Field Crops Research 111 (2009) 81–84

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Biochar amendment techniques for upland rice production in Northern Laos 1. Soil physical properties, leaf SPAD and grain yield

Hidetoshi Asai[a,*], Benjamin K. Samson[b], Haefele M. Stephan[c], Khamdok Songyikhangsuthor[d], Koki Homma[a], Yoshiyuki Kiyono[e], Yoshio Inoue[f], Tatsuhiko Shiraiwa[a], Takeshi Horie[g]

[a] *Graduate School of Agriculture, Kyoto University, Kyoto, Japan*
[b] *International Rice Research Institute, Luang Prabang, Lao Democratic People's Republic*
[c] *International Rice Research Institute, Los Baños, Philippines*
[d] *Northern Agriculture and Forestry Research Center, Luang Prabang, Lao Democratic People's Republic*
[e] *Forestry and Forest Products Research Institute, Tsukuba, Japan*
[f] *National Institute for Agro-Environmental Sciences, Tsukuba, Japan*
[g] *National Agriculture and Food Research Organization, Tsukuba, Japan*

ARTICLE INFO

Article history:
Received 8 August 2008
Received in revised form 28 October 2008
Accepted 29 October 2008

Keywords:
Biochar
Upland rice
Leaf SPAD
Available phosphorus
Nitrogen fertilizer

ABSTRACT

The objective of this study was to investigate the effect of biochar application (CA) on soil physical properties and grain yields of upland rice (*Oryza sativa* L.) in northern Laos. During the 2007 wet season, three different experiments were conducted under upland conditions at 10 sites, combining variations in CA amounts (0–16 t ha^{-1}), fertilizer application rates (N and P) and rice cultivars (improved and traditional) in northern Laos.

CA improved the saturated hydraulic conductivity of the top soil and the xylem sap flow of the rice plant. CA resulted in higher grain yields at sites with low P availability and improved the response to N and NP chemical fertilizer treatments. However, CA reduced leaf SPAD values, possibly through a reduction of the availability of soil nitrogen, indicating that CA without additional N fertilizer application could reduce grain yields in soils with a low indigenous N supply. These results suggest that CA has the potential to improve soil productivity of upland rice production in Laos, but that the effect of CA application is highly dependent on soil fertility and fertilizer management.

1. Introduction

Biochar application (CA) has received a growing interest as a sustainable technology to improve highly weathered or degraded tropical soils (Lehmann and Rondon, 2006). CA can enhance plant growth by improving soil chemical characteristics (i.e., nutrient retention, nutrient availability), soil physical characteristics (i.e., bulk density, water holding capacity, permeability), and soil biological properties, all contributing to an increased crop productivity (Glaser et al., 2002; Lehmann and Rondon, 2006; Yamato et al., 2006). In addition, biochar is highly recalcitrant to microbial decomposition and thus guarantees a long term benefit for soil fertility (Steiner et al., 2007). These actual effects of CA application, however, depend on various factors such as the soil fertility and the water balance at a given site, and possibly even the cultivated genotype. Lehmann et al. (2002) argued that CA might even limit soil N availability in N deficient soils due to the high C/N ratio specific to biochar and, therefore, might reduce crop productivity at least temporarily. Hence, it is necessary to assess the effect of CA on crop productivity under field conditions and in relation to agronomic practices and cultivars used at a given site. However, such research is rare and little is known about possible interaction effects. Therefore, we evaluated the effect of CA techniques on the grain yield of upland rice, which is an important staple food for Lao people. Our objectives were to characterize the effect of CA on selected soil characteristics and crop parameters, thereby evaluating the possible benefits of CA techniques in this agro-ecological environment.

2. Materials and methods

In this study, three experiments were conducted in the Xiengngeun district, Luang Prabang province in northern Laos. Experiment 1 (Exp. 1), conducted at the Houay-Khot (HK1) and Long-Or (LO1), consisted of two fertilizer treatments (main-plot), four application levels of biochar (sub-plot) and two rice cultivars

* Corresponding author at: Laboratory of Crop Science, Graduate School of Agriculture, Kyoto University, Kitashirakawa, Sakyo-ku, Kyoto, 606-8502, Japan. Tel.: +81 75 753 6042; fax: +81 75 753 6065.
E-mail address: asai@kais.kyoto-u.ac.jp (H. Asai).

0378-4290/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.fcr.2008.10.008

(sub-sub-plot) in a split-split-plot design with four replications (plot size of 3.5 m × 2.5 m) at both sites. Fertilizer treatments were (1) control (none) and (2) N fertilizer (50 kg N ha^{-1}; urea). The biochar treatments were (1) control (none), (2) 4 t ha^{-1}, (3) 8 t ha^{-1} and (4) 16 t ha^{-1}. The two rice cultivars: IR55423-01 (Apo: improved cultivar) and Vieng (a traditional cultivar), were grown. Experiment 2 (Exp. 2) was conducted at seven sites: two in HK (HK2, HK3), two in LO (LO2, LO3) and one each in Seng-Oudom (SO), Somusa-Nuck (SN) and Long-Sang (LS). Tested were only two levels of biochar: (1) control (none) and (2) 8 t ha^{-1}. The experiment was laid out in a randomized complete block design with three replications (plot size of 5 m × 5 m). Apo was grown at all sites for this experiment without N fertilizer application. Experiment 3 (Exp. 3) was conducted at HK (HK4). Tested were two application levels of biochar [(1) control (none) and (2) 8 t ha^{-1}], and four fertilizer treatments, [(1) control (none), (2) N fertilizer (50 kg N ha^{-1}; urea), (3) P fertilizer (50 kg P ha^{-1}; triple superphosphate) and (4) 50 kg N and P ha^{-1}], in a split plot design with three replications (plot size of 3 m × 3 m). Only Apo was grown in this experiment.

At all sites, the fields were prepared by plowing with hand tractor. Commercial biochar from wood residues (e.g., teak (*Tectona grandis* L.) and rosewood (*Pterocarpus macrocarpus* Kurz)) of a local lumbermill was used in these experiments. Wood residues were processed into biochar by the earth mound method (FAO, 1983). Biochar was ground to 2 mm particle size, then applied and carefully mixed with the soils after plowing. A third of N fertilizer was broadcasted before sowing, at 40 days after sowing (DAS) and at 80 DAS, respectively. All the P fertilizer was applied just before sowing. Sowing and harvesting were conducted in mid-May and early October, respectively. Planting density was 16 hills m^{-2}.

In Exp. 1, saturated hydraulic conductivity (SHC) of the surface soil was measured at 60 DAS for one undisturbed soil sample from 0–5 cm depth in each plot. At 70 DAS, rice plants were cut at 10 cm above the ground and the xylem sap flow (XSF) was estimated by collecting sap flow from the cut rice culm with a ball of cotton wool between 16:00–4:00. In Exp. 1 and 2, the leaf chlorophyll concentration (SPAD-value; SPAD502, KONICAMINOLTA. Inc., Tokyo) was determined at 90 DAS for the three youngest completely expanded leaves per hill, and the mean of six hills was recorded. In all experiments, grain yields were measured by harvesting the whole plot except for the border plants. Top soil samples from 0–15 cm depth were collected before biochar application. Soil pH was determined in a 1: 1 ratio of soil:water; soil organic carbon by using Walkley method (Walkley, 1947); extractable P by using Bray 2 (Bray and Kurtz, 1945); extractable N by extracting in phosphate buffer solution (Ogawa et al., 1992); cation exchange capacity and exchangeable bases by using ammonium acetate extract method at pH 5.0 and 7.0 (Soil and Plant Analysis Council, 1999); soil texture by using pipette method (Soil and Plant Analysis Council, 1999). For biochar, total carbon and nitrogen content was analyzed with a tracer mass spectrometer (Tracer Mat, Thermo Quest Co. Ltd., Tokyo). Respective properties of biochar and top-soils are shown in Table 1a and b, respectively.

Combined ANOVA was performed across two and seven sites for data obtained in Exp 1 and 2, respectively. In Exp. 1, site, N fertilizer, CA amount and cultivar were considered fixed effects in the statistical analysis of grain yield, leaf SPAD and XSF. Site and CA amount were fixed effects in the analysis of SHC. Similarly, the effects of site and CA amount were considered to be fixed in Exp 2.

3. Results and discussion

3.1. The effect of CA on soil and plant

The effect of biochar application (CA) on saturated hydraulic conductivity (SHC) and xylem sap flow (XSF) in Exp.1 is shown in Table 2. The ANOVA for SHC and XSF indicated that the main effect of CA on SHC and XSF was significant at $P = 0.01$. The significant interaction effect of CA and site (S) on XSF ($P = 0.05$, data not presented) showed that the CA had a different effect at the two sites. For both parameters, no significant difference was detected at HK1, but clear differences in SHC and XSF were observed at LO1. The observation that high CA amounts resulted in higher SHC and XSF at both sites suggested that CA improved not only soil water permeability but also soil water holding capacity and thereby plant water availability. Similar improvements due to CA were reported by Glaser et al. (2002).

Table 1
Mean values of chemical and physical properties of biochar used for amending the soil (1-a) and of soils (1-b) at each the sites used in the experiments. (1-a) Biochar properties.

pH	TC (a) (g kg^{-1})	TN (b) (g kg^{-1})	C/N ratio (a/b)	Avail. P (mg kg^{-1})	CEC (C mol kg^{-1})	K (C mol kg^{-1})	Ca (C mol kg^{-1})	Mg (C mol kg^{-1})	Bulk density (g cm^2)
(1-a) Biochar properties									
7.5	870	3.1	281	47.7	10.7	3.1	4.4	0.3	43.8

	pH	SOC (g kg^{-1})	Avail. P (mg kg^{-1})	Ext. N (mg kg^{-1})	CEC (C mol Kg^{-1})	K (C mol Kg^{-1})	Ca (C mol Kg^{-1})	Mg (C mol Kg^{-1})	Sand (%)	Silt (%)	Clay (%)
(1-b) Soil properties											
Experiment 1											
HK1	5.4	10	4	57	23	0.4	3.9	0.9	18	34	48
LO1	5.2	15	7	55	14	0.4	3.5	1.1	27	45	28
Experiment 2											
HK2	7.1	14	58	57	16	0.6	6.4	1.1	21	34	45
LO2	5.4	13	12	50	11	0.4	3.9	1.0	29	43	28
HK3	8.3	13	20	39	15	0.3	20.9	0.6	28	35	37
LO3	6.2	11	11	52	9	0.4	4.2	0.6	32	39	29
SO	6.8	22	120	49	15	1.2	5.5	1.3	29	41	30
SN	5.6	18	14	40	30	0.3	8.0	2.8	54	21	26
LS	7.7	28	69	47	24	0.5	13.9	0.7	17	43	40
Experiment 3											
HK4	8.3	12	18	34	15	0.2	21.2	0.5	32	32	35

TC: total carbon, TN: total nitrogen, avail. P: available P, CEC: cation exchange capacity
SOC: soil organic carbon, avail. P: available P, ext. N: extractable N, CEC: cation exchange capacity.

Table 2
Saturated hydraulic conductivity (SHC) of surface soil (0–5 cm) and xylem sap flow (XSF) for the different biochar treatments in Experiment 1.

	Amount of biochar (t ha^{-1})				*P*-value
	Control	4	8	16	
(SHC)					
HK1	1.10	0.92	1.09	1.37	0.27 ns
LO1	0.59 b	0.89 b	0.77 b	1.63 a	<0.01
Averag	0.84 b	0.90 b	0.93 b	1.50 b	<0.01
(XSF)					
HK1	8.4	11.3	11.6	9.6	0.37 ns
LO1	12.2 b	12.3 b	17.9 a	16.6 ab	<0.01
Average	10.3 b	11.8 zb	14.8 a	13.1 ab	<0.01

The values of HK1 and LO1 were averaged over four replications, two nitrogen treatments and two cultivars.
Within rows, means followed by the same lowercase letter do not differ significantly at $p = 0.05$.

Leaf SPAD values measured in Exp. 1 and Exp. 2 are shown in Table 3. The main effect of CA and the interaction effects of S × CA and S × CA × N were significant in Exp 1, while only the effect of S × CA was significant in Exp. 2 (data not shown). In contrast to the positive effect on SHX and XSF, CA resulted in decreased leaf SPAD values. The decrease was most prominent at HK1, where leaf SPAD values for treatments without N fertilizer application were lowest at the 16 t ha^{-1} CA-level for Apo and at the 8 t ha^{-1} CA-level for Vieng. Similar trends in leaf SPAD values were observed at LO1, but the differences were not statistically significant. These results indicated that CA decreased plant N uptake, which confirms the results of Lehmann et al. (2002), who also described a decrease in plant N uptake and attributed the effect to N immobilization caused by the high C/N ratio of the applied biochar.

The N fertilizer treatment in Exp. 1 alleviated the CA-induced decrease in leaf SPAD values. However, leaf SPAD values in N-fertilized plots also decreased as the CA amount increased, indicating that excessive CA may offset the effect of N fertilizer.

3.2. The effect of CA on grain yields

In Exp. 1, the grain yields at HK1 ranged between 2.2–3.2 t ha^{-1} for Apo and between 0.5–1.5 t ha^{-1} for Vieng. They were two to three times higher at LO1 (4.8–5.9 t ha^{-1} for Apo and 3.0–4.0 t ha^{-1} for Vieng) (Table 3). Lower yields at HK1 could have been caused by the very low available P and SOM content at this site (Table 1). Surprising was the mostly negative effect of nitrogen application in the plots without CA application; positive yield responses were limited to some of the CA plots. Combined ANOVA across sites suggested that there were no significant CA-related effects on grain yield, probably because severe lodging occurred in all plots at LO1, increasing the experimental error at that site. The separate data analysis for HK1 showed an interaction effect between CA and N at $P = 0.07$ (data not shown). A single CA application (4 t ha^{-1}) resulted in a decreased grain yield for Apo and no change in yield for Vieng. That may be due to the CA-induced reduction of plant N uptake as noted above.

Nitrogen fertilizer application increased grain yield of both cultivars when 4 and 8 t ha^{-1} CA were applied, but no yield response to N application was observed when 16 t ha^{-1} CA were applied. Higher grain yields in 4 and 8 t ha^{-1} CA plots with N fertilizer may be due to the combined effects of the improved soil physical properties and the alleviation of CA-induced N availability. However, the high rate of 16 t ha^{-1} CA application obviously caused N limitation even with N fertilizer application, consequently leading to low grain yields.

No significant CA-related effects on grain yield were observed in Exp. 2 for the combined ANOVA across all sites, but a *t*-test for individual sites indicated that grain yields at LO2 and HK3 were significantly higher in CA-treated plots than in untreated plots ($P < 0.05$) (Table 3). Although not significant, these trends were also observed at other sites with low available phosphorus (P) contents in the soil (LO3, SN; Table 1), whereas lower yields in CA applied plots were observed at all sites with a high P availability (HK2, SO, LS; Table 1). A possible explanation is that CA increased plant available P. A similar effect of CA on P availability was reported in previous studies (Lehmann et al., 2002; Glaser et al.,

Table 3
Leaf SPAD values and grain yields for all treatments in Experiment 1 and 2.

Site	Cultivar	Fertilizer	Leaf SPAD					Grain yield				
			Amount of biochar (t ha^{-1})				*P*-value	Amount of biochar (t ha^{-1})				*P*-value
			Control	4	8	16		Control	4	8	16	
Experiment 1												
HK1	Apo	No N	34.0 a	34.7	a 33.6 a	31.7 b	<0.01**	3.0 a	2.3	b 2.7	ab 2.2 b	<0.05*
		N	37.2 a	35.7	b 34.0 bc	34.6 c	<0.01**	2.8	3.2	3.3	2.7	0.25 ns
	Vieng	No N	33.6 a	32.7	a 29.7 b	31.6 ab	<0.05*	0.7	0.5	0.8	0.7	0.47 ns
		N	37.3 a	38.1	a 32.9 b	33.0 b	<0.01**	0.7 b	1.5	a 1.0	b 0.8 b	<0.01**
LO1	Apo	No N	35.6	34.3	34.8	34.2	0.19 ns	5.7	5.1	5.6	5.9	0.61 ns
		N	38.9	39.4	38.7	39.1	0.68 ns	5.4	4.8	5.6	5.3	0.84 ns
	Vieng	No N	37.6 b	37.9	b 40.9 a	36.6 b	<0.01**	3.8	3.6	4.0	3.7	0.88 ns
		N	42.6	42.1	41.0	42.3	0.18 ns	3.0	3.4	3.7	3.8	0.66 ns
	Average HK1		35.5 a	35.3	a 32.5 b	32.7 b	<0.01*	1.8	1.9	2.0	1.8	0.23 ns
	Average LO1		38.7 ab	38.4	ab 38.9 a	38.0 b	<0.01**	4.5	4.2	4.7	4.7	0.51 ns
Experiment 2												
HK2	Apo	No N	32.0 a	–	31.1 b		<0.05*	4.8	–	4.3	–	0.10 ns
LO2	Apo	No N	34.9	–	34.8		0.83 ns	4.2 b	–	4.7	a	<0.05*
HK3	Apo	No N	30.0	–	30.4		0.48 ns	1.8 b	–	2.2	a	<0.05*
LO3	Apo	No N	30.7	–	30.3		0.48 ns	2.4	–	2.7	–	0.23 ns
SO	Apo	No N	25.7	–	24.8		0.08 ns	1.9	–	1.7	–	0.45 ns
SN	Apo	No N	32.5 b	–	34.1 a		<0.05*	3.2	–	3.5	–	0.32 ns
LS	Apo	No N	33.5	–	33.0		0.43 ns	2.2	–	1.8	–	0.54 ns
Average (Experiment 2)		–	31.2		31.4		0.47 ns	2.9		3.0		0.82 ns

* The values of leaf SPAD and grain yield were averaged over four and three replications in Experiment 1 and Experiment 2, respectively.
** Within rows, means followed by the same lowercase letter do not differ significantly by LSD (0.05).

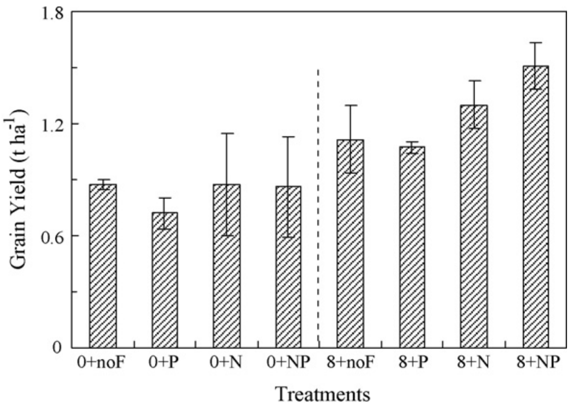

Fig. 1. Grain yields for all treatments in Experiment 3. Error bars represent standard errors ($n = 3$). Biochar amounts applied were 0 and 8 t ha^{-1}. Fertilizer treatments were no fertilizer (no F), single P (P), single N (N) and NP (NP).

2002; Yamato et al., 2006). The negative effect of CA on grain yield at relatively P-rich sites could then have been caused by the decreased N availability due to CA.

Grain yields in Exp. 3 are shown in Fig. 1. The average grain yield in CA-treated plots was significantly higher than in control plots ($P < 0.01$). Since this site (HK4) had a low available P content and a high pH similar to HK3, higher grain yield from the CA plots can be explained by the aforementioned effects of CA on soil P availability. Grain yields showed a better response to NP fertilizer in CA plots than in non-CA plots (Fig. 1). The results are consistent with findings that CA reduced leaching of applied mineral N fertilizer and promoted better use of applied nutrients (Lehmann et al., 2002; Steiner et al., 2007).

3.3. CA performance under N-poor soils in Laos

Although the optimal amount of applied biochar varies among soils, crops and properties of biochar (Lehmann et al., 2002), a recent review indicated that the grain yield did not generally decline with large amount of biochar application (Glaser et al., 2002). However, in our study, CA without N fertilizer led to the reduction of plant uptake of soil nitrogen, and may cause decreased grain yield under upland conditions in Laos despite improved soil physical properties, P availability and nutrient uptake efficiency. This can be explained by the often sever N limitation in upland rice systems of Lao (Saito et al., 2006). Previous research has recommended combining CA with inorganic or organic fertilizer for crop production (Steiner et al., 2007; Yamato et al., 2006). A practical recommendation for Laos upland soils would be to combine N fertilizer application with 4–8 t ha^{-1} CA.

4. Conclusions

Application of biochar materials, utilizing local resources, shows promise as an ecologically sound technology for improvement of soil chemical and physical properties and crop productivity in Laos. The strong resistance of biochar to microbial decomposition and hence its continued persistence in the soil ensure that the benefits of biochar application would be long-term. However, the absence of dramatic gains in rice productivity and the significant alternative uses of biochar as an energy source constitute a major economic constraint to the practical application of CA techniques. Trials to develop more productive management techniques that include CA application to soils (such as finding cheaper sources of biochar and combining CA application with other organic materials) need to be undertaken. Additionally, long-term evaluation of the influences of CA on soil and plant growth would be necessary.

Acknowledgements

This study was conducted with financial support from the Special Initiative Fund of the International Rice Research Institute, Philippines, and from the program of S-2 (3) b. by the Global Environment Research Fund of the Ministry of the Environment, Japan. We thank Mr. Banthasack Vongphouthone and Mr. Visone Navongxay for their field assistance, Dr. Kazuki Saito for his advice and Dr. Keisuke Katsura for reviewing this paper.

References

Bray, R.H., Kurtz, L.T., 1945. Determination of total, organic and available forms of phosphorus in soil. Soil Science 59, 39–45.

Glaser, B., Lehmann, J., Zech, W., 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with bio-char – a review. Biology and Fertility of Soils 35, 219–230.

FAO, 1983. Simple technologies for charcoal making. Forestry Paper no.41. FAO, Rome.

Lehmann, J., da Silva Jr., J.P., Rondon, M., Steiner, C., Nehls, T., Zech, W., Glaser, B., 2002. Nutrient availability and leaching in an archaeological Anthorosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant and Soil 249, 343–357.

Lehmann, J., Rondon, M., 2006. Bio-char soil management on highly weathered soils in the humid tropics. In: Uphoff, N., Ball, A.S., Palm, C., Fernandes, E., Pretty, J., Herrren, H., Sanchez, P., Husson, O., Sanginga, N., Laing, M., Thies, J. (Eds.), Biological Approaches to Sustainable Soil Systems. CRC Press, Boca Raton, FL, pp. 517–530.

Ogawa, Y., Kato, H., Ishikawa, M., 1992. A simple analytical method for index of soil nitrogen availability by extracting in phosphate buffer solution. Japanese Society of Soil Science and Plant Nutrition 60, 160–163 (in Japanese).

Saito, K., Linquist, B., Atlin, G.N., Phanthaboon, K., Shiraiwa, T., Horie, T., 2006. Response of traditional and improved upland rice cultivars to N and P fertilizer in northern Laos. Field Crops Research 96, 216–223.

Soil Plant analysis council, 1999. Soil analysis hand book of reference methods. CRC Press LLC, Boca Raton, 247 pp.

Steiner, C., Teixeira, W.G., Lehmann, J., Nehls, T., de Macedo, J.L.V., Blum, W.E.H., Zech, W., 2007. Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. Plant and Soil 291, 275–290.

Walkley, A., 1947. A critical examination of a rapid method for determining organic carbon in soils. Effect of variations in digestion conditions and of inorganic soil constituents. Soil Science 63, 251–264.

Yamato, M., Okimori, Y., Wibowo, I.F., Anshiori, S., Ogawa, M., 2006. Effects of the application of charred bark of *Acacia mangium* on the yield of maize, cowpea and peanut, and soil chemical properties in South Sumatra, Indonesia. Soil Science and Plant Nutrition 52, 489–495.