[35].

2.3.2 Assessment of nutrient outputs

Nutrient outputs in the banana plantations mainly included crop removal (X_{upt}), ammonia volatilization (N_{NH_3}), nutrient discharge losses to water (X_{out}) and denitrification.

Crop removal

The crop nutrient removal from banana plantations was estimated based on the surveyed crop yield (t·ha^{-1}) and crop nutrient removal per unit yield (kg·t^{-1}). The removal of N, P, K, Ca, and Mg was taken as 2.98, 0.41, 9.86, 0.53 and 0.39 kg·t^{-1} of fresh banana, respectively[35], and the removal rate of S and Cl as 0.37[39] and 3 kg·t^{-1}[40], respectively. The Na removal was not included due to lack of data. According to the survey, farmers rarely remove banana residues from the plantations due to the high cost. Thus, this study only considered the nutrient removal in the fruit and estimated the nutrient surplus as the difference between total input nutrient input and crop removal.

Ammonia volatilization

N_{NH_3} was estimated based on the fertilizer N inputs, assuming that the volatilization ratios were 11% and 23% for mineral and organic fertilizers, respectively[41]. NH_3 volatilization from other sources (e.g., atmospheric deposition and N biological fixation) were not estimated.

Discharge losses to water

Nutrient discharge losses to water, or leaching and runoff losses from the soil layer (X_{out}), were derived based on various assumptions for the different elements involved. For N, this study assumed that NH_4^+ applied to the soil was completely nitrified to nitrate (NO_3^-), and N discharge losses were only in form of NO_3^-, being half of the N_{rest} (total N input minus crop removal and NH_3 emissions)[28]. For P ($H_2PO_4^-$), due to the strong fixation in soils, its water loss was not estimated[42], whereas soil fixations of S (SO_4^{2-}) and Cl^- are generally weak, thus the losses of SO_4^{2-} and Cl^- were assumed to equal to the surplus (the total input minus the crop removal)[28]. As a previous study demonstrated that the leaching of HCO_3^- and H^+ in acidic soils is generally small to affect this calculation[12], the loss of BC was thus estimated based on the charge balance principle according to:

$$BC^+_{out} = NO^-_{3out} + SO^{2-}_{4out} + Cl^-_{out} \quad (3)$$

Denitrification losses (N_2O, NO and N_2)

It was assumed that N loss via nitrogen oxides (NO and N_2O) was 1.8% of the total N application rate[41]. N_2 loss was thus estimated by the difference between total N input and crop removal, ammonia emission, discharge losses to water, and nitrogen oxides losses according to:

$$N_2 = N_{in} - (N_{upt} + N_{NH_3} + NO^-_{3out} + NO + N_2O) \quad (4)$$

To calculate soil acidity production, the element budget above was converted from mass fluxes (kg·ha^{-1}·yr^{-1}) to charge-equilibrium fluxes (keq·ha^{-1}·yr^{-1}) by dividing the mass fluxes by 14, 31, 39, 23 and 35.5 for the monovalent ion N (NH_4^+ and NO_3^-), P ($H_2PO_4^-$), K^+, Na^+ and Cl^-, respectively, and 16, 20 and 12 for divalent ion S (SO_4^{2-}), Ca^{2+} and Mg^{2+}, respectively (details in Zhu et al.[28]).

2.4 Soil acidity budget calculation

Soil acidification rates were estimated based on the main nutrient input-output budget of croplands[28,43]. Since this area is dominated by acidic soil, acidity production processes were considered, including N transformation, H^+ net input and crop removal, but not the HCO_3^- process:

$$\begin{aligned} H_{pro} = {} & (NH^+_{4in} - NH^+_{4out} + NO^-_{3out} - NO^-_{3in}) + (H^+_{in} - H^+_{out}) \\ & + (BC^+_{upt} - SO^{2-}_{4upt} - H_2PO^-_{4upt} - Cl^-_{upt}) \end{aligned} \quad (5)$$

Where the subscript of $_{in}$ and $_{upt}$ were the external input and crop removal of the ion/element, respectively, and the subscript $_{out}$ was the discharge loss to water.

In this study, the net loss rate of BC from the soil, taken as the actual acidification rate (H^+_{act}), and the net accumulation of anions in the soil, called the potential acidification rate (H^+_{pot}) were estimated[43] based on Eqs. (6) and 7, respectively:

$$H^+_{act} = BC^+_{out} + BC^+_{upt} - BC^+_{in} \quad (6)$$

$$H^+_{pot} = An^-_{in} - \left(An^-_{out} + An^-_{upt}\right) \quad (7)$$

Where BC^+_{out} and An^-_{out} are the water discharge loss of BC and anions, respectively; BC^+_{upt} and An^-_{upt} are the ions removed by crop harvesting; BC^+_{in} and An^-_{in} are the external inputs including the soil BC weathering, an average of 1 keq·ha^{-1}·yr^{-1} for the region[44]. No anion input from soil weathering was considered in this study.

2.5 Data processing and statistical analysis

The survey data were analyzed using the software SPSS (IBM SPSS Statistics 20, IBM, NY, USA). Density distributions of the core data, such as plant density, crop yield and fertilizer input were depicted to determine if they approximately fit the normal distribution (Fig. S1). If so, after Levene's test for the equality of variances, a comparison of means by one-way analysis of variance with Tukey's honestly significant difference (HSD) test was conducted among three groups. If not, the Kruskal–Wallis H test was applied to check the significant difference among the three groups, and the Mann–Whitney U test for a paired group.

3 RESULTS

3.1 Plant density and banana yield by farms size

The average planting area of small, medium and large farms was 0.2, 1.1 and 49.8 ha, respectively (Table 2). For plant density, there was no significant difference between small and medium farms, but large farms had a significantly higher plant density ($P < 0.05$). The yield per plant of medium farms was significantly greater than small farms, but there was no significant difference was found between medium and large farms. Overall, large farms had the highest average yield of 48.9 t·ha^{-1}, being 29% and 10% higher than that of small and medium farms. Also, compared to small and medium farms, coefficient of variation of plant density and banana yield per plant on large farms were both significantly less, with 47% to 50% less total yield variation.

3.2 Nutrient input and surplus by farms size

Macronutrient input from fertilizers in the banana plantations of the three sizes varied (Table 3). The average total N input on small, medium and large farms were 42.7, 47.3 and 46.0 keq·ha^{-1}·yr^{-1}, respectively. No significant difference was found in the mineral N input between medium and small farms, except for the significantly greater organic N input on medium farms. For large farms, the NH_4^+ input was significantly less, and the organic N input was further greater compared to medium farms. P input from fertilizers followed a similar trend, with larger farm size, the manure input was 5 to 15 times higher than the reduced in fertilizer input. As a result, the average total P input on large farms (13.1 keq·ha^{-1}·yr^{-1}) was significantly higher than on small and medium farms (6.5 and 7.9 keq·ha^{-1}·yr^{-1}, respectively). The average total K input on small, medium and large farms was 16.5, 20.5 and 27.0 keq·ha^{-1}·yr^{-1}, respectively, with the mineral and organic input both significantly greater on larger farms. Overall, larger farms had greater organically supplied nutrients and mineral K input, and with large farms replacing some mineral N fertilizers with organic fertilizers with a consequent significantly greater total P input.

For Ca and Mg input, both mineral and organic fertilizer applications were greater on larger farms (Table 3). The average total Ca and Mg input of small farms was 2.8 and 1.0 keq·ha^{-1}·yr^{-1}, but this was significantly greater at 7.6 and 3.3 keq·ha^{-1}·yr^{-1} on medium farms and at 16.3 and 9.2 keq·ha^{-1}·yr^{-1} on large farms. For mineral S input, no significant difference was found between small and medium farms, but it was significantly greater on large farms. For Cl, small farms had significantly lower input than medium and large farms, with no significant difference between the latter two.

The average N surplus (total N input minus crop removal) of the farms was 41.3 keq·ha^{-1}·yr^{-1} (or 578 kg·ha^{-1}·yr^{-1}, Fig. 1). No significant difference was found among the three farm sizes. P surplus was significantly greater on larger farms, with an average of 6.1, 7.4 and 12.5 keq·ha^{-1}·yr^{-1} (189, 229 and 387 kg·ha^{-1}·yr^{-1} P) on small, medium and large farms, respectively. BC surplus followed the same trend as P, being 14.8, 23.7 and 43.6 keq·ha^{-1}·yr^{-1} (or 296, 474 and 872 kg·ha^{-1}·yr^{-1} in Ca-equilibrium flux) on small, medium and large farms, respectively. The S surplus was the least of the nutrients (3.5 keq·ha^{-1}·yr^{-1} on average) and varied among the

Table 2 Average planting area and density and total banana yield on small, medium and large farms

Farm group	Average area (ha)	Plant density (plants ha^{-1})		Yield (t·ha^{-1})	
		Mean	Coefficient of variation (%)	Mean	Coefficient of variation (%)
Small farms	0.20	1707^{b}	9.3^{b}	37.9^{c}	24.4^{b}
Medium farms	1.1	1699^{b}	12.9^{b}	44.4^{b}	22.9^{b}
Large farms	49.8	1853^{a}	5.8^{a}	48.9^{a}	11.5^{a}

Note: ^{a,b,c}Values followed by the same letter within columns are not significantly different ($P < 0.05$).

Table 3 Mineral and organic fertilizer input of main nutrients on small, medium and large farms

Fertilizer rate ($keq·ha^{-1}·yr^{-1}$)	Small farms		Medium farms		Large farms	
	Mean	SD	Mean	SD	Mean	SD
Nitrogen						
NH_4^+	22.1[a]	8.1	22.6[a]	10.6	15.8[b]	8.2
NO_3^-	17.9[a]	7.9	18.2[a]	9.9	16.9[a]	8.4
Organic	2.7[c]	1.9	6.5[b]	2.9	13.3[a]	2.0
Phosphorus						
Mineral	5.9[a]	2.5	5.8[a]	3.0	4.4[b]	2.1
Organic	0.64[c]	0.97	2.1[b]	2.7	8.7[a]	2.9
Potassium						
Mineral	15.8[c]	9.3	18.8[b]	11.6	23.4[a]	12.0
Organic	0.67[c]	0.98	1.7[b]	1.6	3.6[a]	1.1
Calcium						
Mineral	0.0[c]	0.0	1.6[b]	7.6	3.6[a]	5.1
Organic	2.8[c]	4.6	6.0[b]	5.0	12.7[a]	4.3
Magnesium						
Mineral	0.0[c]	0.0	0.69[b]	3.3	2.2[a]	3.1
Organic	1.0[c]	1.5	2.6[b]	2.3	7.0[a]	2.6
Sulfate						
Mineral	0.84[b]	3.1	0.88[b]	3.3	3.1[a]	5.1
Organic	0.43[b]	0.63	0.89[a]	0.78	1.0[a]	0.34
Chlorine						
Mineral	12.9[b]	8.2	16.2[a]	11.4	16.9[a]	11.6

Note: Data shown as mean and standard deviation (SD) the charge-equilibrium fluxes ($keq·ha^{-1}·yr^{-1}$) can be converted to mass fluxes ($kg·ha^{-1}·yr^{-1}$) by multiplying by 14, 31, 39, 23 and 35.5 for the monovalent ion N (NH_4^+ and NO_3^-), P ($H_2PO_4^-$), K^+, Na^+ and Cl^-, respectively, and 16, 20 and 12 for divalent ionic S (SO_4^{2-}), Ca^{2+} and Mg^{2+}, respectively (details in Zhu et al.[28]). [a,b,c]Values followed by the same letter within rows are not significantly different ($P < 0.05$).

three farm sizes and within the same farm size due to irrational S fertilizer applications. No significant difference was found between small and medium farms, but large farms had a significantly higher S surplus (5.2 $keq·ha^{-1}·yr^{-1}$, or 83.2 $kg·ha^{-1}·yr^{-1}$).

3.3 Soil acidification by farms size

The main soil acidity production processes varied in banana plantations of the three sizes (Fig. 2). On small farms, N transformation contributed 21.9 $keq·ha^{-1}·yr^{-1}$ H^+ on average; no significant change was found on medium farms, but it was significantly lower by 26% on large farms. Larger farms had enhanced H^+ production from crop removal, rising from 5.5 $keq·ha^{-1}·yr^{-1}$ on small farms to 6.4 and 7.1 $keq·ha^{-1}·yr^{-1}$ on medium and large farms, respectively. Overall, N transformation dominated the soil acidity production processes on all farms irrespective of size.

Overall, the average total soil acidification rate on the farms was 12.1 $keq·ha^{-1}·yr^{-1}$. With larger farms, the actual soil acidification rate was lower but the potential soil acidification rate was higher (Fig. 3). Potential acidification is reflected by the anion accumulation in the soil (Eq. (7)), which indicates a further acidification risk when the accumulated anions are leached, whereas the actual acidification rate is reflected by the net BC losses (Eq. (6)). Compared to the small and medium farms, more organic fertilizers were applied in the large farms, causing a higher phosphorus and BC accumulation (Table S1), thus higher potential acidification rates and lower actual acidification rates were found on large farms compared to the small farms. The average actual and potential acidification rate was 12.5 and 6.1 $keq·ha^{-1}·yr^{-1}$ on small farms, respectively, which was lower at 7.6 $keq·ha^{-1}·yr^{-1}$ and higher at 7.4 $keq·ha^{-1}·yr^{-1}$ on medium farms, respectively, but no significant change in the soil acidification rates was found. On large farms, although the potential acidification rate was higher

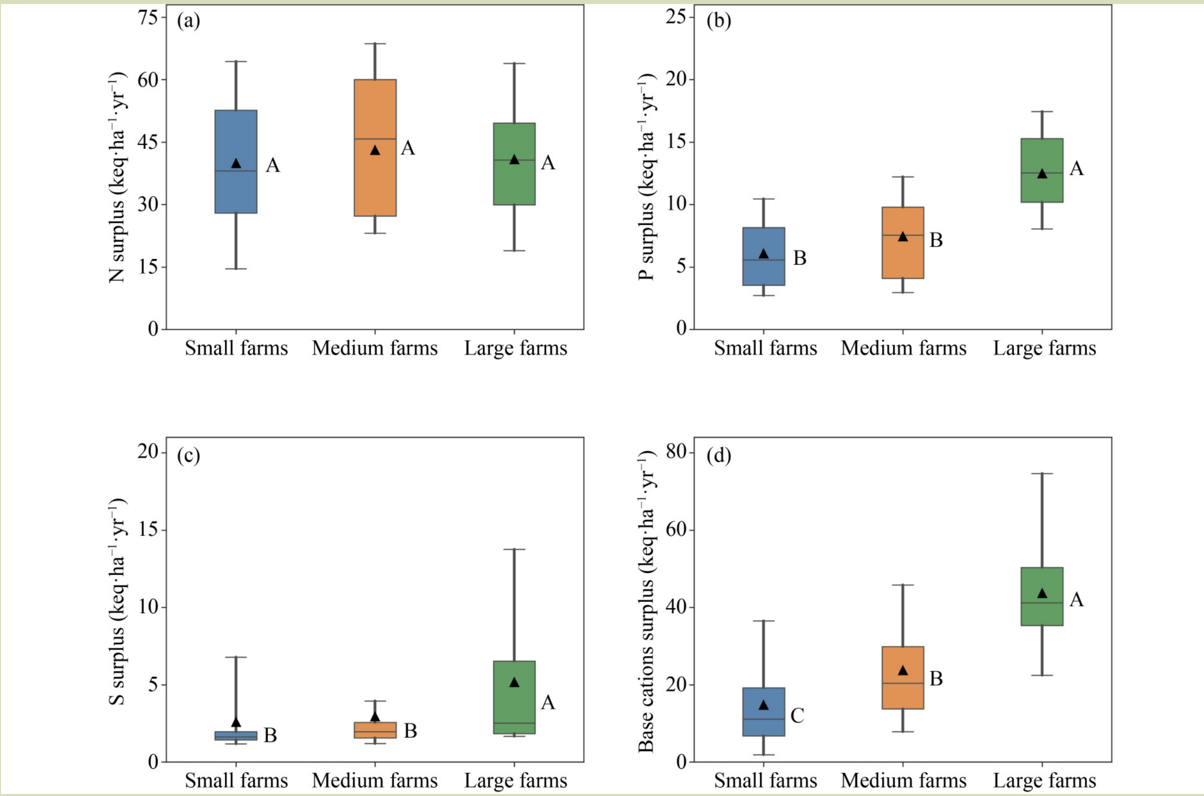


Fig. 1 Nitrogen (a), phosphorus (b), sulfur (c) and base cations (d) surplus on small, medium and large farms. Element surplus was estimated as the difference between total inputs and crop removal (X_{in} − X_{upt}). Solid lines and triangles (▲) indicate median and mean surplus, respectively; the boundaries of the boxes represent the 25th and 75th percentiles range; the whiskers the 5th and 95th percentiles; means followed by the same letters are not significantly different ($P < 0.05$).

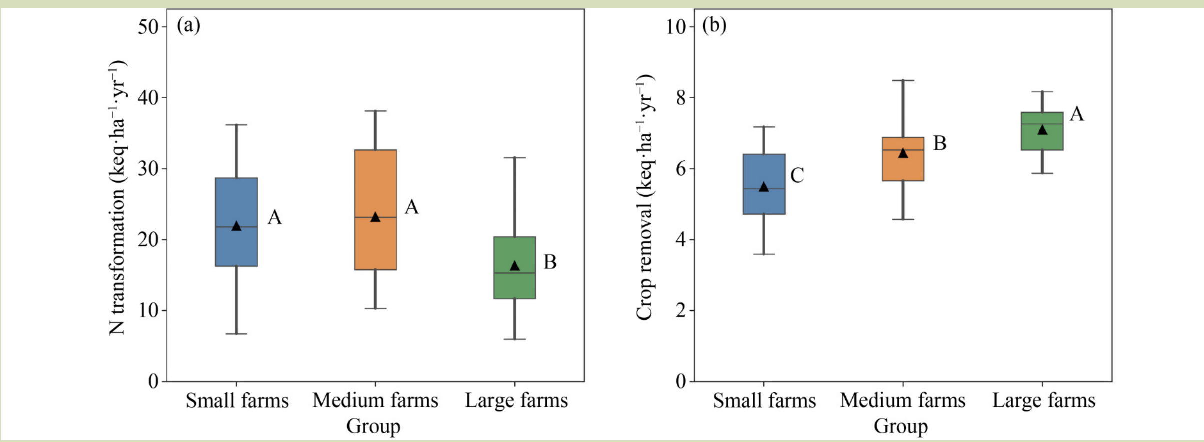


Fig. 2 Soil acidity (H^+) production by N transformations (a) and crop removal (b) on small, medium and large farms. Solid lines and triangles (▲) indicate median and mean surplus, respectively; the boundaries of the boxes represent the 25th and 75th percentiles range; the whiskers the 5th and 95th percentiles; means followed by the same letters are not significantly different ($P < 0.05$).

at 12.5 $keq \cdot ha^{-1} \cdot yr^{-1}$, the actual acidification rate was lower at −11.5 $keq \cdot ha^{-1} \cdot yr^{-1}$; as a result, the average total soil acidification rate was only 1.0 $keq \cdot ha^{-1} \cdot yr^{-1}$, showing that large-scale farming had significantly less soil acidification.

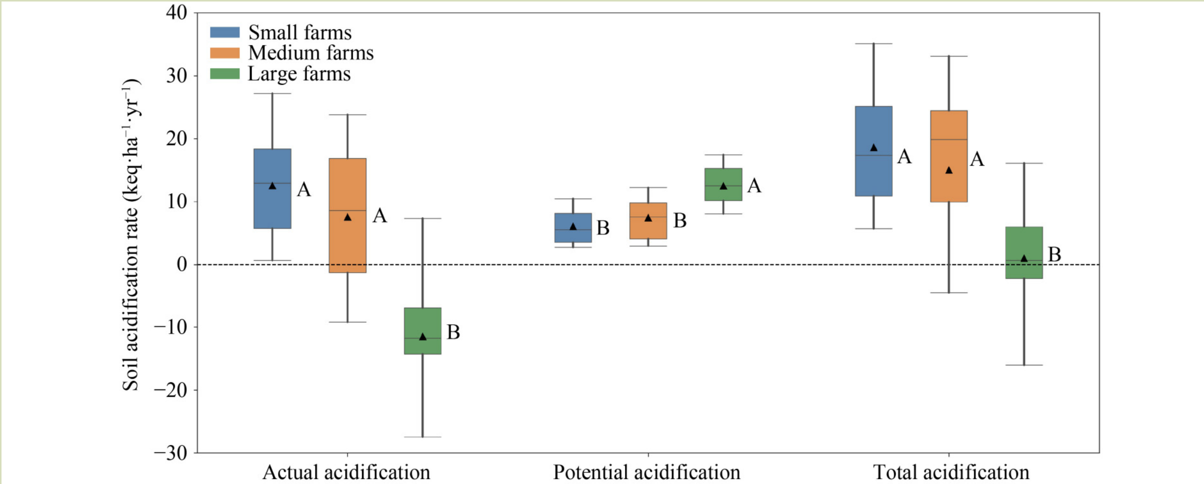


Fig. 3 Actual, potential and total soil acidification rate on small, medium and large farms. Solid lines and triangles (▲) indicate median and mean surplus, respectively; the boundaries of the boxes represent the 25th and 75th percentiles range; the whiskers the 5th and 95th percentiles; means followed by the same letters are not significantly different ($P < 0.05$).

4 DISCUSSION

Smallholders have an important role in agriculture in China to feed over 20% of global population with less than 10% of the arable land, but they often operate with high input at low efficiency, resulting in high environmental costs[4,45,46]. One example is cropland acidification induced by the overuse of N[3]. Many studies have quantified soil acidification rates in cereal crop systems, but only a few have done the same for cash crop systems. There has not been a study on the impacts of farm scale on soil acidification risks in banana production in China. Our study found that large-scale farming (> 6.7 ha) had significantly higher total yield of banana plantations, with the least yield variation as well as actual soil acidification rates by substituting more organic N for part of mineral N fertilizers. This appears to be the first study to systematically evaluate the impacts of large-scale farming on crop production and soil acidification in a cash crop system, giving an insight into the field management in farms of different sizes and proposing recommendations for sustainable soil management and food production.

4.1 Impacts of large-scale farming on soil acidification risks

The average total soil acidification rate was 12.1 $keq \cdot ha^{-1} \cdot yr^{-1}$, which was consistent with the reported acidification rates of fruit production systems in China (between 9.9 and 14.4 $keq \cdot ha^{-1} \cdot yr^{-1}$ in the 2010s[47]). Compared to other regions, the estimated acidification rate in this study was substantially lower, for example, the Qiyang citrus (27.8 $keq \cdot ha^{-1} \cdot yr^{-1}$)[48] and Pinghe honey pomelo (29.6–39.6 $keq \cdot ha^{-1} \cdot yr^{-1}$)[49] systems, which was possibly due to these two systems using less organic fertilizer input for acidity buffering[48] or much higher H^+ induced by N input (around 1.2 $t \cdot ha^{-1} \cdot yr^{-1}$)[49]. Uncertainties of our study mainly came from the estimated N losses to water (leaching and runoff), which was 50% of N_{rest} (N surplus minus NH_3 emission). Estimated N losses to water in this study was 40% of total N input from fertilizer and manure on average (Table S1), which was comparable with the local field experiment carried out by Li et al.[35]. Comparable results have also been reported in the humid tropics banana plantation in Australia (37%–63%)[50] and (Spain)[51], since the great fertilizer inputs and high irrigation rate tend to cause high N losses rates.

In general, soil acidification rates in cash crop systems are higher than those in cereal crops, such as the national average of 8.6 $keq \cdot ha^{-1} \cdot yr^{-1}$ in China[28] or a wheat-maize system under the standard management of 8.7–11.4 $keq \cdot ha^{-1} \cdot yr^{-1}$[13]. Often grown in subtropical soils with poor acid buffering capacity, acidification risks of cash crop systems in southern China require more attention and development of effective mitigation strategies. According to Xu et al.[52], the acid buffering capacity of topsoils (0–20 cm) in southern China is mostly between 9.1 and 32.1 $meq \cdot kg^{-1}$ per pH unit, or only 23.7 to 83.5 $keq \cdot ha^{-1}$ of H^+ can cause the pH decline by one unit (assuming soil bulk density is 1.3 $t \cdot m^{-3}$). It indicates that soil with a pH of 6.5 on the small farms (with 18.6 $keq \cdot ha^{-1} \cdot yr^{-1}$ of total H^+ production) of Long'an County may be acidified to pH 4.5 after

3–9 years, while large-scale farming can effectively delay the acidity-induced threat by more than 45 years. Either field management improvement or transformation of smallholdings into large-scale farming is urgently required to prevent further acidification in the region.

Mineral fertilizer application and crop removal were the main causes of soil acidification, contributing 38%–62%, and 21%–38% of the H^+ production on average, respectively, among the three farm sizes (Fig. 4). For small and medium farms, the ratio was similar to cereal crop systems[28]. However, the proportion and input of organic fertilizers in cash crop systems are generally much higher than in cereal crop systems[53]. Due to the high content of acid buffering elements (e.g., BC), organic fertilizers can effectively reduce the soil acidification rate. In the present study, organic fertilizers application was the most important way to buffer the H^+ production (by 2.5–14.0 keq·ha^{-1}·yr^{-1}) and enhanced with increased farm size (Fig. 4). This finding was consistent with the findings of Zhang et al.[53], who found that farm size had a significant positive correlation with farmer intention to apply manures based on a regional farm survey. On large farms, substituting organic fertilizers for ammonia-based fertilizers led to a much lower contribution of mineral fertilizers to soil acidification and substantially prevented soils from acidifying. Over recent decades, the decoupling of crop and livestock production has raised the mineral N input but decreased the organic manure share in fertilizer application[54]. In this context, large-scaling farming may promote the integration of crop and livestock production[53], thus increasing the nutrient use efficiency and decreasing nutrient emissions to water in the agricultural systems[55]. In other words, large-scale farming reduced soil acidification risks by improving nutrient management strategies, such as reducing acidifying sources (NH_4^+ fertilizer) and adding acid buffering elements (organic fertilizers). The strategies were important to alleviate ongoing soil acidification for sustainable soil management[12], especially in the cash crop systems grown in soils with poor acid buffering capacity.

4.2 Large-scale farming for sustainable food production

As Zhu et al.[5] indicated, even no N fertilizer increase after 2020 in China may lead to 16% of cereal losses due to nationwide soil acidification until 2050, which could be avoided if nutrient management was improved[5]. Transforming the smallholder-dominant agricultural systems

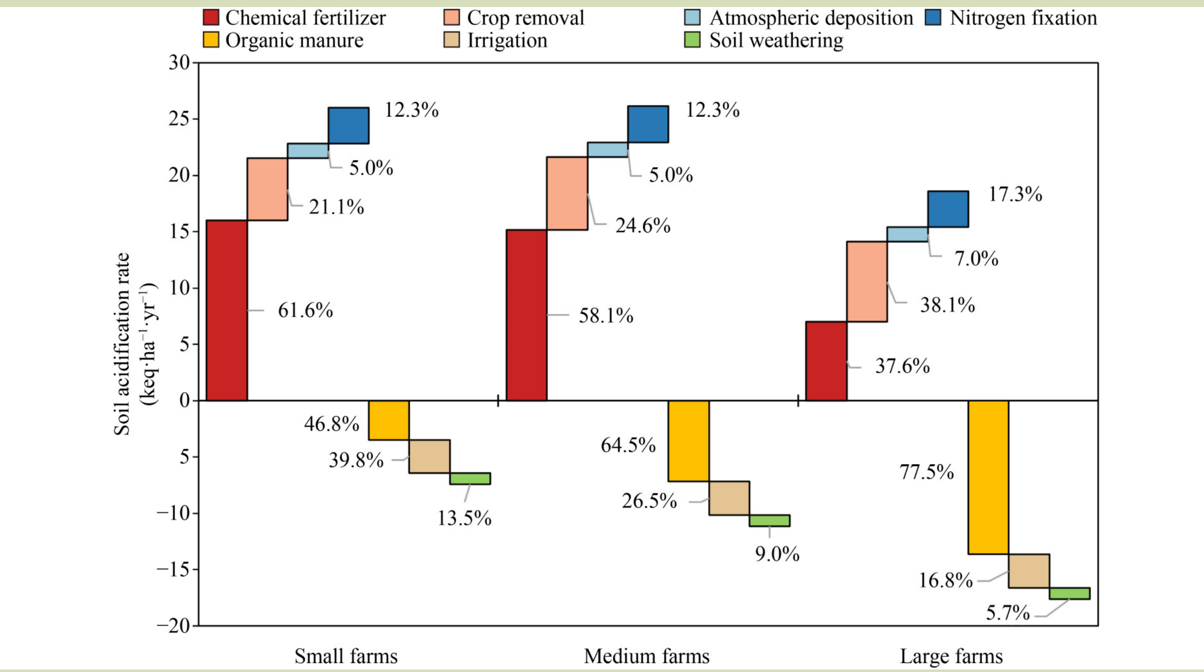


Fig. 4 The soil acidification rate and the contributions of different processes on small, medium and large farms. The percentages in the figure represent the contribution of the corresponding processes in acidity production and consumption. Among them, mineral fertilizer, crop removal, atmospheric deposition and nitrogen fixation are acid-producing processes; organic fertilizer, irrigation and soil weathering are acid-consuming processes.

to large-scale operations may help. Our study showed that large-scale farming provided dual benefits on increased banana yield and mitigation of soil acidification by improving field management. Also, large farms tended to have lower mineral N and P fertilizer inputs with lower variability than medium farms (Table 3), indicating that large-scale operators tended to apply fertilizers more rationally. Smallholders tend to rely more on experience in their agricultural operations, with less access to, and less willingness to adopt, high-efficiency technologies[56]. The North China Plain is one of the major food production regions of China, but at most only 43% of smallholders are willing to adopt the recommended technologies for land preparation, sowing date, planting density and fertilization, resulting in a 26% to 37% gap with the attainable yield that demonstrated by local long-term experiments[57]. While large-scale operators are more motivated for highly efficient technologies. For example, Ju et al.[56] showed that large-scale operators were more willing to optimize fertilizer input due to the contribution of fertilizer being higher in their total cost compared to the smallholders, who often had the most cost in labor (the opportunity cost). Lower fertilizer use on large-scale farms can also decrease soil acidification and alleviate other environmental impacts such as greenhouse gas emissions[31]. In this context, large-scale farming operations can support the transformation of agriculture and food production into a more sustainable system, and the cash crop systems such as fruit and vegetable might be the priority due to their high profits, high fertilizers consumption, and, more importantly, the increasing demand for them as healthy food[58].

However, it is worth noting that more comprehensive management is required for the surveyed banana plantation to realize both soil acidification control and environmentally safety. Our study found no significant difference in N surplus among the three farm size (Fig. 1); the average N surplus (578 kg·ha^{-1}·yr^{-1}) was four times higher than crop demand, leading to substantial soil BC leaching. In a field experiment, Hao et al.[13] reported that optimizing the N application rate given the crop demand can well counteract ongoing acidification due to the decreased NO_3^- and BC leaching. Thus, reducing N application rates based on crop demand and soil nutrient availability is highly recommended, especially for small and medium farms to concurrently reduce costs and alleviate soil acidification. In addition, it has been shown in our study that manure application is capable of mitigating soil acidification, which is consistent with other studies[59,60]. However, greater organic fertilizer (manure) applications also increased the P surplus and huge P accumulation in soils (Fig. 2 and Table S1) and thereby water pollution risks[61]. Therefore, we recommend comprehensive management for the banana plantation by optimizing the total N input to reduce the acidification rates. At the same time, partly substituting N fertilizers with organic manure in view of the P environment risk control is also recommended, to neutralize protons and improve the soil quality. The remaining H^+ produced could be neutralized by frequently liming. In short, more accurate nutrient management is required in the future, to co-realize multi-targets of soil acidification mitigation, food security and environmental protection.

5 CONCLUSIONS

Based on a regional farm survey, this study investigated the field management and soil acidification rates in banana plantations of different sizes (small, medium and large farms) in Long'an County, China. Average soil acidification was 15.0 keq·ha^{-1}·yr^{-1} in the typical cash crop system, primarily caused by mineral fertilizer application and crop removal (harvesting), contributing to 82% of total acidity production. Larger farm had significantly greater yield per unit area. On large farms (> 6.7 ha), banana yields per unit area were 10% to 29% higher than on small and medium farms, with 47% to 50% lower coefficient of variation (both significant, $P < 0.05$). Larger farms had greater additions of organic fertilizers (manure) and BC in the soil, resulting in a significantly lower actual soil acidification rate by 9.1–24.0 keq·ha^{-1}·yr^{-1}. By substituting organic fertilizers for some mineral nitrogen fertilizer, large farms have less N-induced acidity production and prevent soils from further acidifying, with an average total acidification rate of 1.0 keq·ha^{-1}·yr^{-1}. However, the P accumulation in soils was greater, leading to resource wastes and potential environmental pollution. We concluded that promoting large-scale farming can alleviate soil acidification and improve crop production for sustainable agricultural management and food production, while optimal strategies are still required to mitigate acidification and minimize nutrient losses simultaneously.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2022475 contains supplementary materials (Fig. S1; Table S1).

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Compliance with ethics guidelines

Donghao Xu, Jiangzhou Zhang, Yajuan Li, Shiyang Li, Siyang Ren, Yuan Feng, Qichao Zhu, and Fusuo Zhang declare that they have no conflicts of interest or financial conflicts to disclose. All applicable institutional and national guidelines for the care and use of animals were followed.

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