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Responses in growth, yield and cob protein content of baby corn (*Zea mays*) to amendment of an acid sulfate soil with lime, organic fertiliser and biochar

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ABSTRACT

Cropping of acid sulfate soils requires effective treatment of their inherently low pH. We evaluated the efficacy of applications of two levels of lime (0 or 2 Mg/ha), two levels of organic fertiliser (0 or 5 Mg/ha), and three levels of biochar (0, 10 or 30 Mg/ha) in a factorial design for ameliorating acidity in an acid sulfate soil, and measured the subsequent growth and yield of baby corn (*Zea mays* L.). Lime increased soil pH(H_2O) from 3.75 to 4.12, salinity from 1.72 to 1.95 dS/m, and cob yield by 30%. None of the amendments significantly altered total organic carbon or total nitrogen concentrations in the soil. Biochar additions increased cob yields by an average of 28% on both unlimed and limed soil. Addition of organic fertiliser increased cob yield by 45% on unlimed soil but had no significant effect on yields on limed soil. The yields obtained with liming were similar to the highest yields achieved with biochar or organic fertiliser applied either separately or in combinations. Overall, cob yields were increased by 19% with addition of organic fertiliser. The yield increseas from additions of biochar or organic fertiliser were associated with improvements in nutrient supply. However, the increases in cob yield were associated with reduced cob protein, probably resulting from poor availability of nitrogen late in the season. We conclude that biochar and organic fertiliser applied in relatively large quantities can be viable treatments for cropping acid sulfate soils.

Keywords: acid sulfate soils, cob quality, harvest index, liming, organic fertiliser, phenology, rice biochar, Vietnam.

Introduction

Agricultural productivity is generally poor on acid sulfate soils. These soils cover about 12–13 Mha globally, with wide distribution mostly in the coastal tropics of southern and south-eastern Asia (~10 Mha). Other regions with large areas of acid sulfate soils are found along the coasts of northern West Africa, eastern South America and eastern Australia (Andriesse and Van Mensvoort 2006). The widespread distribution of acid sulfate soils exacerbates the decline in availability of arable lands and poses a significant risk to food security in these densely populated regions of the world (Yunusa *et al.* 2018). This risk is likely to be increased by the rising sea levels associated with climate change, predicted to increase by 235 cm by 2100 (Milen 2010).

The poor agricultural potential of acid sulfate soils is associated with their low pH and mobilisation of toxic trace elements (e.g. boron, copper, manganese and zinc) along with reduced availability of macronutrients, especially nitrogen (N), phosphorus (P) and potassium (K) (Golez and Kyuma 1997; Fitzpatrick 2003). An acidic rhizosphere damages and restricts growth of plant roots, mobilises toxic trace elements, and interferes with uptake of key macronutrients (Fitzpatrick 2003; Guong and Hoa 2010). For instance, Marschner and Rengel (2012) reported that poor root growth coupled with weak contact of roots with the soil matrix in acid sulfate soils inhibits uptake of N by the plant even in the presence of high concentrations of total N in the bulk soil. Therefore, poor survival, growth and yields have been observed in plants grown on acid sulfate soils; yield reductions of up to 10% have been reported in maize (*Zea mays* L.) (Sierra *et al.* 2003). Heavy investments to treat acidity are therefore required for viable cultivation of the vast majority of crops on acid sulfate soils.

Liming is the most common treatment for low pH in acid sulfate soils (Bloomfeld and Coulter 1974; Elisa *et al.* 2016; Li *et al.* 2016). Lime addition rates as high as 20 Mg/ha have been used to increase the soil pH by up to 2.0 units in highly acidic soils (Acosta-Martínez and Tabatabai 2000; Hiep 2008). Availability and cost of liming are major constraints on the farmer's capacity to treat acid sulfate soils sufficiently for profitable cultivation, particularly in developing countries such as Vietnam, where acid sulfate soils account for 6% (2 Mha) of the country's total land area (Tran 2015). Hence, other materials such as organic matter (Michael and Ian 2005), biochar (Masulili *et al.* 2010; Manickam *et al.* 2015) and organic fertilisers (Hati *et al.* 2008) are often considered as alternative amendments, or as supplements, to lime for ameliorating acid sulfate soils. Halim *et al.* (2018) reported that organic materials applied in combination with a compound (NPK) fertiliser on an acid sulfate soil raised the soil pH from 3.7 by 0.5–2.0 units within 60 days of treatment and marginally increased rice yield. Organic fertilisers are also viewed as affordable liming agents that have the added benefit of high nutrient contents to benefit crop productivity, especially when used in conjunction with biochar and/or lime to treat acid sulfate soils (Halim *et al.* 2018).

Increased availability of macronutrients (NPK) from biochar additions, alone or in combination with other organic amendments, is associated with significant improvements in the yield of maize on fertilised, moderately acidic Red Ferrosol (Agegnehu *et al.* 2016). The efficacy of organic materials in ameliorating soil acidity depends on their physicochemical properties such as pH, carbon (C):N ratio, alkalinity and mineralisation potential (Xu and Coventry 2003; Gao *et al.* 2019). For instance, Xu and Coventry (2003) reported that addition of dried and ground straws of lupin (*Lupinus alba* L.; C:N 10.5) and shoots of wheat (*Triticum aestivum* L.; C:N 9.0) significantly increased pH in a highly acidic soil (pH <5). The authors attributed the increases in pH to the ash alkalinity and the mineralisation of organic N in the applied plant residues. By contrast, instances of declines in the pH of residue-amended soils were ascribed to nitrification of mineralised N in the applied residues. A meta-analysis by Gao *et al.* (2019) showed that biochar increased P (both available and microbial) by at least 45% and available N (ammonium and nitrate) by an average of 14%. The analysis revealed that N availability in biochar-amended soil depends on the N content and pH of both the biochar and the receiving substrate. The authors concluded that biochar made from materials having low C:N ratio and generated at low temperatures, or applied at high rates, were quite effective for enhancing soil available P.

Rice biochar is generally considered a viable resource for treating acid sulfate soil in Southeast Asia, where managing the large amounts of rice straw produced every season is a major environmental and economic challenge (Shamshuddin *et al.* 2017). Use of the rice straw to manufacture biochar is a viable economic end use, being an alternative to traditional burning while combating air pollution and CO_2 emissions (Van Hung *et al.* 2020). Addition of rice biochar improves soil structure and chemical properties by reducing soil bulk density, soil strength, exchangeable aluminium (Al) and soluble iron (Fe) while enhancing soil nutritional and hydrological properties (Masulili *et al.* 2020). Indeed, Manickam *et al.* (2015) reported that addition of rice biochar to an acidic soil raised the pH by 1.5 units and significantly increased root growth, but produced only a marginal increase in the yield of maize.

The Mekong Delta is a primary agricultural belt of Vietnam accounting for over half of the country's total rice production, mostly on acid sulfate soil that is subjected to intrusion of seasonal seawater (Thong *et al.* 2011). Managing low soil pH and its attendant impacts on soil fertility, crop growth and yield remains the primary constraint on productivity and is a significant impost on farming acid sulfate soils (Guong and Hoa 2010). In addition, it is also not clear whether, or to what extent, addition of rice biochar would effectively relieve the intrinsic acidity of the soil in the short–medium term. Therefore, the present study was undertaken to determine: (*i*) the relative efficacy of lime, organic fertiliser and rice biochar, applied individually or in combinations, for ameliorating the low pH of acid sulfate soil; and (*ii*) the impacts of these amendments and their combinations on growth, yield and cob protein content of baby corn.

Materials and methods

Site details

The study was conducted in a glasshouse at the Department of Soil Science, College of Agriculture and Applied Biology, Can Tho University, Can Tho, Vietnam (10°1′N, 105°45′E). We collected soil from the top 20 cm of the profile near the village of Vinh Vien, Long My district, Hau Giang province (9°40′N, 105°26′E). The soil is classified as HypoSali-Umbri-Epi Orthithionic Gleysol according to the World Reference Base System (IUSS Working Group WRB 2007) and is equivalent to Entisols and Inceptisols as per USDA Soil Taxonomy (Soil Survey Staff 1999). These soils are commonly referred to as hydro-morphic (groundwater) soils and are characterised by a shallow clay horizon (55% clay, 35% silt and 15% sand) to a depth of about 1 m (Minh *et al.* 1998). The soil profile is highly acidic, with total sulfur (as SO_4^{2-}) 2.0%, actual titratable acidity 2790 mol H^+/t, total acidity 8.44 (g/L), exchangeable Al content 6.6 $cmol_c$/kg, and

Table 1. Basic chemical properties of the soil and amendments used in the study.

Study materials	$pH(H_2O)$	EC (dS/m)	OM	Total C	Total N	C:N	Total P	Total K	CaO
				(g/kg)				(g/kg)	
Soil	4.0	1.1	123	72	2.8	26	0.7	10.5	–
Biochar	9.6	1.0	545	317	3.9	81	2.3	6.5	–
Organic fertiliser	7.2	11.4	385	225	16.7	13	17.2	7.0	–
Hydrated lime	12.6	–	–	–	–	–	–	–	622

EC, Electrical conductivity; OM, organic matter; –, data not available or not applicable.

average $pH(H_2O)$ 4.0. Soil total organic matter and total N concentrations were 12% and 0.28%, respectively. Details of soil properties are presented in Table 1. The area experiences transient seawater intrusion between February and April every year.

Treatments and experimental design

Soil samples were air-dried, then sieved to pass 2 mm and used to fill plastic pots (32 cm diameter, 25 cm height) at 10 kg per pot. The treatment factors consisted of three types of amendments applied at different rates as follows: hydrated lime at 0 or 2 Mg/ha; organic fertiliser at 0 or 5 Mg/ha; and biochar at 0, 10 or 30 Mg/ha. Treatments were factorially combined generating 12 treatments, which were individually assigned to the potting soil. The experiment was laid out as a randomised block design with four replicates, making a total of 48 pots (experimental units). Within each block, the treatments were arranged randomly. All pots were supplied with basal NPK fertiliser (2.5 N:1 P_2O_5:1 K_2O) at 26 g/pot, which approximated to (per ha) 150 N applied as urea, 360 kg P, and 100 kg K.

The lime and organic fertiliser were obtained from a commercial supplier (BioPro; MSUN, Ha Noi City, Vietnam). The organic fertiliser was a composted mixture of sugarcane filter cake and fish manure. The biochar was produced from rice husk using a top-lit updraft stove at the Department of Soil Science, College of Agriculture and Applied Biology, Can Tho University, following the procedures described by Hoa *et al.* (2014) and Luong *et al.* (2012). This involved air-drying the rice husks in the sun to ensure efficient combustion when fed into the stove, using burning paper as a starter. The husk combustion lasted about 90 min, during which time the temperatures rose to 500–550°C.

Planting and maintenance

The baby corn variety used in the study was Pacific 421 (Pacific Seeds, Toowoomba, Qld, Australia), known for its high-quality seed and tolerance of diseases (Guong and Hoa 2010). Lime was applied to the relevant pots 14 days before planting, and organic fertiliser, biochar and basal fertiliser (superphosphate, 1/5 urea and 1/5 KCl) were applied 1 day before planting. Four maize seeds were sown in each pot on 17 October 2014. The pots were each placed on trays and arranged in rows 0.7 m long, with pots spaced 0.25 m apart within the row. After germination, the four plants in each pot were gradually thinned to one by cutting a plant at the base and removing it with minimal rhizosphere disturbance at 7, 14 and 28 days after sowing (DAS). The pots were watered every morning to ensure adequate water supply while avoiding drainage by checking for any leakage from the perforation at the bottom of the pots. On the rare occasions when leakage occurred, the drained water was poured back into the respective pots during watering. Fertiliser application was repeated for all pots during the final plant thinning at 28 DAS.

Measurements

Nutritional analysis of soil and amendments

Bulk samples of the soil and the three amendments were analysed to determine their pH, EC, total organic C, total N, total P and total K content. The CaO content of the lime was estimated following the procedures compiled by Rayment and Higginson (1992). Chemical analysis of the potting soil was performed on finely ground samples twice during the trial: first, before sowing soon after adding soil amendments, and then immediately after completion of harvest. Soil pH was determined in deionised water (1:2.5 soil:water) and measured with a pH meter (Metrohm 744; Metrohm, Herisau, Switzerland) (Thomas *et al.* 1996). The soil-water preparations were also used to determine electrical conductivity (EC) with a handheld meter (EC-Lab 960; SCHOTT Instruments, Mainz, Germany). Total organic C and total N were determined by using a C:N analyser (LECO, St. Joseph, MI, USA).

Plant measurements

Plant height, leaf area and leaf chlorophyll contents were determined at 14, 21, 28, 35 and 42 DAS; measurements at 14 and 28 DAS were made on the thinned plants. Plant height was measured from the base of the plant to the base of the topmost fully expanded leaf, using a measuring tape. Leaf area was determined from the length and width of fully expanded leaves as: leaf length × leaf maximum width × 0.75 (Yunusa 1989). Chlorophyll content was determined on the uppermost fully expanded leaves, using a chlorophyll meter (SPAD-502; Konica Minolta, Osaka, Japan) (Coste *et al.* 2010).

Dates of tassel and first silk emergence were recorded, and harvesting was undertaken 2 days after silk emergence between 53 and 64 DAS depending on the treatment. Final plant growth and yield variables at harvest were made on the one plant left in each pot. The cobs were harvested during the 5-day period following silking (i.e. 58–70 DAS) as per established practice in Vietnam. These plants were cut at the soil surface and the ears (consisting of cob, husk and silk) were removed and counted. These plant samples were then dried in an oven at 80°C for 72 h and weighed to determine their total dry matter. The ears were then dehusked and the cob weighed to calculate the harvest index as: cob weight/total plant weight (i.e. shoot + ear). The cobs were then analysed for total N content (%) and crude protein content was estimated as 6.25 × total N (Mariotti *et al.* 2008).

Statistical analyses

All data were evaluated first for normality and homogeneity of variances using the Kolmogorov–Smirnov test and Levene's test, respectively, and then a three way analysis of variance (ANOVA) was performed on the data using SPSS 16 (SPSS, Chicago, IL, USA). When treatment effects were significant ($P < 0.05$), both the main effects and interaction effects of treatments factors were evaluated using a *post hoc* multiple comparison for observed means with Duncan's multiple range test.

Principal component analysis (PCA) was performed to identify the most critical variables and their interrelations, using FactoMineR (Lê *et al.* 2008) package in R software (R Foundation for Statistical Computing, Vienna, Austria). PCA transforms the observed variables linearly into orthogonal uncorrelated variables known as principal components (PC), which maintain the total variance in the original data. This analysis was performed on the correlation matrix, standardising data measured on different scales to unit variance. Therefore, the PCs become independent of the scale and units of the observed variables.

Results

Plant growth and development

The patterns of treatment effects (i.e. liming, organic fertiliser and biochar) on plant height, stem thickness, leaf area and chlorophyll concentrations were consistent at all four sampling dates. Therefore, for brevity we present data for the last sampling only (Table 2). Plants on limed soil and amended with organic fertiliser and/or biochar were taller and thicker, had higher chlorophyll concentration, and developed faster (earlier tasselling and silking) than those

Table 2. Plant growth variables for baby corn in response to applications of lime, organic fertiliser and biochar on an acid sulfate soil.

Organic fertiliser (Mg/ha)	Lime at 0 Mg/ha				Lime at 2 Mg/ha			
	Biochar (Mg/ha)			Mean (org. fert.)	Biochar (Mg/ha)			Mean (org. fert.)
	0	10	30		0	10	30	
				Plant height (m)				
0	1.23a	1.22a	1.41b	*1.28A*	1.49b	1.53b	1.57b	*1.53A*
5	1.34a	1.33a	1.49b	*1.39B*	1.48b	1.58b	1.65c	*1.57A*
Mean (lime)			**1.34A**				**1.55B**	
				Plant leaf area (m^2)				
0	0.23a	0.29a	0.36a	*0.29A*	0.40ab	0.44b	0.43b	*0.42B*
5	0.36a	0.37a	0.44b	*0.39B*	0.49b	0.49b	0.48b	*0.49C*
Mean (lime)			**0.34A**				**0.46B**	
				Total chlorophyll concentration ($\mu g/cm^2$)				
0	40a	41a	43a	*42A*	42a	45b	44b	*44B*
5	44a	42a	44a	*43A*	43a	45b	44b	*43B*
Mean (lime)			**43A**				**44A**	
				Stem diameter (mm)				
0	12a	13a	15b	*13A*	15b	16b	17b	*16B*
5	15b	16b	17b	*16B*	17b	18b	17b	*17B*
Mean (lime)			**15A**				**17B**	

For each plant variable, means followed by the same letter are not significantly different at $P = 0.05$: lower case for biochar treatments, italic upper case for organic fertiliser treatments, and bold upper case for lime treatments.

on unlimed soils without organic fertiliser; these responses marginally increased with biochar addition at 30 Mg/ha. None of the amendments had a significant effect on the number of ears produced per plant, but the weight of ears was significantly higher for plants grown on limed soils and was increased further with additions of organic fertiliser and biochar (Table 3). There was no significant difference in cob weight between biochar applications at 10 and 30 Mg/ha.

Responses in growth variables

Biochar applied at 30 Mg/ha increased plant height, leaf area and stem diameter on unlimed soil irrespective of organic fertiliser addition (Table 2). Chlorophyll concentration was not significantly affected by biochar addition on unlimed soil but was increased when biochar was applied at either 10 or 30 Mg/ha on limed soil with or without organic fertiliser. Organic fertiliser increased plant height, leaf area and stem diameter only on unlimed soil, but had no significant effect on chlorophyll concentration. Lime addition significantly increased all growth variables except chlorophyll concentration.

Responses in phenology, yield and yield variables

Addition of biochar at 30 Mg/ha reduced the time to tasselling and silking by as much as 4 days on unlimed soil, but not on limed soil irrespective of organic fertiliser treatment (Table 3). Organic fertiliser addition hastened tasselling and silking by up to 5 days on unlimed soil but not on limed soil. Plants on limed soil also attained tasselling and silking earlier than those on unlimed soil.

The number of ears produced per plant was not affected by the treatments, in contrast to the yield response (total weights of the cob produced) (Table 3). Biochar applied at 30 Mg/ha increased cob yield on both unlimed and limed soil with or without organic fertiliser addition. Organic fertiliser addition increased cob yield by almost 16% on unlimed soil but not on limed soil, where its impact was modest. Overall, liming of the soil significantly increased cob yield by about 30%.

Biochar applied at 30 Mg/ha significantly reduced cob protein content by up to 13% on all lime and organic fertiliser treatment combinations except on limed soil treated with organic fertiliser, where there was no significant impact (Table 3). Organic fertiliser addition

Table 3. Development, cob yield and yield variables for baby corn in response to applications of lime, organic fertiliser and biochar on an acid sulfate soil.

Organic fertiliser (Mg/ha)	Lime at 0 Mg/ha				Lime at 2 Mg/ha			
	Biochar (Mg/ha)			Mean (org. fert.)	Biochar (Mg/ha)			Mean (org. fert.)
	0	10	30		0	10	30	
No. of days to tasselling after sowing								
0	54b	53b	49a	*52B*	48a	49a	46a	*48A*
5	47a	48a	47a	*47A*	48a	46a	46a	*47A*
Mean (lime)			**50B**				**47A**	
No. of days to silking after sowing								
0	58b	56b	52a	*55B*	50a	51a	50a	*50A*
5	51a	52a	50a	*51A*	52a	49a	49a	*50A*
Mean (lime)			**53B**				**50A**	
No. of ears produced per plant								
0	2.3	3.0	2.5	*2.3*	3.0	3.3	3.0	*3.1*
5	3.0	2.8	3.0	*2.9*	2.9	3.1	3.2	*3.1*
Mean (lime)			**2.7**				**3.0**	
Cob yield (g/plant)								
0	12.5a	14.8a	20.1b	*15.8A*	20.6b	26.4c	27.6c	*24.8B*
5	21.7b	22.1b	24.8bc	*22.8B*	20.8b	26.5c	28.9c	*25.4B*
Mean (lime)			**19.3A**				**25.1B**	
Cob protein content (%)								
0	18.1b	17.0ab	15.9a	*17.0AB*	19.1c	16.7b	16.7b	*17.5B*
5	17.5b	16.2a	16.0a	*16.6A*	16.5a	16.9a	16.2a	*16.5A*
Mean (lime)			**16.9A**				**17.0A**	

For each plant variable, means followed by the same letter are not significantly different at $P = 0.05$: lower case for biochar treatments, italic upper case for organic fertiliser treatments, and bold upper case for lime treatments.

reduced the cob protein significantly only on limed soil, and liming had no significant effect on cob protein.

Shoot weight was significantly increased by biochar addition at 30 Mg/ha with addition of organic fertiliser on unlimed soil (Fig. 1). Liming significantly increased shoot weight and decreased harvest index (Fig. 1).

Soil variables

Before sowing, biochar applied at 30 Mg/ha increased the soil pH on unlimed soil, although not significantly, whereas on limed soil, biochar effects were less evident (Fig. 2). Addition of organic fertiliser marginally increased pH on limed soil. On the other hand, addition of lime significantly increased soil pH by 0.37 units (from 3.75 to 4.12). Soil EC was not significantly affected by the addition of biochar on limed soil with or without organic fertiliser, whereas applying biochar at 30 Mg/ha significantly lowered the EC in both fertilised and unfertilised soils (Fig. 2). Soil EC ranged from 1.60 dS/m in unlimed and unfertilised soil to 2.04 dS/m in limed and fertilised soil, but these values were not statistically different. Total organic C was not affected by any treatment, whereas total N was significantly higher in fertilised and limed soil when biochar was added at 30 Mg/ha (Fig. 2).

There was an almost universal decline in the values of all soil variables measured after plant harvest (Supplementary material Table S1) compared with initial measurements. Reductions in soil pH after plant harvest were larger with biochar addition, except on limed soil that was supplied with organic fertiliser. Changes in the pH were similar on both unlimed and unfertilised soils. The magnitude of reduction in soil EC was significantly lower with biochar addition on unlimed soil and without organic fertiliser, whereas it was similar on the other soils irrespective of lime and organic fertiliser addition. The magnitude of reduction in EC was greater on limed than on unlimed soil. Neither total organic C nor total N was significantly affected after harvest by the additions of any of the three soil amendments or their combinations.

Multivariate analysis

The results of PCA are presented in Fig. 3. PC1 accounted for almost 40% of the total variances and was mostly associated

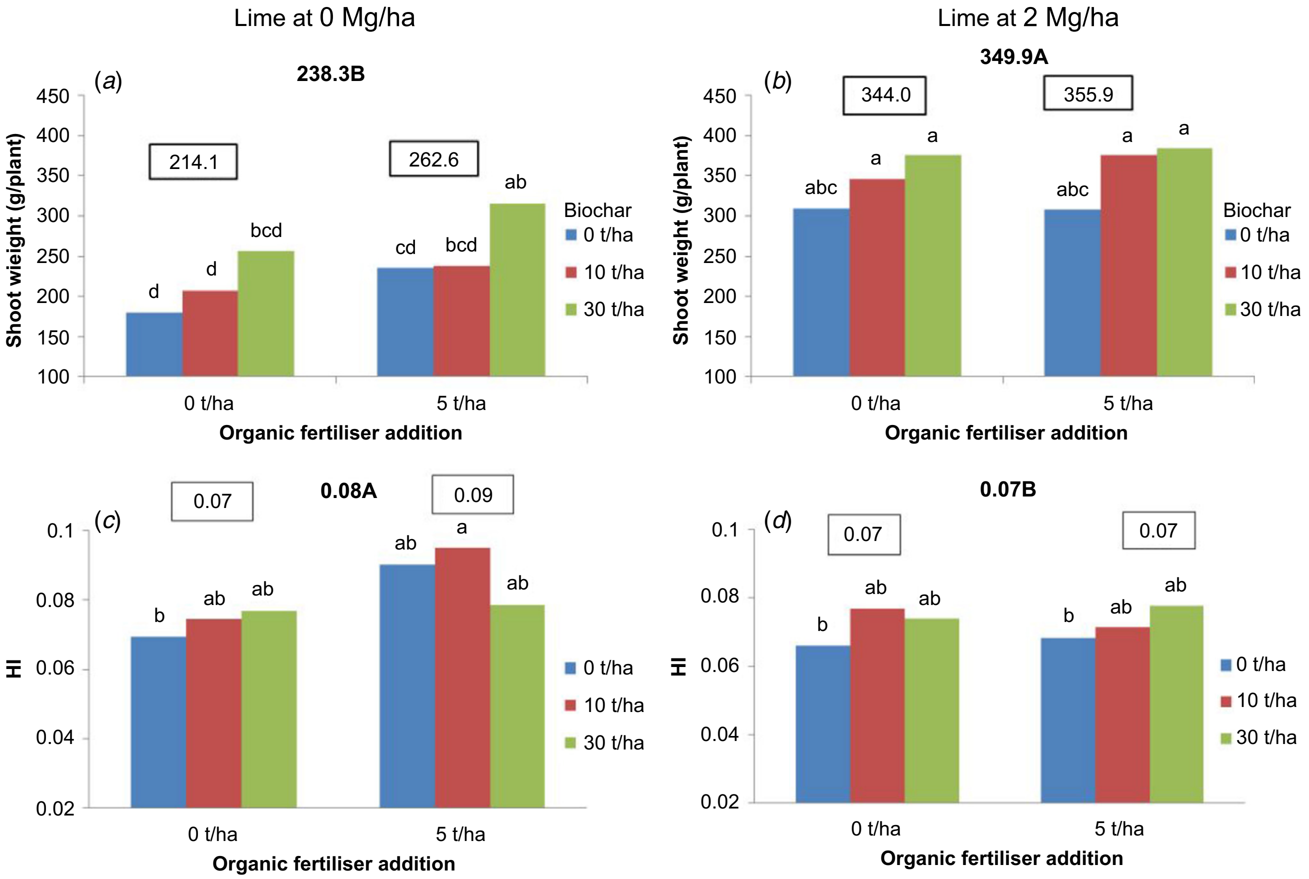

Fig. 1. Responses in shoot growth and harvest index for baby corn plants grown on acid sulfate soil treated with 0 or 2 Mg/ha of hydrated lime, 0 or 5 Mg/ha of organic fertiliser, and 0, 10 or 30 Mg/ha of biochar: (*a*, *b*) shoot weight and (*c*, *d*) harvest index (HI). For each parameter, bars with the same letter are not significantly different at $P = 0.05$. Framed numbers above groups of bars are the means for 0 or 5 Mg/ha of organic fertiliser, and bold numbers at the top of each graph are the means for lime rates.

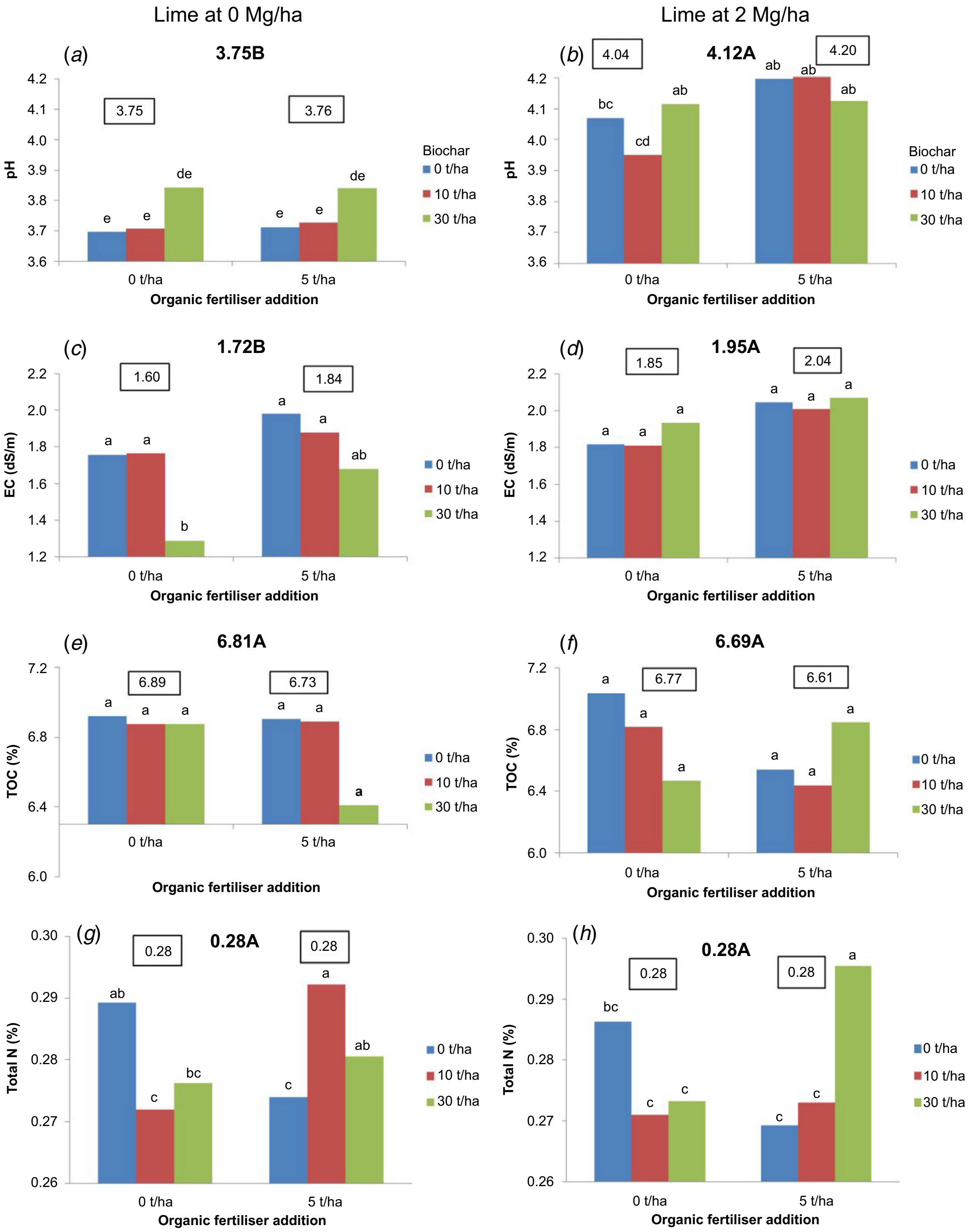

Fig. 2. Responses in selected variables of acid sulfate soil treated with 0 or 2 Mg/ha of lime and amended with 0 or 5 Mg/ha of organic fertiliser and 0, 10 or 10 Mg/ha of biochar, measured before sowing of baby corn: (*a*, *b*) pH; (*c*, *d*) electrical conductivity (EC); (*e*, *f*) total organic carbon (TOC); and (*h*, *g*) total nitrogen (TN). Bars with the same letter are not significantly different at $P = 0.05$. Framed numbers above groups of bars are the means for 0 or 5 Mg/ha of organic fertiliser, and bold numbers at the top of each graph are the means for lime rates.

with the pH gradient. PC2, which represented the fertility (total organic C and total N) spectrum, accounted for just over 11% (Fig. 3*a*). All plant variables (growth and yield) and soil pH measured at both times (before sowing and after harvest) were positively correlated (PC1). However, plant variables were inversely correlated with total soil N

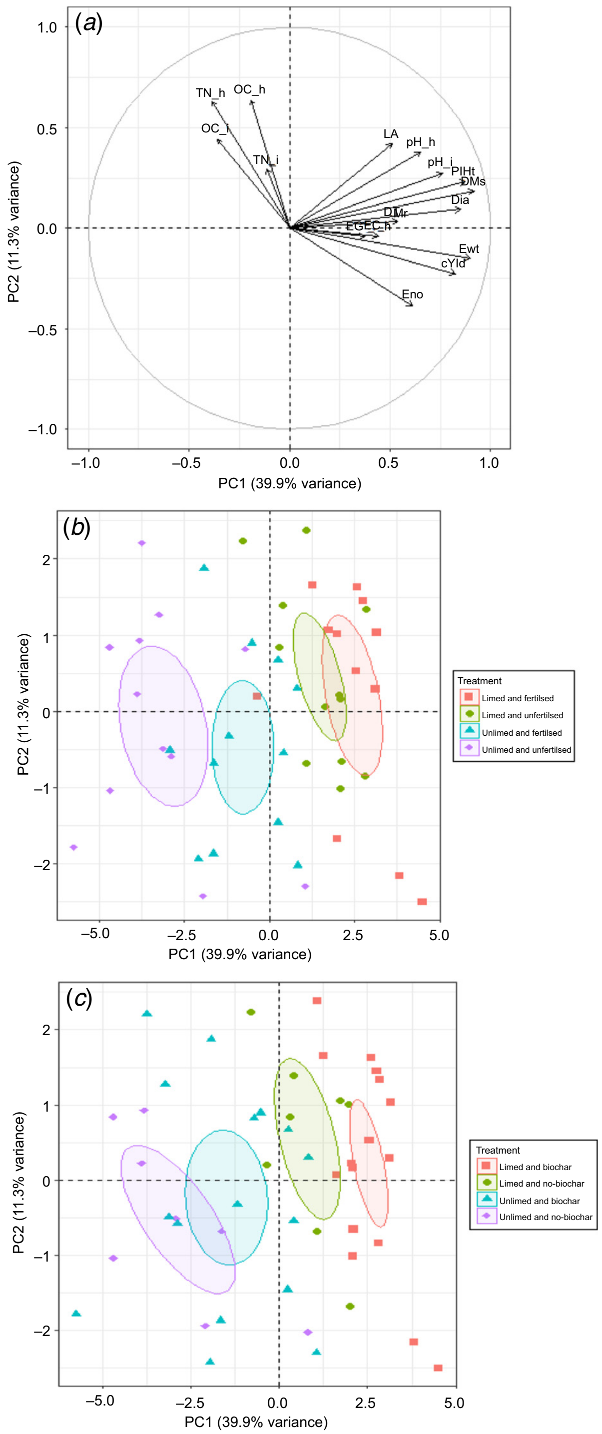

Fig. 3. Principal component analysis of plant and soil variables shown along the first two principal axes of variation: (*a*) vector loadings for response variables; and multivariate separations of the effects of (*b*) liming and organic fertiliser, and of (*c*) liming and biochar. In (*a*) the variables are total soil nitrogen (TN), total organic carbon (OC) and pH at the start (i) or harvest (h), leaf area (LA), plant height (PlHt), stem diameter (Dia), shoot dry matter (DMs), root dry matter (DMr), ear number (Eno), ear weight (Ewt), and cob weight (cYld). In all graphs, principal component 1 (PC1) or axis of variation represents a liming response axis, and PC2 represents a fertility gradient.

and organic C both at sowing and harvest (PC2). The vegetative growth variables (dry matter, leaf area, stem diameter) were inversely correlated with yield and yield component variables (ear number and cob yield) on PC2 axis.

Addition of organic fertiliser generally improved soil and plant variables, but its impact was greater when it was applied in combination with lime as illustrated by the response clusters for the soil treated with organic fertiliser, which shifted further to the right of those for lime-only treatments on the horizontal axis (Fig. 3*b*). A similar response was observed with the biochar treatment, which shifted the response clusters to the right (Fig. 3*c*) on the PC1 axis. Liming alone shifted the response clusters to the right of the vertical reference line (0), which was not achieved with either organic fertiliser or biochar alone.

Discussion

Our primary purpose in this study was to test the liming potentials of biochar and organic fertiliser, which are more affordable and available than agricultural lime in Vietnam. Neither biochar nor organic fertiliser significantly raised the pH of the acid sulfate soil, whereas lime addition raised the soil pH by almost 0.4 units (Fig. 2). The high organic matter contents of acid sulfate soils provide a large buffering capacity, making it difficult to increase soil pH significantly without liming. Both the biochar and organic fertiliser contain high amounts of organic matter, exceeding 35% (Table 1) and their additions to the soil would have further enhanced the soil's buffering capacity and subsequently stabilised its pH. It was only on unlimed soil that biochar applied at the rate of 30 Mg/ha increased the pH by 0.24 units, not dissimilar to the rise of 0.32–1.04 units in pH after 30 days of incubation of an acid sulfate soil amended with rice residues including husk biochar (Masulili *et al.* 2010).

In all treatments, the pH declined from pre-planting values such that the pH at 60 DAS (around the time of final harvest) was lower than at the start of the trial (Table S1). This response was consistent with an earlier observation (Jayalath *et al.* 2016) involving incubation of drained acid sulfate soils with plant residues. Those authors reported declines in pH by >2 units (from 6.5 to 4.0) of the drained hypersulfuric acid soil (pH 4.1, C:N 15) when amended with residues of common reeds (*Phragmites australis*) that have low C:N (28), over a dry period of 11 weeks. By contrast, the pH decline was more gradual (~1.0 unit) when the same soil was treated with pea (*Pisum sativum*) straws (C:N = 50) during the same period. Irrespective of treatment, the authors reported that the decline in pH of treated soil stabilised within 8 weeks of treatment applications. Both the pH and C:N ratio of the acid sulfate soil in that study were similar to those in the present study (Table 1).

The basis for differential amelioration outcome is not entirely clear. However, Xu and Coventry (2003) suggested that declines in soil pH following addition of plant residues are the result of nitrification of ammonium-N to nitrate-N in the substrate and release of hydrogen ions in the process. They further argued that this process was especially strong where the receiving substrate has a low pH and more than compensated for any alkalinising effect of the applied amendment. Similar arguments were presented by Jayalath *et al.* (2016) for the decreases in pH of acid sulfate soils amended with plant residues. Furthermore, both the biochar and organic fertiliser in the present study had relatively high organic matter content (Table 1) to have increased the pH buffering capacity of the soil, as noted by Jayalath *et al.* (2016).

Neither biochar nor organic fertiliser addition had significant impact on soil pH (Fig. 2). This could be the result, at least in part, of enhanced pH buffering capacity of the soil by the additional inputs of organic matter from these two amendments (Table 1). Several previous studies reported relative stability of pH in highly acidic soils due organic matter input from the plant residues added to the soils (Xu and Coventry 2003; Jayalath *et al.* 2016). However, additions of biochar and organic fertilisers increased organic matter input to the soil and would have improved supply of nutrients, especially P and K (Table 1), to account for the significant increases in plant growth and yield (Tables 2 and 3). The yield of 26.4 g/plant obtained with liming alone was similar to that obtained with highest doses of biochar or organic fertiliser applied separately or in combination to soil (Table 3). This demonstrates that because of their high nutrient contents, applications of biochar at 10–30 Mg/ha and organic fertiliser at 5 Mg/ha were as effective as 2 Mg/ha of lime in unlocking the productivity potential of the acid sulfate soils in this study.

Liming had the largest impact on the soil pH and growth and yield of baby corn, whereas the effects of either organic fertiliser or biochar on plant growth characteristics and cob yield were marginal. This is clearly revealed in the PCA, which shows positive correlations of soil pH (both initial and at harvest) with plant growth and yield variables on the PC1 axis. These accounted for almost 40% of the total variability (Fig. 3*a*). PC1 effectively represents a liming threshold that demonstrates improvement in plant performance with rising pH, and plant growth variables being strongly correlated with soil pH. It also shows the inverse correlations of yield variables (ear number and weight) with total N and organic carbon, which was consistent with the suggested occurrence of impaired nutrient availability late in the growing season. Influence of the fertility spectrum, primarily N, is expressed along the PC2 axis, and accounted for a further 11% of the total variance. PC2 reveals a positive association between soil organic C and total N, on the one hand, and plant growth variables such as shoot dry matter, shoot diameter and thickness, on the other. The impacts of lime on both soil and plant variables are demonstrated by the large separation between unlimed and limed treatments in their clusters of response variables (Fig. 3*b*, *c*). Additions of either biochar or organic fertiliser shifted the response clusters positively on both axes, demonstrating that these amendments further enhanced the benefits of liming.

Furthermore, vegetative growth (plant height, plant diameter and shoot weight) were negatively correlated with yield variables on the PC2 axis, suggesting that the early rapid growth was at the expense of the development of yield variables such as the number and weight of ears toward the end of the growing period. This has been commonly observed in such environments with limited growth resources where rapid expansion of the canopy and dry matter accumulation (biological yield) occur early in the season when growth resources are adequate in soil, but the result is poor grain yield due to limited availability of resources later in the season (Donald and Hamblin 1976; Yunusa and Sedgley 1992). It was probable that the baby corn in our study experienced an inadequate supply of available N during the reproductive phase due to persistent low pH, which is consistent with the negative correlation between total N and yield variables on the PC2 axis (Fig. 3*a*). Nugroho and Kuwatsuka (1990) reported that an initial rapid rate of decomposition and nitrification stabilised within 20 days of incubating a mildly acidic soil amended with rice residues. However, they further observed that concurrent with nitrification, a moderate level of denitrification (N loss) started from Day 10. In another study, increased N loss through ammonia volatilisation from soil amended with rice biochar was observed (Huang *et al.* 2018). Both of these studies suggest that continued N losses will deplete N availability. It is therefore likely that only some of the N present at the start of our study was used by the plant to support early growth, and availability might have been limited during the reproductive phase.

A probable loss and/or immobilisation of N late in the season was consistent with the marginal or negative impacts, respectively, of organic fertiliser and biochar on cob protein (Table 3). The reduction in grain protein in baby corn supplied with biochar likely arose from the dilution of cob N content by the continued accumulation of biomass. The plants supplied with biochar attained the reproductive phase early (Table 3), when most well-watered crops attain peak demand for N, often exceeding the capacity of the soil to supply the nutrient through mineralisation or fertilisation (Angus 2001). Without supply of additional N, the tissue N concentration will be diluted by the continued accumulation of biomass; hence, the often-reported reciprocal relationship between grain yield and grain protein in resource-limited environments (Yunusa and Rashid 2007). The remaining principal components (PC3 to PC16) in the PCA individually explained <8% of the total variance (Table S2). These are not considered in detail here but could account for the impacts of other soil characteristics such as C:N ratios, alkalinity and mineralisation potentials (Xu and Coventry 2003; Gao *et al.* 2019).

Conclusions

Additions of organic fertiliser and biochar to acid sulfate soil increased cob yield to a value similar to that obtained with addition of 2 Mg/ha of lime. However, the three amendments reduced cob protein because of limited soil N supply, especially during the reproductive phase, potentially contributing to the dilution of N concentration in the cob tissue. We conclude that biochar and organic fertilisers that are high in key nutrients, such as used in the present study, can be as effective as liming in supporting viable cropping of acid sulfate soils.

Supplementary material

Supplementary material is available online.

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